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# Efficiency Evaluation of Industrial Solid Waste Recycling Utilization Based on Improved DEA Model

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**Abstract.** As an industrial power, China has become increasingly problematic in terms of resource consumption and serious environmental pollution. Encouraging the utilization of industrial solid waste resources is a necessary way to achieve economic and environmental sustainability. Based on the new improved DEA model, this paper studies the utilization efficiency and influencing factors of industrial solid waste resource utilization in 31 regions of China in 2017. The research results show that the average efficiency of China's industrial solid waste resource utilization is at a relatively high level, which is significantly higher than that in 2010; the investment amount of industrial waste treatment in most areas is rationally utilized; nearly half of the areas have excessive storage of industrial solid waste; there is little difference in scale efficiency between the remaining 30 regions except Tibet, but there is a significant difference in pure technical efficiency. Finally, this paper proposes suggestions for improvement from the perspective of coordinating economic, social and environmental sustainability.

## 1. Introduction

It is often said that industrial production is the “culprit” of solid waste. At present, scholars are trying to introduce the concept of sustainable development into solid waste management. Using the concept of sustainable development to guide the utilization of industrial solid waste resources can not only reduce the problem of littering of solid waste, but also reduce the consumption of primary mineral resources in the production process <sup>[1]</sup>.

Foreign research on solid waste management mainly uses different models to identify problems and select solutions. Al-Khatib described, quantified and managed practical research on solid waste characteristics in developing countries through the case of Nablus, Pakistan <sup>[2]</sup>. Rada proposed three indicators for assessing solid waste recycling management performance and quantifying the role of solid waste management in resource recovery <sup>[3]</sup>. Ojo, OO considers a large number of alternatives for various levels of uncertainty in solid waste management <sup>[4]</sup>. Erkut, E. proposed a multi-standard facility location model to evaluate the level of solid waste management in Northern Greece <sup>[5]</sup>. Tsilemou, K et al. evaluated the performance of solid waste management models by comparing two readily available models <sup>[6]</sup>.

Compared with developed countries, China's solid waste resource utilization efficiency, comprehensive utilization level and recycling output value still have room for improvement. Domestic research mainly uses the DEA model to evaluate the efficiency of circular economy in different provinces, cities or industries <sup>[7-10]</sup>. Considering the few articles on undesirable inputs and undesirable outputs, Fan Chen constructed an improved DEA efficiency evaluation model to study the optimal



efficiency improvement direction of invalid units from the perspective of increasing the total amount of solid waste utilization and the total desirable output. Undesirable output is not considered <sup>[11]</sup>. Guozhu Jia used the improved DEA model to evaluate the efficiency of the construction industry in 31 provinces and cities in China <sup>[12]</sup>. The evaluation index added undesirable inputs and undesirable outputs, but did not consider the storage of industrial solid waste, nor did it consider the overall input and Overall output.

According to the existing research results, this paper attempts to innovate from three aspects. First, the storage cost of industrial solid waste occurs before the comprehensive utilization and disposal, and is not included in the investment amount of industrial solid waste treatment. Therefore, the storage of industrial solid waste is included as a desirable input into the evaluation index system. Secondly, it is proposed. The new improved model considers desirable and unanticipated outputs as the overall input, and the desirable output and the undesirable input as the overall output. Finally, the proportion of the increase in overall output is greater than the increase in the overall input. The invalid decision unit is improved.

## 2. Methodology

### 2.1 Construction of industrial solid waste recycling system

According to the characteristics of industrial solid waste resource utilization, this paper constructs an industrial solid waste recycling economic system from the upstream, midstream and downstream. The main body and activities of each stage are shown in Figure 1.

(1) Upstream: the stage of waste generation. At this stage, the huge industrial system emits a large amount of complex solid waste, which puts tremendous pressure on people's health and ecological environment.

(2) Midstream: intermediary for waste recycling and processing. Most of the solid waste discharged from the factory is recycled and remanufactured by large-scale waste resource recycling and processing enterprises, and a small part is handled by the distribution market, small or individual waste resource processing and trading center.

(3) Downstream: the recycling stage of recycled products. There are three main ways to recycle industrial solid waste: material recovery, material conversion and energy conversion<sup>[13]</sup>. Industrial solid waste obtains recycled products into the market through these three ways. After a certain life cycle, some of the available wastes enter the circulation system again, so that the industrial solid waste can be obtained twice or even repeatedly. It is conducive to the sustainability of resources.

