Operation Performance Evaluation of Municipal Wastewater Treatment Plant by Analytic Hierarchy Process

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Abstract. The operation performance evaluation of the municipal wastewater treatment plants in China is a very significant and complex issue. Based on China’s existing municipal wastewater treatment plant operation performance evaluation indicator system as well as the principles and features of analytic hierarchy process (AHP), this paper utilizes the excel tool to conduct the programming calculation, calculating the index weight at each level of municipal wastewater treatment plant operation performance evaluation index system in China.

1. Introduction
The municipal wastewater treatment and recycling facilities are the indispensable infrastructure for the urban development and the significant guarantee of economic development as well as the residents’ safe and healthy life. During the “Thirteenth Five-Year Plan” period, China has further made the overall planning, increased the input, and tried to realize the transition of the construction of municipal wastewater treatment facilities from “scale growth” to “higher quality and enhanced efficiency”, from “Sewage treatment primary, sludge treatment secondary” to “equal treatment of sewage and sludge”, and from “sewage treatment” to “recycling and reuse”, so as to fully enhance the support capacity and service level of China’s municipal wastewater treatment facilities.

At present, some cities have just completed the concept change of sewage treatment from “pursuit of sewage treatment volume” to “pursuit of sewage treatment quality”. As the centralized treatment unit of pollutants, the municipal wastewater treatment plant plays a significant role in China’s pollutant emission reduction strategy. In order to fully realize the function of existing facilities of sewage treatment plant, and enhance the operation and management level of municipal wastewater treatment plant, it is urgent to strengthen the operation performance assessment of sewage treatment plant.

2. Municipal wastewater Treatment Plant Operation Performance Evaluation Index System
According to GlobalersOil’s assessment index system, eight basic principles shall be followed [1]. Combined with the operation features and realities of China’s municipal wastewater treatment plant, we have proposed the municipal wastewater treatment plant operation performance evaluation index system [2], which consisting of three levels, five categories and 23 indexes, as shown in Table 1.
Table 1. Municipal wastewater Treatment Plant Operation Performance Evaluation Index System

| Target Level | Primary Index Level | Secondary Index Level |
|--------------|---------------------|-----------------------|
| Environmental Performance | Annual average water quality compliance rate C1 | ... |
| B1 | Annual average ambient air quality compliance rate C2 | Annual average sludge quality compliance rate C3 |
| | Annual average pollutant integrated reduction rate C4 | ... |
| Resources & Energy Consumption B2 | Power consumption per unit water treatment C5 | Chemical consumption per unit water treatment C6 |
| | Fresh water consumption per unit water treatment C7 | ... |
| | Technical performance requirements C8* | Operation cost per unit water volume C9 |
| | Annually average unit oxygen consumption pollutant reduction power consumption C10 | Annual maintenance fees C11 |
| | Annual labor fee C12 | ... |
| Municipal wastewater Treatment System Operation Performance Evaluation A | Technical & Economic Performance B3 | Rules & regulations C13* |
| | Operation & maintenance ledger & record C16* | Personnel training C14* |
| | Surveillance & analysis record C17* | Emergency response plan C15* |
| Production Management B4 | Annual operation rate C18 | Operation & maintenance ledger & record C16* |
| | Operation hydraulic load C19 | Annual maintenance fees C11 |
| | Operation COD load C20 | Annual labor fee C12 |
| | Structure integrity rate C21 | ... |
| | Critical equipment integrity rate C22 | ... |
| | Critical equipment advancement C23 | ... |

Note: * means that this index is the determinative assessment index.

3. Municipal wastewater Treatment Plant Operation Performance Assessment with AHP Method

AHP method was a simple and practical multi-target decision-making analytic method proposed by USA operational research expert T·L Saaty in 1970s [3]. It utilizes the order of excellence and degree of all the alternative plans judged by the experienced person (experts and etc.) to quantify the qualitative problems and simplify the complex problems, and is extensively applied to the production decision-making, education, medicine, agriculture, economy, safety and other fields. For AHP, it must firstly define the problem to be solved, and then simplify it to the orderly and multi-level hierarchical structure, and finally correspond to many alternative plans [4]. After carefully analyzing and sorting out the essence of complex problem, impact factor and the internal relationship of all factors, AHP shall construct the hierarchical structure model, and then utilizes the less quantitative information to mathematize the decision-making process, so as to solve the multi-target, multi-criteria or structureless complex problem decision-making. According to the basic steps of AHP and the study results of JI Nan et al., this study utilize the excel programming to calculate the weight of municipal wastewater treatment plant operation performance with the AHP method [5]. Taken the calculation and judgment of characteristic value and characteristic vector of matrix with the square root method as an example, the specific steps of calculation with the excel programming is as shown below [6].
3.1. Excel Workbook Establishment

Assume the judgment matrix is 3×3 N-matrix B, and input its matrix elements into the position as shown in the Table below. The calculation results taken according to the corresponding equation are as shown in Table 2.

