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Eco-efficiency Analysis of Urban Agglomeration in the Middle Reaches of the Yangtze River*

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Abstract

Purpose - Urban agglomeration construction is one of national strategic plans to accelerate the development of industrialization and urbanization in China, which has threatened the eco-environmental quality at the same time. This paper selected the urban agglomeration in the middle reaches of the Yangtze River as the research area.
Research design, data, and methodology - The the slack-based measurement (SBM) model considering undesirable outputs is applied to measure the eco-efficiency of this urban agglomerations during 2006-2015.
Results - The empirical results show that average eco-efficiency of the urban agglomeration in the middle reaches of the Yangtze River is 0.595. Regional ecological development is unbalanced. The highest eco-efficiency is recorded at Wuhan Metropolitan Area, and the lowest one is at the Changsha-Zhuzhou-Xiangtan City Group. Energy consumption and waste dust emissions are the key factors led to ecological inefficiency. Based on this, potentials for energy saving and waste dust reducing are calculated.
Conclusions - Finally, this study provides policy implications targeted to promote the coordinating development of economy and eco-environment under the construction of urban agglomeration.

Keywords: Eco-efficiency, SBM Model, Urban Agglomeration, Energy Saving and Emission Reduction.

JEL Classifications: E21, Q53, Q56, Q57.

1. Introduction

China's industrialization and urbanization have made enormous achievements after more than 30 years of reform and opening up policy. This rapid development is accompanied by the emergence of urban agglomerations, which are known as regions with numerous cities around the economic core cities (Jiang, Chen, Lei, He, Jia, & Zhang, 2016). As the National New-type Urbanization Plan (2014-2020) issued by Chinese government, the urban agglomeration has been given the priority to further accelerate the pace of economic development (Fang, 2014). However, the urban agglomeration expansion converts original ecological landscapes and ecosystem structures due to population gathering and economic activities. As a result, the ecological and environmental problems such as energy shortages and air pollution have become a huge challenge for the urban agglomeration. Therefore, it is essential to measure and improve the eco-efficiency of urban agglomeration, which is helpful for making out effective policies to balance the construction between socio-economic development and ecological environmental protection.

The term of eco-efficiency was first proposed as a "business link to sustainable development" (Schaltegger & Sturm, 1989). According to the World Business Council for Sustainable Development (WBCSD), the eco-efficiency refers to produce more value with less undesirable output (WBCSD, 2000). That is, the eco-efficiency can be improved by reducing undesirable output like environment destruction while increasing its economic value (Huppes, 2009). As a main criterion to measure the decision making units (DMUs) from the aspect of economic and environmental targets, the eco-efficiency assessment has been widely adopted in a

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varity of sectors (Dahlstrom & Ekins, 2005; Yu, Shi, Wang, Chang, & Cheng, 2016; Molinos-Senante, Gémar, Gómeze, Caballero, & Sala-Garrido, 2016). Furthermore, governments are also interested in measuring eco-fficiencies at regional levels. Since regional eco-efficiency accounts for the long-term competitiveness advantages of a region or country (Koskela & Vehmas, 2012), it helps government precisely characterize local conditions and target the region-specific problems (Mickwitz, Melanen, Rosenstrom, & Seppala, 2006) which are prerequisites for making reasonable policies.