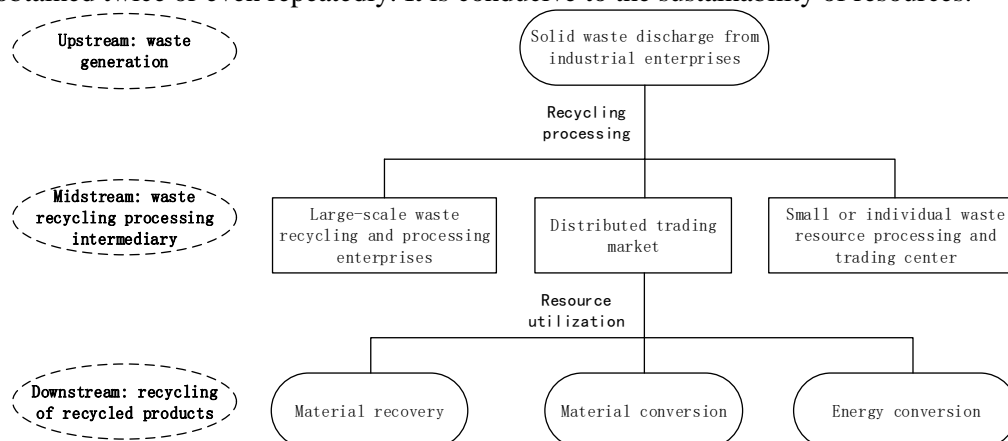


Figure 1 Industrial solid waste recycling system

### 2.2 Selection of evaluation methods

From the perspective of sustainable development, the resource recovery efficiency is mainly based on data envelopment analysis (DEA) <sup>[14-16]</sup>. The DEA method does not need to estimate the parameters

and weight hypothesis, nor does it need to consider the functional relationship between input and output. It can measure the technical efficiency and scale return of different decision-making units, and truly reflect the conversion relationship between multiple inputs and multiple outputs<sup>[17]</sup>. In actual production, because most production units do not reach the optimal production status, this paper evaluates the utilization of solid waste resources in China based on a BCC model with variable scale returns and input-oriented<sup>[18]</sup>.

### 2.3 Establish an improved model

Assume that the industrial solid waste resource utilization efficiency of R regions is evaluated. Each region has M kinds of desirable inputs, N kinds of undesirable inputs, S kinds of desirable outputs and T kinds of undesirable outputs. Let the input variables be X and Y, then  $X_{mr}$  represents the  $m$ -th desirable input of the  $r$ -th region,  $Y_{nr}$  represents the  $n$ th undesirable input of the  $r$ -th region; if the output variables are F and G, then  $F_{sr}$  represents the  $s$ -th desirable output of the  $r$ -th region,  $G_{tr}$  represents the  $t$ -th undesirable output of the  $r$ -th region; if the overall input variable is Z, then  $Z_{mr}$  represents the  $m$ -th overall input of the  $r$ -th region, the overall output variable For H,  $H_{nr}$  represents the  $n$ -th overall output of the  $r$ -th region.

Based on the transformation characteristics of input and output factors of industrial solid waste under circular economy, this paper proposes a new improvement based on the literature, with the proportion of overall output increase greater than the increase of overall input as the objective function<sup>[11]</sup>. To evaluate the efficiency of resource utilization of industrial solid waste in the  $r_0$  region can be expressed as:

$$\begin{aligned}
 \max U_0 &= \sum_{b=1}^q \frac{s_g^+}{h_{b0}} - \sum_{a=1}^p \frac{s_f^-}{z_{a0}} \\
 \text{s.t.} \quad &\sum_{i=1}^n \mu_i f_{ai} + s_a^- = f_{a0}, a=1, 2, \dots, p \\
 &\sum_{i=1}^n \mu_i g_{bi} - s_b^+ = g_{b0}, b=1, 2, \dots, q \\
 &\sum_{i=1}^n \mu_i x_{ci} - s_c^+ = x_{c0}, c=1, 2, \dots, k \\
 &\sum_{i=1}^n \mu_i y_{di} + s_d^- = y_{d0}, d=1, 2, \dots, l \\
 &\sum_{b=1}^q \frac{s_g^+}{h_{b0}} - \sum_{a=1}^p \frac{s_f^-}{z_{a0}} > 0 \\
 &\sum_{i=1}^n \mu_i = 1 \\
 &\mu_i, s_f^-, s_g^+ \geq 0, \quad i=1, 2, \dots, n
 \end{aligned} \tag{1}$$

