Safety performance and technology heterogeneity in China’s provincial construction industry

Liangguo Kang⁎, Chao Wu, Xiuping Liao, Bing Wang⁎

School of Resources and Safety Engineering, Central South University, Changsha 410083, Hunan, PR China
Safety & Security Theory Innovation and Promotion Center, Central South University, Changsha 410083, Hunan, PR China

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ABSTRACT
The technology heterogeneity in the construction industry causes difficulties for an unbiased evaluation of safety performance. The non-parametric and two-hierarchy frontier data envelopment analysis (DEA) model was constructed according to the inputs and outputs of China’s provincial construction industry in 2017. Safety performance and its potential as well as undesirable output potential were analyzed from the aspect of technology gap and management efficiency. The results showed that the average safety performance in China’s provincial construction industry was calculated to be 0.715, which was caused by technology gap and management efficiency. Northwest China has good performance in technology gap ratio and Central China performs well in management efficiency. Meanwhile, the strategies to improve safety performance in China’s provincial construction industry were developed. In addition, potential of the safety technology gap and safety management efficiency took up 70.18% and 29.82% in terms of the undesirable output control. East, Central, South and Southwest China are the main areas needing to strengthen accident prevention practice. The findings can be used to help scholars understand the condition of safety performance in China’s provincial construction industry, and provide guidelines to evaluate the performance in construction safety considering production technology heterogeneity.

1. Introduction

Over the past four decades, the Chinese government has implemented various economic policies to develop the productive forces of different industries (Fei and Lin, 2016). By the end of 2012, China became the second largest economic power in the world (Li, 2018). Also, the construction industry has become a pillar industry of the national economy, and its total output value reached 21.394 trillion CNY (1 CNY is approximately 0.145 USD) in 2017, which accounted for 25.94% of gross domestic product (National Bureau of Statistics of PRC, 2018). Accompanied by the considerable economic contributions the construction industry makes, the safety issue in the construction industry has become a major concern in many countries (Bavafa et al., 2018). Statistically, the construction industry employed only about 7% of the world’s work force but was responsible for 30–40% of fatalities (Sunindijo and Zou, 2011). In China, construction accidents have taken the largest percentage of industrial accidents since 2012 (Zhang et al., 2019), and over 2850 construction workers died from construction activities during 2012–2016 (Shao et al., 2019). In the United States, more than 21,000 construction workers lost their lives following occupational injuries sustained in the construction industry from 1992 to 2010 (Kang et al., 2017). The construction environment is the most hazardous compared to other labor enforced industries (Gunduz and Ahsan, 2018). Because the construction industry is highly risk prone, the performance evaluation in construction safety is of great importance to further improve the practice of safety management. Undesirable output such as injury, death, and property damage, plays a key role in safety performance evaluation (Cagno et al., 2014). It is often considered identical performance in construction safety when two contractors suffer the same numbers and types of accidents according to traditional methods of performance evaluation, while ignoring the effect of safety-related input in construction activities (El-Mashaleh et al., 2010). In addition, the evaluation indicators of safety performance can be classified into partial-factor and total-factor types. For partial-factor indicators, a general definition is the specific value of output and input (Lin and Moubarak, 2014). Due to operational ease and easy interpretability, the single-factor indicator represented by casualty rates is often used to reflect the condition of construction safety. China has formed its own special features in term of partial-factor indicators of construction safety performance evaluation,
including death toll, injury rate of per one thousand persons, mortality rate of per ten thousand persons, mortality rate of per ten billion output values, and mortality rate of per one hundred thousand square meters (Wang et al., 2012), which reflects the Chinese government’s determination and effort to decrease the number of casualties in the construction industry. Partial-factor indicators have their own demerits as academic scholars investigated this issue further (Stern, 2012), namely that partial-factor indicators were not applicable to a large extend and might be misleading (Hu and Wang, 2006; Boyd, 2008). Take the mortality rate of per ten billion output values as an example, it reflects the occupational safety condition considering the economic development status of the construction industry. However, the results can’t fully indicate safety condition owing to the fact that the indicators do not involve the effects of other input factors in the construction activity, such as the unbalanced development of regional construction industry.

