Study on evaluation index system of operational performance of municipal wastewater treatment plants in China

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Abstract. According to the undeveloped evaluation method for the operational performance of the municipal wastewater treatment plants, this paper analyzes the policies related to sewage treatment industry based on the investigation of the municipal wastewater treatment plants. The applicable evaluation method for the operational performance was proposed from environmental protection performance, resources and energy consumption, technical and economic performance, production management and main equipment, providing a reliable basis for scientific evaluation of the operation as well as improving the operational performance of municipal wastewater treatment plant.

1. Introduction
Water resources are the basic natural and strategic economic resources. As important support for the economic and social development, water resources are also the significant controlling elements of ecology and environment, which is important part reflecting the comprehensive national strength. China is a country lack of water resources. At present, among more than 600 cities in China, 2/3 of the cities are lack of water and 1/6 of the cities are in great shortage of water. Major cities, such as Beijing and Tianjin, are suffering from water shortage[1]. At present, China's economy is developing with high quality rather than at high speed. In order to solve the problem of water resource shortage, the overall strategy of water resources in China has changed into all-around sustainable utilization of water resources from the simple water resources control. While limiting the water pollution trends, the evaluation system of development and management of the sewage treatment technology shall be speeded up.

2. Research advance of operational performance evaluation of sewage treatment plant
2.1. Operational performance evaluation of sewage treatment plants abroad
Developed countries have mature experience in the operation of municipal wastewater treatment plants. Some European countries have invested more in the treatment of municipal water pollution due to the industrial revolution and economic development, such as Britain, Germany, Finland and Holland[2], Japan, Singapore, the United States and Australia also invested significantly in the municipal wastewater treatment[3]. Different from the operation and management of the sewage treatment plant in China, the foreign countries pay more attention to the establishment of the guarantee mechanism and measures for the operation and management of sewage treatment plants. On the one hand, the advanced modern science and technology, especially the high-level automation control
technology, are used to provide great support for the discharge of reaching standard and the development of sewage treatment. At present, the automation control of sewage treatment plants in developed countries has reached a higher level. The modern technologies such as computer automatic control, remote management and closed-circuit television is widely used[4]. The high-level automatic control standardizes the operation and management of the sewage treatment plant to a certain extent, and stabilizes the quality of the sewage treatment[5]. On the other hand, these countries provide effective guarantee for the sustainable development of water resources via improved laws and regulations for sewage treatment and water management, effective government and people management, as well as supervision mechanism.

The current Federal Water Pollution Control Act of the United States adopts a multi-layer management mode for water pollution[6], forming the control system with “command control” as core, “economic stimulation” as auxiliary and supplemented by public participation[7]. Germany strictly implements the water resources management law, emphasizing the strictly controlling the water by law with prevention as principle, and developing the standard of sewage treatment technology in the form of national laws[8]. The sewage management fully utilizes the sewage industry association and intermediary organizations to assist, supplement and coordinate the macro management of government[9-11]. In Japan, the responsibility division for the water resources management of the central government and the local government is clear. The Ministry of Land, Infrastructure and Transport is responsible for the construction and management of sewage facilities, and the water resources agency of Japan is responsible for the supervision[12]. As a result of strict discharging standards and legal control, the treatment rate of industrial sewage and municipal wastewater in Japan was above 98% by 2008[13].

There are more researches of municipal wastewater treatment in developed countries due to the earlier proposing of the clean production concept in the industry. In recent years, some researchers have made study on the evaluation of municipal wastewater treatment plants. Xavier Flores-Alsina has screened out 12 feasible indicators for comprehensive evaluation of sewage treatment plants from the aspects of economic benefits and processing technologies through comprehensive analysis of municipal wastewater treatment plants[14]. M. Ortiz et al. found several sewage treatment process with high efficiency and less environmental impact through the analysis and research of different sewage treatment processes, and tried to evaluate the processes to some extent[15]. Flores-Alsina evaluated the sewage treatment plants from the environmental benefits, economic benefits and technological feasibility through the study of sewage treatment technology[16]. As a feasible environmental management tool, some researchers apply the life cycle evaluation method to evaluate the sewage treatment plants while carrying out multi-objective evaluation[17,18].

2.2. Operational performance evaluation of domestic sewage treatment plants
The sewage treatment and recycling facilities are indispensable infrastructure for the development of urban and are important guarantee for the economic development and the safe healthy living of the residents. By 2015, the municipal wastewater treatment capacity has reached 217 million m$^3$/d in China, and the municipal wastewater treatment rate has reached 92%, the rural sewage treatment rate has reached 85%. The “12th Five-Year” planning goal for national sewage treatment facilities is basically completed. During “13th Five-Year” planning period, the state will make further overall plan, increase the investment, and strive to achieve the construction transformation of municipal wastewater treatment facilities, from the “scale increase” to “quality and efficiency improvement”, from “paying more attention to water treatment while ignoring sludge treatment” to “pay attention to both water and sludge treatment”, from “sewage treatment” to “reuse and recycling”, improving the guarantee ability and service level of municipal wastewater treatment facilities in China. With the application of various mature sewage treatment technologies in municipal wastewater treatment plants, the water pollution in China has been greatly controlled[19].