Where  $s_a^-, s_b^+, s_c^+$  and  $s_d^-$  are slacks of desirable inputs, desirable outputs, undesirable inputs, and undesirable outputs, respectively. The desirable inputs and the undesirable outputs are regarded as the overall input. The desirable output and the undesirable input are regarded as the overall output, and the effective decision-making unit is improved with the proportion of the increase of the overall output greater than the proportion of the overall investment increase.  $s_f^-$  is the overall input slack, that is, the overall investment is excessive,  $s_g^+$  is the overall output slack, that is, the overall output is insufficient, so the first four constraints of the above model can be simplified into two constraints, and the simplified model can be expressed as:

$$\begin{aligned}
 \max U_0 &= \sum_{b=1}^q \frac{s_g^+}{h_{b0}} - \sum_{a=1}^p \frac{s_f^-}{z_{a0}} \\
 \text{s.t.} \quad &\sum_{i=1}^n \mu_i f_{ai} + s_f^- = f_{a0}, a=1, 2, \dots, p \\
 &\sum_{i=1}^n \mu_i g_{bi} - s_g^+ = g_{b0}, b=1, 2, \dots, q \\
 &\sum_{b=1}^q \frac{s_g^+}{h_{b0}} - \sum_{a=1}^p \frac{s_f^-}{z_{a0}} > 0 \\
 &\sum_{i=1}^n \mu_i = 1 \\
 &\mu_i, s_f^-, s_g^+ \geq 0, \quad i=1, 2, \dots, n
 \end{aligned} \tag{2}$$

Among them, Constraint 1 indicates that the overall input should be as small as possible; Constraint 2 indicates that the overall output should be as much as possible; Constraint 3 indicates that the proportion of overall output increase is greater than the increase in overall input, that is, the increase in scale returns; Constraint 4 indicates that the scale return is variable.

According to the above model, it can be concluded that if  $U_0=0, s_f^-=0, s_g^+=0$ , the decision unit  $DMU_0$  is relatively valid for DEA. Otherwise, it is non-DEA effective. The overall input and overall output target values of each decision unit are Equation (3) and Equation (4), respectively, and the optimal improvement direction of the invalid unit can be determined according to Equations (3) and (4).

$$f'_{a0} = f_{a0} + s_f^-, a=1,2,\dots,p \quad (3)$$

$$g'_{b0} = g_{b0} + s_g^+, b=1,2,\dots,q \quad (4)$$

The improved DEA model can improve the utilization rate of industrial solid waste resources, and can point out the optimal improvement path of invalid decision-making units to effective decision-making units.

## 2.4 Selection of indicators and data

Table 1. Evaluation index system of industrial solid waste resource utilization efficiency.

Evaluation Indicators		Variables	Unit/ $10^4$
Overall inputs	Desirable inputs	Production	ton
		Treatment investment	yuan
		Storage	ton
Overall outputs	Undesirable output	Discharge	ton
	Desirable output	Disposal	ton
	Undesirable input	Comprehensive utilization	ton

Based on the availability and accuracy of the sample data, this study takes industrial solid waste production, industrial solid waste treatment investment, industrial solid waste storage as the desirable input, and industrial solid waste disposal as the desirable output <sup>[19-20]</sup>. The industrial solid waste comprehensive utilization is regarded as an undesirable input, and the industrial solid waste discharge is an undesirable output. In addition, this paper regards desirable and undesirable output as the overall input, and regards desirable output and undesirable input as the overall output, and builds an evaluation index system for industrial solid waste resource utilization efficiency under circular economy (see Table 1). The data comes from the statistics of China Statistical Yearbook 2018 and the statistical yearbooks of various regions <sup>[21]</sup>.

## 3. Facet analysis on BCC model

Table 2. The recycling efficiency values and scale returns.

DMUs	Comprehensive efficiency	Pure technical efficiency	Scale efficiency	Scale remuneration	Ranking
Beijing	1.000	1.000	1.000	Constant	1
Tianjin	1.000	1.000	1.000	Constant	1
Hebei	1.000	1.000	1.000	Constant	1
Shanxi	1.000	1.000	1.000	Constant	1
Inner Mongolia	0.734	0.744	0.987	Decrease	12
Liaoning	0.600	0.611	0.981	Decrease	16
Jilin	0.796	0.796	1.000	Constant	9
Heilongjiang	0.757	0.763	0.992	Increase	10
Shanghai	1.000	1.000	1.000	Constant	1
Jiangsu	0.987	1.000	0.987	Decrease	2
Zhejiang	1.000	1.000	1.000	Constant	1

