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A Performance Evaluation System for PPP Sewage Treatment Plants at the Operation-maintenance Stage

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ABSTRACT

Sewage treatment plants are essential in improving the quality of receiving water bodies, contributing to healthy and sustainable urban development. The increasingly common public-private partnership (PPP) model of sewage treatment facilities may not yield the expected benefits, often compromised by inadequacies in the complex operation-maintenance stage. Holistic criteria and methods to define and judge a plant's performance are lacking. To fill the knowledge gap, this study established a performance evaluation system applicable to the critical operation-maintenance stage of China's PPP sewage-treatment industry. First, the range of quantitative and qualitative indicators was surveyed by literature review, and an appropriate subset was selected according to expert judgment. Second, the multilevel extension principle of matter-element analysis was combined with the analytic hierarchy process to determine the performance level and establish a comprehensive, efficient and practical evaluation system. The proposed method was tested on two PPP plants to confirm its applicability and reliability in assessing operation-maintenance functions. The study identified the diagnostic criteria to refine the design, operation and maintenance parameters to optimize plant performance. The findings provided an assured and comprehensive quality control scheme and a practical tool for governments and other parties to assess the service delivery quality of PPP plants.

1. Introduction

Fast and massive urbanization coupled with population growth has accelerated the generation of industrial, commercial and domestic sewage in many cities (Morallos et al., 2009; Alnashiri, 2021). China has built many sewage treatment plants to tackle the rising demands in recent decades (Wang and Jin, 2016). The conventional way of using government resources alone may not be adequate and timely to fulfill the substantial and increasing demands. Urban sewage treatment is amenable to marketization by attracting investor participation in the public service and mobilizing the potential contributions of the private sector (Yang et al., 2016; Benbachir et al., 2021). However, it is difficult for commercial enterprises to enter the market due to policy constraints and considerable investment in construction (Cruz and Marques, 2013).

The alternative public-private partnership model (PPP) (Tang et al., 2022) could enlist considerable latent social capital. It includes private and state-owned enterprises according to China's national conditions. The private partner can participate in the investment, construction and operation, and the government in regulation, coordination and supervision (Liu et al., 2022). The entrepreneurial and financial capability of the private sector can be fruitfully tapped. Relevant government units can offer technical advice and support. The synergistic approach can solve the problem of insufficient public funds and bring investment opportunities to enterprises (El-Kholy and Akal, 2020).

The current PPP model can solve the above thorny financing problems to a certain extent (Sun et al., 2018; Gonzalez-Ruiz et al., 2019). However, other significant technical and managerial difficulties would need to be resolved, especially in the operation-maintenance stage (Tariq and Zhang, 2021). Unfortunately, some companies may provide substandard management and operation. Some may focus on maximizing returns for their investments. Others could use monopolistic means to raise the costs of products and services. Such actions could reduce service quality and harm public interests. In addition, some government units could fail to forecast accurately the community's daily sewage treatment

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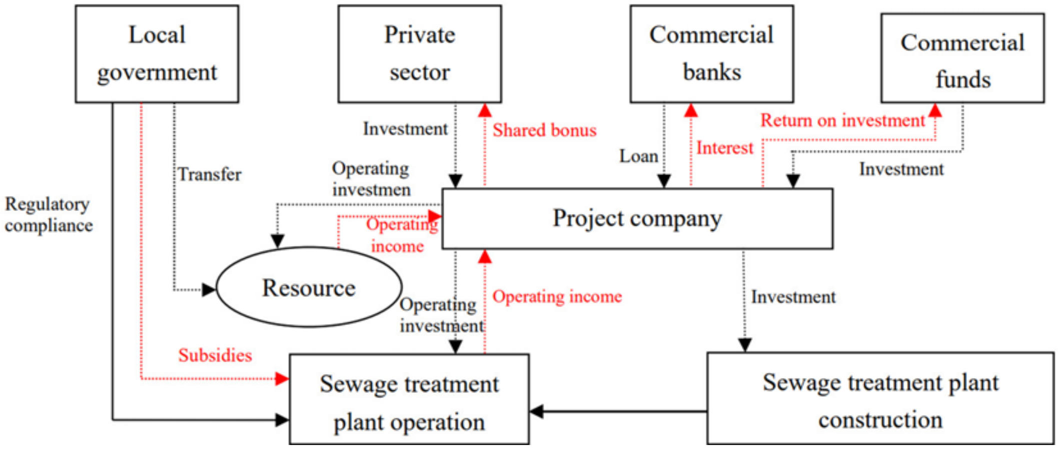

Fig. 1. Interactions and Flows between the Main Stakeholders and Components of a PPP Sewage Treatment Plant are Implemented in the Build-Operate-Transfer (BOT) Mode (The Black Annotations and Arrows Denote System Input and the Red System Output)

needs, resulting in chronic low-load operation of the plant, wasteful over-capacity, low operation efficiency and high unit cost (Xu and Xu, 2022).

PPP sewage treatment projects often adopt the build-operate-transfer (BOT) model (Bae et al., 2019). The main stakeholders and components of the BOT system and the interactive linkages, divided into inputs and outputs, are depicted synoptically in Fig. 1. This current system demarcates and assigns key responsibilities and benefits to the leading players. However, it suffers from a pitfall that the government could not adequately comprehend and oversee the project's operation (Lu et al., 2022). An effective mechanism is lacking for the administration to control and ascertain operation quality and delivery. Insufficient supervision and regulatory restraint constitute loopholes that the private partner company could exploit. Glitches such as low management efficiency, cost overrun, and substandard service quality may plague the operation-maintenance process. These potential problems call for establishing a rational and effective supervision regime to bring acceptable performance, to be enforced by an appropriate government department.

The PPP research association of Australia conducted a study on the effect of project performance evaluation. The results show that scientific and sensible performance evaluation can improve management, optimize resource use and reduce waste (Li, 2014). Regular assessments of operation performance can include documentary reviews, on-site inspections, and checking adherence to statutory standards (Lan, 2016). Therefore, it is more appropriate to implement a scheduled government monitoring program than the one-off contractual stipulations and incentive mechanisms (Surachman et al., 2020).

The performance appraisal of PPP sewage treatment plants can follow various approaches (Mayer et al., 2021). Recent research indicates that a thorough scientific performance system should appraise a PPP project's effectiveness. Differences in indicator choice and assessment can lead to opposite results (Chan et al., 2010; Zhang et al., 2010; Ye and Qi, 2015; Seo and Kim, 2016; Ahmed et al., 2018; Liu et al., 2018; Long et al., 2019). Some current performance evaluation methods are narrowly focused on specific traits, such as technology (Ganesan and Namasivayan, 2015), social benefit (Ahn et al., 2020), environmental protection (Vinardell et al., 2021; Fallahiarezouda et al., 2022) and economics (Kotagama et al., 2016; Feng and Zhu, 2019). The detailed preoccupation with a single or a few issues cannot meet the expectation of a comprehensive perspective.

Many researchers have conducted an in-depth performance evaluation of the operation-maintenance stage (Tserng et al., 2015; Alver, 2019; Bhave et al., 2020; Yazdian and Shervin, 2021), with some focusing on the method (Chen et al., 2013; Li and Zhu, 2014; Li et al., 2021). Others have studied specific cases in a given area and made suggestions to managers with limited relevance to other sites (Meng et al., 2012; Guo et al., 2015; Fang et al., 2016; Ayyildiz et al., 2020; Zhang et al., 2020). More importantly, few provided a universally applicable method for the operation-maintenance stage from the government's perspective. This study intended to establish a comprehensive indicator system to fill these research gaps.

This study constructed a comprehensive performance evaluation model of the PPP sewage treatment plant at the critical operation and maintenance stage, using the analytic hierarchy process (AHP) combined with the matter element analysis (MEA), and verified by two case-study plants in China. The study aimed to achieve three objectives: 1) To establish a comprehensive system of contributing factors to judge plant performance that included key factors of operational quality, operational efficiency, energy-material consumption, equipment and facility management, and the hitherto neglected dimension of social satisfaction. 2) To design an inclusive evaluation index system from the government's perspective to strengthen project control effectively. 3) To develop an analytic approach of jointly applying the AHP and MEA quantitative methods and testing their feasibility for evaluating plant performance.

