Efficiency Analysis of Industrial Water Treatment in China Based on Two-stage Undesirable Fixed-sum Output DEA Model

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Abstract China is a country with the most water consumption, so it is lack of water resources. Industry has brought serious water pollution while driving economic development, which leads to the destruction of ecological environment. With the improvement of environmental awareness, many scholars have shifted their research direction to how to improve the ecological environment. Most studies consider the whole system as a “black box”, regardless of its internal structure. Therefore, a method to identify inefficiency is necessary and some suggestions for optimization are given. In this paper, a two-stage undesirable fixed-sum output data envelopment analysis (DEA) model is proposed. The industrial chemical oxygen demand (COD) emission during 2011–2015 are adjusted, and the efficiency values are calculated by heuristic search algorithm. The efficiency of 30 provinces and cities is divided into eastern, central and western regions. The model can identify the inefficient stage in industrial system, and find the source of low efficiency in the system. The analysis shows that the efficiency of eastern region is the highest, while the overall efficiency is inclined to the pollutant treatment stage. Finally, the paper puts forward some suggestions for the low efficiency areas, which can save water while ensuring economic benefits, and provide new direction for water pollution reduction and improve the ecological environment.

Keywords industrial wastewater COD emission; two-stage; undesirable fixed-sum outputs

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1 Introduction

Since the reform and opening-up, with the rapid economic development, China's industrial system has made great achievements, and has surpassed the United States to become the world's largest industrial producer^[1]. As is known to all, water is vital to human life and social development. Due to the rapid growth of population and climate change, water shortage has become a worldwide problem^[2, 3]. Due to the large population, the per capita water resources are relatively low, the utilization and protection of water resources in China is particularly important. With the increasing attention to environmental protection, China began to take the road of green economic development^[4]. The state has also formulated some environmental protection policies. For example, in the notice of "The State Council on the Issuance of the Comprehensive Work Plan for Energy Conservation and Emission Reduction During the 13th Five-Year Plan Period", the environmental and resource indicators are further strengthened: by 2020, the energy consumption per 10,000 yuan of GDP will be reduced by 15% compared with 2015, the national COD and AN will be reduced by 10%, and the emissions of SO₂ and NO_x will be reduced by 15%. To achieve this goal, we need to effectively coordinate economic development and enhance the awareness of ecological and environmental protection. In order to coordinate the relationship between economic development and ecological environment protection, it is necessary for us to find a suitable method to evaluate the efficiency between economy and environment.

2 Literature Review

Data envelopment analysis (DEA) is a relatively effective linear programming method for the evaluation of decision-making unit (DMU) input and output. As a non-parametric method, it doesn't need to clarify the functional relationship between variables and dimensionless, as well as it has obvious advantages in dealing with multi-input and output indicators^[5]. Therefore, many scholars apply DEA method to the evaluation of various fields in China, such as regional transportation system (RTS)^[6], aircraft support concept evaluation^[7], regional energy efficiency in China^[8], and also use DEA method to evaluate environmental problems. Wang, et al.^[9] proposed a two-stage model based on DEA to analyze the efficiency of industrial water system. Tian, et al.^[10] used DEA method to analyze the agricultural high-efficiency water-saving efficiency of counties in Xinjiang. Pan, et al.^[11] proposed an integrated DEA model. Deng, et al.^[12] and Chang, et al.^[13] using the slack based measure data envelopment analysis (SBM-DEA) model to estimate China's water resources utilization efficiency. Zhu, et al.^[14] analyzed and evaluated the water resource utilization efficiency based on the DEA method. Li, et al.^[15] evaluated the environmental efficiency of industrial systems with new network slack-based model (NSBM) and DEA window analysis. Hu, et al.^[16] used the ecological efficiency model focusing on undesirable output to evaluate the water utilization efficiency. Wang, et al.^[17] proposed a two-stage DEA approach with game cross efficiency. Song, et al.^[18] made a systematic study on the SBM model considering undesirable output, and further extended the SBM model from the perspective of network analysis. Chen, et al.^[19] analyzed the efficiency of representative sewage treatment plants in 31 provinces. Zhang, et al.^[20] established a super DEA model with undesirable output based on DEA to evaluate the regional water utilization

efficiency in China.

In the actual production process, input minimization and output maximization are followed. When certain resources, such as labor and capital are invested, the desirable output will inevitably produce undesirable output, such as industrial wastewater, waste gas and solid waste. At that time, it can not be judged according to the traditional DEA model that the greater the output, the higher the efficiency. Therefore, when considering the efficiency evaluation of DMU with undesirable output, many scholars have carried out research on DMU with undesirable output. Hailu, et al.^[21] treated undesirable output as input and minimized input and undesirable output at the same time. Seiford and Zhu^[22] performed function transformation on the undesirable output. Here, the undesirable output is still regarded as the output, and the undesirable output multiplied by -1 is transformed into the desirable output form of the bigger the better to evaluate the environmental efficiency. However, the non-negative condition of output may not be met. Therefore, Ali, Seiford^[23] and Pastor^[24] proposed to multiply the undesirable output by -1 first, and then add a large enough positive number to ensure that the undesirable output after processing is positive. In addition, Färe, et al.^[25] took the inverse of the undesirable output through nonlinear function transformation, but the model will become nonlinear and is not conducive to solution.

In practice, DEA method can not only evaluate the cost^[26–29], but also analyze the efficiency of outputs^[30, 31]. The traditional DEA model ignores the internal structure, which makes the calculation efficiency high. Dividing the system into two stages can increase the calculation efficiency accurately^[32–36]. Compared with the existing literature, this paper adopts the two-stage undesirable fixed-sum output DEA model to analyze China's industrial system from 2011 to 2015. In order to respond to the national energy-saving and emission reduction policies, this paper analyzes the problems existing in China's industrial system from the two-stage of industrial water utilization and pollutant treatment. COD can reflect the degree of effluent pollution. High COD indicates serious water pollution^[37]. Because of the country has a clear emission standard for COD, the paper fixed the COD emission of undesirable output so that it is fixed at the emission level of the current year. The first step generates the equilibrium efficient frontier, and the annual fixed industrial COD emissions will be in 30 regions (including provinces, municipalities and autonomous regions, hereinafter collectively referred to as provinces. Tibet, Taiwan, Hong Kong and Macao not included) are adjusted to make all regions effective. The second step uses heuristic search algorithm to obtain the overall efficiency and the efficiency of each stage based on the equilibrium effective frontier, find out the reasons for the low efficiency, and give improvement plans and suggestions.

