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Dynamic analysis of the sustainable development capability of coal cities

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ABSTRACT

Due to the decline of resources and a lack of motivation for development, coal cities encounter problems related to sustainable development. This paper focuses on the analysis of the capability of different types of coal cities for sustainable development. We synthetically evaluated this capability for four typical coal cities (in terms of growth, maturity, recession, and regeneration) in China from 2012 to 2016 by using the Super-SBM model. The Malmquist index is used to dynamically decompose changes in the capability for sustainable development. We also analyze the ineffectiveness distribution of the input and output indicators, and suggest directions for optimization. The results show the following: (1) the capability for sustainable development of coal cities in China was low (0.6704) and unstable overall. Major inefficiencies persist in resource allocation and utilization. (2) The four coal cities were ranked in the order of growth > regeneration > maturity > recession. (3) Technological progress was the main factor affecting changes in the capability for sustainable development of China's coal cities. (4) Inefficiency was mainly distributed over the economic output, and inadequate economic output capability was the main factor hindering the sustainable development of most coal cities in China.

1. Introduction

With aims of the exploration and exploitation of coal, a number of coal cities have been established in China. They have provided rich mineral resources and raw materials for national economic construction, and have promoted local economic development and enhanced China's regional economic strength. Of the 118 resource-based cities in the country, 63 are coal cities, accounting for 53%. Coal accounts for more than 90% of China's primary source of energy and its proportion of consumption is over 60% (Hou et al., 2018). Coal endowment determines the importance of the coal industry in the social and economic development of China. In the foreseeable future, coal will continue to dominate the primary energy structure (Fig. 1). Coal cities play an important role in the construction of urban areas in China. They have unique laws of development in terms of the orientation, mechanism of growth, and industrial structure of cities. However, owing to the excessive economic development of coal cities in the early stages of China's growth, the lack of scientific planning and reasonable guidance for urban development have led to conflicts among resource systems, socio-economic systems, and ecological and environmental systems that have become increasingly prominent in recent years. This has rendered the development of coal cities difficult to sustain. The serious challenges faced by these cities include a single industrial structure and lack of driving forces for economic development (Ye et al., 2011). These cities have large numbers of unemployed people and attendant pressures, which lead to low standards of living among residents and social strife. The ecology in these cities has been seriously damaged, and some mining areas also pose geological hazards.

China's coal cities are significantly affected by the planned economic system. In the country's implementation of a planned economy to the market economy, it has become challenging for the coal-based city to sustain development. The industrial structure of coal cities is singular and their ecological environment has been damaged. They can no longer continue to adopt extensive modes of economic development. Socio-economic transformation, optimization of the industrial structure, and improvements to sustainable development capability are urgently needed. To solve the problem of the sustainable development of resource-based cities, the State Council of China issued the National Sustainable Development Plan for Resource-based Cities (2013–2020) in November 2013, which divided all resource-based cities into four types—growth, maturity, recession and regeneration—based on their economic, environmental, resource-related, and social

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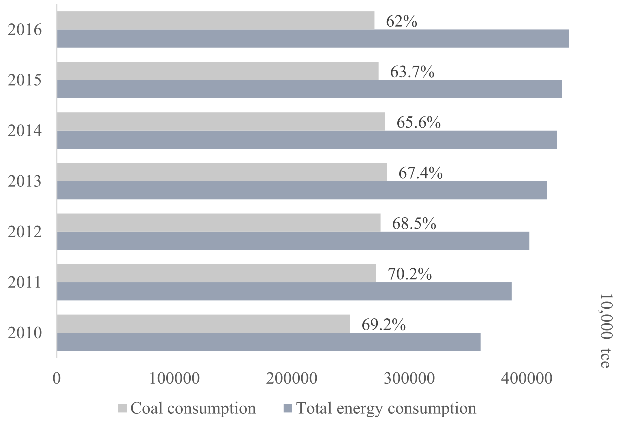

Fig. 1. Coal consumption in China.

development-related conditions. In this context, it is important to research the sustainable development capability of different coal cities. The sustainable development capability of coal cities, that is, the problem of efficiency in economics has been considered with regard to the quality and efficiency of production in the development of coal cities. This capability reflects the quality of a city's socio-economic development, and its efficiency of resource allocation and utilization.

Research in the area has focused on the transformation of coal cities and adjustment of the industrial structure. Few studies have considered the quantitative evaluation of sustainable development capability, and even fewer have examined the impact of stages of development on sustainable development capability of coal cities. The development and utilization of coal resources are not identical across these developmental stages, and the problems they face are thus also different. Therefore, this paper explores the sustainable development capability of different coal cities. Our contributions are as follows: (1) A comprehensive evaluation and comparison of the sustainable development capabilities of different coal cities are carried out from the perspective of efficiency, which is conducive to understanding their sustainable development-related situation and formulating targeted development strategies. (2) The index decomposition method is used to analyze the changing trend of the sustainable development capability of different coal cities to help clarify key factors affecting it. (3) An analysis of the ineffectiveness of the input and output indicators helps determine the distribution of ineffectiveness indicators in the development process and improve the developmental efficiency of coal cities.

The remainder of this paper is organized as follows: in Section 2, we briefly discuss related research; the methodology, and data for the evaluation and analysis of sustainable development capability is introduced in Section 3. Section 4 contains the analysis and discussion of the empirical results; finally, we offer our conclusions and discuss the policy implications of our findings in Section 5.