Eco-efficiency evaluation is a complex and multidisciplinary work (Zhao, Cheng, Chau, & Li, 2006). Recently, the academic circles have proposed a number of approaches to cope with this problem, such as ecological footprint (Cerutti, Beccaro, Bagliani, Donno, Bounous, & Cerutti, 2013), life cycle analysis (Avadí, Vázquez-Rowe, & Fréon, 2014), factor analysis (Singh, Mutry, Gupta, & Dikshit, 2012) and so on. However, most of them may generate inaccurate results, due to the weights allocated to criteria are subjective. Instead, the data envelopment analysis (DEA) can effectively evaluate relative efficiency of DMUs, especially under the situation of different inputs and outputs. As a non-parametric approach initially proposed by Charnes and Cooper (1978), DEA does not need a specific production function (Cook & Zhu, 2007) or weight setting prior. Actually, DEA assigns optimal weights to criteria without personal judgment (Farzipoor Saen, 2009; Azadi & Farzipoor Saen, 2012). However, the traditional DEA models are radial measures, which assume that all inputs and/or outputs change in the proportional way. The radial models have another drawback that it may overestimate the efficiency on the condition of non-zero slacks (Fukuyama & Weber, 2009). To improve it, Tone proposed a non-radial model called the slack-based measurement (SBM) (Tone, 2001), which does not stick to the assumption of proportional changes and deal with slacks directly (Chen & Jia, 2016). Thus, the SBM model is considered preferable to traditional ones and more in line with reality. Despite the SBM model has the above advantages, it still cannot conduct undesirable output. Generally speaking, there are two kinds of DEA methods to dispose undesirable outputs. The first way is directional distance function which proposed by Chambers, Chung, and Färe (1996). The second one is the slack-based approach involves undesirable output called the SBM-undesirable model (Tone, 2003), which can deal with input and output slacks at the same time without requiring strict proportionate changes of input and output. It is adopted by many scholars to investigate efficiency (e.g. Li & Hu, 2012; Chang, Zhang, Danao, & Zhang, 2013).

A common feature of the previous studies on regional eco-efficiency measurement is that most of them focused on national level (Chu, Wu, Zhu, An, & Xiong, 2016) and provincial level (Liu, Li, & Xu, 2015). However, little research has assessed the eco-efficiency of an urban agglomeration, let alone how to improve it. As the main spatial component of new types of urbanization over the next decade, the urban agglomeration deserves more attention. On the other hand, without exploring ecological inefficiency from each input and output, most previous researches could not disclose that to what extent the input can be saved and to what extent the undesirable output can be reduced, which are favourable for improving eco-efficiency.

In this paper, we selected the urban agglomeration in the middle reaches of the Yangtze River as the study area, which is one of the most important urban agglomerations in China. The SBM-undesirable approach is adopted to measure the eco-efficiencies of 28 cities in this area from 2006 to 2015. The remainder of this paper is structured as follows. Section 2 is devoted to the data and methodology used in this study and Section 3 analyzes the empirical results in detail. Finally, concluding remarks are drawn in Section 4. The Findings show that average eco-efficiency of the urban agglomeration in the middle reaches of the Yangtze River is 0.595. Regional ecological development is unbalanced. Energy consumption and waste dust emissions are the key factors led to ecological inefficiency.

2. Data and Methodology

2.1. Study area

According to the Development Planning of the Urban Agglomeration in the Middle Reaches of the Yangtze River issued by National Development and Reform Commission of China on April 6, 2015, the middle reaches of the Yangtze River city group includes the Wuhan Metropolitan Area (abbreviated as WMA) in Hubei province, the Changsha-Zhuzhou-Xiangtan City Group (abbreviated as CZX) in Hunan province and the Central Poyang Lake City Group (abbreviated as CPL) in Jiangxi province.

Table 1: Study area

The Urban Agglomeration in the Middle Reaches of the Yangtze River	
Three Regions	**Cities**
Wuhan Metropolitan Area (WMA)	Wuhan, Huangshi, Ezhou, Xiaogan, Huanggang, Xianning, Yichang, Xiangyang, Jingmen, Jingzhou
Changsha-Zhuzhou-Xiangtan City Group (CZX)	Changsha, Zhuzhou, Xiangtan, Hengyang, Yueyang, Changde, Yiyang Loudi
Changsha-Zhuzhou-Xiangtan City Group (CPL)	Nanchang, Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Jian, Yichun, Fuzhou and Shangrao

Given the availabity of data, we select 28 cities among the urban agglomeration as the research samples (excluding Xiantao, Tianmen and Qianjiang). WMA includes Wuhan, Huangshi, Ezhou, Xiaogan, Huanggang, Xianning, Yichang, Xiangyang, Jingmen, Jingzhou; CZX includes Changsha, Zhuzhou, Xiangtan, Hengyang, Yueyang, Changde, Yiyang Loudi; CPL includes Nanchang, Jingdezhen, Pingxiang, Jiujiang, Xinyu, Yingtan, Jian, Yichun, Fuzhou and Shangrao.