3 Model Review

3.1 Fixed-sum Output GEEFDEA Model

The GEEFDEA method proposed by Yang et al. consists of two steps^[38]. The first step constructs the equilibrium effective frontier, and the second step calculates the efficiency value for each DMU based on this frontier.

Suppose there are n DMUs and that each DMU _{j} ($j = 1, 2, \dots, n$) consumes m inputs x_{ij} ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$) to produce s variable-sum outputs y_{rj} ($r = 1, 2, \dots, s$), and

l fixed-sum outputs f_{tj} ($t = 1, 2, \dots, l$). Variable-sum outputs can be adjusted freely, while fixed-sum outputs need to satisfy the constraint $\sum_{j=1}^n f_{tj} = F_t$ ($t = 1, 2, \dots, l$), where F_t is a constant. Based on minimal reduction strategy^[39], the model is as follows:

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l w_t \alpha_{tj} \\
 \text{s.t.} \quad & \frac{\sum_{r=1}^s u_r y_{rj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj}) + \mu_0}{\sum_{i=1}^m v_i x_{ij}} = 1, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n \delta_{tj} = 0, \\
 & \alpha_{tj} = \max\{\delta_{tj}, 0\}, \quad j = 1, 2, \dots, n, \\
 & f_{tj} + \delta_{tj} \geq 0, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t \geq 0; \delta_{tj}, \mu_0 \text{ are free,}
 \end{aligned} \tag{1}$$

where u_r, w_t, v_i respectively represent the weight of the r th variable-sum output, the t th fixed-sum output, and the i th input, δ_{tj} represents the adjustment quantity of the t th fixed-sum output of DMU, and δ_{tj} is free, indicating that the adjustment quantity can be positive, negative or zero.

3.2 GEEFDEA Model of Undesirable Fixed-sum Output

The GEEFDEA model of undesirable fixed-sum output is similar to model (1). The difference is that for a certain amount of input, the more desirable output is more effective, while the less undesirable output is better. Therefore, the undesirable output can be regarded as input to minimize it, and model (2) can be obtained as follows:

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l w_t \alpha_{tj} \\
 \text{s.t.} \quad & \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0}{\sum_{i=1}^m v_i x_{ij} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj})} = 1, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n \delta_{tj} = 0, \\
 & \alpha_{tj} = \max\{\delta_{tj}, 0\}, \quad j = 1, 2, \dots, n, \\
 & f_{tj} + \delta_{tj} \geq 0, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t \geq 0; \delta_{tj}, \mu_0 \text{ are free.}
 \end{aligned} \tag{2}$$

Assuming that the optimal solution of the adjustment quantity of the model is δ_{tj}^* , then each DMU _{j} will adjust the fixed-sum output from f_{tj} to $f_{tj} + \delta_{tj}^*$, while ensuring that the input and the undesirable fixed-sum output remain unchanged, and the adjusted DMUs are all effective under the constraint conditions. That is, they are all on the front of equilibrium efficiency.

4 Two-stage Undesirable Fixed-Sum Output DEA Model

Figure 1 shows the two-stage system structure diagram of undesirable fixed-sum output. Assuming that there are n DMU, each DMU is composed of two stages. In the first stage, m

initial inputs x_{ij} ($i = 1, 2, \dots, m; j = 1, 2, \dots, n$) are consumed to obtain B desirable outputs G_{bj} ($b = 1, 2, \dots, B$) and D undesirable outputs Z_{dj} ($d = 1, 2, \dots, D$). All the undesirable outputs in the first stage are put into the second stage as inputs, and q exogenous inputs C_{pj} ($p = 1, 2, \dots, q$) are put into the second stage to get s variable-sum output y_{rj} ($r = 1, 2, \dots, s$) and l undesirable fixed-sum output f_{tj} ($t = 1, 2, \dots, l$).

Figure 1 Two-stage system structure diagram of undesirable fixed-sum output

Since there are undesirable fixed-sum outputs in the second stage, we can build an equilibrium efficient frontier based on the GEEFDEA model and evaluate all DMUs on the frontier. In the study of undesirable outputs, the situation of fixed-sum output is very common. Therefore, it is necessary to make the undesirable fixed-sum output constraints into consideration. For industrial water system, opening the “black box” can evaluate the system better, making the evaluation more accurate. Since there are undesirable outputs in the intermediate outputs and final outputs, we hope that as few undesirable outputs as possible, which has the same property as the input. It is used as input when dealing with undesirable outputs. The obtained two-stage undesirable fixed-sum output DEA model as follows:

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l w_t \alpha_{tj} \\
 \text{s.t.} \quad & \frac{\sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1}{\sum_{i=1}^m v_i x_{ij} + \sum_{d=1}^D n_d Z_{dj}} \leq 1, \quad j = 1, 2, \dots, n, \\
 & \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj})} = 1, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n \delta_{tj} = 0, \\
 & \alpha_{tj} = \max\{\delta_{tj}, 0\}, \quad j = 1, 2, \dots, n, \\
 & f_{tj} + \delta_{tj} \geq 0, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \quad \delta_{tj}, \mu_0^1, \mu_0^2 \text{ are free.}
 \end{aligned} \tag{3}$$

Set the weight of intermediate output Z in the first and second stages to be consistent^[40, 41]. Since the intermediate output are both the undesirable output of the first stage and the desirable inputs of the second stage, we treat the intermediate output Z as the input of the second stage. Although model (3) requires only one step to construct the equilibrium effective front, the fourth constraint makes model (3) difficult to solve, so we use the following model to replace model (3):

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l w_t |\delta_{tj}| \\
 \text{s.t.} \quad & \frac{\sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1}{\sum_{i=1}^m v_i x_{ij} + \sum_{d=1}^D n_d Z_{dj}} \leq 1, \quad j = 1, 2, \dots, n, \\
 & \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj})} = 1, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n \delta_{tj} = 0, \\
 & f_{tj} + \delta_{tj} \geq 0, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \delta_{tj}, \mu_0^1, \mu_0^2 \text{ are free.}
 \end{aligned} \tag{4}$$

