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Study on Operation Efficiency of Urban Sewage Treatment Plants Based on DEA Model Analysis

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Abstract: The operation efficiency of urban sewage treatment plants directly affects the economic benefits of investment and operation units. Most sewage treatment plants are constructed in BOT mode. It is particularly necessary to discuss the input-output relationship of sewage treatment plants from the perspective of engineering economy. With the help of the application of data envelopment analysis (DEA) in efficiency evaluation, this paper selects four indicators of total project investment, annual power consumption, annual pharmaceutical cost and number of employees as input variables, and takes the reduction of chemical oxygen demand as output variable to analyze. We calculate and analyze the overall operation efficiency, the efficiency value of DEA effective units and the efficiency value of DEA ineffective units, so as to provide experience for other similar plants.

1. Introduction

With the continuous and rapid development of China's economy, the resulting environmental pollution problem is becoming more and more serious, particularly the water pollution problem. The State Council issued the Action Plan for Water Pollution Prevention and Control (GF [2015] No. 17) in April 2015, proposing to establish a new mechanism for water pollution prevention and control with "government leadership, enterprise governance, market driven, and public participation", focusing on improving water environment quality. It is proposed that by 2020, the national water environment quality will be improved in stages, and the seriously polluted water bodies will be reduced significantly. Urban domestic sewage is an important source of water pollution, and urban sewage treatment plants play an important role in urban water pollution control. In order to solve the increasingly prominent problem of water environment pollution, it is necessary to accelerate the construction of urban sewage treatment plants and expand their treatment scale, but also to improve the operation efficiency of sewage treatment plants.

In recent years, China's urban construction has been accelerating, and the number of urban centralized domestic sewage treatment plants has been increasing. The operation of these sewage treatment plants has brought great improvement to the local water environment. According to the Notice of the State Council on Printing and Distributing the Action Plan for Water Pollution

Prevention and Control (GF [2015] No. 17), urban sewage treatment facilities in sensitive areas (key lakes, key reservoirs, and catchment areas in coastal waters) should fully meet the Class A discharge standard by the end of 2017. In cities where the water quality in the built-up area fails to meet the Class IV standard for surface water, the new urban sewage treatment facilities shall comply with the Class A discharge standard. According to the requirements of the national new urbanization plan, by 2020, all counties and key towns in the country will have sewage collection and treatment capacity, and the sewage treatment rates of counties and cities will reach about 85% and 95% respectively. Beijing Tianjin Hebei, Yangtze River Delta, Pearl River Delta and other regions should be completed one year ahead of schedule. Therefore, it is necessary to discuss the input-output relationship of urban domestic sewage treatment plants from the perspective of engineering economy, so as to provide reference for the economic benefits of the subsequent construction of urban domestic sewage treatment plants.

The domestic understanding of the efficiency of sewage treatment plants mainly comes from qualitative judgment, lacking systematic quantitative research. Chu Junying et al. [1] conducted a quantitative analysis on the investment efficiency of urban sewage treatment plants in China with the index method, and compared the resource allocation efficiency of urban sewage treatment plants in China with the DEA method. They concluded that capital has the largest output elasticity to urban sewage treatment plants in China, followed by operating power consumption, and then labor. Zhao Qiang et al. [2] used DEA method to evaluate the relative effectiveness of the scale and technology of 7 sewage treatment plants in Tianjin, Shanghai, Haikou, etc., and pointed out their improvement values. Wang Furong et al. [3] constructed a quantitative evaluation model for the operational efficiency of sewage treatment plants by using DEA method in efficiency evaluation, evaluated 22 sewage treatment plants of the same scale and pointed out the improvement direction. Wang Jiawei et al. [4] built a cost model for reducing the total amount of COD and ammonia nitrogen in sewage treatment plants and found that the operation cost could stimulate the improvement of emission reduction effectiveness, and there were other influencing factors including inlet and outlet concentration, design scale, water load rate, etc. A few scholars conduct efficiency evaluation after quantitatively identifying the influencing factors of the efficiency of sewage treatment plants, so as to select more scientific and comparable evaluation indicators to ensure the reliability of the evaluation results. For example, Zhao Zebin et al. [5] used the correlation analysis method to determine the influencing factors of urban sewage treatment efficiency in Northeast China, and concluded that the sewage treatment efficiency increased with the increase of investment costs.