2.2. The indicators and data sources

Table 2: Descriptive statistics of inputs and outputs (2006-2015)

Inputs and outputs	Variable	Units	Mean
Input	Labor Force	millionperson	115.44
	Energy Consumption	10^4TCEs	2151.70
	Construction Land Area	Square kilometers	2473.13
The desirable output	Regional GDP	million Yuan	7773.70
The Undesirable Output	SO_2Emission	10^4tons	123.89
	Waste Water	10^4tons	192496.7
	Waste Dust	10^4tons	74.52

The eco-efficiency is a management philosophy to minimize ecological damage while maximize economic value (Rashidi & Farzipoor Saen, 2015). According to this definition, the input and output indicators of the case study in this paper are selected as follows:

Inputs are labor force, energy consumption and construction land area. Labor force is usually used as input in papers concerning the environmental performance measurement (e.g. Färe, Grosskopf, & Hernandez-Sancho, 2004; Tao, Wang, & Zhu, 2016). It includes all employees of each city at the end of a year. There are many papers took energy consumption into account when deal with eco-efficiency (e.g. Tao et al., 2016; Rashidi & Farzipoor Saen, 2015). Like most of them, this paper considers the consumption of coal, oil and natural gas (converted into TCE) as energy consumption. When the proportion of construction land area of city area exceeds 50%, which is its maximum ecological limit, the ecological environment will be greatly impacted. So city construction land is selected as the third input.

The desirable output and undesirable output are usually represented by regional GDP and environmental pollution separately. GDP is widely treated as economic values in eco-efficiency analysis (e.g. Zhang & Choi, 2013; Song, Song, Yu, & Wang, 2013). In this paper, GDP of each city converted into the 1987 constant price is selected as desirable output. Given that sulfur dioxide (SO_2) emission is mainly produced by fossil fuel consumption and for the lack of data availability, SO_2 emission, waste water and waste dust are selected out as environmental pollution. To estimate eco-efficiency of the urban agglomeration, both economic and environmental factors are considered in this paper.

All the corresponding data (2006-2015) was collected from China City Statistical Yearbook (2006-2015), Hubei Statistical Yearbook (2006-2015), Hunan Statistical Yearbook (2006-2015) and Jiangxi Statistical Yearbook (2006-2015).

It is worth noting that the research period is from 2006 to 2015 which includes the years of the Chinese 11th five-year plan (2006-2010) as well as Chinese 12th five-year plan (2011-2015). Therefore, this study may provide reasonable guidance for policy-making and implementation during the next five-year plan years.

2.3. The model

DEA models are classified into two categories, namely radial models and non-radial models (Rashidi & Farzipoor Saen 2015). As a non-radial model, the SBM model not only put away the assumption that all inputs and outputs should change proportionately, but also incorporate slacks into objective function. It assumes that there are n DMUs (j=1, 2, ... n), each of which consumes m inputs $x_{ij} \in R^m$ toyield r outputs $y_{rj} \in R^s$. Here x_{ij} and y_{rj} are assumed positive for computational tractability. Thematrices X and Y are definedas $X = [x_1, x_2, ... x_n] \in R^{m \times n}, Y = [y_1, y_2, ... y_n] \in R^{s \times n}$. The production possibility set (PPS) under the constant return to scale (CRS) assumption is defined as:

$$p = \{(x, y) | x \geq X\lambda, y \leq Y\lambda, \lambda \geq 0\} \tag{1}$$

The SBM model (Tone, 2001) is defined as follows:

$$\rho^* = \min \frac{1 - \frac{1}{m} \sum_{i=1}^{m} \frac{s_i^-}{x_{io}}}{1 + \frac{1}{n} \sum_{r=1}^{s} \frac{s_r^+}{y_{ro}}}$$
$$s.t. \begin{cases} x_0 = X\lambda + s^- \\ y_0 = Y\lambda - s^+ \\ \lambda \geq 0;\ s^- \geq 0;\ s^+ \geq 0 \end{cases} \tag{2}$$

Where s^-, s^+ indicate the slack variables of inputs and outputs respectively. The λ is weight vectors for projecting the DMUs. The objective function strictly descends in relationto s^-, s^+ and the value of ρ^* is between 0 and 1. If and only if $\rho^* = 1$ and $s^- = 0, s^+ = 0$ the DMU is said to be efficient.