### Table 2. Characteristic Value & Characteristic Vector Calculated with Excel

|    | A   | B   | C   | D   | E   | F   |
|----|-----|-----|-----|-----|-----|-----|
| 1  | b11 | b12 | b13 | D1  | E1  | F1  |
| 2  | B21 | B22 | B23 | D2  | E2  | F2  |
| 3  | B31 | B32 | B33 | D3  | E3  | F3  |
| 4  | A4  | B4  | —   | D4  | E4  | F4  |
| 5  | A5  | B5  | —   | D5  | E5  | F5  |
| 6  | A6  | B6  | —   | D6  | E6  | F6  |
| 7  | —   | B7  | C7  | —   | —   | —   |

Note: A1~C3 are judgment matrixes, while F1~F3 are judgment vectors and C7 are characteristic values.

3.2. Corresponding Equations

The calculation equations that are used to calculate the relevant elements of matrix with excel are as shown below:

1. \( D1 = A1 \times B1 \times C1 \), \( D2 = A2 \times B2 \times C2 \), \( D3 = A3 \times B3 \times C3 \);
2. \( E1 = \text{POWER} (D1, 1/3) \), \( E2 = \text{POWER} (D2, 1/3) \), \( E3 = \text{POWER} (D3, 1/3) \), \( E4 = \text{SUM} (E1:E3) \);
3. \( F1 = E1 / E4 \), \( F2 = E2 / E4 \), \( F3 = E3 / E4 \);
4. \( A4 = \text{MMULT} (A1:C1, F1:F3) \), \( A5 = \text{MMULT} (A2:C2, F1:F3) \), \( A6 = \text{MMULT} (A3:C3, F1:F3) \);
5. \( B4 = A4 / F1 \), \( B5 = A5 / F2 \), \( B6 = A6 / F3 \), \( B7 = \text{SUM} (B4:B6) \);
6. \( C7 = B7 / 3 \)

Among these, function \( \text{POWER} (a, 1/n) \) intends to return the \( 1/n \) root of numeric value \( a \), while function \( \text{MMULT} ( ) \) intends to return the product of two array matrixes, and function \( \text{SUM} ( ) \) intends to return the sum 0 of all numeric values within the cell range.

4. Weight Calculation of Municipal wastewater Treatment Plant Operation Performance Assessment Index

In order to ensure the scientificity and practicability of this assessment, when the index weight is determined, the experts and scholars engaged in the ecological protection and environmental contamination study, the relevant directors of the municipal wastewater treatment plants and others are invited to provide the mutually independent judgment. Meanwhile, the relative importance assessment is conducted for the relevant factors of sewage treatment plant in combination with the survey results of China’s municipal wastewater treatment plants. Thus, the corresponding weight values are taken. The primary index three-scale matrix of municipal wastewater treatment plant operation performance evaluation is as shown in Table 3.

### Table 3. Primary Index Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Integrated Assessment A | B1 | B2 | B3 | B4 | B5 |
|-------------------------|----|----|----|----|----|
| Environmental Performance B1 | 1  | 2  | 2  | 2  | 2  |
| Resources and Energy Consumption B2 | 0  | 1  | 0  | 1  | 0  |
| Technical and Economic Performance B3 | 0  | 2  | 1  | 2  | 1  |
| Operation Management B4 | 0  | 1  | 0  | 1  | 0  |
| Major facilities and Equipment Status B5 | 0  | 2  | 1  | 2  | 1  |
According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and the maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 4.