Scholars outside China started to study the factors affecting the efficiency of sewage treatment plants earlier, and the research focus varies in different periods, which has a deeper research foundation. Before the 21st century, foreign scholars paid more attention to the impact of influent water quality on sewage treatment efficiency, and paid less attention to environmental factors. In the past 20-30 years, with the attention paid by countries to energy conservation and emission reduction, large-scale construction of sewage treatment plants has been carried out in various regions, and the energy consumption cost, which accounts for 25% - 40% of the total operating cost of sewage treatment plants, has increased by 30% - 40%, The energy consumption of sewage treatment plants has gradually become the focus of current efficiency research. For example, Hernandez-Sancho et al. [6] analyzed the energy efficiency of 177 sewage treatment plants in Spain and found that the size of the wastewater treatment plant, the removal rate of organic matter and the type of aerator were the key influencing factors, while the age of the plant construction was not critical. JaimeRojas, ToshkoZheev found that the key factors affecting energy consumption optimization are gas flow, reaction time and sludge flow through the aerobic digestion model of automatic temperature adaptatio. In addition, some scholars pay attention to the water pollutant removal efficiency of the sewage treatment plant and find that the sewage treatment process has the greatest impact on it [7,8].

Moreover, some scholars suggested that energy efficiency should be evaluated in combination with water quality and water pollutant removal rate, and energy efficiency should be analyzed through sewage treatment process and equipment [9].

Based on the actual survey data, this study used DEA method to construct a quantitative evaluation model for the operation efficiency of sewage treatment plants, and used this model to scientifically evaluate the operation efficiency of urban domestic sewage treatment plants. The conclusion obtained by using the relevant formula points out the direction for improving the efficiency of urban sewage treatment plants.

2. DEA Model Method and Characteristics

Data Envelopment Analysis (DEA for short) is an efficiency evaluation method proposed by operations research experts James and Cooper, who use mathematical programming models to evaluate the relative effectiveness (called DEA effectiveness) between decision making units (DMUs for short) with multiple inputs and outputs.

The essence of DEA method is that if there are n units or departments (called DMUs), these n DMUs are comparable. Each DMU has m types of inputs and s types of outputs. The actual input and output data of these DMUs can be used to determine the effective production frontier, and then the relative efficiency of each DMU can be measured according to the deviation between each DMU and the effective production frontier. Common evaluation models are C2R model and C2GS2 model. In the process of actual processing and operation, some input elements cannot be changed. In the actual processing process, some input elements cannot be changed. For this case, R.D.Banker et al. gives a DEA model to evaluate the relative effectiveness of DMU with invariant input.

The main features of Data Envelopment Analysis (DEA).

(1) Data can self-generate efficiency boundary.

(2) It is a structural model suitable for multi input and multi output.

(3) It does not need to establish a functional equation to determine the corresponding parameters, but uses the structural characteristics of the input-output data set to form an efficiency boundary containing all data points. The boundary is formed by linear combination of data points with relatively optimal efficiency (the efficiency value is equal to 1). The other points can be compared with this boundary linearly to calculate the corresponding efficiency ratio (ER). Obviously, the value range of ER is $0 \leq ER \leq 1$. Since this analysis is based on the selected data set, the calculated relative efficiency values are within the structure of the data itself.

(4) It is without loss of generality. There are m inputs and k outputs. There are n groups of data in total. Let X be the input data matrix ($m \times n$), Y is the output data matrix ($k \times n$), then there are the following matrices.

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1m} \\ x_{21} & x_{22} & \cdots & x_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ x_{n1} & x_{n2} & \cdots & x_{nm} \end{bmatrix} \tag{1}$$

$$Y = \begin{bmatrix} y_{11} & y_{12} & \cdots & y_{1k} \\ y_{21} & y_{22} & \cdots & y_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ y_{n1} & y_{n2} & \cdots & y_{nk} \end{bmatrix} \tag{2}$$

λ is the row matrix of n-dimensional variables.

$$\lambda = (\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_n) \tag{3}$$

The input matrix and output matrix of data points that desire efficiency.

$$\hat{X} = (x_{i1} \quad x_{i2} \quad \cdots \quad x_{im}) \tag{4}$$

$$\hat{Y} = (y_{i1} \quad y_{i2} \quad \cdots \quad y_{ik}) \tag{5}$$

Then its efficiency value ER can be obtained by solving the following linear programming problems.