2. Establishing the Performance Evaluation Indicator System

2.1 Methods of Selecting Performance Indicators

The basis of performance evaluation is to select the most appropriate indicators to build an evaluation indicator system. It entails choosing the suitable model construction method to render the process objective, scientific and convincing (Keivanpour, 2021; Tiruneh and Fayek, 2021). This study adopted calculated or expert-recommended values as performance indicators. The following paragraphs provide a concise introduction to the three methods adopted in this study to construct the index system?

1. Theoretical analysis method: This method is based on perceptual knowledge, using rational thinking to explore the nature and laws of things. It can comprehensively analyze the characteristics of the wide range of performance indicators relevant to the research objectives (Fanaei et al., 2019). It then examines the essential attributes of the indicators and explores the relationships between them. The results are used to choose suitable indicators, assign them to a primary-secondary indicator structure, and build the evaluation indicator system.
2. Cross-analysis method: Also known as the three-dimensional analysis method, it is the first longitudinal-cum-transverse analysis. From the cross or three-dimensional perspective, the method explores the performance indicators from different angles and depths (Li et al., 2021). In establishing the evaluation indicator system, this study analyzed the relationships between the indicators and then selected some primary and secondary indicators judiciously to render the system more comprehensive, accurate, scientific, and rational.
3. Frequency statistics method: This method mainly analyzes the occurrence frequency of a basket of relevant indicators gleaned from research reports, papers and other sources and then retains the more frequently used indicators (Luo et al., 2016).

It was followed by consulting the sewage treatment experts and government management departments in Fuzhou, Shenzhen and Wuhan cities in China. All 20 interviewed experts had more than five years of experience in the industry, meeting the requirements of the semi-structured interview method used in this study. Additionally, due to the COVID-19 restrictions, the interviews were conducted by email and phone. Their inputs were used to optimize the choice of indicators. Finally, the identified indicators were classified.

2.2 Criteria for Selecting Performance Indicators

Two key technical documents were consulted to help select performance indicators. They were “The national evaluation standards for operation quality of urban sewage treatment plants” (CJJ/T 228-2014) and “Traditional infrastructure implementation guidelines for the government and social capital cooperation projects”, hereinafter referred to as “the evaluation standards” and “the work guidelines”, respectively. Covering 14 indicators, the evaluation criteria included facilities and equipment utilization rate and intact rate (the proportion of equipment remaining in good working order in all production units), environmental benefits, and energy and material consumption (Ministry of Housing and Urban-rural Development of the People's Republic of China, 2014).

Secondly, relevant literature items were reviewed, and the extracted performance indicators were statistically analyzed. The results helped identify the critical performance indicators for our study. Concerning energy conservation and pollution abatement,

Table 1. Classification of Experts’ Characteristics

Category	Attribute	Number	Proportion (%)	Attribute	Number	Proportion (%)
Gender	Male	11	55	Female	9	45
Age	Under 30	3	15	31 – 40 years old	6	30
	41 – 50 years old	7	35	51 – 60 years old	4	20
Position	Sewage treatment plant manager	4	20	PPP project operation and maintenance staff	8	40
	Environmental Protection Bureau employee	5	25	University researchers	3	15
Education	Junior college or below	2	10	Undergraduate	6	30
	Master degree	7	35	Doctoral degree	5	25
Region	Fuzhou	8	40	Wuhan	3	15
	Jiangxi	3	15	Zhejiang	2	10
	Beijing	2	10	Shanghai	2	10
Working time	< 5 years	3	15	5 – 10 years	5	15
	11 – 20 years	9	45	> 20 years	3	15
Professional category	Operation management	3	15	Performance evaluation	10	50
	Financial management	3	15	Government regulation	4	20
Title	Primary professional title	4	20	Intermediate professional title	8	40
	Senior professional title	8	40			

we considered chemical oxygen demand (COD) reduction per unit treatment capacity and chemical agent consumption per unit of sludge treatment (Wu et al., 2015; Zhang et al., 2021). Regarding operation efficiency, we considered sewage treatment load, water-quality standard index, sludge standard index, and operation cost were used (Mai et al., 2015). For comprehensive benefits, we considered the COD removal rate, biochemical oxygen demand (BOD) removal rate, total nitrogen (TN) removal rate, total phosphorus (TP) removal rate, unit sewage treatment chemical agent consumption, and unit sewage treatment power consumption (Janna, 2016; Yazdian and Shervin, 2021).

Finally, this study embraced the expert consultation method to refine the choice of performance indicators. A semi-structured interview method was adopted to conduct telephone interviews with about 20 experts with over five years of relevant working experience. They included sewage treatment plant managers, PPP project operation and maintenance staff, Environmental Protection Bureau employees, university researchers, and evaluation institutions. Their work units were situated in major Chinese cities and provinces, including Fuzhou, Wuhan, and Jiangxi. The detailed background of the experts is summarized in Table 1. Therefore, our comprehensive selection and analysis of the indicators rested on extensive practical engineering experience and field survey data.

2.3 Selecting Primary and Secondary Performance Indicators

The performance indicators of PPP wastewater treatment plants should fully reflect the typical and unique operating conditions and avoid overlaps. The indicators were grouped under five main categories to represent the multiple functions of the plants. Every primary indicator contains some secondary indicators. The five primary indicators were coded as C_1, C_2, C_3, C_4 and C_5, respectively. The second numeric subscript digit coded the corresponding secondary indicators, such as C_{11} and C_{12} under C_1. The final selection of indicators arranged as a two-tier primary-secondary indicator system is shown in Table 2. The indicators are further explained below.

2.3.1 Operation Quality Indicators

The primary purpose of the PPP sewage treatment plant is to treat sewage and improve urban environmental quality. Different plants may adopt different treatment processes to bring different performance delivery. Even if the same process is adopted, the pollutant concentrations of the influent water may differ, leading to varying concentrations of the effluent water. Therefore, it is not comprehensive enough to take the treated water quality as the evaluation standard. Since pollutants mainly include eutrophication ingredients, heavy metals and sludge in the effluent, the water quality compliance rate, the sludge compliance rate, and the organic matter in the effluent are the focus of pollution reduction. As organic matter in the effluent is of particular environmental concern, compliance in COD, BOD, SS, TP, NH_3-N, TN, and fecal coliform present the key indicators (Pipi et al., 2018; Bhave et al., 2020; Mali et al., 2020; Dantas et al., 2021). Considering PPP project characteristics and reflecting operation quality, they are labeled as operation quality indicators. To trim the number of secondary indicators to a manageable level, we adopted the two most critical ones that often cause environmental concerns in the receiving water bodies in Chinese cities, namely the average annual COD removal rate and average annual BOD removal rate, as the proxy of the string of individual indicators.

2.3.2 Operation Efficiency Indicators

The design and production capacity of sewage treatment plants are different. If a plant has a high construction cost but a low facility and equipment utilization rate during operation, it incurs inefficient utilization and waste of community resources. The enterprise partner expects to invest in the project for a given benefit and at a reasonable cost. An efficiency decline would lower the return on investment. Therefore, in addition to operation quality, a plant's efficiency must be appraised (Li and Zhu, 2014; Aishwarya et al., 2016; Bao et al., 2019) to ensure a high rate of resource use. The operation efficiency of a sewage treatment

Table 2. Selection of the Final Two-Tier Primary-Secondary Indicator System to Evaluate the Operation-Maintenance Performance of PPP Sewage Treatment Plants

Primary indicator (code)	Secondary indicator (code)	Primary indicator (code)	Secondary indicator (code)
Operation quality (C_1)	Average annual water-quality compliance rate (C_{11})	Facility management (C_4)	Pipe network maintenance quality (C_{41})
	Sludge moisture content (C_{12})		Equipment maintenance quality (C_{42})
	Average annual COD removal rate (C_{13})		Performance of the daily management system (C_{43})
	Average annual BOD removal rate (C_{14})		Performance of the emergency management system (C_{44})
Operation efficiency (C_2)	Annual operating rate (C_{21})	Social satisfaction (C_5)	Satisfaction of surrounding residents (C_{51})
	Average annual hydraulic load rate (C_{22})		Investor satisfaction (C_{52})
	Average annual COD load rate (C_{23})		Policy response (C_{53})
Energy-material consumption (C_3)	Average annual water consumption per unit sewage treatment (C_{31})		
	Average annual consumption of dry solid dehydration agent (C_{32})		
	Average annual electricity consumption per unit sewage treatment (C_{33})		

plant depends on its annual plant operation rate, average annual hydraulic load rate, and average annual COD load rate. If these three indicators are high, it means a large treatment capacity, a high utilization rate of equipment and facilities, and an overall high efficiency.