However, the SBM model does not take account of undesirable output factors. In order to make up for this disadvantage, Tone (2003) defined $X = (x_1, x_2, \cdots, x_n) \in R^{m \times n}$, $Y^g = (y_1^g, y_2^g, \cdots, y_n^g) \in R^{s_1 \times n}$, $Y^b = (y_1^b, y_2^b, \cdots, y_n^b) \in R^{s_2 \times n}$, are inputs, desirable outputs and undesirable outputs, respectively. Here, $x_i > 0, y_i^g > 0, y_i^b > 0$. The new production possibility set Pu is definedas:

$$P_u = \{(x, y^g, y^b) | x \geq X\lambda, y^g \leq Y^g\lambda, \lambda \geq 0\} \tag{3}$$

The non-radial SBM model based on undesirable outputs can be expressed as follows:

$$\rho^* = \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)}$$

$$s.t.\begin{cases} x_o = X\lambda + s^- \\ y^g = Y^g\lambda - s^g \\ y^b = Y^b\lambda + s^b \\ s^- \ge 0, s^g \ge 0, s^b \ge 0, \lambda \ge 0 \end{cases} \quad (4)$$

Where s_i^-, s_r^g, s_r^b respectively represent the slacks of inputs, desirable and undesirable outputs, the optimal ρ^* represents the efficiency under the condition of all slacks. s_1, s_2 represent the number of the desirable and undesirable outputs.

Definition 1: DMU0, after running the model (4) is said to be eco-efficient, if and only if $\rho^* = 1$ and all slacks $s^- = s^g = s^b = 0$.

3. The empirical results

3.1. General eco-efficiency analysis

The eco-efficiency of 28 researched cities from 2006 to 2015 is calculated by DEA Solver 5.0 software under constant returns to scale. It should be pointed out that the higher the eco-efficiency value is the better the city perform.

Table 3: Eco-efficiency values for 28 cities in the Middle Reaches of Yangtze River (2006-2015)

Cities	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Mean
Wuhan	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Huangshi	0.428	0.438	0.425	0.310	0.330	0.434	0.442	0.490	0.320	0.351	0.397
Ezhou	0.305	0.344	0.354	0.309	0.380	0.336	0.343	0.402	0.287	0.327	0.339
Xiaogan	0.633	0.626	0.586	1.000	1.000	1.000	1.000	0.500	0.441	0.456	0.724
Huanggang	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Xianning	0.505	0.578	0.504	0.534	0.611	0.821	0.686	1.000	0.601	0.716	0.656
Yichang	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.515	0.952
Xiangyang	1.000	0.822	0.791	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.961
Jingmen	0.646	0.589	0.526	0.413	0.488	0.582	0.488	0.607	0.488	0.532	0.536
Jingzhou	0.447	0.472	0.451	0.394	0.564	0.609	0.621	0.678	0.434	0.427	0.510
Changsha	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Zhuzhou	0.448	0.470	0.451	0.381	0.563	0.426	0.517	0.518	0.520	0.406	0.470
Xiangtan	0.314	0.312	0.313	0.301	0.351	0.335	0.358	0.400	0.255	0.285	0.322
Hengyang	0.347	0.384	0.350	0.310	0.417	0.360	0.363	0.423	0.297	0.332	0.358
Yueyang	1.000	0.564	0.488	0.361	0.485	0.549	0.552	0.628	0.459	0.535	0.562
Changde	1.000	1.000	1.000	1.000	0.823	0.791	0.882	1.000	0.620	0.673	0.879
Yiyang	0.375	0.401	0.381	0.337	0.394	0.410	0.369	0.402	0.382	0.356	0.381
Loudi	0.353	0.355	0.359	0.311	0.370	1.000	1.000	0.393	0.367	0.344	0.485
Nanchang	1.000	1.000	1.000	1.000	0.828	0.546	0.574	0.525	0.509	0.503	0.748
Jingdezhen	0.297	0.294	0.293	0.273	0.330	0.305	0.314	0.350	0.240	0.259	0.296
Pingxiang	0.448	0.544	0.572	0.543	0.568	0.484	0.689	0.460	0.332	0.445	0.508
Jiujiang	0.391	0.445	0.431	0.422	0.469	0.511	0.412	0.519	0.364	0.355	0.432
Xinyu	0.127	0.154	0.284	1.000	1.000	1.000	1.000	1.000	0.338	0.356	0.626
Yingtan	0.457	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.946
Ji'an	0.631	0.646	1.000	1.000	1.000	0.780	0.878	0.579	0.518	0.495	0.753
Yichun	1.000	1.000	1.000	0.783	0.752	0.585	0.513	0.516	0.444	0.483	0.708
Fuzhou	0.513	0.554	0.474	0.410	0.582	0.604	0.394	0.417	0.433	0.441	0.482
Shangrao	1.000	0.676	0.562	1.000	1.000	1.000	0.716	0.772	1.000	0.477	0.820
WMA	0.696	0.687	0.664	0.696	0.737	0.778	0.758	0.768	0.657	0.632	0.707
CZX	0.605	0.561	0.543	0.500	0.550	0.609	0.630	0.596	0.488	0.491	0.557
CPL	0.586	0.631	0.662	0.743	0.753	0.682	0.649	0.614	0.518	0.481	0.632
Total Urban Agglomeration	0.617	0.629	0.631	0.644	0.678	0.684	0.681	0.660	0.543	0.540	0.631