### Table 4. Primary Index Nine-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Assessment

| Integrated Assessment A | B1 | B2 | B3 | B4 | B5 | W  | Consistency Check |
|-------------------------|----|----|----|----|----|-----|------------------|
| Environmental Performance B1 | 1  | 8  | 4  | 8  | 4  | 0.47 | λ_{max}=5.135    |
| Resources and Energy Consumption B2 | 1/8 | 1  | 1/5 | 1  | 1/5 | 0.04 | 1               |
| Technical and Economic Performance B3 | 1/4 | 5  | 1  | 5  | 1  | 0.17 | C.R=C.I./R.I =0.339/1.12 =0.030 |
| Operation Management B4 | 1/8 | 1  | 1/5 | 1  | 1/5 | 0.04 | 1               |
| Major facilities and Equipment Status B5 | 1/4 | 5  | 1  | 5  | 1  | 0.17 | 3               |

CR is less than 0.1, which conforms to the consistency.

### 4.1. Determination of Environmental Performance Index Weight

The secondary index (environmental performance index) three-scale matrix of municipal wastewater treatment plant operation performance evaluation is shown in Table 5.

### Table 5. Secondary Index (Environmental Performance Index) Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Environmental Performance B1 | C1 | C2 | C3 | C4 |
|-------------------------------|----|----|----|----|
| Annual average water quality compliance rate C1 | 1  | 2  | 2  | 1  |
| Annual average ambient air quality compliance rate C2 | 1  | 1  | 1  | 1  |
| Annual average Sludge quality compliance rate C3 | 1  | 1  | 1  | 1  |
| Annual average pollutant integrated reduction rate C4 | 1  | 2  | 2  | 1  |

According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 6.
Table 6. Secondary Index (Environmental Performance Index) Nine-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Environmental Performance B1 | C1  | C2  | C3  | C4  | W   | Consistency Check |
|-------------------------------|-----|-----|-----|-----|-----|-------------------|
| Annual average water quality compliance rate C1 | 1   | 3   | 3   | 1   | 0.375 | λ_{max}=4.9       |
| Annual average ambient air quality compliance rate C2 | 1/3 | 1   | 1   | 1/3 | 0.125 | C.R=C.I./R.I 0/0.89=0 |
| Annual average Sludge quality compliance rate C3 | 1/3 | 1   | 1   | 1/3 | 0.125 |               |
| Annual average pollutant integrated reduction rate C4 | 1   | 3   | 3   | 1   | 0.375 |               |

CR is less than 0.1, which conforms to the consistency.

4.2. Determination of Resources & Energy Consumption Assessment Index Weight

The secondary index (resources & energy consumption index) three-scale matrix of municipal wastewater treatment plant operation performance evaluation is as shown in Table 7.

Table 7. Secondary Index (Resources & Energy Consumption Index) Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Resources & Energy Consumption B2 | C5  | C6  | C7  |
|-----------------------------------|-----|-----|-----|
| Power consumption per unit water treatment C5 | 1   | 1   | 1   |
| Chemical consumption per unit water treatment C6 | 1   | 1   | 1   |
| Fresh water consumption per unit water treatment C7 | 1   | 1   | 1   |

According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and the maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 8.
Table 8. Secondary Index (Resources & Energy Consumption Index) of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Resources & Energy Consumption B2 | C5  | C6  | C7  | W    | Consistency Check |
|-----------------------------------|-----|-----|-----|------|-------------------|
| Power consumption per unit water treatment C5 | 1   | 1   | 1   | 0.333 | $\lambda_{\text{max}}=3.0$ |
| Chemical consumption per unit water treatment C6 | 1   | 1   | 1   | 0.333 | C.R=C.I./R.I =0/0.58 =0 |
| Fresh water consumption per unit water treatment C7 | 1   | 1   | 1   | 0.333 | |

CR is less than 0.1, which conforms to the consistency.

4.3. Determination of Technical & Economic Performance Index Weight

The secondary index (technical & economic performance index) three-scale matrix of municipal wastewater treatment plant operation performance evaluation is as shown in Table 9.

Table 9. Secondary Index (Technical & Economic Performance Index) Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Technical & Economic Performance B3 | C8  | C9  | C10 | C11 | C12 |
|-------------------------------------|-----|-----|-----|-----|-----|
| Technical performance requirements C8 | 1   | 1   | 1   | 1   | 1 |
| Operation cost per unit water volume C9 | 1   | 1   | 1   | 1   | 1 |
| Unit COD Reduction Cost C10 | 1   | 1   | 1   | 1   | 1 |
| Annual maintenance fees C11 | 1   | 1   | 1   | 1   | 1 |
| Annual labor fee C12 | 1   | 1   | 1   | 1   | 1 |

According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and the maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 10.