The total-factor indicators are measured based on the multiple input and output, which could effectively improve the shortage of partial-factor indicators (Feng and Wang, 2017a). Data envelopment analysis (DEA) has been recognized as an effective method for measuring the efficiency of the decision-making units (DMUs) by using total-factor indicators (Emrouznejad and Yang, 2018), which has been widely used for the research objects such as countries (Zhang et al., 2011; Djordjević et al., 2018), regions (Lin and Du, 2014), cities (Wang et al., 2015), and industries (Li and Lin, 2017). Also, DEA method has been used for safety performance evaluation in various fields, for example, construction safety performance (Nahangi et al., 2019), road safety performance (Ganjil and Rassaf, 2018), safety performance at railway level crossings (Djordjević et al., 2018), and airlines safety performance (Barak and Dahooee, 2018). Meanwhile, DEA became the principal method for measuring efficiency related to multiple inputs and outputs in construction (Hu and Liu, 2018). In general, DEA model assumes that the DMUs have the same external environments, input and output indicators, which may have significant negative influence on the evaluation of management decisions (Song et al., 2019). This is due to the fact that the production technology heterogeneities among regions are inevitable because of uneven development (Li and Lin, 2015). Also, there are few studies evaluating the safety performance in the construction industry according to the heterogeneity of production technology. A meta-frontier approach marks the maturation of a new approach to evaluate the construction safety performance from the perspective of different production technologies (Song et al., 2019). In addition, China’s construction industry is still in the extensive mode of development, and increasing the output-input ratio is an important way for the structural upgrading of the construction industry (Gao and Liu, 2014). There exists a remarkable regional disparity in construction efficiency by analyzing the four main geographical regions in China, viz., the northeastern, eastern, central and western region, which is caused by differences in the regional production technology (Xue et al., 2008; Wang et al., 2013b).

Based on what has been discussed above, we construct a non-parametric and two-hierarchy frontier DEA model according to production technology heterogeneity among regions, which can evaluate the safety performance of China’s provincial construction industry. After modeling, we measure the potential of the provincial construction industry in China as regards the safety performance improvement and undesirable output control, which will help the Chinese policy makers find out the focuses of their future work in safety. Also, provinces that do not show good construction safety performance can learn the successful initiatives taken in by best performing provinces.

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

2. Methods and data sources

2.1. Construction production technology

The production technology describes the ability to obtain outputs with the given inputs (Feng and Wang, 2017b). It can be concluded that the construction production technology of this study describes the ability to obtain safety-related outputs with the given safety-related inputs. Identifying inputs and outputs is very important for performance evaluation in construction safety. According to the major indicators of the provincial construction industry in “China Statistical Yearbook 2018”, including the number of enterprises, the number of employees, total output value of the construction industry, value added of construction, construction area, profits, taxes, etc (National Bureau of Statistics of PRC, 2018). Also, these indicators at the provincial level can be classified into four groups: people, machine, environment, and economy. In the manufacturing process, people and objects interact, expressed in the customary designation the “people-machine-environment” system (Liu et al., 2016; Kang et al., 2019), which is also the three basic elements of safety management in the construction industry. So, safety-related input of this study would focus on people, machine, and environment factors in construction activities. On this basis, the safety-related inputs are discussed regrading building practitioner (BP), construction machinery and equipment (CME), and construction area (CA), which represent the key factors of safety management such as people, machine, and environment respectively, and reflect the scale of the construction industry.

The desirable and undesirable outputs of construction activity are simultaneous appearance, which exist independent of human consciousness. The number of incidents is often taken as the output for measuring the performance of construction contractors or construction sites (El-Mashaleh et al., 2010; Nahangi et al., 2019). Besides, the number of incidents and death toll are closely related. As the largest developing country, limiting the casualties is the top priority in Chinese local governments. Especially, the number of fatalities is an important dimension of the safety record in the provincial construction industry (Wang et al., 2018). Hence, reducing the number of casualties is one of the core tasks of safety management in Chinese construction enterprises under the current environment. Also, the fatality rate is taken as one of the output variables when using DEA to analyze provincial road safety performance (Bastos et al., 2015; Ganji and Rassaf, 2018). Meanwhile, the economic development is a priority for all levels of government, irrespective of the country, the constitution or the system of governance (Pugalis and Tan, 2017). In this study, safety-related output is discussed regarding the value added of construction (VAC) and death toll (DT), which represents important influence of construction activities such as desirable and undesirable output respectively. According to the output-input ratio, the research framework may be mathematically presented as:

\[
F(VAC, DT) = f(BP, CME, CA)
\]  

(1)