The objective function is as follow.

$$\theta^* = \min_{\theta,\lambda} \theta \tag{6}$$

The constraints are as follows.

$$\lambda Y \geq \hat{Y} \tag{7}$$

$$\theta\hat{X} - \lambda X \geq 0 \tag{8}$$

$$\lambda \geq 0 \tag{9}$$

The minimum value of single variable is the required efficiency value ER.

$$\theta^*, (0 \leq \theta^* \leq 1) \tag{10}$$

(5) With the solution of linear programming, the corresponding relaxation variable S can be obtained at the same time. The above model is a problem of seeking efficiency for the minimum input under the condition that the output is constant. Therefore, the input value when maintaining the original output unchanged and achieving the optimal efficiency can be calculated by the following formula.

$$\hat{X}_0 = \theta^*\hat{X} - S \tag{11}$$

3. Analysis on Operation Efficiency of Sewage Treatment Plant

3.1. Evaluation Index System

Table 1: Evaluation indicators of operation efficiency of sewage treatment plant.

	Indicators		Indicator explanation
Output indicators	Y	COD reduction (t/a)	(COD concentration of influent - COD concentration of effluent) * Annual sewage treatment capacity
Input indicators	X_1	Total project investment (10000 yuan)	Total investment cost of project infrastructure
	X_2	Annual power consumption (10000 kw•h)	Total annual power consumption of sewage treatment equipment
	X_3	Annual reagent cost (10000 yuan)	Total cost of reagents for sewage treatment process
	X_4	Number of employees	Number of employees

To calculate the operation efficiency of sewage treatment plant through DEA model, it must be based on the clear input and output indicators. In this study, based on the actual situation of urban domestic sewage treatment plants and the index system selected by previous researches on efficiency, as well as the availability of data, the evaluation index of sewage treatment plant operation efficiency was set up. In terms of investment indicators, this paper mainly defines the existing main resources of the sewage treatment plant from four indicators: total project investment, annual power consumption, annual reagent cost and number of employees. Details are shown in Table 1.

3.2. Basic Data Sources

The data in this paper comes from the data of urban sewage treatment plants monitored by the Ministry of Environmental Protection. The selected urban sewage treatment plants in this study are shown in Table 2.

3.3. Model Calculation Results and Analysis

In this study, DEAP software is used to calculate the operation efficiency, pure technical efficiency and scale efficiency of sewage treatment plants. Among them, the operating efficiency is equal to the pure technical efficiency multiplied by the scale efficiency. The results of operation efficiency measurement and relaxation variables are shown in Table 3 and Table 4.

3.3.1. Low Overall Operation Efficiency

Table 2: Input and output indicators of each sewage treatment plant.

Unit/DMU	Input				Output
	X_1 Total project investment (10,000 Yuan)	X_2 Annual power consumption (10000 kw●h)	X_3 Annual reagent cost (10000 Yuan)	X_4 Number of employees	Y COD reduction (t/a)
1	6162.86	492.6	39.41	46	5602.57
2	5000.00	126.70	2.27	24	803.46
3	7868.45	196.00	2.60	34	357.63
4	9300.00	634.76	56.10	37	26201.91
5	7800.00	446.00	23.44	36	5565.56
6	18000.00	1020.00	21.00	55	11008.77
7	4002.86	100.14	0.00	41	409.98
8	3150.00	140.09	34.61	32	405.32
9	13388.40	583.60	54.47	48	6201.58
10	5269.05	355.57	15.49	42	4957.28
11	12600.00	144.00	98.13	57	9477.64
12	9196.07	595.00	46.70	39	4691.67
13	4116.14	300.85	9.75	30	3714.14
14	4366.87	530.87	40.50	58	5735.75
15	4700.00	239.74	53.62	24	2782.46
16	4786.51	280.00	170.00	60	9639.00
17	6200.00	246.00	5.96	21	303.66
18	4590.33	308.00	4.50	25	2019.25
19	7638.50	416.00	11.22	25	44215.47
20	6323.26	505.65	54.21	57	3930.65
21	7304.71	459.77	30.57	53	3903.33
22	32283.73	3353.20	167.64	115	23471.71
23	8000.00	172.00	35.00	26	780.52
24	23200.00	1241.00	84.43	55	5936.97
25	20000.00	537.72	194.00	61	4250.92
26	12800.00	600.04	150.01	56	11978.88
27	7513.48	1153.00	199.08	90	56948.44
28	10362.45	892.48	151.82	82	17721.62
29	8225.57	165.68	3.81	15	596.75
30	10100.00	4505.10	204.00	38	10803.00
31	18912.64	991.47	109.97	58	23131.74
32	8193.00	670.70	187.80	50	17302.82
33	22000.00	2865.05	394.69	72	67961.88
34	11672.00	311.00	30.00	50	4672.97
35	154300.00	2769.62	138.04	192	1476.73
36	4423.80	419.94	40.51	64	8227.71