Anhui	0.978	1.000	0.978	Decrease	4
Fujian	0.987	1.000	0.987	Decrease	2
Jiangxi	0.454	0.481	0.945	Decrease	17
Shandong	1.000	1.000	1.000	Constant	1
Henan	0.939	0.996	0.944	Decrease	7
Hubei	0.722	0.730	0.989	Decrease	13
Hunan	1.000	1.000	1.000	Constant	1
Guangdong	0.958	1.000	0.958	Decrease	5
Guangxi	0.757	0.766	0.988	Decrease	10
Hainan	1.000	1.000	1.000	Constant	1
Chongqing	0.980	1.000	0.980	Increase	3
Sichuan	0.636	0.650	0.979	Decrease	15
Guizhou	0.941	0.945	0.996	Decrease	6
Yunnan	0.923	0.928	0.995	Decrease	8
Tibet	0.032	1.000	0.032	Increase	17
Shaanxi	1.000	1.000	1.000	Constant	1
Gansu	0.746	0.805	0.926	Increase	11
Qinghai	1.000	1.000	1.000	Constant	1
Ningxia	1.000	1.000	1.000	Constant	1
Xinjiang	0.668	0.668	1.000	Constant	14
Mean	0.858	0.899	0.956	-	-

This paper uses DEAP2.1 software to evaluate the utilization efficiency of urban solid waste resources in 31 regions in China in 2017. In actual production, most production units do not reach the optimal production state. Therefore, this paper selects the BCC model with variable scale returns and input-oriented to obtain comprehensive efficiency, pure technical efficiency, scale efficiency, and their average value and scale. The specific results are shown in Table 2.

As can be seen from Table 2, (1) The average efficiency of industrial solid waste recycling in 31 regions in China in 2017 was 0.858, indicating that the national industrial solid waste recycling level was higher in the year. The comprehensive efficiency values of 12 regions reached 1, which means that DEA is relatively effective. The pure technical efficiency of 6 regions is 1, but the scale efficiency has not reached 1, especially the scale efficiency of Tibet is only 0.032. The six regions should control the storage of industrial solid waste and rationally adjust the scale of investment. (2) 13 regions are decreasing in scale, indicating that they have invested too much and should reduce their input. The economies of scale between the remaining 30 regions except Tibet are not much different, but the differences in pure technical efficiency are large, indicating that there are significant differences in technology of various regions. Tibet is located in the western part of China, with low per capita GDP and a small number of waste resource recycling and processing enterprises, which leads to low efficiency of resource utilization. (3) Compared with the 2010 industrial solid waste management efficiency studied by Juan Liu (2013), the average efficiency of industrial solid waste resource utilization in 31 regions in China increased by 8.6% in 2017<sup>[9]</sup>. It indicates that the country vigorously developing clean production and sustainable development have played a very good role.

Table 3. The amount of input slacks in DEA relative ineffective areas

DMUs	Industrial solid waste storage	Industrial solid waste management investment	Industrial solid waste discharge
Inner Mongolia	4862.154	1428.986	2.214
Liaoning	7138.236	0.000	0.820
Jilin	843.686	0.000	0.480

Heilongjiang	1332.596	0.000	24.467
Jiangxi	2848.866	0.000	0.182
Henan	185.471	0.000	0.837
Hubei	1774.350	28.865	0.000
Guangxi	1273.309	0.000	0.087
Sichuan	3872.451	0.000	1.309
Guizhou	658.103	0.000	2.354
Yunnan	420.340	450.851	3.882
Gansu	1017.030	0.000	0.000
Xinjiang	2024.176	0.000	9.265
Mean	911.315	61.571	1.481

In addition, the amount of input slacks in the relatively ineffective area of DEA is also obtained (see Table 3). It can be seen from the results of DEAP2.1 that the investment slack in 18 regions is 0, indicating that there is no redundant investment in these areas, and no discussion is made here. There are 13 regions have excessive input in the storage of industrial solid waste. Excessive storage not only reduces the efficiency of industrial solid waste transfer between recycling, processing and recycling enterprises and the market, but also requires a large number of solid waste storage sites to prevent leakage or spread, increasing costs. The investment in industrial solid waste management in Inner Mongolia, Hubei and Yunnan has not been fully utilized, especially the investment in industrial solid waste management in Inner Mongolia Autonomous Region is 142.889 million yuan. These three regions need to adjust the investment structure of treatment.

#### 4. Conclusion

Based on the principle of “reduction, recycling and reuse” of circular economy, this paper evaluates the efficiency of industrial solid waste recycling in 31 regions of China in 2017. A new improved DEA model is proposed, considering the desirable input, desirable output, undesirable input and undesirable output, and the invalid unit is improved from the perspective that the overall output increase ratio is greater than the overall input increase ratio. The results show that the average recycling efficiency of industrial solid waste is relatively high, and 12 regions are relatively effective in achieving DEA. The technical level of industrial solid waste treatment varies greatly among regions. Nearly half of the regions have excessive storage of solid waste. Therefore, governments in different regions need to encourage waste recycling and processing enterprises to rationally adjust the scale of investment, and carry out technological innovations to diversify the use of industrial solid waste resources and reduce the storage of industrial solid waste. To improve the utilization efficiency of industrial solid waste resources contributes to achieve sustainable economic, social and environmental development.

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