2.2. The two-hierarchy frontier DEA

DEA was initiated by Charnes et al., and many studies across different disciplines have utilized DEA (El-Mashaleh et al., 2010). It can be seen as a benchmarking tool which could help those underperforming DMUs learn from the best performers. DEA assumes that a better safety performance of DMUs can be gained by more desirable outputs and fewer inputs. The basis of safety performance evaluation in this study is the input and output data of DMUs as well as the output-input ratio, namely the amount of output gained by one unit of input. The efficiency of a DMU varies between 0 and 1, with 0 corresponding to the most
inefficient and 1 to the most efficient DMU. Also, DMUs are located at the frontier where the maximum outputs are generated at a minimum level of inputs, with its efficiency peaking at 1. More and more are put into such as financial resources, material resources, and human resources for the construction industry so as to promote the economic development, especially in the underdeveloped provinces. Hence, this study chooses an output-oriented DEA model, namely the maximum increase of output in the same input.

There are three possible types of returns to scale: increasing returns to scale, constant returns to scale, and decreasing returns to scale. The safety performance is evaluated by assuming a constant return to scale (CCR model) when taking into consideration of competition fairness among all DMUs. The CCR model occur when increasing the number of inputs, leading to an equivalent increase in the output. Due to the uneven development of regions, it may cause biased evaluation of safety performance when all DMUs are required to be measured sharing a common production technology. Construction safety performance with heterogeneous technology hypothesis takes shape under the meta-frontier framework. Hayami (1969) firstly proposed the conception of meta-frontier and the concept of meta-frontier has been widely introduced for efficiency measurement. The basic idea is that the DMUs can be divided into independent subgroups according to a certain criterion which indicates the sources of technology heterogeneity. In this way, the safety performance of the construction industry relative to different frontiers have different values.

The sources of production technology heterogeneity in the construction industry are varied, which poses difficulties for group formulation of DMUs. Generally speaking, the production technology in geographically adjacent places always tends to be similar (O’Donnell et al., 2008). Also, technology heterogeneity among geographically-distant regions will progress greater due to geographical barriers (Oh, 2010). To analyze the safety performance of the construction industry considering technology heterogeneity, this paper took China’s provincial construction industries as the sample, so the DMUs of this study refers to the provinces being evaluated. According to statistical index system of the provincial construction industry in “China Statistical Yearbook”, DMUs were divided into seven groups (National Bureau of Statistics of PRC, 2018), i.e., the north group, the northeast group, the east group, the central group, the south group, the southwest group, and the northwest group. This classification system has been widely used in the macro-level statistics in China. Different groups had different production technologies, and the provinces within one group were generally considered to be at the same or similar technological level. Provinces in the north, northeast, east, central, south, southwest, and northwest group constituted the group-frontier I, II, III, IV, V, VI, and VII respectively, whereas the meta-frontier enveloped all the seven group frontiers.

The conceptual analysis of safety performance measurement is shown in Fig. 1. The meta-frontier relative to the optimal production technology and other group frontiers relative to group-specific production technologies are shown in it. DMUs that lie on the frontier production boundary are deemed efficient in DEA, while those DMUs that do not are termed inefficient (Yang, 2006). In other words, production technology has not been fully utilized when the DMUs deviates from the frontier production boundary. The horizontal axis x represents the input and the longitudinal axis y represents the output. Point A indicates the input of a DMU. Points P, Q and R represent the output of the DMUs. Points B, C and D represent the DMUs. The line segments OP, OQ and OR represent the output score of points B, C and D respectively. The maximization of output increase in the same input is required to measure the safety performance, i.e., point B moves towards point C on group-frontier V and point D on the meta-frontier. Point D is on the meta-frontier and its safety performance is scored 1.000 according to the meta-frontier. Point C is on the group-frontier V and its safety performance is scored 1.000 according to the group-frontier V, but it is inefficient according to the meta-frontier. Point B deviates from both the meta-frontier and the group-frontier V, and it is inefficient either at the meta-frontier or the group-frontier V.