Model (4) is a nonlinear model, so it needs to be transformed into a linear model for solving. This transformation requires two steps: The first step, let $\delta'_{tj} = w_t \delta_{tj}$ to get the following model (5):

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l |\delta'_{tj}| \\
 \text{s.t.} \quad & \sum_{b=1}^B \varphi_b G_{bj} - \sum_{i=1}^m v_i x_{ij} - \sum_{d=1}^D n_d Z_{dj} + \mu_0^1 \leq 0, \quad j = 1, 2, \dots, n, \\
 & \sum_{r=1}^s u_r y_{rj} - \sum_{d=1}^D n_d Z_{dj} - \sum_{p=1}^q \lambda_p C_{pj} - \sum_{t=1}^l (w_t f_{tj} + \delta'_{tj}) + \mu_0^2 = 0, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n \delta'_{tj} = 0, \\
 & \sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l (w_t f_{tj} + \delta'_{tj}) \geq K, \quad j = 1, 2, \dots, n, \\
 & w_t f_{tj} + \delta'_{tj} \geq 0, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \delta'_{tj}, \mu_0^1, \mu_0^2 \text{ are free,}
 \end{aligned} \tag{5}$$

where K is a given positive constant whose purpose is to ensure that $\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l (w_t f_{tj} + \delta'_{tj})$ is positive, and here we set $K = 1$ to ensure that the target function of the model is positive. The following is the second step of transformation. The transformation process uses the method of Si, et al.^[42], let $a_{tj} = \frac{1}{2}(|\delta'_{tj}| + \delta'_{tj})$, $b_{tj} = \frac{1}{2}(|\delta'_{tj}| - \delta'_{tj})$ can get

$|\delta'_{tj}| = a_{tj} + b_{tj}$, $\delta'_{tj} = a_{tj} - b_{tj}$, model (5) can be transformed into the following form:

$$\begin{aligned}
 \min \quad & \sum_{j=1}^n \sum_{t=1}^l (a_{tj} + b_{tj}) \\
 \text{s.t.} \quad & \sum_{b=1}^B \varphi_b G_{bj} - \sum_{i=1}^m v_i x_{ij} - \sum_{d=1}^D n_d Z_{dj} + \mu_0^1 \leq 0, \quad j = 1, 2, \dots, n, \\
 & \sum_{r=1}^s u_r y_{rj} - \sum_{d=1}^D n_d Z_{dj} - \sum_{p=1}^q \lambda_p C_{pj} - \sum_{t=1}^l w_t f_{tj} - \sum_{t=1}^l (a_{tj} - b_{tj}) + \mu_0^2 = 0, \quad j = 1, 2, \dots, n, \\
 & \sum_{j=1}^n (a_{tj} - b_{tj}) = 0, \\
 & \sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t f_{tj} + \sum_{t=1}^l (a_{tj} - b_{tj}) \geq K, \quad j = 1, 2, \dots, n, \\
 & w_t f_{tj} + a_{tj} - b_{tj} \geq \pi, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t, n_d, \lambda_p, \varphi_b, a_{tj}, b_{tj} \geq 0; \quad \mu_0^1, \mu_0^2 \text{ are free.}
 \end{aligned} \tag{6}$$

Model (6) can construct the equilibrium effective frontier of all DMU in one step. Because of $\delta'_{tj} = a_{tj} + b_{tj}$ and $\delta'_{tj} = \sum_{t=1}^l w_t^* \delta_{tj}^*$, the undesirable fixed-sum output adjustment can be expressed as

$$\delta_{tj}^* = \frac{\delta'_{tj}}{w_t^*} = \frac{a_{tj} - b_{tj}}{w_t^*},$$

and then we can obtain the adjusted output $f_{tj} \delta_{tj}^*$.

The following is the evaluation model based on the equilibrium effective frontier. The whole system efficiency is equal to the product of efficiency of two stages to calculate efficiency. The model is as follows:

$$\begin{aligned}
 e_k &= \max e_k^1 \times e_k^2 \\
 &= \max \frac{\sum_{b=1}^B \varphi_b G_{bk} + \mu_0^1}{\sum_{i=1}^m v_i x_{ik} + \sum_{d=1}^D n_d Z_{dk}} \times \frac{\sum_{r=1}^s u_r y_{rk} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dk} + \sum_{p=1}^q \lambda_p C_{pk} + \sum_{t=1}^l w_t f_{tk}} \\
 \text{s.t.} \quad & \frac{\sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1}{\sum_{i=1}^m v_i x_{ij} + \sum_{d=1}^D n_d Z_{dj}} \leq 1, \quad j = 1, 2, \dots, n, \\
 & \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj}^*)} \leq 1, \quad j = 1, 2, \dots, n, \\
 & u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \quad \mu_0^1, \mu_0^2 \text{ are free.}
 \end{aligned} \tag{7}$$

The above model is an input-oriented fractional programming. Due to the existence of free variables and exogenous inputs, it is difficult to transform it into a linear model. Therefore, we use the heuristic search algorithm proposed by Liang, et al.^[43] to linearize the model. The heuristic search algorithm fixes the efficiency value of a certain stage in an interval, divide the interval into several parts, and find the optimal overall efficiency value in each DMU. We can fix the efficiency value of the first stage, and obtain the efficiency of the first stage. The model is as follows:

$$\begin{aligned}
e_k^{1\text{CCR}} = \max & \frac{\sum_{b=1}^B \varphi_b G_{bk} + \mu_0^1}{\sum_{i=1}^m v_i x_{ik} + \sum_{d=1}^D n_d Z_{dk}} \\
\text{s.t.} & \frac{\sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1}{\sum_{i=1}^m v_i x_{ij} + \sum_{d=1}^D n_d Z_{dj}} \leq 1, \quad j = 1, 2, \dots, n, \\
& \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj}^*)} \leq 1, \quad j = 1, 2, \dots, n, \\
& \mu_0^1 = \mu_0^2 = 0, \\
& u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0.
\end{aligned} \tag{8}$$

The optimal objective function value of the model is denoted as $e_k^{1\text{CCR}}$. The first two constraints guarantee that the efficiency value of the two-stage does not exceed 1. The third constraint indicates that what we measure is CCR efficiency, so the efficiency value of the first stage can be fixed at $[0, e_k^{1\text{CCR}}]$, that is $e_k^1 \in [0, e_k^{1\text{CCR}}]$.