2. Literature review

Research on the sustainable development of coal cities has focused on exploring their mode of development and path of transformation (Cao et al., 2016; Brathwaite et al., 2010; Klaus et al., 2003). The traditional development mode of coal city involves promoting its economic development through primary processing enterprises. This mode has clear path-dependence characteristics, which makes enterprises unwilling to invest manpower and funds to promote the development of new technologies (Guo et al., 2016; Suutarinen, 2014), therefore, coal cities are generally more closed. Urban functions and industrial structures are dominated by coal enterprises, and there is a lack of communication between enterprises and outside these clusters. Knowledge spillovers rarely occur, and enterprise development lacks consciousness of innovation. The development of the coal city thus falls into a vicious circle: seeking path dependence — an increase in inertia — an increase in dependence (Gan et al., 2013).

With the growing prominence of the problem of sustainable development, authorities in coal cities are realizing the shortcomings of the traditional development model, and scholars are focusing on the sustainable development of coal cities. Because the primary processing industry of coal has made huge profits, enterprises lack the motivation to invest in more complex industries, which causes capital to flow from the manufacturing industry, with more stringent requirements for R&D and more complex technologies, to the primary processing industry (Brathwaite et al., 2010). This leads to the shrinking of manufacturing industry in coal cities and the formation of an industrial pattern with a single primary processing industry as the main industry (Świąder, 2018). In addition, the lack of human capital is an important factor hindering the optimization of the industrial structure and sustainable development (Kobayashi et al., 2013). Most coal cities pay insufficient attention to investment in education, insisting that resources are the most important asset and neglecting the accumulation of human capital. This results in a negative correlation between resource endowment and the accumulation of human capital in these cities (Chen et al., 2017). In China, direct allocation under a planned economy and price imbalance during the transition caused coal cities fall into an abnormal track of development and systemic factors exacerbated this situation.

Some scholars have explored new modes of development of coal cities, and generally believe that their sustainable development requires promoting all-round transformation by innovating and upgrading the industrial structure (Li et al., 2016; Wan et al., 2015). Industrial transformation then becomes a parallel path for the sustainable development of coal cities (Wang and Guo, 2012; Hu et al., 2016). Zhang et al. (2015) analyzed the main problems in PingXiang city's transformation, noted its main direction from economic transformation, social transformation, and ecological transformation, and concluded that it is necessary to construct multiple types for support for the development of industry. Wadin et al. (2015) claimed that the transformational development of an eco-city is designed to create a new techno-social regime based on sustainable solutions, whereas their respective national capabilities must be emphasized with an eye to efficiency, economy, and effectiveness simultaneously. With the acceleration of economic globalization, the prosperity and decline of the industry, along with the continual prosperity and recession of the international economic cycle, economic externality has become an objective factor affecting the fate of coal cities (Gechev, 2011). The foundation of the transformation of coal cities is the all-round change caused by the innovation and upgrade of the industrial structure (Wątróbski et al., 2016; Chen et al., 2017).

Measuring the sustainable development capability of coal cities from the perspective of efficiency provides an objective reflection of the locked-in degree of these cities. Only by objectively evaluating the current capability for sustainable development of these cities and analyzing internal reasons hindering it can we devise a scientific way to address the situation. Therefore, for coal cities facing the pressures of economic development and depletion of resources in the environment, improving the city's sustainable development capability is an important way to accelerate their transformation (Li and Dewan, 2017). Many qualitative and quantitative methods of analysis have been developed for comprehensive evaluation (Choi et al., 2010; Lou et al., 2015; Shah and Unnikrishnan, 2018). And the evaluation of sustainable development ability of coal cities involves multiple input and output indicators, and it is difficult to express the relationship between them using exact functions. Therefore, traditional methods cannot be used to adequately assess the sustainable development capability of coal cities.

Data envelopment analysis (DEA) is a non-parametric method for evaluating the relative efficiency of units. It can solve the multi-input and multi-output problem, and can overcome the shortcomings of traditional methods of evaluation. It is thus, widely used to evaluate the efficiency of municipal development. Hou et al. (2018) synthetically evaluated the lock-in breakthrough ability of 43 typical coal cities in China in terms of the economy, environment, and sustainable development in 2012–2016, and found that in recent years, the overall level of the lock-in breakthrough ability of China's coal cities has not changed significantly. The range of fluctuation of each city was relatively large and there were no benchmark cities. Based on the scope-adjusted measurement model of DEA, Liu and Yao (2015) constructed the indicators of operational efficiency, environmental efficiency, and uniform efficiency to reflect the impact of integration policies on sustainability and evaluated the effect of policies for the transformation of the coal-mining industry on sustainable development.

Many studies on the evaluation of municipal developmental efficiency have used data envelopment analysis that expands the scope of application of the DEA model, and supports and promotes development. However, such research has been undertaken at only the static level in general to calculate efficiency, and rarely has the dynamic point of view been used to analyze the changing trend of efficiency and internal reasons for it. Therefore, current research does not reflect changes in the efficiency of municipal development, cannot reflect the level of sustainable development from the perspective of resource efficiency, and thus cannot provide practical strategies for improvement. Because of this, this paper uses coal cities of China as an example to use the DEA method to dynamically evaluate their sustainable development capability. On this basis, the Malmquist index method is used to dynamically analyze the changing trend of sustainable development capability of different types of coal cities and identify key factors affecting it. In addition, this paper analyzes the ineffective distribution of specific input–output indicators to determine ineffective input indicators in the development process, which can help reduce ineffective input in the process of development of coal cities. Under limited input of resources, a higher output can be achieved to improve the development of cities. This can provide a basis the coal cities to improve their sustainable development capability.