From table 1, conclusions can be drawn as follows. Firstly, the overall eco-efficiency of the Urban Agglomeration in the Middle Reaches of Yangtze River is 0.595, which implies that the overall eco-efficiency can be improved by 40.5% under the current level of production technology. Secondly, among the three regions, the Wuhan Metropolitan Area's eco-efficiency value is the highest, with the mean of 0.707. The average eco-efficiency of the Central Poyang Lake City Group is nearly equal to that of the Urban Agglomeration in the Middle Reaches of Yangtze River. The Changsha-Zhuzhou-Xiangtan City Group performs the worst, it has the lowest average eco-efficiency as 0.557, which is below the average eco-efficiency at the whole urban agglomeration level. Thirdly, in the Wuhan Metropolitan Area, Wuhan and Huanggang always performed well for their eco-efficiency scores are all equal to 1 in 10 years. This means that they are on efficiency frontier every year. In contrast, the eco-efficiency values of Huangshi, Ezhou, Jingmen and Jingzhou is relative low and all under the average level of the Wuhan Metropolitan Area. Fourthly, more than half cities in the Changsha-Zhuzhou-Xiangtan City Group generated average eco-efficiencies that do not exceeded 0.5. Most of them show a kind of stable case except Loudi, whose eco-efficiency fluctuated observably with an inverted U-shape curing during the researched period. The eco-efficiency of Changde and Yueyang presents a descending trend as a whole from 2006 to 2015. Only Changsha is always environmentally efficient for its eco-efficiency scores all reached 1. Finally, most cities in the Central Poyang Lake City Group show an uptrend from 2006 to 2009, however, then show a downtrend from 2013 to 2015, which is not a promising phenomenon. Take Xinyu as an example, its eco-efficiency surged from 0.284 to 1 (2008-2009). After remain unchanged for 5 years, it drops from 1 to 0.338 (2013-2014) dramatically.

3.2. Trends of regional eco-efficiency

As previously mentioned, our research period includes the Chinese 11th five-year plan (2006-2010) and the 12th five-year plan (2011-2015). In order to provide reasonable recommendations for policy-making in next five-year, we analyze the trends of average eco-efficiency of the three regions and the whole urban agglomeration. Fig. 1 gives the comparison of the computational results. We can see that eco-efficiency of the Wuhan Metropolitan Area is generally higher than that of the other two and the gap becomes even bigger during the12th five-year plan period. It implies that regional differences appeared in the urban agglomeration in the middle reaches of the Yangtze River due to different regional economic development and industrial structures. The Changsha-Zhuzhou-Xiangtan City Group performed really bad in the 11th fiver-year plan period, while narrows its gap with the Central Poyang Lake City Group in the 12th five-year period. This indicates that stricter ecological protection measures have been take to improve the eco-efficiency in this area. Unfortunately, the value of eco-efficiencies for the three regions as well as the whole urban agglomeration show a sharp drop after reaching their peak, and then fall to the lowest level over the research period in 2015. This phenomenon suggests that government and industries attached less importance to ecological protection in the11th five-year plan period than in the 12th five-year. Blind expansion of urban construction and one-sided pursuit of GDP growth destroyed the ecological balance and brought huge pressure on natural resources.