Since the interval of efficiency value in the first stage is known, model (7) can be converted into:

$$\begin{aligned}
e_k = \max & e_k^1 \times e_k^2 = \max e_k^1 \times \frac{\sum_{r=1}^s u_r y_{rk} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dk} + \sum_{p=1}^q \lambda_p C_{pk} + \sum_{t=1}^l w_t f_{tk}} \\
\text{s.t.} & \frac{\sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1}{\sum_{i=1}^m v_i x_{ij} + \sum_{d=1}^D n_d Z_{dj}} \leq 1, \quad j = 1, 2, \dots, n, \\
& \frac{\sum_{r=1}^s u_r y_{rj} + \mu_0^2}{\sum_{d=1}^D n_d Z_{dj} + \sum_{p=1}^q \lambda_p C_{pj} + \sum_{t=1}^l w_t (f_{tj} + \delta_{tj}^*)} \leq 1, \quad j = 1, 2, \dots, n, \\
& e_k^1 = \frac{\sum_{b=1}^B \varphi_b G_{bk} + \mu_0^1}{\sum_{i=1}^m v_i x_{ik} + \sum_{d=1}^D n_d Z_{dk}}, \\
& e_k^1 \in [0, e_k^{1\text{CCR}}], \\
& u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \quad \mu_0^1, \mu_0^2 \text{ are free.}
\end{aligned} \tag{9}$$

the model can be transformed into the following model through C-C transformation:

$$\begin{aligned}
e_k = \max & e_k^1 \times e_k^2 = \max e_k^1 \times \sum_{r=1}^s u_r y_{rk} + \mu_0^2 \\
\text{s.t.} & \sum_{b=1}^B \varphi_b G_{bj} + \mu_0^1 - \sum_{i=1}^m v_i x_{ij} - \sum_{d=1}^D n_d Z_{dj} \leq 0, \quad j = 1, 2, \dots, n, \\
& \sum_{r=1}^s u_r y_{rj} + \mu_0^2 - \sum_{d=1}^D n_d Z_{dj} - \sum_{p=1}^q \lambda_p C_{pj} - \sum_{t=1}^l w_t (f_{tj} + \delta_{tj}^*) \leq 0, \quad j = 1, 2, \dots, n, \\
& \sum_{b=1}^B \varphi_b G_{bk} + \mu_0^1 - e_k^1 \times \sum_{i=1}^m v_i x_{ik} - e_k^1 \times \sum_{d=1}^D n_d Z_{dk} = 0, \\
& \sum_{d=1}^D n_d Z_{dk} + \sum_{p=1}^q \lambda_p C_{pk} + \sum_{t=1}^l w_t f_{tk} = 1, \\
& e_k^1 \in [0, e_k^{1\text{CCR}}], \\
& u_r, v_i, w_t, n_d, \lambda_p, \varphi_b \geq 0; \quad \mu_0^1, \mu_0^2 \text{ are free.}
\end{aligned} \tag{10}$$

Model (10) is the final efficiency evaluation model. In order to calculate the optimal solution of the model, let $e_k^1 = e_k^{1CCR} - t\varepsilon$, and ε be the step size of the heuristic search algorithm. The smaller the step size is, the more accurate the result will be. Let $\varepsilon = 0.005$, $t = 0, 1, \dots, [t_{\max}] + 1$, where $[t_{\max}]$ is the largest integer value that $\frac{e_k^{1CCR}}{\varepsilon}$ can obtain, when t increases from 0 to $[t_{\max}] + 1$. For each t , we have a $e_k^1(t)$, and the global optimal solution corresponding to each t is denoted as $e_k(t)$, then the global optimal solution of the total efficiency of the whole two-stage system is $e_k^* = \max e_k(t)$. At the same time, the efficiency value of the first stage is $e_k^1 = e_k^1(t^*) = e_k^{1CCR} - t^*\varepsilon$, where $t^* = \min\{t | e_k^* = e_k(t)\}$. Therefore, the corresponding efficiency value of the second stage is $e_k^2 = \frac{e_k^*}{e_k^1}$, then $e_k^* = \max e_k^1 \times e_k^2$. We get the global optimal solution and the unique two-stage decomposition efficiency.

5 Application in China's Regional Industrial System

5.1 Indicators and Data Sources

The development of industry will bring serious water pollution. We divide the industrial system of China's 30 provinces into two stages. The first stage is industrial water utilization stage and the second stage is pollutant treatment stage. The specific structure is shown in Figure 2.

Figure 2 Two-stage structure of industrial production system

With the emphasis on ecological environment, many scholars began to apply DEA method to evaluate the utilization efficiency of water resources in China. For example, based on the two-stage SBM model of undesirable output, Ren, et al. selected water resources, capital, labor and additional pollutant treatment investment as input indicators, GDP, COD and AN as output indicators to analyze the efficiency of inter provincial water resources in China^[44]. Xie, et al. used industrial water consumption, power consumption, labor, industrial pollution and wastewater treatment investment as input indicators, industrial wastewater COD emission and total industrial output value as output indicators, and used DEA to allocate wastewater emission^[45]. In addition, there are many studies on input-output indicators of water resources utilization^[46–50].

In this paper, according to previous studies on the utilization of water resources, the input-output indicators select the industrial employees, industrial water consumption and industrial fixed assets investment as input indicators in industrial water utilization stage. Industrial added value can directly reflect the economic value brought by industrial water utilization stage, so

it is regarded as desirable output. Industrial wastewater treatment capacity is regarded as undesirable output, and we treat it as input in the pollutant treatment stage. When the generated industrial wastewater treatment capacity is treated in the pollutant treatment stage, we take the industrial wastewater treatment capacity as input index. In addition, the industrial wastewater treatment investment is exogenous input, and the industrial wastewater discharge and industrial COD emission are undesirable outputs, in which the industrial COD emission is fixed-sum output.