3. Methodology and data

3.1. DEA model

Traditional DEA model can measure and evaluate the efficiency of decision-making units (DMUs), but it is inevitable that multiple DMUs are effective at the same time. When the traditional DEA model is used for comprehensive evaluation, it is likely that multiple DMUs are effective at the same time (the efficiency value is 1), which makes these DMUs unable to rank. To solve the problem of ordering of the DMUs, it is necessary to clarify the efficiency value of each effective unit, that is, allow for the existence of a super efficiency value (efficiency value exceeds one). Tone (2004) constructed a non-angle and non-radial super-SBM model based on the idea of super efficiency that can solve the problem of effective DMU ordering, and problems of undesired outputs, and the looseness of the input and output.

We assume that a production system has n DMUs, and each contains three vectors of the input, expected output, and undesired output (such as industrial waste). The corresponding vector is expressed as $X_j = (x_{1j,}x_{2j,}\dots,x_{mj})^T$, $Y_j = (y_{1j,}y_{2j,}\dots,y_{qj})^T$, and $U_j = (u_{1j,}u_{2j,}\dots,u_{pj})^T$, and the specific form of the super-SBM model is:

$$\begin{aligned}
\min \quad & \rho^* = k - \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{i0}} \\
s.t. \quad & 1 = k + \frac{1}{s+q}\left(\sum_{r=1}^{s}\frac{s_r^+}{y_{r0}} + \sum_{p=1}^{q}\frac{s_p^-}{u_{p0}}\right) \\
& kx_{i0} = \sum_{j=1,j\neq 0}^{n} A_j x_{ij} + s_i^- \\
& ky_{r0} = \sum_{j=1,j\neq 0}^{n} A_j y_{rj} - s_r^+ \\
& ku_{p0} = \sum_{j=1,j\neq 0}^{n} A_j u_{pj} + s_p^- \\
& A_j \geq 0,\ \ s_i^- \geq 0,\ \ s_r^+ \geq 0, s_p^- \geq 0, k \geq 0
\end{aligned} \tag{1}$$

In the above, ρ^* denotes the efficiency value to be solved for, s_i^-, s_r^+, and s_p^- denote slack variables for the input, desired output, and undesired output, respectively, $m,\ s,\ q$ are types of elements for the input, desired output, and undesired output, respectively, $x_{ij},\ y_{ij},\ u_{ij}$ represent the i_{th} input of the DMU, r_{th} desired output, and the p_{th} undesired output, respectively, k is a variable, A represents a matrix of planning coefficients, and A_j denotes the value of the j_{th} planning coefficient when evaluating j_0. In this paper, the super-SBM method is used to measure values representing the sustainable development capability of China's coal cities.

3.2. Malmquist index

The dynamic DEA method is used to study the change in production efficiency when the input or output of the DMU changes in different periods. That is to say, the characteristics of the time dimension were considered in the analysis of relative efficiency. The basis of the dynamic DEA is the Malmquist index first proposed by Malmquist (1953). It reflects changes in the productivity of DMUs over time, that is, the total factor growth. Assuming a DMU with constant returns to scale, its input and output are expressed as $(x_j,\ y_j)$. During the production period from t to t+1, the Malmquist index (M_{st}) can be expressed as the geometric average ratio of the distance function:

$$\begin{aligned}
M_{\mathrm{st}} &= \left[\frac{D_i^s(x^t, y^t)}{D_i^s(x^s, y^s)} \times \frac{D_i^t(x^t, y^t)}{D_i^t(x^s, y^s)}\right]^{1/2} \\
&= \frac{D_i^t(x^t, y^t)}{D_i^s(x^s, y^s)} \times \left[\frac{D_i^s(x^t, y^t)}{D_i^t(x^t, y^t)} \times \frac{D_i^s(x^t, y^t)}{D_i^t(x^s, y^s)}\right]^{1/2}
\end{aligned} \tag{2}$$

According to Färe et al. the Malmquist index contains the technical efficiency change index (Effch) and the technology change index (Techch) (1994), where Effch $= \frac{D_i^t(x^t,y^t)}{D_i^s(x^s,y^s)}$ represents the relative technical efficiency change index occurring from time s to t. Techch $= \left[\frac{D_i^s(x^t,y^t)}{D_i^t(x^t,y^t)} \times \frac{D_i^s(x^t,y^t)}{D_i^t(x^s,y^s)}\right]^{1/2}$, which represents the technological progress index from time s to t. The technological efficiency change index reflects the capability of the decision making unit to obtain the optimal output at a given time of investment, and measures the allocation and efficiency of utilization of various factors of production. The technology progress index reflects the impact of technological advances on productivity. When Effch >1 or Techch >1, this indicates that technical efficiency or technological progress promotes the improvement in total factor efficiency. If the index is smaller than one, it hinders the progress of total productivity.