Table 10. Secondary Index (Technical & Economic Performance Index) Nine-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Technical & Economic Performance B3 | C8  | C9  | C10 | C11 | C12 | W    | Consistency Check |
|-------------------------------------|-----|-----|-----|-----|-----|------|-------------------|
| Technical performance requirements C8 | 1   | 1   | 1   | 1   | 1   | 0.200 | $\lambda_{\text{max}}=5.0$ |
| Operation cost per unit water volume C9 | 1   | 1   | 1   | 1   | 1   | 0.200 | |
| Unit COD Reduction Cost C10 | 1   | 1   | 1   | 1   | 1   | 0.200 | C.R=C.I./R.I =0/1.12 =0 |
| Annual maintenance fees C11 | 1   | 1   | 1   | 1   | 1   | 0.200 | |
| Annual labor fee C12 | 1   | 1   | 1   | 1   | 1   | 0.200 | CR is less than 0.1, which conforms to the consistency. |

4.4. Determination of Operation Management Index Weight

The secondary index (operation management index) three-scale matrix of municipal wastewater treatment plant operation performance evaluation is as shown in Table 11.
Table 11. Secondary Index (Operation Management Index) Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Operation Management | C13 | C14 | C15 | C16 | C17 |
|-----------------------|-----|-----|-----|-----|-----|
| Rules & regulations   | 1   | 1   | 1   | 1   | 1   |
| Personnel training    | 1   | 1   | 1   | 1   | 1   |
| Emergency response    | 1   | 1   | 1   | 1   | 1   |
| Operation &           | 1   | 1   | 1   | 1   | 1   |
| maintenance ledger &  | 1   | 1   | 1   | 1   | 1   |
| record                | 1   | 1   | 1   | 1   | 1   |

According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and the maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 12.

Table 12. Secondary Index (Operation Management Index) Nine-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Operation Management | C13 | C14 | C15 | C16 | C17 | W  | Consistency Check |
|-----------------------|-----|-----|-----|-----|-----|----|-------------------|
| Rules & regulations   | 1   | 1   | 1   | 1   | 1   | 0.200 | λ_{max}=5.0         |
| Personnel training    | 1   | 1   | 1   | 1   | 1   | 0.200 | C.R=C.I./R.I       |
| Emergency response    | 1   | 1   | 1   | 1   | 1   | 0.200 | =0/1.12           |
| Operation &           | 1   | 1   | 1   | 1   | 1   | 0.200 |
| maintenance ledger &  | 1   | 1   | 1   | 1   | 1   | 0.200 |
| record                | 1   | 1   | 1   | 1   | 1   | 0.200 |

CR is less than 0.1, which conforms to the consistency.

4.5. Determination of Major Facilities & Equipment Status Index Weight

The secondary index (major facilities & equipment status index) three-scale matrix of municipal wastewater treatment plant operation performance evaluation is as shown in Table 13.
Table 13. Secondary Index (Major Facilities & Equipment Status Index) Three-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Major Facilities & Equipment Status B5 | C18 | C19 | C20 | C21 | C22 | C23 |
|---------------------------------------|-----|-----|-----|-----|-----|-----|
| Annual operation rate C18             | 1   | 1   | 1   | 1   | 1   | 0   |
| Operation hydraulic load C19          | 1   | 1   | 1   | 1   | 1   | 0   |
| Operation COD load C20                | 1   | 1   | 1   | 1   | 1   | 0   |
| Structure integrity rate C21          | 1   | 1   | 1   | 1   | 1   | 0   |
| Critical equipment integrity rate C22 | 1   | 1   | 1   | 1   | 1   | 0   |
| Critical equipment advancement C23    | 2   | 2   | 2   | 2   | 2   | 1   |

According to equation (1)-(3), the three-scale matrix is converted into nine-scale matrix, and the maximum characteristic root and corresponding characteristic vector of judgment matrix are solved with the excel, as shown in Table 14.