Since the National Bureau of statistics stopped publishing the data of industrial wastewater treatment capacity and industrial COD emission after 2015. In this section, the two-stage undesirable fixed-sum output DEA model proposed in this paper is applied to analyze the environmental efficiency of industrial water system in 30 provinces during the 12th Five Year Plan (2011–2015) to verify the rationality of the proposed model. The index data of industrial employees, industrial water consumption, industrial fixed assets investment and industrial added value are from the “China Statistical Yearbook” (2011–2015), and the relevant data of industrial wastewater treatment investment, industrial wastewater discharge, industrial wastewater treatment capacity and industrial COD emission are from the “China Environmental Statistical Yearbook” (2011–2015). The relevant descriptions of the inputs and outputs of the industrial water system in each province are shown in Table 1.

Table 1 Descriptive statistical analysis results of original data

Category	Stage	Variable	Unit	Mean	Std. Dev	Max	Min
Inputs	1	Industrial employees	10,000 persons	192.1	182.3	1055.4	11.4
	1	Industrial water consumption	Billion cubic meters	46.5	45.4	239.0	2.4
	1	Industrial fixed assets investment	100 million yuan	5898.2	4681.5	23302.0	245.1
	2	Industrial wastewater treatment investment	10,000 yuan	43649.1	45451.9	295540.0	90.0
Desirable output	1	Industrial added value	100 million yuan	8646.7	6916.5	30259.5	472.4
Undesirable output	2	Industrial wastewater discharge	10,000 tons	71129.2	56843.2	246298.0	6744.0
	2	Industrial COD emission	tons	107805.8	59734.0	243959.0	4738.0
Join variable	1~2	Industrial wastewater treatment capacity	10,000 tons	169638.1	160182.9	933519.0	6474.0

5.2 Analysis of Regional Differences

China's Seventh Five Year Plan (1986–1990) proposed to divide the country into three major economic regions, namely eastern, central and western regions. Industrial water can bring economic benefits. Due to the difference of geographical location, the distribution of water resources in various regions of China is not balanced. In Table 2, the efficiency values of the whole system from 2011 to 2015 are listed according to the method we proposed, and compared with the BCC efficiency. BCC model is used to measure pure technology and scale efficiency, assuming that DMU is in variable return to scale. But BCC model regards the industrial water system as a “black box”, it is using the initial input and final output calculation efficiency value, ignoring system internal structure, which greatly reduces the recognition of inefficient DMU in the system. This paper open the black box, makes the evaluation of DMU more accurate and reasonable. In terms of overall efficiency, among the 11 provinces in the eastern region: Beijing, Tianjin, Shanghai and Hainan are effective, only Jilin is effective in the central region, and Inner Mongolia, Chongqing, Guizhou, Shaanxi and Qinghai are effective in the western region.

Among the 30 provinces, Beijing has the highest efficiency, which is 24.75, and Jiangsu has the lowest efficiency, which is 0.02. In Table 3, we can analyze the reasons for the efficiency difference from the efficiency values of the two stages. Beijing ranks first in the efficiency value in both stages. In the first stage, due to the development of industrial technology and efficient water facilities, water resources have been fully utilized. In the second stage, Beijing has little industrial wastewater treatment capacity, little investment in wastewater treatment, and the industrial COD emission is the lowest among the 30 provinces, so it has high efficiency in the second stage. The efficiency of Jiangsu province in the first stage is 0.79, and the efficiency in the second stage is 0.03, ranking 30. Due to the rapid economic development of coastal areas in Jiangsu, most industrial enterprises not only brings economic benefits, but also produces a lot of industrial wastewater, and a large amount of COD emission. Among them, cotton and chemical fiber products manufacturing and other traditional industries have the largest industrial COD emission intensity, which causes great ecological damage and low efficiency in the second stage. It shows that the growth of economic scale is accompanied by the pressure of pollutant emission. Comparing the two stages efficiency with the overall efficiency, we can find that the overall efficiency is more inclined to the efficiency value of pollutant treatment stage, which shows that the second stage plays a decisive role in the whole system. Excessive industrial COD emission and insufficient treatment in various regions will lead to low overall efficiency, which also reflects the importance of pollutant treatment in the industrial system.

Comparing the efficiency values of the eastern, central and western regions from Table 3, there are 15 regions with the efficiency value of 0.8~1 in the first stage, which are efficient in the industrial system. Among them, Beijing, Tianjin, Shanghai and Inner Mongolia are effective in the first stage, indicating that these four provinces have reached the best state in the first stage, and the input-output structure is reasonable. Among the five-year average efficiency, the three provinces with the lowest efficiency in the first stage are Ningxia, Gansu and Xinjiang, which are 0.56, 0.61 and 0.62, respectively. There are great room for improvement in the industrial water utilization efficiency, so these provinces should pay more attention to the distribution of water resources in the future. In the past five years, the first stage efficiency of 30 provinces in