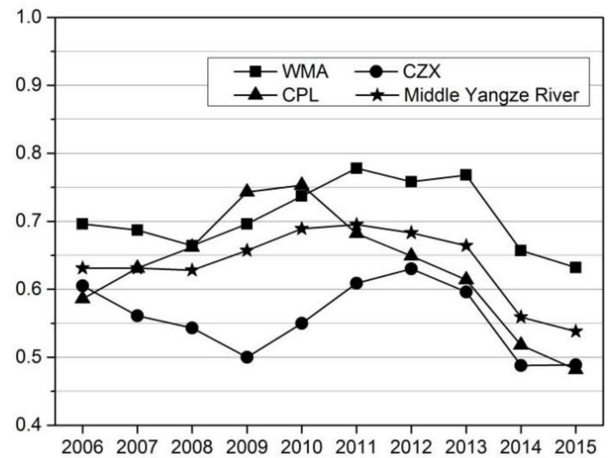

Figure 1: Trends of eco-efficiency for the three regions and the whole urban agglomeration (2006-2015)

3.3. Decomposition of eco-efficiency

In order to reveal the reasons for differences existing in eco-efficiencies for the three regions, we have made research on each input's and output's efficiency. Eco-efficiency in this paper is decomposed into five aspects based on model (4): labor inefficiency, construction land inefficiency, energy inefficiency, GDP inefficiency, waste water inefficiency, waste dust inefficiency, and SO_2 emission inefficiency. From the empirical results, we find that redundancy rate of GDP is 0, which means that GDP has already reached the maximum efficiency. The rest of inefficiencies mean that under the current level of technology, how much labor, construction land and energy could have been saved and how much waste water, waste dust and SO_2 emission could have been reduced during the production process for achieving the same level of GDP.