2.3.3 Energy-Material Consumption Indicators

Sewage treatment involves transforming sewage into reusable water. The process consumes large amounts of energy and materials. For plants employing the same production process, if the energy and material consumption are quite different but the effluent quality and treatment volume are almost the same, the discrepancy signifies a serious waste of operating resources. During the operation-maintenance stage, due to the shared risk arrangement of the two partners, abnormally high energy-material consumption can harm the interests of investors and increase financial pressure on the government. Therefore, the plant's operation should be monitored by energy-material consumption indicators (Figueiredo et al., 2021; Yadav, 2021). Three essential indicators, namely the average annual water consumption per unit of sewage treatment, average annual electricity consumption per unit of sewage treatment, and average annual dry solid dehydrating agent consumption, can fully reflect the energy-material consumption at the operation stage. Plant size can influence operation efficiency. The average annual electricity consumption per unit of sewage treatment of small plants is usually higher than large ones.

2.3.4 Equipment and Facilities Management Indicators

The smooth functioning of equipment and facilities is an essential basis for the routine operation of a sewage treatment plant. For example, the sewage pipe network is a critical installation for conveying a large fluid volume in the plant. Pipe leakage or blockage will pollute the environment or reduce environmental benefits. Therefore, the equipment and facilities should be maintained at scheduled intervals to sustain working order and repaired promptly to ensure efficient operation. Meritorious equipment upkeep can contribute to economic benefits (Liu and Li, 2018). Under the PPP mode, the equipment and facilities are reckoned as fixed assets shared and jointly maintained by the government and the private partner during plant operation. Firstly, the pipe network is the most pivotal installation in facility management and is most prone to failure. It demands regular and meticulous maintenance and prompt repair to forestall damage, leakage or blockage. Its management quality can be represented by its direct performance indicator, i.e., the annual failure rate of the pipe network. Secondly, the normal functioning of the equipment is critical to the treatment process. The annual equipment failure rate can echo the maintenance quality of equipment. Thirdly, the performance of the daily and emergency management systems reflects the inherent weaknesses in the facility management regime.

2.3.5 Social Satisfaction Indicators

A sewage treatment plant is a public utility project that should prioritize public interest (Singh, 2021). If the plant operation brings disturbance or nuisance to the surrounding residents, compromising their right to live and work normally will impose adverse social impacts (Herrera-Navarrete et al., 2021). In addition, if the investors are not satisfied with the project's income, it will dampen their interest in the whole PPP sewage treatment market. It may have repercussions on the achievability of future PPP projects. Three aspects of a plant could involve the social dimension. Firstly, it may generate nuisances such as noise and odor when operating. Produced at a high level, they will affect the daily life of nearby residents and workers. The social satisfaction survey mainly considers whether the surrounding residents have complained about the plant. In addition, prompt handling and satisfactory resolution of complaints can raise the plant's performance and boost the corporate image. Secondly, the satisfaction of the investors can be investigated, mainly concerning the rate of return on investment. Thirdly, the government's satisfaction primarily depends on whether the policies and regulations can be successfully implemented. They may include, for instance, whether the government responds to the terms of bid selection and whether the cleaning audit is in place. Therefore, government satisfaction was changed to policy response, assessed and scored by experts.

According to the principles and the methods of indicator selection, their sources and conceptual basis were clarified. A comprehensive indicator system was established to serve as the core of this study.

3. Developing the Evaluation Methods

3.1 Selecting the Evaluation Methods

The following research step involved constructing a performance evaluation model for the operation-maintenance stage of the PPP mode sewage treatment plant. This goal was achieved by applying two research methods: the analytic hierarchy process (AHP) and the matter element analysis (MEA). The AHP can reduce individual differences and integrate individual decision-making results into group decision-making, but it entails subjectivity (Karuppiah et al., 2022). As a more objective method, MEA can determine the performance level by calculating the correlation between factors and their standards (Xiao et al., 2018). Thus, it was enlisted to tackle the objective incompatibility problem. By combining the multilevel extension principle of MEA with AHP, the differential weights of evaluation indicators and model establishment problems were effectively resolved, giving full play to their respective advantages (Zhang et al., 2020). The final evaluation results were reversed to the problems regarding operation and maintenance, and practical suggestions were distilled to resolve them.

3.2 Implementation Steps of the Analytic Hierarchy Process

The AHP is a systematic multi-index and multi-plan optimization decision-making method (Zhang et al., 2020). The technique divides the complex target into multiple layers step-by-step and then decomposes the target layer into multiple indexes (Yildiz et al., 2020). It then quantifies the qualitative indexes fuzzily and calculates the ranking of indexes and the overall ranking of the target layer to reach the decision.

The AHP involves scrutinizing the decision problem's structure and decomposing it into different levels such as decision-making problem, index, evaluating potential, alternatives, etc. By comparing the scoring method to form the judgment matrix, the matrix eigenvector can be solved as the weight of the corresponding indicator (Majidipour et al., 2021). Applying the weighted average method, the index weights of individual layers can be classified into alternatives to solve problems, and the weight of the biggest is the optimal solution (Wang, 2017; Selvam et al., 2021). The following steps were followed in implementing the AHP:

3.2.1 Determine the Preliminary Weight

Experts were engaged in comparing and scoring the indicators at all levels in pairs. They chose ai and aj from a.1, a.2,...a.n. to compare their importance to y. A value was assigned to a.ij = a.i/ a.j. according to the scale given in Table 3. The average values of the experts' scores were rounded to get the judgment matrix A (Deng et al., 2012).

The final judgment matrix A was:

$$A=\begin{bmatrix} a_{11} & a_{12} & a_{13} & a_{14} \\ a_{21} & a_{22} & a_{23} & a_{24} \\ a_{31} & a_{32} & a_{33} & a_{34} \\ a_{41} & a_{42} & a_{43} & a_{44} \end{bmatrix}. \tag{1}$$

The eigenvectors of each matrix are obtained using the product square root method $W_i=(w_1,w_2,...,w_n)^T$:

$$w_i=\frac{\sqrt[n]{\prod_{j=1}^{n}a_{ij}}}{\sum_{i=1}^{n}\sqrt[n]{\prod_{j=1}^{n}a_{ij}}},(i,j=1,2,...,n)\ . \tag{2}$$

Using the judgment matrix, the maximum eigenvalue is obtained. Then using $AW=\lambda_{\max}W$, $\lambda_{\max}$ is computed by Eq. (3):

$$\lambda_{\max}=\frac{1}{n}\sum_{i=1}^{n}\frac{\sum_{j=1}^{n}a_{ij}w_j}{w_i},(\mathrm{i},j=1,2,...,n)\cdot \tag{3}$$

3.2.2 Conduct the Consistency Test

The consistency index $C.I.$ is calculated as follows:

$$C.I.=(\lambda_m-n)/(n-1)\,. \tag{4}$$

The value of the average random index is selected according to the order of the matrix. $R.I.$ The values of orders 1 – 10 are shown in Table 4 (Bhushan, 2018):

3.2.3 Judge Whether There is Consistency

The judgment matrix is considered consistent when the ratio of criticality $C.R.$ between the consistency index $C.I.$ and the average random consistency index $R.I.$ is satisfied. When $C.R.=\frac{C.I.}{R.I.}<0.1$, the judgment matrix is rated as inconsistent. At this point, the factors need to be reassigned in pairs until the consistency test is passed. When the single sort consistency test is passed, the consistency of the total sort is tested:

$$C.R._{Total}=\frac{\sum_{i=1}^{n}u_iC..I._i}{\sum_{i=1}^{n}u_iR.I._i}\,, \tag{5}$$

where u_i is the weight of the target layer corresponding to the primary indicator, and $C.I.$ and $R.I.$ are the consistency index and average random consistency index of the secondary indicator matrix under the primary indicator.

When the overall consistency test was rated pass, the eigenvector corresponding to $\lambda_{\max}$ is the factor's weight corresponding to the matrix.