Table 2 Efficiency of industrial system in different provinces from 2011 to 2015

Region	Overall efficiency						BCC efficiency					
	2011	2012	2013	2014	2015	average	2011	2012	2013	2014	2015	average
Beijing	22.94	24.76	23.70	24.09	28.27	24.75	1.00	1.00	1.00	1.00	1.00	1.00
Tianjin	6.42	5.60	5.37	4.91	4.54	5.37	1.00	1.00	1.00	1.00	1.00	1.00
Hebei	0.47	0.42	0.46	0.42	0.55	0.46	1.00	0.99	1.00	0.95	1.00	0.99
Liaoning	0.87	0.90	1.05	0.93	1.02	0.96	0.92	1.00	0.98	0.96	1.00	0.97
Shanghai	5.10	5.00	4.82	4.89	4.73	4.91	1.00	1.00	1.00	1.00	1.00	1.00
Jiangsu	0.02	0.02	0.02	0.03	0.02	0.02	0.91	1.00	0.79	0.74	0.74	0.84
Zhejiang	0.23	0.21	0.24	0.26	0.27	0.24	0.90	0.84	0.94	0.92	0.97	0.91
Fujian	0.29	0.57	0.76	0.80	0.81	0.64	0.59	0.62	0.76	0.77	0.79	0.71
Shandong	0.32	0.27	0.21	0.16	0.13	0.22	0.99	0.92	0.87	0.87	0.89	0.91
Guangdong	0.21	0.16	0.14	0.09	0.12	0.14	1.00	1.00	1.00	0.79	0.77	0.91
Hainan	9.54	8.75	8.06	10.11	13.03	9.90	1.00	1.00	1.00	1.00	1.00	1.00
Eastern	4.22	4.24	4.08	4.24	4.86	4.33	0.94	0.94	0.94	0.91	0.92	0.93
Shanxi	1.31	1.03	0.94	0.89	0.75	0.99	0.84	0.69	0.62	0.55	0.46	0.63
Jilin	1.48	1.28	1.57	1.52	1.53	1.47	0.89	1.00	0.98	1.00	0.86	0.95
Heilongjiang	1.00	0.85	0.89	0.95	0.82	0.90	0.85	1.00	0.74	0.84	0.64	0.81
Anhui	0.93	0.98	0.97	1.03	0.78	0.94	0.94	1.00	0.98	0.88	0.88	0.93
Jiangxi	0.66	0.72	0.75	0.87	0.55	0.71	0.85	0.84	0.69	0.68	0.61	0.73
Henan	0.33	0.32	0.26	0.24	0.22	0.27	0.99	0.99	0.68	0.63	0.64	0.79
Hubei	0.49	0.57	0.57	0.59	0.54	0.55	0.79	0.85	0.90	0.84	0.85	0.84
Hunan	0.49	0.55	0.61	0.69	0.62	0.59	0.80	0.85	0.93	0.98	0.96	0.90
Central	0.83	0.79	0.82	0.85	0.73	0.80	0.87	0.90	0.81	0.80	0.74	0.82
Inner Mongolia	1.55	1.53	1.39	1.25	1.21	1.39	1.00	1.00	1.00	1.00	1.00	1.00
Guangxi	0.43	0.36	0.45	0.55	0.54	0.47	0.86	0.81	0.84	0.89	0.94	0.87
Chongqing	2.53	2.68	2.08	1.96	2.09	2.27	0.86	0.92	0.89	0.94	0.89	0.90
Sichuan	0.75	0.86	0.91	0.92	0.81	0.85	0.84	0.90	0.88	0.93	0.88	0.88
Guizhou	1.20	1.24	1.55	1.52	1.71	1.44	0.92	0.63	0.75	0.81	0.89	0.80
Yunnan	0.46	0.46	0.51	0.54	0.54	0.50	0.60	0.61	0.69	0.72	0.71	0.67
Shaanxi	1.31	1.35	1.20	1.18	0.86	1.18	0.99	0.97	0.88	0.89	0.80	0.91
Gansu	1.20	1.03	0.92	0.93	0.77	0.97	0.67	0.67	0.64	0.60	0.55	0.63
Qinghai	3.00	2.91	2.44	2.59	2.15	2.62	1.00	1.00	1.00	1.00	1.00	1.00
Ningxia	0.83	0.79	0.81	0.83	0.95	0.84	0.78	0.74	0.79	0.74	0.76	0.76
Xinjiang	0.55	0.51	0.43	0.44	0.34	0.45	0.72	0.67	0.66	0.65	0.58	0.66
Western	1.25	1.25	1.15	1.15	1.09	1.18	0.84	0.81	0.82	0.83	0.82	0.82
National	2.23	2.22	2.14	2.21	2.38	2.23	0.88	0.88	0.86	0.85	0.84	0.86

Table 3 Efficiency of water utilization and treatment in 30 provinces of China from 2011 to 2015

Region	Stage 1 efficiency						Stage 2 efficiency					
	2011	2012	2013	2014	2015	average	2011	2012	2013	2014	2015	average
Beijing	1.00	1.00	1.00	1.00	1.00	1.00	22.94	24.76	23.70	24.09	28.27	24.75
Tianjin	1.00	1.00	1.00	1.00	1.00	1.00	6.42	5.60	5.37	4.91	4.54	5.37
Hebei	1.00	0.99	1.00	0.95	0.93	0.97	0.47	0.42	0.46	0.45	0.60	0.48
Liaoning	0.88	0.89	0.88	0.90	0.93	0.90	0.99	1.02	1.19	1.03	1.10	1.07
Shanghai	1.00	1.00	1.00	1.00	1.00	1.00	5.10	5.00	4.82	4.89	4.73	4.91
Jiangsu	0.84	0.88	0.79	0.74	0.72	0.79	0.03	0.03	0.03	0.03	0.03	0.03
Zhejiang	0.90	0.84	0.94	0.92	0.97	0.91	0.26	0.25	0.25	0.28	0.28	0.26
Fujian	0.54	0.57	0.76	0.77	0.78	0.68	0.54	1.01	1.00	1.03	1.04	0.92
Shandong	0.99	0.92	0.86	0.85	0.85	0.89	0.32	0.29	0.24	0.19	0.15	0.24
Guangdong	1.00	1.00	0.82	0.78	0.77	0.87	0.21	0.16	0.17	0.11	0.16	0.16
Hainan	0.72	0.70	0.68	0.74	0.84	0.74	13.16	12.46	11.93	13.59	15.53	13.33
Eastern	0.90	0.89	0.88	0.88	0.89	0.89	4.58	4.64	4.47	4.60	5.13	4.68
Shanxi	0.84	0.69	0.62	0.55	0.45	0.63	1.57	1.50	1.53	1.62	1.64	1.57
Jilin	0.82	0.74	0.82	0.83	0.81	0.80	1.80	1.73	1.92	1.84	1.88	1.83
Heilongjiang	0.73	0.68	0.70	0.73	0.64	0.70	1.37	1.25	1.27	1.30	1.29	1.30
Anhui	0.71	0.75	0.79	0.82	0.68	0.75	1.30	1.31	1.22	1.26	1.15	1.25
Jiangxi	0.63	0.62	0.65	0.65	0.56	0.62	1.04	1.16	1.15	1.33	0.99	1.14
Henan	0.82	0.81	0.67	0.63	0.58	0.70	0.40	0.40	0.39	0.39	0.38	0.39
Hubei	0.70	0.76	0.76	0.78	0.72	0.74	0.69	0.75	0.76	0.75	0.75	0.74
Hunan	0.80	0.85	0.93	0.98	0.85	0.88	0.61	0.65	0.65	0.70	0.74	0.67
Central	0.76	0.74	0.74	0.75	0.66	0.73	1.10	1.09	1.11	1.15	1.10	1.11
Inner Mongolia	1.00	1.00	1.00	1.00	1.00	1.00	1.55	1.53	1.39	1.25	1.21	1.39
Guangxi	0.86	0.81	0.84	0.89	0.78	0.83	0.50	0.44	0.53	0.62	0.69	0.56
Chongqing	1.00	0.93	0.82	0.82	0.88	0.89	2.53	2.87	2.55	2.39	2.37	2.54
Sichuan	0.83	0.89	0.88	0.93	0.88	0.88	0.90	0.97	1.03	0.99	0.92	0.96
Guizhou	0.50	0.55	0.71	0.79	0.85	0.68	2.37	2.25	2.18	1.92	2.00	2.15
Yunnan	0.58	0.59	0.68	0.71	0.70	0.65	0.79	0.78	0.75	0.76	0.76	0.77
Shaanxi	0.98	0.98	0.88	0.89	0.80	0.91	1.33	1.38	1.35	1.32	1.08	1.29
Gansu	0.74	0.64	0.60	0.59	0.49	0.61	1.62	1.60	1.55	1.56	1.57	1.58
Qinghai	0.75	0.78	0.69	0.73	0.63	0.72	4.02	3.71	3.52	3.54	3.40	3.64
Ningxia	0.59	0.55	0.58	0.58	0.49	0.56	1.40	1.43	1.39	1.42	1.94	1.51
Xinjiang	0.68	0.67	0.62	0.64	0.50	0.62	0.80	0.76	0.70	0.69	0.68	0.73
Western	0.77	0.76	0.75	0.78	0.73	0.76	1.62	1.61	1.54	1.50	1.51	1.56
National	0.81	0.80	0.80	0.81	0.77	0.80	2.57	2.58	2.50	2.54	2.73	2.58