The average value of the overall operational efficiency of the selected 36 sample plants is 0.263, the average value of the pure technical efficiency is 0.375, and the average value of the scale efficiency is 0.720. It can be seen that the overall operation efficiency of the sample plant is low, which is mainly caused by the low pure technical efficiency.

As far as the input-output redundancy is concerned, in terms of input indicators, 49% of the sewage treatment plants have redundancy on average, among which, the average value of the input redundancy of the total project investment is 71.92511 million yuan, and 50% of the sewage treatment plants have no input redundancy. The average input redundancy of annual power consumption is 2.997 million kw•h, and 55.6% of sewage treatment plants have no input redundancy. The average input redundancy of annual reagent consumption cost is 304100 yuan, and 52.8% of sewage treatment plants have no input redundancy. The average input redundancy of the total number of full-time personnel is 16, and 58.3% of sewage treatment plants have no input redundancy. In terms of output indicators, the average output deficit of COD reduction is 838.6 tons, and 83.3% of sewage treatment plants have no output deficit. It can be seen that the overall investment of the sewage treatment plant should pay attention to the rational allocation of resources to reduce the occurrence of waste, especially in terms of staffing, attention should be paid to the introduction of talents from different aspects and at different levels.

Table 3: Analysis results of operation efficiency of sewage treatment plant with DEA model.

Unit/DMU	Operational efficiency	Pure technical efficiency	Scale efficiency	Scale compensation
1	0.147	0.157	0.937	Increase progressively
2	0.095	0.122	0.775	Increase progressively
3	0.034	0.035	0.955	Increase progressively
4	0.470	0.556	0.845	Decrease progressively
5	0.122	0.124	0.982	Decrease progressively
6	0.133	0.245	0.541	Decrease progressively
7	1.000	1.000	1.000	Unchanged
8	0.030	0.123	0.246	Increase progressively
9	0.100	0.132	0.759	Decrease progressively
10	0.159	0.229	0.696	Increase progressively
11	0.619	0.816	0.759	Increase progressively
12	0.087	0.105	0.827	Decrease progressively
13	0.190	1.000	0.190	Increase progressively
14	0.217	0.261	0.830	Increase progressively
15	0.109	0.153	0.714	Increase progressively
16	0.619	0.747	0.828	Increase progressively
17	0.016	0.020	0.796	Increase progressively
18	0.113	0.460	0.245	Increase progressively
19	1.000	1.000	1.000	Unchanged
20	0.099	0.104	0.954	Increase progressively
21	0.090	0.091	0.991	Increase progressively
22	0.122	0.478	0.255	Decrease progressively
23	0.043	0.052	0.819	Increase progressively
24	0.083	0.183	0.455	Decrease progressively
25	0.074	0.093	0.801	Decrease progressively
26	0.188	0.253	0.743	Decrease progressively
27	1.000	1.000	1.000	Unchanged
28	0.269	0.338	0.796	Decrease progressively
29	0.052	1.000	0.052	Increase progressively
30	0.201	0.265	0.756	Decrease progressively
31	0.225	0.455	0.496	Decrease progressively
32	0.336	0.356	0.944	Decrease progressively
33	1.000	1.000	1.000	Unchanged
34	0.141	0.148	0.957	Increase progressively
35	0.005	0.028	0.179	Decrease progressively
36	0.291	0.367	0.793	Increase progressively

Table 4: Relaxation variable results with DEA model.