3.3. Samples and indicators

3.3.1. Sample distribution

The spatial distribution of coal resources in China shows prominent regional characteristics, with a focus on the Qinling-Huaihe River. The spatial distribution of China's coal cities exhibits the prominent regional characteristics of the imbalance in the country's spatial distribution of resources. This poses difficulties for China's economic and social development. According to the National Sustainable Development Plan for Resource-Based Cities (2013–2020), 43 pre-prefecture-level coal cities are divided into growth, maturity, recession, and regeneration (see Table 1 for details). By studying the characteristics of the spatial distribution of coal cities combined with the local level of social and economic development, an in-depth analysis of their status of development has significant practical significance for effectively improving their sustainable development.

3.3.2. Indicator selection

According to Daly and Cobb, 2017 four criteria for the goals of sustainable development, the index system used here covers four aspects: resources, environment, economy, and society. At the same time, because characteristics of the path dependence of coal cities are mainly distributed in four aspects of urban function, technology, industrial structure, and system, the comprehensive evaluation of urban sustainable development capability should mainly include these four categories of indicators.

Considering current research and the availability of data, we constructed an indicator system to evaluate the sustainable development capability of coal cities (Table 2). According to the indicator system in Table 2, we collected data on the four types of coal cities. Given that when using DEA to calculate relative efficiency, if the number of indicators is too large and the number of DMUs is small, there is a large error in the result. In general, the number of DMUs is more than three times the number of indicators. We thus used only first-level indicators in the table when using super-SBM to calculate the sustainable development capability of coal cities.

Note in particular that due to differences in the number of dimensions and units of the secondary indicators in Table 2, the primary indicators cannot be synthesized according to weight. However, the DEA method measures relative efficiency, and the absolute size of the indicator does not affect the final value. Therefore, we first standardize the secondary indicators, then calculate first-level indicators according to the average weight of each in the table, and finally use super-SBM to calculate the sustainable development capability of cities.

4. Results and discussion

4.1. Analysis of sustainable development capability of coal cities

We evaluated the sustainable development capability of four types of coal cities. The steps of evaluation were as follows: (1) Collect data on 43 coal cities according to the indicator system in Table 2. (2) Standardize and weigh the data. (3) Calculate the sustainable development capability of the 43 cities by the Super-SBM model. (4) Calculate the average of the sustainable development capabilities of each type of coal city.

Table 1
Classification of 43 coal cities in China.

Type	Number	Name
Growth	7	Ordos, Liupanshui, Shuozhou, Hulunbeier, Xianyang, Yan'an, Yulin
Maturity	21	Datong, Yangquan, Changzhi, Jincheng, Linfen, Chifeng, Jixi, Pingdingshan, Hebi, Huainan, Handan, Xingtai, Zhangjiakou, Jinzhong, Xinzhou, Luliang, Jining, Guangyuan, Dazhou, Anshun, Qujing
Recession	13	Wuhai, Hegang, Shuangyashan, Jiaozuo, Huaibei, Fushun, Fuxin, Shizuishan, Liaoyuan, Qitaihe, Pingxiang, Zaozhuang and Tongchuan
Regeneration	2	Tangshan, Xuzhou

Table 2
Indicator system to evaluate the sustainable development capability of coal cities.

Indicator types	First-level indicators	Second-level indicators
Input indicators	Resource utilization	Per capita occupied land area (1/4) Per capita water use (1/4) Per capita electricity consumption (1/4) Per capita LPG consumption (1/4)
	Pollution treatment	Comprehensive utilization rate of general industrial solid waste (1/3) Centralized treatment rate of sewage treatment plant (1/3) Harmless treatment rate of domestic waste (1/3)
Output indicators	Economic growth	Gross domestic product growth rate (1)
	Economic scale	Per capita GDP (1/2) Per capita fixed assets (1/2)
	Economic structure	The ratio of tertiary industry to GDP (1)
	Social development	Total retail sales of consumer goods per capita (1/3) Number of teachers in universities and colleges per 100,000 (1/3) Per capita green space area (1/3)
Undesired output indicators	Three wastes of industry	Per capita industrial wastewater discharge (1/3) Per capita sulfur dioxide emissions (1/3) Per capita emissions of smoke (powder) and dust (1/3)

The values in Table 3 are the average results of the sustainable development capability of cities belonging to the four types, reflecting the average level of each type of coal city. For example, the sustainable development capability of growth cities in 2012 was 0.7163, which was determined from the average value of the sustainable development capability of seven growth cities in Table 1. Because we focus on analyzing the sustainable development capabilities of different types of coal cities, the sustainable development capability discussed later refer to the average values of each type of coal cities.

From the perspective of the overall sustainable development capability of coal cities in China, none of the 20 evaluation units was on the production frontier. That is to say, the sustainable development capability of the four types of coal cities in 2012–2016 was invalid. From 2012 to 2016, the average sustainable development capability of all coal cities is 0.6704, a low level, and needs to be significantly improved. From the trend of change, the sustainable development capability fluctuated greatly, with a highest value of 0.8878 in 2013, which indicates that the resource allocation and utilization efficiency were higher, and the sustainable development capability was stronger in the course of the development of coal cities in China in this year. In other years, the value was lower than 0.7. That is to say, when the output was fixed, there was redundancy in the input, and the allocation and utilization of resources were not effective.

Specifically to different types of coal cities, we find that in recent

Table 3
Sustainable development capability of coal cities in China from 2012 to 2016.