3.3 Implementation Steps of the Matter Element Analysis

The MEA is an innovative research method developed recently based on classical and fuzzy mathematics, but it differs from the parents and is not a branch of mathematics (Cai, 1987). The mathematical analysis part of MEA is contingent upon the principle of extenics. Compared with the traditional mathematical model concepts, MEA has more formal and dialectical logic and is more akin to artificial intelligence. Due to the need to consider many factors and complex indicators in the operation-maintenance stage of PPP sewage treatment plants, the analytical power of MEA was enlisted. Five steps were involved in its implementation.

Table 3. The Element aij Value Rule Used by the Evaluations Experts to Assess the Performance Indicators[a]

a.ij = a.i/ aj	a.i/ aj = 1	a.i With aj Of equal importance
	a.i/ aj = 3	a.i More than aj Slightly more important
	a.i/ aj = 5	a.i More than aj Moderately more importance
	a.i/ aj = 7	a.i More than aj Notably more important
	a.i/ aj = 9	a.i More than aj Absolutely more important

[a]The ratios 2, 4, 6 and 8 are rated as the intermediate state.

Table 4. The Random Consistency Index (R.I.)

Order number	1	2	3	4	5	6	7	8	9
R.I.	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.49

3.3.1 Determine the Classical Domain and Node Domain

Let Q be the matter element and C the set of factors to be evaluated. According to the size of the evaluated object, it was divided into different levels, and the level domain was established. $M = \{m_1, m_2, m_j\}$, j is the number of levels. $C = \{c_1, c_2, \ldots, c_i\}$, i represents the number of evaluation indicators (You et al., 2017).

$$Q_i = [M_i, \quad C, \quad V_i] = \begin{bmatrix} M_i, & c_1, & v_{i1} \\ & c_2, & v_{i2} \\ & \vdots & \vdots \\ & c_n, & v_{in} \end{bmatrix} = \begin{bmatrix} M_i, & c_1, & <a_{i1}, b_{i1}> \\ & c_2, & <a_{i2}, b_{i2}> \\ & \vdots & \vdots \\ & c_n, & <a_{in}, b_{in}> \end{bmatrix}, \tag{6}$$

where M_i is the i quality grade; c_n is the evaluation index of the grade Q_i; V_{im} is the range of magnitude determined by Q_i on the evaluation index c_n, i.e., the range of data taken for the corresponding characteristics of each level - the classical domain $<a_{in}, b_{in}>$.

$$Q_M = [M, \quad C, \quad V_M] = \begin{bmatrix} M & c_1 & <a_{M1}, b_{M1}> \\ & c_2 & <a_{M2}, b_{M2}> \\ & \vdots & \vdots \\ & c_n & <a_{Mn}, b_{Mn}> \end{bmatrix}, \tag{7}$$

where V_M is the range of magnitude value determined by C concerning the evaluation index c_n, which is the node domain of M $<a_{Mi}, b_{Mi}>$.

3.3.2 Determine the Matter Element to be Evaluated

For the indicators to be evaluated, the data results obtained from the actual investigation were expressed by the matter-element Q as follows:

$$Q_i = (R, C_i, V_i) = \begin{bmatrix} R & c_{i1} & v_{i1} \\ & c_{i2} & v_{i2} \\ & \cdots & \cdots \\ & c_{ip} & v_{ip} \end{bmatrix}, \tag{8}$$

where Q is the matter-element level to be evaluated; V_i is the quantity value of N with respect to c_{ip}, which is the specific value of the object to be evaluated. $K = 1, 2, \ldots, p$, and p is the number of secondary indicators.

3.3.3 Determine the Correlation Strength Function

According to the definition of the correlation function, the correlation strength of the secondary index c_{ik} of the object to be evaluated c_i concerning the comprehensive performance level j was determined by:

$$K_j(v_{ik}) = \begin{cases} \dfrac{\rho(v_{ik}, V_j)}{\rho(v_{ik}, V_M) - \rho(v_{ik}, V_j)} & , \quad \rho(v_{ik}, V_M) - \rho(v_{ik}, V_j) \neq 0 \\ -\rho(v_{ik}, V_j)\text{-}1 & , \quad \rho(v_{ik}, V_M) - \rho(v_{ik}, V_j) = 0 \end{cases}, \tag{9}$$

$$\rho(v_{ik}, V_j) = \begin{cases} v_{ik} - b_{ji} & v_{ik} \geq \dfrac{a_{ji} + b_{ji}}{2} \\ a_{ji} - v_{ik} & v_{ik} < \dfrac{a_{ji} + b_{ji}}{2} \end{cases}, \tag{10}$$

$$\rho(v_{ik}, V_M) = \begin{cases} v_{ik} - b_{Mi} & v_{ik} \geq \dfrac{a_{Mi} + b_{Mi}}{2} \\ a_{Mi} - v_{ik} & v_{ik} < \dfrac{a_{Mi} + b_{Mi}}{2} \end{cases}. \tag{11}$$

3.3.4 Establish the Comprehensive Model

The transformation matrix of comprehensive performance evaluation is as follows:

$$K = \begin{bmatrix} K_1(L_1) & K_2(L_1) & \cdots & K_n(L_1) \\ K_2(L_1) & K_2(L_2) & \cdots & K_n(L_2) \\ \vdots & \vdots & \cdots & \vdots \\ K_n(L_m) & K_n(L_m) & \cdots & K_n(L_m) \end{bmatrix}. \tag{12}$$

Let the weight of the primary index subset $\{L_1, L_2, ..., L_m\}$ be $W = \{w_1, w_2, ..., w_m\}$ and $\sum_{i=1}^{m} w_i = 1$, then the multistage extension evaluation model of comprehensive performance Y of the sewage treatment plant was:

$$Y = W \cdot K = (Y_1, Y_2, \ldots, Y_n). \tag{13}$$

3.3.5 Determine the Evaluation Grade

Assuming that the weight of the performance indicator factors c_{ki} to be evaluated is t_{ki}, and $\sum_{k=1}^{l} t_{ki} = 1$, the correlation strength of the comprehensive performance of the sewage treatment plant L_i to be evaluated concerning the level j is:

$$K_j(L_i) = \sum_{k=1}^{l} t_{ki} K_j(v_{ki}). \tag{14}$$

If $K_j = \max\{K_j(L_i)\}$ $(j = 1, 2, ..., m)$ (Eqs. (4) – (14)), then the comprehensive performance of the underlying sewage treatment plant L_i belonged to grade j (Liu et al., 2015).

3.4 Establishing the Weights of Performance Indicators

The experts in sewage treatment plants were engaged to determine the relative weights of the performance indicators. They were professionals with PPP project operation-maintenance experience, officers from the environmental protection bureaus, university researchers, and personnel of independent evaluation agencies. The expert scoring method used the nine-point scale method to score the indicators. Different judgment standards were devised separately for quantitative and qualitative indicators. Finally, a complete model to realize the performance evaluation was established.

After inviting experts to grade the indicators in pairs, the crowd value of each grade result was taken after summarizing, and the final judgment matrix was as follows:

The calculations found that the *C.R.* of all matrices are < 0.1, which met the requirements of the consistency test. Next, the consistency of the total sorting was tested:

$$C.I._{Total} = 0 \times 0.28 + 0 \times 0.28 + 0 \times 0.12 + 0 \times 0.28 + 0 \times 0.04 = 0, \quad (15)$$

$$R.I. = 0.28 \times 0.90 + 0.28 \times 0.58 + 0.12 \times 0.58 + 0.28 \times 0.90 + 0.04 \times 0.58 = 0.7592, \quad (16)$$

$C.R._{Total} = \frac{C.I._{Total}}{R.I._{Total}} = 0$, C.R. < 0.1, so it met the consistency requirement.

After passing the overall consistency test, the corresponding feature vector was normalized as the final weight for correlation calculation, as summarized in Table 5.

3.5 Determining the Criteria for Indicator Evaluation

The performance indicator system included quantitative and qualitative indicators. Most quantitative indicators were specific that could be expressed by digital means. Most qualitative indicators were general expressions of a specific operation part, assessed by expert scoring. Table 6 present the diagnostic scoring criteria.