According to the total-factor efficiency, the safety performance (SP) can be decomposed into two components, i.e., technology gap ratio (TGR) as well as technical efficiency (TE) (O’Donnell et al., 2008). TGR refers to the gap between the group-frontier production technology and the optimal production technology (Zhang et al., 2013). When TGR is close to 1.000, the heterogeneity of production technology is smaller, and the group technology approaches the optimal production technology. When TGR is close to 0, the heterogeneity of production technology is greater, and the group technology lags far behind the optimal production technology. TE refers to the effectiveness as a result of a given set of inputs being used to produce an output. With a similar production technology and similar returns to scale, the safety performance then usually depends on the management efficiency (Wang et al., 2013a). TE in this study is called management efficiency (ME), so that the source of safety performance loss in the same group can be considered as management inefficiency. Thus, SP is decomposed into two components, i.e., TGR and ME. Taking point B for example, its SP, ME and TGR can be expressed as:

\[
SP = \theta^T = OP/OR
\]

\[
ME = \delta^T = OP/OQ
\]

\[
TGR = OQ/OR = \theta^T/\delta^T
\]

According to the meta-frontier, the linear programming for measuring SP can be described as: \(SP = \max \\theta^T\).

\[
\begin{align*}
\sum_{j=1}^{v} \lambda_j y_{ij} &\leq x_{i0}, \; i = 1, 2, ..., m \\
\sum_{j=1}^{v} \theta_j y_{ij} &\geq \theta y_{i0}, \; r = 1, 2, ..., s \\
\lambda_j &\geq 0, \; j = 1, 2, ..., n_g
\end{align*}
\]

According to the group-frontier, the linear programming for measuring ME can be described as: \(ME = \max \\delta^T\).

\[
\begin{align*}
\sum_{j=1}^{v} \lambda_j y_{ij} &\leq x_{i0}, \; i = 1, 2, ..., m \\
\sum_{j=1}^{v} \theta_j y_{ij} &\geq \theta y_{i0}, \; r = 1, 2, ..., s \\
\lambda_j &\geq 0, \; j = 1, 2, ..., n_k
\end{align*}
\]

where n_k and n_g refer to the numbers of DMUs within the meta-frontier and the group-frontier respectively, under the condition of n_k \leq n_g, m and s refer to the numbers of input and output indicators respectively. \(\lambda_j\) refers to the weight produced by DMUj, \(x_{i0}\) and \(y_{i0}\) refer to the known ith input and rth output respectively produced by DMUj, \(x_{i0}\) and \(y_{i0}\) refer to the known ith input and rth output respectively produced by
DMUs (the DMU under evaluation).

Safety performance inefficiency (SPI) can be decomposed into two components: management inefficiency (MI), and technology gap inefficiency (TGI). Taking point B for example, its SPI, MI and TGI can be expressed as:

\[ \text{SPI} = \text{PR}/\text{OR} = (\text{OR} - \text{OP})/\text{OR} = 1 - \text{OPT} \]  

(7)

\[ \text{MI} = \text{PO}/\text{OQ} = (\text{OQ} - \text{OP})/\text{OQ} = 1 - \text{OPT} \]  

(8)

\[ \text{TGI} = \text{SPI} - \text{MI} = \text{OPT} - \text{OPT} \]  

(9)

As previously mentioned, safety performance potential (SPP), and technology gap potential (TGP), which can be expressed as:

\[ \text{SPP} = (1 - \text{OPT}) \times \text{OS} \]  

(10)

\[ \text{MEP} = (1 - \text{OPT}) \times \text{OS} \]  

(11)

\[ \text{TGP} = (\text{OPT} - \text{OPT}) \times \text{OS} \]  

(12)

where OS refers to the output score in the construction industry, including score (scale of 0–100) of desirable and undesirable output.

Limiting casualties is a necessary step for the government and enterprises to improve safety record in the construction industry. Generally speaking, the more the number of casualties currently, the greater potential of decline in undesirable output in the future, and the less personal costs in accident prevention. In addition, the decline of construction undesirable output in this study benefits from the two aspects: upgrading safety management efficiency and narrowing safety technology gap. So, undesirable output potential (UOP) could be decomposed into two components: safety management efficiency potential (SMEP), and safety technology gap potential (STGP), which can be expressed as:

\[ \text{UOP} = (1 - \text{OPT}) \times \text{UO} \]  

(13)

\[ \text{SMEP} = (1 - \text{OPT}) \times \text{UO} \]  

(14)

\[ \text{STGP} = (\text{OPT} - \text{OPT}) \times \text{UO} \]  

(15)

where UO refers to the percentage of undesirable output in the construction industry, and the data is a scale of 0–100.