	Growth	Maturity	Recession	Regeneration	Mean
2012	0.7163	0.5596	0.6008	0.6533	0.6325
2013	0.9215	0.8429	0.8997	0.8871	0.8878
2014	0.7071	0.6102	0.5626	0.5750	0.6137
2015	0.6910	0.6048	0.6243	0.6892	0.6523
2016	0.5847	0.5813	0.5085	0.5884	0.5657
mean	0.7241	0.6398	0.6392	0.6786	0.6704

years, growing coal cities have had the highest average sustainable development capability, followed by regenerating cities, and mature cities and those in recession. The sustainable development capability values of the four types of cities have not reached the production frontier, and the input of resources is ineffective. In particular in mature cities and those in recession, the level of sustainable development was low, and capability value was below 0.64. Fig. 2 reflects changes in the sustainable development capability of coal cities in 2012–2016. It is clear that the sustainable development capability of growing coal cities in recent years has been higher than that of other types of coal cities, and their performance has been relatively stable. This has become a benchmark for other types of coal cities to learn from. Regenerating coal cities fluctuated greatly, and their capability increases rapidly after 2015. Mature coal cities fluctuated less after 2014, and their capability was around 0.6, which is low. The overall sustainable development capability of cities in recession exhibited a downward trend, and the level of sustainable development was relatively low.

4.2. *Dynamic decomposition of sustainable development capability of coal cities*

The above analysis shows a significant inefficiency of resources in the development of coal cities in China, and exhibits a certain trend of fluctuation. Therefore, the analysis of inefficiency and fluctuation causes has a great role in promoting the sustainable development of coal cities in China. According to the Malmquist index, we dynamically analyzed the trend of development of the capability of coal cities in China sustainable development as well as internal reasons for changes to it.

Table 4 shows that the overall TFP level of China's coal cities did not change significantly in 2012–2016, with an average value of 1.005. From the perspective of dynamic time, there was a downward–upward trend of fluctuation that was unstable. Specifically in recent years, excluding 2013 when the total factor efficiency value was greater than 1.451 and the efficiency of resource utilization progressed, the total factor efficiency value in other years was less than one. In particular in 2014, the efficiency was 0.735, which indicates a significant inefficiency of resource utilization in the development of coal cities. Resource utilization thus needs to be urgently improved. The main reason for the fluctuation in TFP value is the change in total factor efficiency caused by changes in technical efficiency and technological progress.

From the analysis of changes in technical efficiency, the overall level of technical efficiency of China's coal cities in 2012–2016 showed a decline, with an average of 0.99, and the range of fluctuation in each year was controlled to within 5%. Specifically, in the sustainable development of coal cities, the change in technological efficiency showed an inverted U-shaped trend, which first increased and then decreased. In 2014, the value of technological efficiency was greater than one, and was smaller in other years. This is because the efficiency of resource management and scale of the cities fluctuated, and was embodied in changes in pure technical efficiency and efficiency of scale. Overall, the efficiencies of resource management and scale of China's coal cities were relatively stable. This also shows that the change in technical efficiency in recent years has not made a significant contribution to improvement in the sustainable development capability of coal cities in China, which also requires all coal cities to need resource management and allocation in the future.

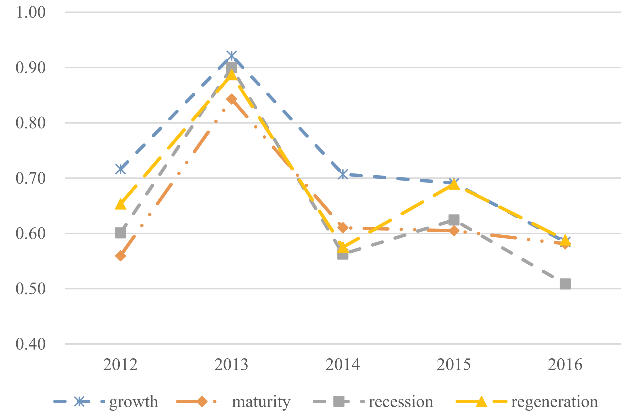

Fig. 2. Changes in sustainable development capability of different types of coal cities.

Table 4
TFP index and decomposition of coal cities in China from 2012 to 2016.

year	effch	techch	pech	sech	tfpch
2012–2013	0.982	1.477	1.039	0.945	1.451
2013–2014	1.039	0.708	0.991	1.049	0.735
2014–2015	0.978	0.977	1.015	0.964	0.956
2015–2016	0.964	1.036	0.999	0.965	0.999
mean	0.99	1.014	1.011	0.98	1.005

The average value of technological progress for the sustainable development of coal cities in China was 1.014 and its growth rate was 1.4% between 2012 and 2016, which is also the main reason for promoting the sustainable development capability of coal cities in China. Specifically, the annual change in technological progress shows that its range of fluctuation in China's coal cities was relatively large. The growth rate of technological progress was 47.7% in 2012–2013 while its index dropped to 29.2% in 2013–2014. The unstable value also caused a fluctuation in the level of sustainable development capability of coal cities fluctuate.

Overall, in recent years, the total factor efficiency of the sustainable development of coal cities in China has not changed significantly, with an average growth rate of 0.5%, but the overall trend is unstable, and has exhibited a trend of fluctuation. Through exponential decomposition, we found that technological progress was the main factor affecting the change in the total factor efficiency in the development of coal cities in China, and its range of fluctuation was large. Technical efficiency was another factor affecting the total factor efficiency of coal city development, but in recent years, the technical efficiency of this development has been relatively stable, showing a slight trend of regression, however. In conclusion, to promote the capability of coal cities for sustainable development in China, we need to start from two aspects: to improve the efficiency of resource management and allocation, and maintain the stability of technological progress.