The qualitative indicators included the maintenance quality of the pipe network, failure rate of the pipe network, performance of the safety management system, performance of the emergency management system, satisfaction of surrounding residents, satisfaction of investors, and policy response

The quantitative indicators included the average annual water-quality compliance rate, average annual sludge moisture content, average annual COD removal rate, average annual BOD removal rate, annual plant operation rate, average annual hydraulic load rate, average annual COD load rate, average annual consumption of dry solid dehydration agent, unit sewage treatment water consumption, and unit sewage treatment electricity consumption. The equations to calculate the quantitative indicators are:

$$\text{Annual average water quality compliance rate} = \frac{\text{Annual water quality compliance days}}{\text{Number of days of operation}} \times 100\%, \quad (17)$$

$$\text{Average annual sludge moisture content} = \left(1 - \frac{\text{Dewatered sludge quality}}{\text{Total sludge quality}}\right) \times 100\%, \quad (18)$$

$$\text{Annual average COD removal rate} = \left(1 - \frac{\text{Total COD export volume}}{\text{Total COD imports}}\right) \times 100\%, \quad (19)$$

$$\text{Annual average BOD removal rate} = \left(1 - \frac{\text{Total BOD export volume}}{\text{Total BOD imports}}\right) \times 100\%, \quad (20)$$

Table 5. The Judgment Matrix C_i-C_j Used by the Evaluation Experts

	C_1	C_2	C_3	C_4	C_5	U_j
C_1	1	1	3	1	5	0.28
C_2	1	1	3	1	5	0.28
C_3	1/3	1/3	1	1/3	5	0.12
C_4	1	1	3	1	5	0.28
C_5	1/5	1/5	1/5	1/5	1	0.04
λ_{max} = 5.15, C.R. = 0.033						

Table 6. The Computed Weights of the Primary and Secondary Indicators

Primary indicator (code)	Primary indicator weight	Secondary indicator (code)	Secondary indicator weight
Operation quality (C_1)	0.28	Average annual water-quality compliance rate (C_{11})	0.30
		Sludge moisture content C_{12})	0.10
		Average annual COD removal rate (C_{13})	0.30
		Average annual BOD removal rate (C_{14})	0.30
Operation efficiency (C_2)	0.28	Annual plant operating rate (C_{21})	0.50
		Average annual hydraulic load rate (C_{22})	0.25
		Average annual COD load rate (C_{23})	0.25
Energy-material consumption (C_3)	0.12	Water consumption per unit sewage treatment (C_{31})	0.20
		Average annual consumption of dry solid dehydration agent (C_{32})	0.40
		Electricity consumption per unit sewage treatment (C_{33})	0.40
Facility management (C_4)	0.28	Pipe network maintenance quality (C_{41})	0.38
		Equipment maintenance quality (C_{42})	0.38
		Performance of the daily management system (C_{43})	0.12
		Performance of the emergency management system (C_{44})	0.12
Social satisfaction (C_5)	0.04	Satisfaction of surrounding residents (C_{51})	0.25
		Investor satisfaction (C_{52})	0.25
		Policy response (C_{53})	0.50

$$\text{Annual operating rate} = \frac{\text{Years of operation}}{\text{365 days}} \times 100\%, \tag{21}$$

$$\text{Annual average hydraulic load rate} = \frac{\text{Actual sewage treatment capacity}}{\text{Annual design sewage treatment capacity}} \times 100\%, \tag{22}$$

$$\text{Annual average COD load rate} = \frac{\text{Annual total influent COD}}{\text{Annual design of influent COD}} \times 100\% \tag{23}$$

$$\text{Unit sewage treatment water consumption} = \frac{\text{Annual total fresh sewage consumption}}{\text{Total annual sewage treatment}} \times 100\%, \tag{24}$$

$$\text{Annual average dry solid dehydration agent consumption} = \frac{\text{Annual agent consumption}}{\text{Total annual sewage treatment}} \times 100\%, \tag{25}$$

$$\text{Unit sewage treatment electricity consumption} = \frac{\text{Annual total electricity consumption}}{\text{Total annual sewage treatment}} \times 100\%. \tag{26}$$

Given the categorical nature of the qualitative indicators, the expert scores were obtained and then converted by an ordinal scale with four categories, as shown in Table 7.

For the quantitative indicators, the evaluation followed a set of proposed criteria. The statistical data on the operation-maintenance profile of sewage treatment plants in the Fujian

Table 7. The Scoring Standard for the Qualitative Secondary Indicators Using a Four-step Ordinal Scale

Secondary indicator (code)	Scoring criteria			
	100 – 90	90 – 80	80 – 70	70 – 0
Pipe network maintenance quality (C_{41})	Very good	Good	Average	Poor
Equipment maintenance quality (C_{42})	Very low	Low	Medium	High
Performance of the daily management system (C_{43})	High	Medium	Low	Very low
Performance of the emergency management system (C_{44})	High	Medium	Low	Very low
Satisfaction of surrounding residents (C_{51})	High	Medium	Low	Very low
Investor satisfaction (C_{52})	High	Medium	Low	Very low
Policy response (C_{53})	Very strong	Strong	Average	Weak

Table 8. The Scoring Standard for the Quantitative Secondary Indicators (Each Indicator Score Lies in the 0 to 100 Range)

Secondary indicator (code)	Scoring criteria
Average annual water-quality compliance rate (C_{11})	Award a full score of 100 if the annual water-quality compliance rate is 100; deduct 1 point for every 1 reduction in the compliance rate.
Average annual sludge moisture content (C_{12})	Award a full score of 100 if the average annual sludge water content does not exceed 40; deduct 1 point for every 1 increase in the average annual sludge water content.
Average annual COD removal rate (C_{13})	Award a full score of 100 if the average annual COD removal rate reaches 100; deduct 1 point for every 1 decrease in the removal rate.
Average annual BOD removal rate (C_{14})	Award a full score of 100 if the average annual BOD removal rate reaches 100; deduct 1 point for every 1 decrease in the removal rate.
Annual plant operating rate (C_{21})	Award a full score of 100 if the annual plant operation rate is 100; deduct 1 point for every 1 decrease in the annual plant operation rate.
Average annual hydraulic load rate (C_{22})	Award a full score of 100 if the average annual hydraulic load rate is 100; deduct 1 point for every 1 decrease in the load rate.
Average annual COD load rate (C_{23})	Award a full score of 100 if the average annual COD load rate is 100; deduct 1 point for every 1 decrease in the load rate.
Water consumption per unit sewage treatment (C_{31})	Award a full score of 100 if the water consumption per unit sewage treatment does not exceed the prescribed upper threshold of 1.5 m^3; deduct 1 point for every 0.1 m^3 per unit sewage treatment of extra water consumption exceeding the prescribed threshold.
Average annual consumption of dry solid dehydration agent per unit sewage treatment (C_{32})	Award a full score of 100 if the average annual consumption of dry solid dehydrating agent per unit of sewage treatment does not exceed the prescribed upper threshold of 1.5 kg/t; deduct 1 point for every 1 kg/t per unit sewage treatment of extra dehydrating agent consumption exceeding the prescribed threshold.
Electricity consumption per unit sewage treatment (C_{33})	For a plant design size below 10,000 m^3/d, award a full score of 100 if the electricity consumption per unit of sewage treatment does not exceed the upper threshold of 0.2 kWh; deduct 15 points for every 0.1 kWh extra electrical consumption per unit of sewage treatment above the upper threshold. For a plant design size above 10,000 m^3/d, award a full score of 100 if the electricity consumption per unit of sewage treatment does not exceed the upper threshold of 0.15 kWh; deduct 15 points for every 0.1 kWh of extra electrical consumption per unit of sewage treatment above the upper threshold.

Province were gleaned. The data were then combined with the operation quality standards of urban sewage treatment plants, taking into account the PPP project's nature, to develop the scoring criteria for individual indicators. The evaluation standard of the quantitative indicators was then determined, as shown in Table 8.

Out of a total score of 100 points, four grades were established: excellent (90 – 100), good (80 – 90), average (70 – 80), and poor (< 70) based on the government's "the evaluation standards". The high score thresholds reflected the stringent standard imposed on sewage treatment performance.