Table 14. Secondary Index (Major Facilities & Equipment Status Index) Nine-Scale Matrix of Municipal wastewater Treatment Plant Operation Performance Evaluation

| Major Facilities & Equipment Status B5 | C18 | C19 | C20 | C21 | C22 | C23 | W | Consistency Check |
|---------------------------------------|-----|-----|-----|-----|-----|-----|---|-------------------|
| Annual operation rate C18             | 1   | 1   | 1   | 1   | 1   | 5/11| 0.139 | λ\text{max}=5.305 |
| Operation hydraulic load C19          | 1   | 1   | 1   | 1   | 1   | 5/11| 0.139 |                 |
| Operation COD load C20                | 1   | 1   | 1   | 1   | 1   | 5/11| 0.139 |                 |
| Structure integrity rate C21          | 1   | 1   | 1   | 1   | 1   | 5/11| 0.139 |                 |
| Critical equipment integrity rate C22 | 1   | 1   | 1   | 1   | 1   | 5/11| 0.139 |                 |
| Critical equipment advancement C23    | 11/5| 11/5| 11/5| 11/5| 11/5| 1   | 0.306 |                 |

CR is less than 0.1, which conforms to the consistency.

4.6. Total Hierarchy Ordering

As calculated above, the single hierarchy ordering is accomplished. As a result, the total hierarchy ordering should be conducted, while the order of excellence between each level and its upper level will be concluded, as shown in Table 15.
Table 15. Total Hierarchy Ordering Results

| Level | B1   | B2   | B3   | B4   | B5   | Total Ordering Weight at Level A |
|-------|------|------|------|------|------|----------------------------------|
|       | 0.479| 0.041| 0.173| 0.041| 0.173|                                 |
| C1    | 0.375|      |      |      |      | 0.178                           |
| C2    | 0.125|      |      |      |      | 0.060                           |
| C3    | 0.125|      |      |      |      | 0.060                           |
| C4    | 0.375|      |      |      |      | 0.178                           |
| C5    |      | 0.333|      |      |      | 0.014                           |
| C6    |      | 0.333|      |      |      | 0.014                           |
| C7    |      | 0.333|      |      |      | 0.014                           |
| C8    |      |      | 0.200|      |      | 0.035                           |
| C9    |      |      | 0.200|      |      | 0.035                           |
| C10   |      |      | 0.200|      |      | 0.035                           |
| C11   |      |      | 0.200|      |      | 0.035                           |
| C12   |      |      | 0.200|      |      | 0.035                           |
| C13   |      |      |      | 0.200|      | 0.008                           |
| C14   |      |      |      | 0.200|      | 0.008                           |
| C15   |      |      |      | 0.200|      | 0.008                           |
| C16   |      |      |      | 0.200|      | 0.008                           |
| C17   |      |      |      | 0.200|      | 0.008                           |
| C18   |      |      |      |      | 0.139| 0.024                           |
| C19   |      |      |      |      | 0.139| 0.024                           |
| C20   |      |      |      |      | 0.139| 0.024                           |
| C21   |      |      |      |      | 0.139| 0.024                           |
| C22   |      |      |      |      | 0.139| 0.024                           |
| C23   |      |      |      |      | 0.306| 0.053                           |

The consistency check results are as shown below:
\[
CT = \sum_{i=1}^{5} B_i \times C_i = 0.479 \times 0 + 0.041 \times 0 + 0.173 \times 0 + 0.041 \times 0 + 0.173 \times 0.076 = 0.013
\]
\[
RT = \sum_{i=1}^{5} B_i \times R_i = 0.479 \times 0.089 + 0.041 \times 0.058 + 0.173 \times 1.12 + 0.041 \times 1.12 + 0.173 \times 1.26 = 0.721
\]
\[
CR' = CT/RT = 0.013/0.721 = 0.018 < 0.1. Therefore, it conforms to the consistency. As shown from the weight results of each index, the impact of environmental performance is the largest (0.479), followed by technical & economic performance and major facilities & equipment status, which is 0.173 separately. Meanwhile, the impact of resources and energy consumption and operation management is the smallest, which is 0.041 separately.

5. Conclusions
The study utilized the excel programming to conduct the integrated hierarchy analysis and evaluation of the municipal wastewater treatment plant operation performance, determined the relative importance degree of each index in this integrated evaluation index system. The conclusion is as follows: the impact of environmental performance is the largest (0.479), followed by technical & economic performance and major facilities & equipment status, which is 0.173 separately. Meanwhile, the impact of resources and energy consumption and operation management is the smallest, which is 0.041 separately.

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