4.3. *Ineffectiveness analysis of evaluation indicators*

With the state's attention focused on the transformation and development of coal cities, the government's support is increasing, as are the disposable resources of these cities. Improving the efficiency of the management and allocation of the numerous resources, and the capability of coal cities for sustainable development as much as possible by increasing resources are pressing problems. Therefore, it is necessary to analyze coal cities in terms of means of improving resource input and output. According to the above results, in recent years, the development efficiency of all types of coal cities in China has not reached the production frontier, and the utilization of resources has been inefficient. This paper reports a concrete analysis of the input–output optimization of the four types of coal cities considered here.

We compare the optimal input and output values on the production frontier of each evaluation unit with the actual input and output values, define the ineffectiveness of each indicator = (optimal value - actual value)/actual value, and analyze internal reasons for why the sustainable development capability of various coal cities remains wanting, and provide suggestions for improvements (Battista et al., 2014).

Fig. 3 shows the inefficiency of the input–output indicators in the

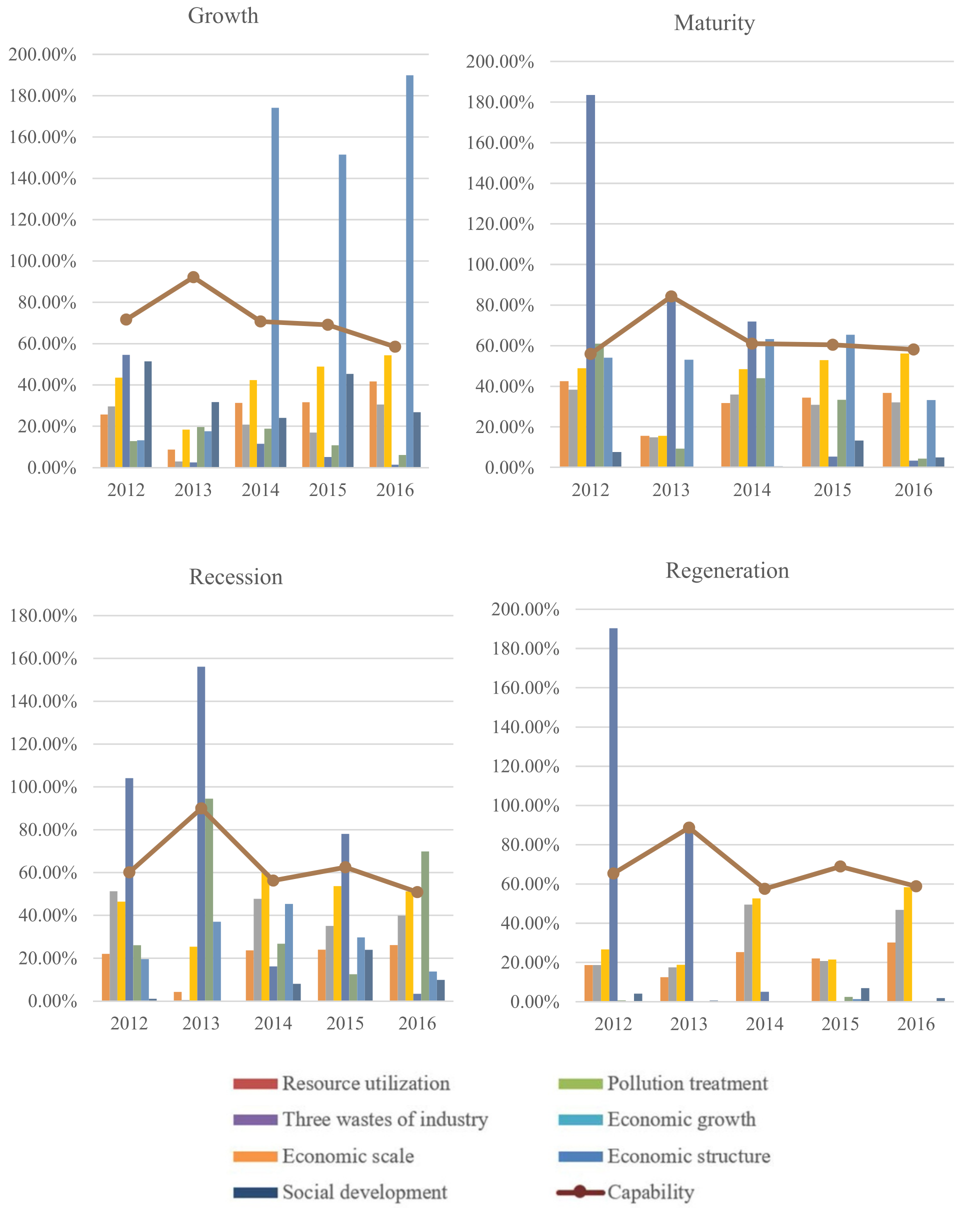

Fig. 3. Ineffectiveness distribution of input–output indicators for coal cities.