2.3. Data collection and preprocessing

Due to the lack of complete data, the industries of Tibet, Hong Kong, Macao, and Taiwan were excluded from our sample. This paper selected the input and output data of 30 provinces in China. On this basis, 30 provinces were divided into seven independent subgroups. Specifically, the north group consisted of five provinces, i.e., Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia. The northeast group consisted of three provinces, i.e., Liaoning, Jilin, Heilongjiang. The east group consisted of seven provinces, i.e., Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong. The central group consisted of three provinces, i.e., Henan, Hubei, Hunan. The southwest group consisted of three provinces, i.e., Guangdong, Guangxi, Hainan. The northwest group consisted of five provinces, i.e., Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang.

In this study, there are three inputs, BP, CME, and CA, a desirable output of VAC, and an undesirable output of DT. Thus, we obtained the provincial data of 2017 in terms of these five variables. The sources of the input and output data are as follows:

(i) Data on BP, CME, CA, and VAC were obtained from the “China Statistical Yearbook 2018” issued by the National Bureau of Statistics of PRC (National Bureau of Statistics of PRC, 2018).

(ii) Data on DT were obtained from the “Annual Notification of Construction Accidents in 2017” issued by the Ministry of Housing and Urban-Rural development of PRC (MOHURD, 2018).

DEA assumes that more desirable outputs with fewer inputs improve the safety performance of DMUs. However, DT is an undesirable output, namely that less is better. Besides, the output-input ratio of the DMUs are evaluated by assuming a constant return to scale. Consequently, the original data need to be preprocessed before it was substituted into Eqs. (5), (6). Original data preprocessing steps are as follows:

(i) Data on the input and desirable output are normalized based on a scale of 0–100, and the total score of every indicator is 100. For example, \{1, 2, 3, 4, 5\} are normalized as \{6.667, 13.333, 20, 26.667, 33.333\}.

(ii) Data on the undesirable output are reversely processed, resulting in a lower DT and a higher score. Then, the data are normalized based on a scale of 0–100, and the total score of every indicator is 100. For example, \{1, 2, 3, 4, 5\} are reversely processed as \{15, 7.5, 5, 3.75, 3\}, and then they are normalized as \{43.796, 21.898, 14.599, 10.949, 8.759\}.

Score of inputs and outputs are presented in Table 1 after the original data preprocess.

3. Results and discussion

3.1. Safety performance and its decompositions

SP, ME, and TGR were calculated based on Eqs. (5), (6), and (4), their results are shown in Table 2. ME of Beijing, Tianjin, Inner Mongolia, Jilin, Heilongjiang, Shanghai, Jiangsu, Fujian, Henan, Hunan, Guangdong, Hainan, Chongqing, Guizhou, Yunnan, Qinghai, Ningxia and Xinjiang provinces is scored 1.000, which indicates they make good use of the group-frontier production technology to increase the economic benefit and control the number of accidents. However, only Beijing, Fujian, Chongqing, Qinghai, Ningxia and Xinjiang provinces are scored 1.000 in safety performance, which reflects most provinces have potential to improve safety performance according to the meta-frontier production technology. Among them, three are located in the Northwest China, one in North China, one in East China, and the one in Southwest China, so other provinces can take these provinces as fine examples to adjust their technology components. TGR of Beijing, Fujian, Chongqing, Shaanxi, Gansu, Qinghai, Ningxia and Xinjiang provinces is scored 1.000, which indicates the group-frontier production technology of these provinces approaches the meta-frontier production
technology. Among them, five are located in the Northwest China, one in North China, one in East China, and the one in Southwest China, which reflects most provinces can improve safety performance by narrowing the production technology gap between group-frontier and meta-frontier. Therefore, it can be inferred that technology heterogeneity of the construction industry have an effect on safety performance evaluation among most provinces.

From Fig. 2, the average SP of China's provincial construction industry is scored 0.715, which shows the potential of SP is 28.5% according to the meta-frontier production technology. Meanwhile, SP of Northwest and South China is above the average. Specifically, Northwest China is ranked first benefiting from good performance in accident prevention, and South China ranks second in safety performance benefiting from the balance of economic benefit and accident prevention. Although East China has good performance in terms of desirable output, inadequate control of accidents leads to a large drop in its ranking. Also, Central China ranks last because of the inadequate control of accidents and the poor output-input ratio.