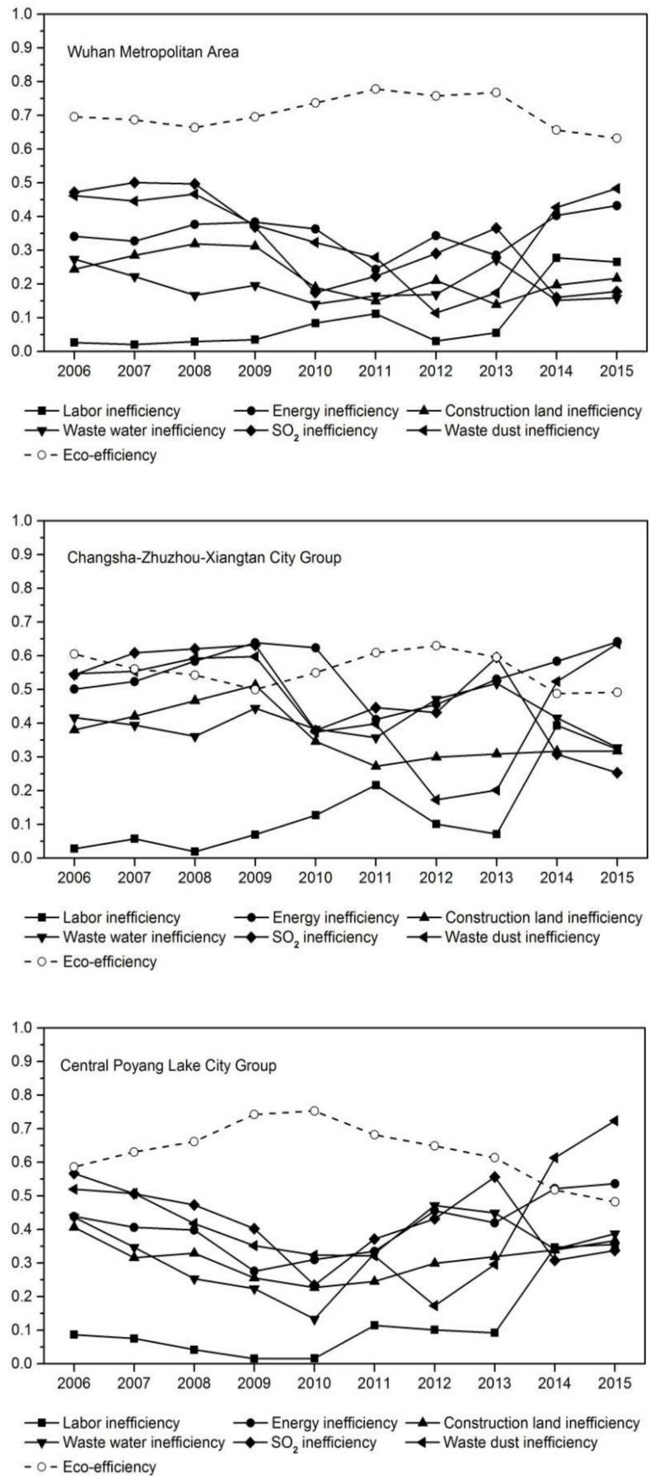

Figure 2: Decomposition of eco-efficiency for the three regions

Fig. 2 shows the redundancy rate changes of three inputs and three undesirable outputs during the study period. It can be seen that regions with lower redundancy rate generally have higher eco-efficiency value. Overall, redundancy rate of energy consumption is the highest among three input indicators and shows an increasing trend from 2010 to 2015, namely the period of 12th five-year plan. With regard to undesirable output indicators, the redundancy rates of SO_2 emissions and waste dust are much higher that of waste water. The difference is that the redundancy rates of SO_2 emissions shows an obvious decreasing trend as a whole during the ten years, while the redundancy rates of waste dust fluctuated with a U-shape curve and increasing dramatically from 2012 to 2015. These results tell us that ecological inefficiencies of these three regions are mainly due to industrial excessive energy consumption and waste dust emissions. With the implementation of Development for the Urban Agglomeration in the Middle Reaches of the Yangtze River, economic development is emphasized while ecological protection draws little attention, which accounts for high level of the energy inefficiency and waste dust inefficiency. Therefore, as to improve the eco-efficiency, clean production technologies should be adopted as to save energy consumption and reduce the industrial waste dust emissions.

3.4. Energy saving and waste dust abatement potentials

As has mentioned above, inefficiencies of energy consumption and waste dust play a big part in ecological inefficiency in the Middle Reaches of the Yangtze River. In this paper, we use energy saving potential (ESP) and waste dust abatement potential (WDAP) to determine how much energy input can be saved and how much waste dust outputs can be reduced in each city. The amount of ESP is calculated by energy redundancy and the amount of WDAP is calculated by waste dust excess, correspondingly.