development of coal cities in China. Under current input conditions of resources, the economic and social development of coal cities in China is far lower than the optimal output, while such unexpected output as environmental pollution is far higher than the optimal value. The main reason for the low level of sustainable development capability of growing coal cities is that in recent years, the economic structure of these cities has shown significant imbalance, which is contrary to the optimal economic structure of cities. From 2014 to 2016, the inefficiency of economic structure has risen to over 15%, which has led to a low level of overall sustainable development of cities. The inefficiency indicators of mature, recessive, and regenerative coal cities are mainly reflected in economic growth, and the low level of sustainable development capability was mainly affected by these indicators. The inefficiency of economic growth indicators of mature coal cities showed a decreasing trend over time, and the inefficiency was controlled within 10% from 2015 to 2016. The inefficiency of economic growth indicators in recessive coal cities fluctuated, but the overall inefficiency level was high. In addition, such cities were also affected by the scale of economic development, and their overall level of sustainable development was low. Compared with other types of cities, the input and output of regenerating cities improved significantly. Except for the inefficiency of economic growth indicators in 2012–2013, other indicators got them, especially economic scale, economic structure, and social development, reached a fully effective state. The ineffectiveness of industrial waste and wastewater treatment indicators in all four types of cities maintained a stable level, where the ineffectiveness of industrial waste was 50%. Therefore, on the whole, China's coal cities need to improve their capability of resource transformation, and promote rapid economic development and the effective improvement of sustainable development capability through the steady progress of economic strength.

5. Conclusions and implications

5.1. Conclusions

On the basis of building a system of indicators to evaluate the sustainable development capability of coal cities, this paper used four types of coal cities as research object. First, the sustainable development capability of various coal cities in China from 2012 to 2016 was estimated by using the DEA model. Second, reasons for fluctuations in the sustainable development capability of coal cities were dynamically decomposed, and the influence of technological efficiency and technological progress on it was discussed. Finally, the inefficiency distribution of input–output indicators in the development of different types of coal cities was analyzed, and suggestions for optimization were proposed. The following conclusions and implications can be offered:

(1) The average sustainable development capability of China's coal cities in the period 2012–2016 was 0.6704. The overall level of sustainable development capability of coal cities in China was low and unstable, and there were serious inefficiencies in resource allocation and utilization. According to the ineffectiveness analysis, insufficient economic output capability has become the main obstacle to the sustainable development of most coal cities in China. This inefficiency was reflected in the economic output indicators, especially the inefficiency of economic growth and structure, which significantly hinders sustainable development.

(2) There were some differences in the sustainable development capability of different types of coal cities. The order of sustainable development capability is was growing cities > regenerating cities > mature cities > cities in recession. The level of sustainable development capability of different types of coal cities was low, and they were not effective. Therefore, there is no benchmark city for other coal cities to learn from these four types of coal cities.

(3) The TFP average of the total factor efficiency of coal cities in China was 1.005 in 2012–2016, which means that the overall levels of resource allocation and efficiency of utilization of coal cities have not changed significantly in recent years. From the point of view of the trend of change, the downward–upward fluctuation was unstable. Regarding driving factors, the average technological progress index of the sustainable development of coal cities was 1.014 from 2012 to 2016, which is the main factor affecting changes to the sustainable development capability of coal cities in China. The growth rate of technological progress was 1.4%, and was the fundamental driving force to promote the sustainable development of coal cities. However, in recent years, the technological efficiency of coal cities was relatively stable, and has not significantly improved.

5.2. *Implications*

(1) The root cause of the low and fluctuating sustainable development capability of coal cities is insufficient economic output. Therefore, economic development remains the primary task. On the one hand, by relying on coal resources, and transforming and upgrading traditional industries, more resources for coal can be explored, and the efficiency of coal mining and use can be improved to ensure the stability of production. On the other hand, while developing and utilizing coal resources, it is necessary to dig for various non-coal resources and accelerate the development of new materials' industries to ensure the sustainability of economic growth. The coal city itself must avoid the short-sighted development behavior that is guided by the sole development of coal resources. It needs to adjust its economic benefit strategy from task-based one to a sustainable economic benefit-based one.

(2) The results show that the ineffectiveness of economic growth and structure hinder the sustainable development of coal cities because technical efficiency does not play a significant role. Therefore, coal cities need to redesign the overall business chain to exploit the value of the raw materials of coal resources. In addition, increased investment in science and technology, attaching importance to the adjustment of the industrial structure, and the cultivation of new industries—especially high-tech and tertiary industries—should be pursued. The states of coal cities that are too dependent on the coal mining industry should be changed to develop comprehensive, modern cities with multiple leading and pillar industries, including the coal mining industry.

(3) A comparative analysis showed that of the four types of cities, growth cities had the highest sustainable development capability. Growth cities with low levels of resource development need to pay attention to environmental pollution and resource utilization efficiency in the development process, and avoid taking the road of "first pollution, then governance." For mature and recession cities, it is necessary to strengthen policy support and investment to improve efficiency. On the one hand, they should find new areas to grow economic output, promote the development of tertiary industries, and eliminate dependence on coal. On the other hand, the central government should provide special subsidies to coal cities to support the development of alternative industries, and control environmental pollution, prevent water damage, and implement ecological reconstruction, including subsidence land management.

Author statement

The authors declare that they have no conflict of interest. This paper has not been submitted elsewhere in identical or similar form, nor will it be during the first three months after its submission to the Publisher.

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References

Battista, G., Evangelisti, L., Guattari, C., 2014. Buildings energy efficiency interventions analysis under a smart cities approach. Sustainability 6 (8), 4694–4705.