The average ME of China's provincial construction industry is scored 0.915, which shows the potential of ME is 8.5% according to the group-frontier production technology. Meanwhile, ME of Northeast, East, Central and South China is above the average. Specifically, Central China is ranked first, which indicates ME of those three provinces in the region is at the similar level according to the group-frontier IV production technology. Northwest China ranks last, which indicates ME of those five provinces in the region is quite different according to the group-frontier VII production technology, namely a low efficiency of regional production technology. It can be inferred that SP is always less than or equal to ME. It is mostly because the meta-frontier is constructed by 30 provinces, and the group-frontier is constructed by provinces in the region, i.e., the group-frontier I, II, III, IV, V, VI, VII are constructed by 5, 3, 7, 3, 3, 4, 5 provinces respectively.

TGR is an important indicator that evaluates the gap between group

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<th>Province</th>
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<th>TGR</th>
<th>ME</th>
<th>Province</th>
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<th>TGR</th>
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Fig. 2. Safety performance and its decompositions of China's seven regions in 2017.
production technology and optimal production technology. Specifically, Northwest China is ranked first (TGR = 1.000), which indicates the five provinces in the region possess the highest utilization in the optimal production technology, followed by North (TGR = 0.815) and Southwest (TGR = 0.781) China. Central China ranks last (TGR = 0.609), which indicates the three provinces in the region possess the lowest utilization in the optimal production technology, i.e., the group-frontier IV production technology lags behind the meta-frontier production technology.

3.2. Safety performance potential and its decompositions

SPI, MI, and TGI were calculated based on Eqs. (7)–(9). From Fig. 3, TGI of Hunan, Jiangxi and Guizhou provinces ranks top three, implying that the production technology gap is the main reason leading to the poor safety performance in these provinces. MI of Gansu, Hebei and Sichuan provinces is in the top three, meaning that the management efficiency is the main reason leading to poor safety performance in these provinces. Moreover, TGI is higher than MI in most provinces, hence, narrowing production technology gap may be a more effective way to improve safety performance for many provinces. SPI of Hebei, Hunan and Sichuan provinces is in the top three, indicating that they should adopt different countermeasures to improve safety performance according to their own situation. For example, Hunan province should focus on narrowing the gap between the group-frontier IV production technology and the meta-frontier production technology.

SPP, MEP, and TGP were calculated based on Eqs. (10)–(12), their results are shown in Table 3. SPP of Zhejiang, Jiangsu, Hebei, Shandong and Sichuan provinces is more than 3.1. Also, Zhejiang has the largest potential in safety performance, scoring 6.097, which is owing to both technology gap and management inefficiency. TGP of Jiangsu, Hunan, Zhejiang, Shandong and Hebei provinces is more than 2.4. Also, Jiangsu has the largest potential in the technology gap, scoring 5.619, which is due to economic development imbalance in the construction industry. MEP of Hebei, Zhejiang, Sichuan, Shanxi and Shandxi provinces is more than 1.3. Also, Hebei has the largest potential in the management efficiency, and its score is 3.869, which is caused by lower utilization rate in construction inputs.

According to what has been discussed above, this paper can develop the strategies to improve safety performance in China's provincial construction industry by bridging technology gap and upgrading management efficiency. From Table 4, it is clearly demonstrated that strategies for improving construction safety performance among China's provinces vary. For construction industries in North (except Beijing), Northeast, East (except Fujian), Central, South, and Southwest (except Chongqing) China, they should focus on narrowing the gap between the group-frontier production technology and the meta-frontier production technology. The technological transformation in construction projects needs speeding up to improve construction economic benefit. Besides, using new protective technologies to reduce risk of construction site is of critical significance.

Hebei and Shanxi in North China, Liaoning in Northeast China, Zhejiang, Anhui, Jiangxi and Shandong in East China, Hebei in Central China, Guangxi in South China, Sichuan in Southwest China, and Shaanxi and Gansu in Northwest China, they should focus on upgrading their management efficiency of the construction industry. For one thing, it focuses on reducing record construction site is of critical significance.

Hebei and Shanxi in North China, Liaoning in Northeast China, Zhejiang, Anhui, Jiangxi and Shandong in East China, Hebei in Central China, Guangxi in South China, Sichuan in Southwest China, and Shaanxi and Gansu in Northwest China, they should focus on upgrading their management efficiency of the construction industry. For one thing, it focuses on reducing record construction site is of critical significance.
construction enterprises should quickly increase the steps of construction economic development by improving management efficiency. In addition, Hebei, Shanxi, Liaoning, Zhejiang, Anhui, Jiangxi, Shandong, Hubei, Guangxi and Sichuan provinces can improve construction safety performance through both technology gap narrowing and management efficiency improvement.