China has shown differences. Most of the provinces with high efficiency are concentrated in the eastern region. The average value of the first stage efficiency in the eastern region is 0.89, in the central region is 0.73, and in the western region is 0.76. They have not achieved effective efficiency, but they are greater than 0.7.

Figure 3 Average efficiency of industrial water utilization in 2011–2015

Figure 3 demonstrate that the difference of the first stage efficiency between the eastern, central and western regions of China from 2011 to 2015. The eastern region has the highest efficiency and the central region has the lowest efficiency. This is because the eastern region is mostly coastal provinces, with relatively concentrated industries and developed economy, and pays more attention to the introduction of technology. Due to better resources and jobs in the eastern region, China's labor force is gradually concentrated from the central and western regions to the eastern region, and a large number of excellent talents are introduced. At the same time, the awareness of environmental protection is stronger than that of the central and western regions, the industrial development is relatively mature, and more attention is paid to the recycling of industrial water, which is conducive to the improvement of industrial water efficiency. Due to the difference of geographical location, the development level of central region is relatively backward. In order to accelerate economic development and improve GDP, the emission of industrial wastewater increases significantly, resulting in waste of water resources and low input-output benefits. Compared with the eastern and central regions, the western region mainly develops the local economy by rough processing mineral resources and heavy industry. The technical level is low, water resources are scarce, and the protection of water resources is not enough. The production and processing is mainly extensive, resulting in low efficiency. However, the efficiency in Inner Mongolia has been effective, due to there are few large-scale production enterprises in Inner Mongolia, the output and investment are low, and the water use structure is relatively reasonable, so it can achieve effective.

The second stage is the pollutant treatment stage. Regarding industrial COD emission as undesirable fixed-sum output, but we treat it as input in the model, which is more in line with

the objective fact of input-oriented. Among them, there are 5 effective areas in the eastern, namely Beijing, Tianjin, Liaoning, Shanghai and Hainan. There are 5 effective areas in the middle, namely Shanxi, Jilin, Heilongjiang, Anhui and Jiangxi. There are 7 effective areas in the western, namely Inner Mongolia, Chongqing, Guizhou, Shaanxi, Gansu, Qinghai and Ningxia. Due to the high efficiency of Beijing and Hainan in the second stage (the average efficiency of Beijing is 24.75 and Hainan is 9.9), the average efficiency of the eastern region is 4.68, which is a relatively high efficiency value.

Figure 4 Average efficiency of pollutant treatment stage from 2011 to 2015

Figure 4 demonstrates that the efficiency values of the pollutant treatment stage in the eastern region reached the lowest in 2013, which is 4.47, and then increased significantly, reaching the maximum in 2015. The average efficiency value of the central region is 1.11, and the average efficiency value of the western region is 1.56. We observe that the pollutant treatment stage shows the characteristics related to geographical location in different regions, which is also closely related to national policies. In October 2010, the State Council promulgated “the Decision of the State Council on Accelerating the Cultivation and Development of Strategic Emerging Industries”, which regarded energy conservation and environmental protection as one of the seven strategic emerging industries. In April 2015, the State Council promulgated the “Water Pollution Prevention and Control Action Plan” (the “Ten Articles on Water”), supervised industrial wastewater treatment for the first time, and issued the notice on energy conservation and emission reduction in the “12th Five Year Plan”, “13th Five Year Plan”, which shows that while vigorously developing the economy, China has begun to pay attention to the protection of environmental resources. Under the national policy, China’s wastewater treatment technology has also been greatly improved, and gradually realize the coordinated development of economy and environmental protection.

These results demonstrate that for different provinces, the industrial water utilization and pollution treatment efficiency showed different trends from 2011 to 2015. Industrial system efficiency is the product of industrial water utilization and pollutant treatment efficiency, and the average value of overall efficiency in most regions is between the average efficiency values of the two stages, indicating that China’s industrial system efficiency is affected by the efficiency of the two stages. In Table 2, we list the efficiency values that treat each province as a “black

box". We compare the average efficiency of fixed-sum output of each province in the two stages from 2011 to 2015 with the average efficiency of BCC. There are 6 effective regions in BCC efficiency, namely Beijing, Tianjin, Shanghai, Hainan, Inner Mongolia and Qinghai. Their efficiency values are all 1. It is impossible to effectively rank to judge who is more efficient. The two-stage undesirable fixed-sum output DEA model can rank effective DMUs, that is, the higher the efficiency, the higher the ranking.