3.6 Further Analysis to Establish the Final Performance Evaluation Model

To complete the evaluation, this study adopted the AHP and MEA methods to analyze the data concerning the particular operational traits of the PPP plant. Deep analysis of the indicator data and calculated statistics yielded the corresponding scoring points. Then, the multilevel extension principle of MEA was applied to compute the correlation strength between the primary indicators and the assessment grades. Finally, the operation-maintenance performance of the target layer, the PPP sewage treatment plant, was calculated to determine its operation status level.

According to the operation-maintenance levels of a PPP plant divided above, the level domain L = {excellent, good, average, poor} was established, and the level domain was L = {L_1, L_2, L_3, L_4}, and the index set was $C = \{c_1, c_2, c_3, c_4, c_5\}$. Taking the sludge treatment environmental benefits as an example, the classical domain:

$$Q_1(c_1) = \begin{bmatrix} L_1 & c_{11} & <90,100> \\ & c_{12} & <90,100> \\ & c_{13} & <90,100> \\ & c_{14} & <90,100> \end{bmatrix}, \tag{27}$$

$$Q_1(c_1) = \begin{bmatrix} L_2 & c_{11} & <80,90> \\ & c_{12} & <80,90> \\ & c_{13} & <80,90> \\ & c_{14} & <80,90> \end{bmatrix}, \tag{28}$$

$$Q_1(c_1) = \begin{bmatrix} L_3 & c_{11} & <70,80> \\ & c_{12} & <70,80> \\ & c_{13} & <70,80> \\ & c_{14} & <70,80> \end{bmatrix}, \tag{29}$$

$$Q_1(c_1) = \begin{bmatrix} L_4 & c_{11} & <0,70> \\ & c_{12} & <0,70> \\ & c_{13} & <0,70> \\ & c_{14} & <0,70> \end{bmatrix}. \tag{30}$$

The node domain is:

$$Q_1(c_1) = \begin{bmatrix} L & c_{11} & <0,100> \\ & c_{12} & <0,100> \\ & c_{13} & <0,100> \\ & c_{14} & <0,100> \end{bmatrix}. \tag{31}$$

The grade is set at $L = \{L_1, L_2, L_3, L_4\}$, the weights of the primary indicators are $W = \{0.28, 0.28, 0.12, 0.28, 0.04\}$

Fig. 2. The Sewage Treatment Plant (Plant B) in Fuzhou, Fujian Province, China, was Used as the Case Study to Test the Proposed Performance Evaluation System

Table 9. Evaluation of the Operation-Maintenance Performance of Plant B by Quantitative Index Scores

Primary indicator (code)	Secondary indicator (code)	Index score	Final score
Operation quality (C_1)	Average annual water-quality compliance rate (C_{11})	93	93
	Sludge moisture content C_{12})	60	80
	Average annual COD removal rate (C_{13})	88.1	88
	Average annual BOD removal rate (C_{14})	87.3	87
Operation efficiency (C_2)	Annual plant operating rate (C_{21})	87	87
	Average annual hydraulic load rate (C_{22})	65.6	66
	Average annual COD load rate (C_{23})	73.8	74
Energy and material consumption (C_3)	Water consumption per unit sewage treatment (C_{31})	$4.7 \times 10^{-4} m^3/t$	68
	Average annual consumption of dry solid dehydration agent (C_{32})	2.85 kg/t	87
	Electricity consumption per unit sewage treatment (C_{33})	$0.23\ kWh/m^3$	88

respectively, and the multi-stage extension evaluation model of plant performance was:

$$Y = W \cdot K = (0.28, 0.28, 0.12, 0.28, 0.04) \cdot K, \tag{32}$$

$$K = \begin{bmatrix} K_1(L_1) & K_2(L_1) & \cdots & K_n(L_1) \\ K_2(L_1) & K_2(L_2) & \cdots & K_n(L_2) \\ \vdots & \vdots & \cdots & \vdots \\ K_n(L_m) & K_n(L_m) & \cdots & K_n(L_m) \end{bmatrix}. \tag{33}$$

4. Application to and Analysis of Two Case Studies

4.1 The Case-Study Sewage Treatment Plant in Fuzhou

A PPP sewage treatment plant (hereinafter “Plant B”), situated in Fuzhou city in Fujian Province, China, was chosen as a case study to test and verify the proposed performance evaluation method (Fig. 2). It was established in July 2009 and started operation in December 2010. The plant’s total planned land area is 18.53 ha. Developed in phases, the present land area is 10.37 ha. The treatment capacity of the first phase (2010) was 100,000 t/day, and the second phase (2016) expanded it to 200,000 t/day, reaching (2020) 400,000 t/day. The sewage originates mainly from urban areas, plus some industrial wastewater. Currently, in line with the development strategy of Fuzhou, the service range that can be covered in the short term is 60 km^2, and in the long term, it can reach 83.6 km^2.

The project adopted the BOT mode, which was invested and constructed by the CYTF water company. The government granted a franchise right of 27 years. The plant will be handed over to the government free of charge after the franchise expiration. During the franchise period, the CYFT is responsible for the project's operation and sewage treatment and collects fees at the rates stipulated in the contract. The government is responsible for supporting facilities such as electricity needed to run the plant.

Plant B contributes to the service of the Fuzhou water bureau. Fuzhou's ecological and environmental protection technology company will handle the sludge generated in the production process. The Fujian solid waste center will recycle and dispose of hazardous wastes.

4.1.1 Operation Status

In 2017, Plant B's annual inflow and output were 47,948,528 t and 47,843,134 t, respectively. The designed influent COD was 300 mg/L, and the effluent COD was 60 mg/L. The designed COD removal rate was 80%, while the actual COD removal rate was 88.1%. The designed influent BOD was 150 mg/L, and the effluent BOD was 20 mg/L. The designed BOD removal rate was 87%, and the average annual BOD removal rate was 87.3%. The electricity consumption per sewage treatment unit was 0.23 kWh/m^3, and the average annual dry solid dehydration agent consumption was 2.85 kg/t.

4.1.2 Computing the Indicator Scores

This evaluation's statistical data were derived from Plant B's actual operation records in 2017. The statistical data were analyzed for the quantitative indicators, and the final scores were presented in Table 9 based on the scoring criteria explained in Section 3.

For the qualitative indicators, three experts were engaged to execute the expert scoring method. The results are summarized in Table 10.

4.1.3 Calculating the Correlation of Secondary Indicators

According to the divided classical domain and node domain, the correlation strength of the secondary indicators of the sewage treatment plant was calculated, taking the average annual water-quality compliance rate C_{11} as an example. The calculation process is as follows:

$$\rho(v_{11}, V_1) = \left| 93 - \frac{100+90}{2} \right| - \frac{100-90}{2} = -3, \tag{34}$$

$$\rho(v_{11}, V_2) = \left| 93 - \frac{90+80}{2} \right| - \frac{90-80}{2} = 3, \tag{35}$$

$$\rho(v_{11}, V_3) = \left| 93 - \frac{80+70}{2} \right| - \frac{80-70}{2} = 13, \tag{36}$$

$$\rho(v_{11}, V_4) = \left| 93 - \frac{70+0}{2} \right| - \frac{70-0}{2} = 23, \tag{37}$$

$$\rho(v_{11}, V_5) = \left| 93 - \frac{100+0}{2} \right| - \frac{100-0}{2} = -7. \tag{38}$$

Table 10. Evaluation of the Operation-Maintenance Performance of Plant B by Qualitative Index Scores Judged by Three Experts

Primary indicator (code)	Secondary indicator (code)	Expert 1	Expert2	Expert 3	Average score
Facility management (C_4)	Pipe network maintenance quality (C_{41})	83	86	87	85
	Equipment maintenance quality (C_{42})	90	86	88	88
	performance of the daily management system (C_{43})	70	72	72	71
	Performance of the emergency management system (C_{44})	78	74	75	76
Social satisfaction (C_5)	Satisfaction of surrounding residents (C_{51})	70	78	77	75
	Investor satisfaction (C_{52})	78	76	80	78
	Policy response (C_{53})	90	92	90	91

Table 11. The Operation-Maintenance Performance of Plant B Assessed by the Correlation Strength of Secondary Indexes