Unit/DMU	S^{1-}	S^{2-}	S^{3-}	S^{4-}	S^{5+}
1	0.000	33.051	0.000	19.615	0.000
2	0.000	11.358	0.000	0.000	517.313
3	2659.596	33.037	0.000	0.000	0.000
4	1749.006	3.787	0.000	0.000	0.000
5	166.589	0.000	4.573	8.354	0.000
6	10368.009	565.632	0.000	26.616	0.000
7	0.000	0.000	0.000	0.000	0.000
8	0.000	0.000	0.065	0.000	845.727
9	5778.331	0.000	0.529	8.218	0.000
10	0.000	94.271	0.000	0.000	0.000
11	7211.016	0.000	94.624	36.442	0.000
12	1589.082	132.363	28.178	13.105	0.000
13	0.000	0.000	0.000	0.000	0.000
14	0.000	239.336	0.000	29.725	0.000
15	0.000	0.000	25.437	0.000	0.000
16	0.000	0.000	142.742	3.449	10345.431
17	0.000	34.054	0.000	0.000	3226.340
18	0.000	143.964	0.000	0.000	0.000
19	0.000	0.000	0.000	0.000	0.000
20	0.000	0.000	0.000	22.993	0.000
21	0.000	0.000	2.108	23.190	0.000
22	24988.025	2429.869	76.983	80.264	0.000
23	2379.448	0.000	30.700	4.985	0.000
24	15561.500	825.000	73.210	30.000	11749.692
25	12416.372	0.000	158.403	29.932	0.000
26	5192.719	0.000	91.879	14.769	0.000
27	0.000	0.000	0.000	0.000	0.000
28	2804.777	0.000	19.146	14.977	0.000
29	0.000	0.000	0.000	0.000	0.000
30	2461.500	4089.100	192.780	13.000	3506.165
31	11358.932	175.186	0.000	0.000	0.000
32	597.706	0.000	111.657	2.537	0.000
33	0.000	0.000	0.000	0.000	0.000
34	4901.879	0.000	29.758	26.715	0.000
35	146745.898	1856.088	0.000	123.120	0.000
36	0.000	124.734	0.000	37.353	0.000

Combining Table 3 and Table 4, the following results are obtained.

3.3.2. Few DEA Effective Units

There are 4 DMUs valid for DEA, and the numbers are -7, 19, 27 and 33 respectively. Not only the operating efficiency is 1, but also the pure technical efficiency and scale efficiency are equal to 1. In addition, the return to scale is unchanged, and there is no redundancy in the input and output indicators, that is, the existing input resources are fully allocated and their emission reduction potential is brought into play. Compared with other sample plants, it can be called a benchmark plant with relatively high efficiency, which can be used for reference by other plants.

4. Conclusions and Suggestions

4.1. Conclusions

In this paper, data envelopment analysis (DEA) is used to evaluate the operation efficiency of urban domestic sewage treatment plants. Select input indicators and output indicators, and use the output oriented BCC model in DEA method to calculate. The input indicators include the total project investment, annual power consumption, annual reagent cost and number of employees, and the output indicator is COD reduction. The research results are shown as follows. Ⅰ: The overall operation comprehensive efficiency of the sample plant is low, mainly driven by the pure technical efficiency. On average, 49% of the sample plants have redundancy in various input indicators, while only 16.7% of urban sewage treatment plants have insufficient output in terms of COD reduction. Ⅱ: There are only 4 DEA valid units, while the number of DEA invalid units is most.

4.2. Suggestions

There are many kinds of urban domestic sewage treatment processes, and the processes of each sewage treatment plant are different. Even if the same treatment process is used, the treatment effect will be different due to the different water quality of the incoming plant. Therefore, how to objectively and quantitatively evaluate the operation efficiency of sewage treatment plants, and propose targeted improvement measures on the basis of efficiency evaluation to help urban sewage treatment plants improve their operation efficiency is an important direction of future sewage treatment industry research.

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