Brathwaite, J., Horst, S., Iacobucci, J., 2010. Maximizing efficiency in the transition to a coal-based economy. Energy Pol. 38 (10), 6084–6091.

Cao, Y., Bai, Z., Zhou, W., Zhang, X., 2016. Analyses of traits and driving forces on urban land expansion in a typical coal-resource-based city in a loess area. Environ. Earth Sci. 75 (16), 1191.

Chen, Y., Hsu, C., Hsiau, S., Ma, S., 2017. Clean coal technology for removal dust using moving granular bed filter. Energy 120, 441–449.

Choi, J., Kim, K., Lee, S., Won, J., 2010. Application of a fuzzy operator to susceptibility estimations of coal mine subsidence in Taebaek City, Korea. Environ. Earth Sci. 59 (5), 1009–1022.

Daly, H.E., Cobb, J.B.J., 2017. For the Common Good: Redirecting the Economy towards Community, the Environment and a Sustainable Future, 2. Boston Massachusetts Beacon Press, pp. 346–347, 4.

Färe, R., Grosskopf, S., Lindgren, B., 1994. Productivity Developments in Swedish Hospitals: A Malmquist Output Index Approach. Data Envelopment Analysis Theory Methodology & Applications.

Gan, Y., Zhang, T., Liang, S., Zhao, Z., Li, N., 2013. How to deal with resource productivity. J. Ind. Ecol. 17 (3), 440–451.

Gechev, 2011. Natural resources and economic growth. Economics 26 (Eng 1).

General Office of the State Council, 2013-2020. National Sustainable Development Plan for Resource-Based Cities [EB/OL]. (2013-12-03).

Guo, P., Wang, T., Li, D., Zhou, X., 2016. How energy technology innovation affects transition of coal resource-based economy in China. Energy Pol. 92, 1–6.

Hou, Y., Long, R., Chen, H., Zhang, L., 2018. Research on the sustainable development of China's coal cities based on lock-in effect. Resour. Pol. 59, 479–486.

Hu, M., Wadin, J., Lo, H., Huang, J., 2016. Transformation toward an eco-city: lessons from three Asian cities. J. Clean. Prod. 123, 77–87.

Klaus, U., Klaus, E., Michael, A., 2003. Organizational transformation in transition economies: resource-based and organizational learning perspectives. J. Manag. Stud. 40 (2), 257–282.

Kobayashi, T., Kawachi, I., Iwase, T., Suzuki, E., Takao, S., 2013. Individual-level social capital and self-rated health in Japan: an application of the Resource Generator. Soc. Sci. Med. 85 (3), 32.

Li, B., Dewan, H., 2017. Efficiency differences among China's resource-based cities and their determinants. Resour. Pol. 51, 31–38.

Li, L., Lei, Y., Pan, D., Si, C., 2016. Research on sustainable development of resource-based cities based on the DEA approach: a case study of Jiaozuo, China. Math. Probl Eng. 1–10.

Liu, Y., Yao, X., 2015. Evaluating the sustainability impact of consolidation policy in China's coal mining industry: a data envelopment analysis. J. Clean. Prod. 112, 2969–2976.

Lou, B., Qiu, Y., Ulgiati, S., 2015. Emergy-based indicators of regional environmental sustainability: a case study in Shanwei, Guangdong, China. Ecol. Indicat. 57, 514–524.

Malmquist, S., 1953. Index numbers and indifference surfaces. Trab. Estadística (4), 209–242.

Shah, B., Unnikrishnan, S., 2018. Sustainability assessment of gas based power generation using a life cycle assessment approach: a case study from India. Manag. Environ. Qual. Int. J. 29 (5), 826–841.

Suutarinen, T., 2014. Resource-based development & the challenge of economic diversification in the mining communities of the Murmansk region. FEBS Lett. 231 (2), 397–401.

Świąder, M., 2018. The implementation of the concept of environmental carrying capacity into spatial management of cities. Manag. Environ. Qual. 29 (6), 1059–1074.

Tone, K., 2004. Dealing with Undesirable Outputs in DEA: a Slacks-Based Measure (SBM) Approach. Presentation at NAPW III, Toronto.

Wadin, J., Hu, M., Lo, H., Huang, J., 2015. Transformation toward an eco-city: lessons from three asian cities. J. Clean. Prod. 123.

Wan, L., Ye, X., Lee, J., Lu, X., Zhang, L., Wu, K., 2015. Effects of urbanization on ecosystem service values in a mineral resource-based city. Habitat Int. 46, 54–63.

Wang, S., Guo, S., 2012. Study on countermeasures for sustainable development of resource-exhausted cities. China Soft Sci. (1), 1–13 (In Chinese).

Wątróbski, J., Ziemba, P., Jankowski, J., Zioło, M., 2016. Green energy for a green city—a multi-perspective model approach. Sustainability 8 (8), 702.

Ye, W., Zhang, Z., Xiu, C., 2011. Social space structure of coal city in transition: a case study of Fuxin City, China. Sci. Geogr. Sin. 31 (7), 850–857.

Zhang, X., Niu, X., Yao, C., Wang, X., Xu, H., 2015. Paths and strategies of resource-exhausted city transformation: a case study in coal city Pingxiang of Jiangxi Province. Ecol. Econ. (1), 43–53.