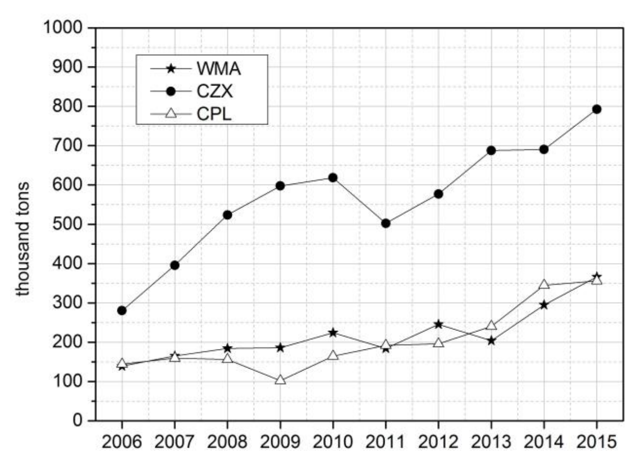

Figure 3: Energy redundancy in each region

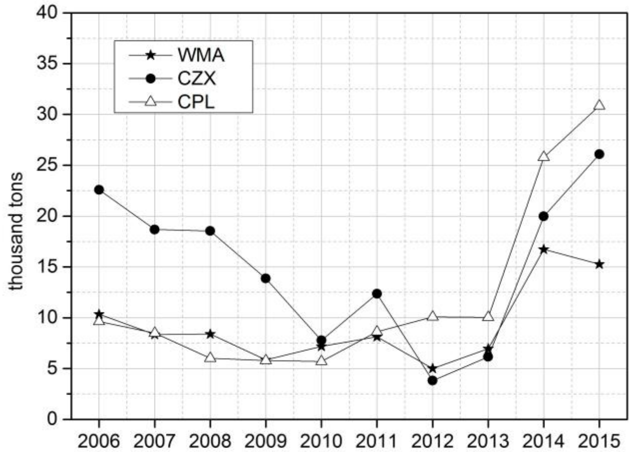

Figure 4: Waste dust emissions excess in each region

According to Fig. 3, energy redundancies of the three regions (WMA, CZX and CPL) are all rising during the research period. The Changsha-Zhuzhou-Xiangtan City Group has the highest energy redundancy, which increased dramatically since 2011 and reached to 793 thousand tons in 2015. It suggests that energy-wasting is a severe problem in this area. Energy redundancies of the other two regions are very close with a relatively slow uptrend during research period. From Fig. 4, we can see that waste dust excess in the Central Poyang Lake City Group started low and maintained a slight decrease trend in the period of 11th five-year plan. However, the value shows converse change tendency and exceeds that of the other two regions in the period of 12th five-year plan. This may account for the decline of eco-efficiency in this area. The amount of waste dust excess in the Changsha-Zhuzhou-Xiangtan City Group is quite larger than that of the other two regions in the period of 11^{th} five-year plan, but the gap tends to narrow down in the next five years. Among the three regions, after a surge of waste dust excesses in 2014, only Wuhan Metropolitan Area take actions to reduce its emissions of waste dust.

4. Conclusions

Accompanied by the rapid acceleration of urbanization and industrialization process in China, urban agglomerations have become the most dynamic and potential core areas, which play an important role in national economic development. However, a serious environmental problem occurs during the construction of urban agglomeration.

In this paper, with the consideration of undesirable outputs, the eco-efficiency of urban agglomeration in the middle reaches of the Yangtze River from 2006 to 2015 was measured by using the SBM model. Then, in order to find effective ways to improve the eco-efficiency, potentials for reducing both energy consumption and waste dust emissions of each region were estimated.

The empirical study suggests the following results. First, differences exist in different regions obviously. Wuhan Metropolitan Area has the highest value of eco-efficiency, followed by the Central Poyang Lake City Group. While the eco-efficiency of the Changsha-Zhuzhou-Xiangtan City Group is at the bottom, which has much room for improvement. Second, the whole urban agglomeration performs better in the11th five-year plan period than the 12th five-year plan period as the overall eco-efficiency shows a downward tendency during the latter period. Third, the inefficiency of each input and output is different. Generally speaking, energy and waste dust are the key inefficient factors as the redundancy rates of them are high and with an uprising trend. Finally, potentials for energy saving and waste dust reduction present different features. Energy redundancies in the three regions increase year by year, while waste dust excesses fluctuated with a U-shape curve.

Based on the above conclusions, some policy implications can be formulated as follows. First, it requires more effort to accelerate the industrial structural transformation. Heavy industries should be controlled because they not only have heavy demand for fossil energy but also bring about serious environmental problems.

Heavy industry, which leads to increased fossil energy consumption and serious environmental problems, should be controlled.

The third industry development like tourism and information services should be supported. Second, making targeted policies and regulations for different cities and strengthening the cooperation among them. At last but not least, industrial enterprises' awareness of environment protection should be enhanced. Encouraging clean energy technology development by providing financial support.

For further research, eco-efficiencies of other important urban agglomerations in China can be investigated to make comparison among them. Recently, Malmquist index is applied in dynamic analysis of region development. It is useful to use the method that combines DEA and Malmquist index in future research.

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