Primary indicator (code)	Secondary indicator (code)	Correlation strength of secondary indicator			
		$K_{\cdot 1}$	$K_{\cdot 2}$	$K_{\cdot 3}$	$K_{\cdot 4}$
Operation quality (C_1)	Average annual water-quality compliance rate (C_{11})	0.75	0.30	0.65	0.77
	Sludge moisture content C_{12})	0.33	0.00	0.00	0.33
	Average annual COD removal rate (C_{13})	0.14	0.20	0.40	0.60
	Average annual BOD removal rate (C_{14})	0.19	0.30	0.35	0.57
Operation efficiency (C_2)	Annual plant operating rate (C_{21})	0.19	0.30	0.35	0.57
	Average annual hydraulic load rate (C_{22})	0.41	0.29	0.36	0.13
	Average annual COD load rate (C_{23})	0.38	0.19	0.18	0.13
Energy and material consumption (C_3)	Water consumption per unit sewage treatment (C_{31})	0.41	0.27	0.06	0.07
	Average annual consumption of dry solid dehydration agent (C_{32})	0.19	0.30	0.35	0.57
	Electricity consumption per unit sewage treatment (C_{33})	0.14	0.20	0.40	0.60
Facility management (C_4)	Pipe network maintenance quality (C_{41})	0.25	0.50	0.25	0.50
	Pipe network facilities availability rate (C_{42})	0.14	0.20	0.40	0.60
	Performance of the daily management system (C_{43})	0.40	0.24	0.04	0.03
	Performance of the emergency management system (C_{44})	0.37	0.14	0.20	0.20
Social satisfaction (C_5)	Satisfaction of surrounding residents (C_{51})	0.38	0.17	0.25	0.17
	Investor satisfaction (C_{52})	0.35	0.08	0.10	0.27
	Policy response (C_{53})	0.13	0.10	0.55	0.70

Therefore,

$$k_1(c_{11}) = \frac{-3}{-7-(-3)} = 0.75, \tag{39}$$

$$k_2(c_{11}) = \frac{3}{-7-3} = \text{-}0.3, \tag{40}$$

$$k_3(c_{11}) = \frac{13}{-7-13} = \text{-}0.65, \tag{41}$$

$$k_4(c_{11}) = \frac{23}{-7-23} = \text{-}0.77\ . \tag{42}$$

The correlation strengths of the secondary indicators are shown in Table 11.

4.1.4 Calculating the Correlation of Primary Indicators

Similarly, according to the weight of the secondary indicators, the correlation strengths of the primary indicators were calculated, taking the operation quality C_1 as an example:

$$K(C_1) = [0.30, 0.10, 0.30, 0.30] \begin{bmatrix} 0.75 & -0.30 & -0.65 & -0.77 \\ -0.33 & 0 & 0 & -0.33 \\ -0.14 & 0.20 & -0.40 & -0.60 \\ -0.19 & 0.30 & -0.35 & -0.57 \end{bmatrix} \tag{43}$$

$$= [0.09, 0.06 - 0.42, -0.62].$$

The correlation strengths of the primary indicators are summarized in Table 12.

Finally, according to the weight of the primary indicators, the correlation strength of Plant B was calculated:

$$K(L_i) = [0.28, 0.28, 0.12, 0.28, 0.04] \begin{bmatrix} 0.09 & 0.06 & -0.24 & -0.62 \\ -0.29 & 0.03 & -0.22 & -0.29 \\ -0.21 & 0.15 & -0.31 & -0.45 \\ -0.24 & 0.22 & -0.23 & -0.45 \\ -0.12 & -0.11 & -0.19 & -0.46 \end{bmatrix} \tag{44}$$

$$= [-0.15, 0.10, -0.24, -0.45].$$

$k_2 = \max\{K_j(L_i)\}$, so j = 2, and the performance evaluation result of Plant B was rated as good.

Table 12. The Correlation Strength of the Primary Indicators

Primary indicator (code)	Correlation strength of primary indicator				Rating
	$K_{\cdot 1}$	$K_{\cdot 2}$	$K_{\cdot 3}$	$K_{\cdot 4}$	
Operation quality (C_1)	0.09	0.06	0.24	0.62	Good
Operation efficiency (C_2)	0.29	0.03	0.22	0.29	Good
Energy-material consumption (C_3)	0.21	0.15	0.31	0.45	Good
Facility management (C_4)	0.24	0.22	0.23	0.45	Good
Social satisfaction (C_5)	0.12	0.11	0.19	0.46	Average

Table 13. Evaluation of the Operation-Maintenance Performance of Plant H by Quantitative Index Scores

Primary indicator (code)	Secondary indicator (code)	Index score	Final score
Operation quality (C_1)	Average annual water-quality compliance rate (C_{11})	91	91
	Sludge moisture content C_{12})	53	87
	Average annual COD removal rate (C_{13})	90	90
	Average annual BOD removal rate (C_{14})	88.6	89
Operation efficiency (C_2)	Annual plant operating rate (C_{21})	85	85
	Average annual hydraulic load rate (C_{22})	65.6	66
	Average annual COD load rate (C_{23})	75.7	76
Energy and material consumption (C_3)	Water consumption per unit sewage treatment (C_{31})	$5.2 \times 10^{-4} m^3/t$	63
	Average annual consumption of dry solid dehydration agent (C_{32})	2.77 kg/t	87
	Electricity consumption per unit sewage treatment (C_{33})	0.21 kWh/m^3	91

Table 14. Evaluation of the Operation-Maintenance Performance of Plant H by Qualitative Index Scores Judged by Three Experts

Primary indicator (code)	Secondary indicator (code)	Expert 1	Expert2	Expert 3	Average score
Facility management (C_4)	Pipe network maintenance quality (C_{41})	85	83	82	83
	Equipment maintenance quality (C_{42})	92	90	89	90
	performance of the daily management system (C_{43})	71	72	70	71
	Performance of the emergency management system (C_{44})	80	76	77	78
Social satisfaction (C_5)	Satisfaction of surrounding residents (C_{51})	68	75	72	72
	Investor satisfaction (C_{52})	80	78	79	79
	Policy response (C_{53})	92	90	91	91

From Table 12, the operation quality of Plant B has been rated at a good level, consistent with the general operational track records. Its operating efficiency, energy-material consumption, and facility management indicators were rated at a good level. However, the social satisfaction indicator was placed at the average level. The testing results using Plant B signified that the proposed evaluation method was feasible, effective and credible.

4.2 The Case-study Sewage Treatment Plant in Wuhan

4.2.1 Operation Status

The first phase of the Wuhan H sewage treatment project (hereinafter "Plant H") is designed to treat 800,000 m^3 of sewage per day, up to 1.5 million m^3 in the long term. The service area is 130 $km^{2,}$ and the service population is about 2.5 million. The plant is expected to reduce the pollutants in the main water-course outlet of the area by more than 60%. The design COD of inlet water is 250 mg/L, and the paper COD of effluent is 40 mg/L. The design COD removal rate is 84%, but the actual COD removal rate is 90%. The design BOD of inlet water is 120 mg/L, and the paper BOD of effluent is 10 mg/L. The designed BOD removal rate is 83.3%, and the actual annual BOD removal rate is 88.6%. The power consumption per unit of effluent removal was 0.21 kWh/m^3, and the average annual consumption per unit of dry solid dehydrant was 2.77 kg/t.

4.2.2 Computing the Indicator Scores

This evaluation's statistical data were derived from Plant H's actual operation records in 2017. The statistical data were analyzed for the quantitative indicators, and the final scores were presented in Table 13 based on the scoring criteria explained in Section 3.

For the qualitative indicators, three experts were engaged to implement the expert scoring method. The results are summarized in Table 14.