### 3.3. Undesirable output potential and its decompositions

UOP, SMEP, and STGP were calculated based on Eqs. (13)–(15). The potential of safety management efficiency and safety technology gap varies by the province in terms of the undesirable output control. From Fig. 4, SMEP of Shanxi, Zhejiang, Guangxi, Sichuan and Gansu provinces is more than 0.4, they should enhance the construction safety supervision and regulate the construction enterprise production and the management behavior to control the undesirable output such as injury and death. Also, Gansu has the largest potential of safety management efficiency to control the undesirable output based on the group-frontier VII production technology, and its score is 1.459, which is caused by the low percentage of desirable output in Gansu and its high undesirable output, compared to other four provinces in the region. So, it reduces the accident from the perspective of enhancing the construction economic vitality and establishing safety management system. From Fig. 5, STGP of Jiangsu, Anhui, Jiangxi, Hunan and Guangdong provinces is more than 1.2, so they should narrow the gap in the safety production technology to reduce the risk degree of construction sites. Also, Jiangsu has the largest potential of safety technology gap to control the undesirable output based on the gap between the group-frontier III production technology and the meta-frontier production technology, scoring 3.58. The reason is that the percentage of undesirable output in Jiangsu is the highest, meaning an inadequate control of accidents. So, it needs to increase safety inputs to reduce risk in construction sites. From Fig. 6, UOP of Jiangsu, Zhejiang, Anhui, Jiangxi, Hubei, Hunan, Guangdong and Guangxi provinces is more than 1.5. Jiangsu is of largest potential to control the undesirable output. In addition, Anhui has a great potential both in safety management efficiency and safety technology gap, namely that it should learn from the experience of both utilizing the group-frontier production technology and bridging the

<table>
<thead>
<tr>
<th>Region</th>
<th>Province</th>
<th>Bridge technology gap</th>
<th>Upgrade management efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>North China</td>
<td>Beijing</td>
<td>▲</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tianjin</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Hebei</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Shanxi</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Inner Mongolia</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>Northeast China</td>
<td>Liaoning</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Jilin</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>East China</td>
<td>Hebei</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Jiangsu</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Zhejiang</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Anhui</td>
<td>▲</td>
<td>■</td>
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<tr>
<td></td>
<td>Fujian</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Jiangxi</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Shandong</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>Central China</td>
<td>Henan</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Hubei</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>South China</td>
<td>Guangdong</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Hubei</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>South China</td>
<td>Hainan</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Chongqing</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>Southwest China</td>
<td>Sichuan</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Guizhou</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Yunnan</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td>Northwest China</td>
<td>Shaanxi</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Gansu</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Qinghai</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Ningxia</td>
<td>▲</td>
<td>■</td>
</tr>
<tr>
<td></td>
<td>Xinjiang</td>
<td>▲</td>
<td>■</td>
</tr>
</tbody>
</table>

**Fig. 4.** SMEP of China’s provincial construction industry in 2017.
technology gap from those provinces with good performance.

From Table 5, the score of UOP was 28.5, which indicates a large potential to control the undesirable output in the future. Thereinto, the potential of safety technology gap and safety management efficiency account for 70.18% and 29.82% respectively, so that the way of improving safety technology level should be placed in a highlighted position to control the undesirable output. According to UOP among seven regions, East China is ranked first, with a percentage of 36.06%, which is largely due to the death toll of seven provinces accounted for 32.838% of the national total. Also, Northwest China ranks last, with a percentage of 4.14%, which is largely due to the death toll of five provinces accounting for 8.674% of the national total. Also, it can be inferred that East, Central, South, and Southwest China are the key areas needed to control their undesirable output by analyzing the average of the region potential.

4. Conclusions and recommendations

The construction production technology and the two-hierarchy frontier DEA model were developed to evaluate the safety performance of China’s provincial construction industry, considering both undesirable outputs and regional technology heterogeneities. Also, this study
discusses the strategies to improve safety performance and control undesirable output in China’s provincial construction industry from two aspects: the technology gap, and management efficiency. The key findings of this study are listed as follows:

(1) Safety performance of China’s provincial construction industry is generally at a medium level. Only six provinces are scored 1.000 in their safety performance, which reflects the fact that most provinces have great space to improve their safety performance by bridging technology gap or upgrading management efficiency. Also, these six provinces are going to be modelled after by other provinces which have not yet utilized the optimal production technology. Different from the traditional classification into three or four groups, this study divides the DMUs into seven groups. Specifically, Central China has a poor performance in the technology gap ratio, i.e., it should narrow the gap between the group-frontier IV production technology and meta-frontier production technology, and technology advancement should be placed in a highlighted position. Northwest China has a poor performance in management efficiency, i.e., it should improve the efficiency of regional production technology while increasing the vitality of construction economy. Regarding provinces, Zhejiang has the highest potential in safety performance, i.e., it should take active measures to improve the safety performance by both bridging technology gap and upgrading management efficiency. According to the safety performance potential, this study develops the strategies to improve the safety performance of China’s provincial construction industry from the perspective of technology gap narrowing and management efficiency improvement, indicating that the focus of future work safety should vary by province.

(2) Jiangsu province has the largest potential to control undesirable output, i.e., it should take active measures to improve the safety performance by bridging safety technology gap. Also, Jiangsu and Guangdong provinces, as developed provinces in the eastern coastal region of China, they together account for 21.44% of the national total death toll, suggesting that they should strengthen safety management in their future work to decrease the number of injuries and deaths. In addition, East, Central, South and Southwest China are the main areas in need of a reduced undesirable output. Specifically, Southwest China should learn from the experience of the undesirable output control from Northwest China, with the similar economic development level. East, Central, and South China should increase capital investment in accident prevention based on the level of the construction activity currently. As a pillar industry, the safety record of construction should meet a good balance with economic growth. Thus, Chinese governments should focus on decreasing the number of injuries and deaths while maintaining the good momentum of construction economic growth.

The above findings imply that the current level of safety performance possess considerable potential of improvement. Specifically, safety performance and its potential as well as undesirable output potential in China’s provincial construction industry mainly derive from two components, i.e., the technology gap, and the management efficiency. Chinese governments should take corresponding measures to improve their records of construction safety according to distinct spatial characteristics of safety performance. Also, it is required not only to consider the national conditions but also to pay attention to the realities of each province when developing construction safety management policies. For the common improvement of the safety performance, communication and cooperation related to construction safety should be promoted actively among the provinces and regions in order to ensure that the advanced construction production technology and construction safety management experience have been diffused effectively. This study can improve the performance evaluation system in safety management based on partial-factor indicators, and expand the boundary of construction safety knowledge into a macro level. The approach could be applied to analyze the impact of technology heterogeneity on safety performance of other industry.

It is noted that the inputs and outputs of performance evaluation with the Chinese characteristics may be not well suited to all countries. Other countries or regions need to make dynamic adjustment and improvement based on their own situations when adopting the approach. Also, serious or minor injuries as well as the accidents with greater influence on public should also be taken as the undesirable outputs of construction activities, which is a direction for further improvement in the future work, and researchers will then be required to collect more data. To reveal the phasic characteristics over time, the sample period is expanding according to the actual application requirement.

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Table 5 Undesirable output potential and its decompositions in 2017.

<table>
<thead>
<tr>
<th>Variable</th>
<th>North China</th>
<th>Northeast China</th>
<th>East China</th>
<th>Central China</th>
<th>South China</th>
<th>Southwest China</th>
<th>Northwest China</th>
<th>Total</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>STGP</td>
<td>1.447</td>
<td>1.927</td>
<td>8.144</td>
<td>4.05</td>
<td>3.263</td>
<td>3.329</td>
<td>0</td>
<td>20</td>
<td>70.18%</td>
</tr>
<tr>
<td>SMEP</td>
<td>1.212</td>
<td>0.2</td>
<td>2.134</td>
<td>0.288</td>
<td>1.109</td>
<td>1.539</td>
<td>1.180</td>
<td>8.5</td>
<td>29.82%</td>
</tr>
<tr>
<td>UOP</td>
<td>2.659</td>
<td>2.126</td>
<td>10.278</td>
<td>4.337</td>
<td>4.372</td>
<td>4.868</td>
<td>1.180</td>
<td>28.5</td>
<td>100%</td>
</tr>
<tr>
<td>Percentage</td>
<td>9.33%</td>
<td>7.46%</td>
<td>36.06%</td>
<td>15.22%</td>
<td>15.34%</td>
<td>17.08%</td>
<td>4.14%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1.87%</td>
<td>2.49%</td>
<td>5.15%</td>
<td>5.07%</td>
<td>5.11%</td>
<td>4.27%</td>
<td>0.83%</td>
<td>3.33%</td>
<td></td>
</tr>
</tbody>
</table>

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