Through the two-stage undesirable fixed-sum output DEA model proposed in this paper, we can analyze the reasons for the low efficiency of each province and put forward effective improvement schemes. As shown in Figure 5, the average environmental efficiency of the two stages is used to draw the efficiency matrix. The horizontal axis of the efficiency matrix represents the efficiency of the industrial water utilization stage, and the vertical axis represents the efficiency of the pollutant treatment stage^[51]. The matrix is divided into four quadrants, each province is in four quadrants, of which the average efficiency of the industrial water utilization stage is 0.8, The average efficiency of pollutant treatment stage is 2.58. We can put forward suggestions and policies to improve environmental efficiency according to the location of each province. Provinces in the first quadrant have high efficiency values in both water utilization stage and pollutant treatment stage. Beijing, Tianjin and Shanghai are in the first quadrant, which perform well in both stages. Hainan and Qinghai are in the second quadrant. Provinces in this quadrant have low efficiency in water utilization stage and high efficiency in pollutant treatment stage, Shanxi, Heilongjiang, Jiangsu, Anhui, Fujian, Jiangxi, Henan, Hubei, Guizhou, Yunnan, Gansu, Ningxia and Xinjiang are in the third quadrant, these provinces in this quadrant have low efficiency in both stages. Hebei, Inner Mongolia, Liaoning, Jilin, Zhejiang, Shandong, Hunan, Guangdong, Guangxi, Chongqing, Sichuan and Shaanxi are in the fourth quadrant, these provinces have high efficiency in the water utilization stage and low efficiency in the pollutant treatment stage. For example, Hebei has high efficiency in the water utilization stage, but it does not reach the average value in the pollutant treatment stage. If we want to improve the efficiency in the whole system, we should increase investment in the pollutant treatment stage and pay more attention to environmental protection while accelerating economic development.

Figure 5 Environmental efficiency description of two stages

Comparing the two-stage overall efficiency values of 30 provinces according to the eastern, central and western regions with the national efficiency. The eastern region has the best efficiency in the industrial water system is presented in Figure 6. Most of the eastern regions are coastal regions, with relatively perfect infrastructure, developed industrial industries and advanced water equipment, which is higher than the resource allocation in the central and western regions. Due to the backward economy, the number of industrial enterprises above designated size in the western region is far less than that in the eastern region, and many regions are dominated by tourism, the industrialization level is relatively low, which makes the industrial COD emission lower than that in the eastern and central regions. The central region is in a period of vigorous development. In order to drive the national economic development, industry is the largest industry. With the development of industry, the output increases and the pollutant emission is becoming more and more serious. In the pursuit of economy, the treatment of industrial wastewater is particularly important. While pursuing economic development, the central region should introduce advanced water-saving and emission reduction technologies to ensure the synchronous development of economy and environment.

Figure 6 Line chart of system efficiency in different regions

6 Conclusions and Policy Recommendations

The level of industrialization represents the speed of a country's economic development, and the ecological environment determines whether the industrialization development can be long-term. Since the reform and opening-up, China has taken economic construction as the center and vigorously developed productive forces. Up to now, China has established the concept of sustainable development precisely because China has realized that it can not exchange economic growth at the cost of consuming resources and destroying the ecological environment. In the production process, apart from the desirable output generated by the treatment consumption input, it also produce undesirable output. The state has restricted the emission of COD in industrial wastewater. Therefore, it seems reasonable to fix the annual industrial COD emission in the current environment efficiency analysis of the 30 provinces and cities. The traditional DEA model regards the industrial water system as a "black box", does not consider the internal structure, can only analyze the efficiency of the whole system from the initial input and final

output. With the understanding of the interior of industrial water system, a DEA model with two-stage network structure is proposed. The method proposed in this paper can identify inefficient provinces, provide more accurate information for decision-makers, facilitate decision-makers to put forward improvement policies and suggestions, and provide effective schemes for the improvement of ecological environment.

1) Industrial water utilization stage

In order to make each region have sufficient water resources, China has implemented various plans and strategies, such as “the South-to-North Water Transfer Project” and “the Three Gorges Dam Project”, to maintain the balance of water resources. In “the Guidance Catalogue for Industrial Structure Adjustment”, it proposes efficient water transmission and distribution, water-saving irrigation technology, encouraging comprehensive utilization of environmental protection and resource conservation, implementing national water-saving actions, strengthening water-saving and efficiency in agriculture, reducing industrial water emissions, and encouraging water recycling. For traditional industries with high water consumption and low efficiency, it is necessary to accelerate the transformation of management forms, optimize the industrial structure, eliminate backward production capacity according to law, reduce the production of industrial wastewater from the source, and introduce new water-saving and emission reduction technologies in areas with conditions. It is necessary to strengthen industrial water recycling and take the road of sustainable development.

2) Pollutant treatment stage

Rapid economic growth is the main reason for the increase of pollutants. Provinces with strong industrial industries, such as Jiangsu, Guangdong and Hebei, have high industrial added value, but the ecological pollution problem is also very serious. While maintaining economic development, these provinces should make full use of their own economic and talent advantages, improve the cleaner production level of enterprises, improve the technical improvement of industrial wastewater treatment facilities, ensure the synchronous development of pollution control and economy, and take the new road of industrialization. Xinjiang has redundant input but insufficient output, slow GDP growth and high COD emission. It is necessary to increase the investment in industrial wastewater treatment facilities to ensure that COD emission meets the standard.

3) Policy suggestion

In order to build a society in which human beings and ecology coexist harmoniously, relevant departments should improve the legal system, actively formulate policies conducive to ecological environment protection and pollutant emission, strengthen inter regional cooperation and learn from areas with good ecological environment. Enterprises should adhere to optimizing industrial structure and promoting technological progress. All regions can take the pollutant emission compliance rate as the work assessment of local governments and enterprises. All provinces should vigorously introduce scientific and technological innovative talents, improve the compliance rate of industrial wastewater treatment, actively publicize water conservation, improve the awareness of water conservation and emission reduction of enterprises. Improve the level of public participation, and promote the coordination between economic and social development and ecological environment.

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