Table 15. The Operation-Maintenance Performance of Plant H Assessed by the Correlation Strength of Secondary Indexes

Primary indicator (code)	Secondary indicator (code)	Correlation strength of secondary indicator			
		$K_{\cdot 1}$	$K_{\cdot 2}$	$K_{\cdot 3}$	$K_{\cdot 4}$
Operation quality (C_1)	Average annual water-quality compliance rate (C_{11})	0.13	-0.10	-0.55	-0.70
	Sludge moisture content C_{12})	-0.19	0.30	-0.35	-0.57
	Average annual COD removal rate (C_{13})	0.00	0.00	-0.50	-0.67
	Average annual BOD removal rate (C_{14})	-0.08	0.10	-0.45	-0.63
Operation efficiency (C_2)	Annual plant operating rate (C_{21})	-0.25	0.50	-0.25	-0.50
	Average annual hydraulic load rate (C_{22})	-0.41	-0.29	-0.11	0.13
	Average annual COD load rate (C_{23})	-0.37	-0.14	0.20	-0.20
Energy and material consumption (C_3)	Water consumption per unit sewage treatment (C_{31})	-0.42	-0.31	-0.16	0.23
	Average annual consumption of dry solid dehydration agent (C_{32})	-0.19	0.30	-0.35	-0.57
	Electricity consumption per unit sewage treatment (C_{33})	0.13	-0.10	-0.55	-0.70
Facility management (C_4)	Pipe network maintenance quality (C_{41})	-0.29	0.21	-0.15	-0.43
	Pipe network facilities availability rate (C_{42})	0.00	0.00	-0.50	-0.67
	Performance of the daily management system (C_{43})	-0.40	-0.24	-0.04	-0.03
	Performance of the emergency management system (C_{44})	-0.35	-0.08	0.10	-0.27
Social satisfaction (C_5)	Satisfaction of surrounding residents (C_{51})	-0.39	-0.22	0.08	-0.07
	Investor satisfaction (C_{52})	-0.34	-0.05	0.05	-0.30
	Policy response (C_{53})	0.13	-0.10	-0.55	-0.70

Table 16. The Correlation Strength of the Primary Indicators

Primary indicator (code)	Correlation strength of primary indicator				Rating
	$K_{\cdot 1}$	$K_{\cdot 2}$	$K_{\cdot 3}$	$K_{\cdot 4}$	
Operation quality (C_1)	0.00	0.03	-0.49	-0.66	Good
Operation efficiency (C_2)	-0.32	0.14	-0.10	-0.27	Good
Energy-material consumption (C_3)	-0.11	0.02	-0.39	-0.46	Good
Facility management (C_4)	-0.20	0.04	-0.24	-0.45	Good
Social satisfaction (C_5)	-0.24	-0.15	-0.09	-0.29	Average

4.2.3 Calculating the Correlation of Secondary Indicators

According to the divided classical domain and node domain, the correlation strength of the secondary indicators of the sewage treatment plant was calculated, and the correlation strengths of the secondary indicators are shown in Table 15.

4.2.4 Calculating the Correlation of Primary Indicators

Similarly, the primary indicators' correlation strengths were calculated according to the secondary indicators' weight. The correlation strengths of primary indicators were summarized as shown in Table 16.

Finally, according to the weight of the primary indicators, the correlation strength of Plant H was calculated:

$$K(L_i) = [0.26, 0.26, 0.14, 0.26, 0.08]\begin{bmatrix} 0.00 & 0.03 & -0.49 & -0.66 \\ -0.32 & 0.14 & -0.10 & -0.27 \\ -0.11 & 0.02 & -0.39 & -0.46 \\ -0.20 & 0.04 & -0.24 & -0.45 \\ -0.24 & -0.15 & -0.09 & -0.29 \end{bmatrix} = [0.17, 0.05, -0.28, 0.45]. \quad (45)$$

$K_2 = \max\{K_j(L_i)\}$, so j = 2, and the performance evaluation result of Plant H was rated as good.

The above model was applied to evaluate the performance of this case. Table 16 shows that Plant H's operation quality, efficiency, energy-material consumption, and equipment and facilities management are rated a good grade. However, social satisfaction during its operation is not high, which is rated as average. The results are consistent with the general operational track records. As a key project, the sewage treatment plant combines photovoltaic power generation clean energy and adopts improved advanced treatment technology, which have been widely praised. The test results of Plant H show that the evaluation method is feasible, effective and credible.

5. General Discussion

From the calculated weights, the operational quality, operational efficiency and equipment management indicators have the most significant impact on sewage treatment plants' performance, energy and material consumption, and social satisfaction. The results show the current development status of PPP projects. As countries have strict regulations on BOD and COD effluent concentration and treatment efficiency (Engstler et al., 2022; Rajpal et al., 2022), strict conditions such as the capacity and equipment of the plant are accorded the most critical status. However, energy and material consumption and social satisfaction are relatively neglected.

The index parameters of the case study Plant B can evaluate the operation-maintenance performance. They can identify the weak links in the operation-maintenance stage of most PPP sewage treatment plants represented by Plant B and identify and predict possible problems. The findings can help governments and managers make effective and timely improvements. Plant B was rated excellent in operational quality due to the high BOD and COD removal rates exceeding the design values. However, Plant B's operating efficiency was slightly lower at a good level, with an average annual hydraulic load rate of only 65.6%. This evaluation result reflects the outcomes of the on-site investigations. Some sewage pipe networks in various parts of Fuzhou are still under construction. Many old communities, shanty towns, townships and villages in Cangshan District have not built roads and supporting sewage pipes. Therefore, Plant B's present catchment area has not fully realized the original plan, and the low average annual sewage load rate directly affects the average annual COD load rate.

Plant B was rated a good level in energy saving and material consumption, reflecting some inadequacies. The sewage treatment technology, facilities and management methods are relatively basic and lack innovative energy-saving and consumption-reducing installations. The facility management indicator echoes that the daily and emergency management system of Plant B equipment and facilities is good but not excellent. This metric aims to predict the likelihood of network and equipment failures, which can indirectly compromise operational quality and efficiency (Łój-Pilch and Zakrzewska, 2019).

The satisfaction scores of surrounding residents and investors were only moderate. This result is consistent with the issues found in the field survey. Plant B occasionally produced a foul odor affecting the residents' daily lives. Due to the missing parts of the planned sewer network, the hydraulic load rate could not reach the optimal level. This shortcoming has reduced the expected profit and caused dissatisfaction among investors.

The case-study validation results indicated that the proposed performance evaluation system, based on a combined analytic hierarchy process and matter-element analysis, can evaluate the performance of the PPP sewage treatment plant in the operation-maintenance stage. The analysis has verified the feasibility of the index system and confirmed the validity and reliability of the performance evaluation model.

This study has made improvements based on previous studies. The literature indicates that most studies are limited to a particular performance indicator in evaluating PPP sewage treatment plants. In contrast, our proposed performance indicators cover a broad spectrum and include social satisfaction, which has been ignored by most studies (Ananda, 2020). We believe our method is more relevant to the real-world situations of the projects.

6. Conclusions

With further promotion and application of the PPP mode sewage treatment projects by the Chinese government, proper and accountable performance evaluation of the operation-maintenance stage has important implications for different stakeholders. Compared with other research, this study contributes an objective and scientific performance evaluation system in the crucial operation-maintenance stage to achieve the goals of supervision and monitoring. The practical results show that the proposed evaluation system can effectively resolve the concerns about the poor performance of PPP sewage treatment plants. The model analysis results can be applied to formulate specific measures for the government, often beset by inadequate information, to rectify the improper behavior of social enterprises, thereby improving the quality of public services. In establishing the evaluation model, the following innovations could be recapitulated:

1. The study surveyed the present status of research and practice of PPP projects in China, based on the PPP model of a sewage treatment plant and focusing on the pivotal operation-maintenance stage.
2. Based on the analysis of the chosen five-dimensional indicators, this study established an inclusive set of calculation methods to analyze the multiple and complex regimes of performance factors and processes.
3. This research filled the knowledge and practice gap by including the administrative concerns in ascertaining the quality delivery and efficiency of PPP sewage treatment plants.

This study is one of the few focusing on the performance evaluation of the PPP sewage treatment plant at the operation-maintenance stage. As such, it could fill a research gap and offer a feasible indicator system as a reference for other studies. The enhanced accuracy and hierarchical structure of the evaluation indicator system could raise operation and maintenance performance. The proposed evaluation system could provide quantitative-objective guidance for enterprises and governments to improve management at the key operation-maintenance stage. The findings could also furnish hints to refine the planning and design stage.

Although the objectives of this research were achieved, some limitations could be mentioned. First, the study was based on the context of the Fujian Province in China. Additional studies could test its applicability in other jurisdictions and circumstances. Second, due to the restrictions of COVID-19, the expert interview and consultation process had been hindered to a certain extent. In future research, the qualitative indicators are worthy of in-depth investigations to improve their accuracy and contributions to the evaluation system.

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