However, there are still many shortcomings in the municipal wastewater treatment industry in China. First, most of the municipal wastewater treatment plants adopt the activated sludge process in
China. This process is provided with high energy consumption and organic carbon source. The consumption of energy and other resources not only increases the operation cost of the sewage plants, but also affects the sustainable utilization of limited resources and energy. Secondly, various secondary pollutants will be generated in the process of sewage treatment, such as excess sludge, grid slag, odor, noise and various kinds of air pollutants discharged during the production process. In addition, due to less developed technology and equipment, poor management, low level of labor operation and low comprehensive utilization of resources, many domestic sewage treatment plants have problems such as poor water quality, high chemical and energy consumption, high treatment cost [20].

The concept about the sewage treatment in partial cities has just achieved the transformation from “pursuit of the sewage treatment quantity” to “pursuit of sewage treatment quality”. As the centralized management unit of pollutants, municipal wastewater treatment plants play an important part in reducing the pollutant emissions strategy. In order to fully utilize the functions of the existing facilities of sewage treatment plants, improve the operation and management level of municipal wastewater treatment plants, it is urgent to strengthen the evaluation of the operation and management effect of sewage treatment plants. Yu Jianpeng et al. define the whole life cycle of the sewage treatment plant, and make comprehensive analysis of the environmental impact brought by each stage in the process of sewage treatment [21,22]. Meng Fanyu et al. evaluate the sewage treatment plant by life cycle assessment method, so as to build a comprehensive evaluation index system for municipal wastewater treatment plants [23]. Qiu Zhongli established the operational performance evaluation system by analysis of the operation management, effluent concentration and finance of small-scale sewage treatment plants [24]. So far, China has made less study on clean production in municipal wastewater treatment industry. Xing Guangdong illustrated the clean production audit of municipal wastewater treatment in details according to the clean production approval steps, and also briefly discussed the evaluation index system of the sewage treatment industry clean production [25].

3. Construction of evaluation index system for operational performance of municipal wastewater treatment plant in China

3.1. Current situation of municipal wastewater treatment standards in China

According to the policy requirements specified in Deepen Standardization Reform Proposal and National Standardization System Establishment Development Planning, in order to solve the problems of aging and shortage of sewage processing industry standard, the low standard effective supply rate for long term, and to reflect the actual demand of the environmental protection industry, the standard system frame of municipal wastewater treatment system is preliminarily built as shown in Figure 1.
As shown in Figure 1, the first level in the municipal wastewater treatment standard system includes the discharging standard subsystem, engineering technical standard subsystem, monitoring and analysis standard subsystem, equipment product subsystem, resource recycling standard subsystem and evaluation management standard subsystem. The second level includes 30 national standards involving municipal wastewater treatment. Among them, 4 discharging standards, such as the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB 18918-2002); 8 project technical specification standards, such as Sewage Treatment Equipment Prevention and Treatment of Water Pollution (GB/T 28742-2012); 4 equipment standards, such as Waste Submersible Motor-pumps (GB/T 24674-2009); 7 sewage recycling standards, such as The Reuse of Urban Recycling Water--Classified Standard (GB/T 18919-2002); 7 sludge treatment standards, such as the Disposal of Sludge from Municipal Wastewater Treatment Plant-- Classification (GB/T 23484-2009). Refer to Figure 2 for the standard type distribution chart.

As for the performance evaluation, China Urban Water Association (CUWA) carried out systematic assessment of the operation of domestic sewage treatment plant in 2008. The assessment divided the sewage treatment plants into large, medium and small categories. Based on the Discharge Standard of Pollutants for Municipal Wastewater Treatment Plant (GB18918 - 2002), Technical Specifications for Operation, Maintenance and Safety of Municipal Wastewater Treatment Plant
(CJJ60), the *Quality of Sludge for Municipal Wastewater Treatment Plant* (CJ247-2007), the effective treatment of sewage, sewage and sludge treatment quality, operation cost and sewage treatment unit consumption, production operation management and security management are assessed. The investigation emphasized the efficient, economic and stable operation of the municipal wastewater treatment plant, and especially focused on the assessment of the operation and management level of the plants. Since the evaluation index system of the operation effect of municipal wastewater treatment plant has not been established yet, and there is no national standard related to the operation effect evaluation of municipal wastewater treatment plant, it is difficult to evaluate the performance level of municipal wastewater treatment plant scientifically, and guarantee the operational performance.

In summary, in the current municipal wastewater treatment standard system, the discharging standard subsystem, engineering technical standard subsystem, equipment product standards subsystem and resource recycling standards subsystem standards are less in quantity, with unbalanced distribution; in the meanwhile, there is no relevant national standards concerning monitoring and analysis standard subsystems and the evaluation management standards subsystem. The scientificalness, integrity, systematicness, coordination and operability of the whole standard system need to be improved. The standards are not able to satisfy the regulation and development of the industry. As for the evaluation of the operational performance of the municipal wastewater treatment system, the state has not established scientific, formal and improved performance evaluation standard system. With the economic development and the enhanced awareness of energy saving and environmental protection, it is more important to implement the unified effective municipal wastewater treatment system evaluation, and a set of scientific reasonable national practical standards is urgently need, to fill the gap in effect evaluation standard of domestic sewage treatment system and to improve the standard system of municipal wastewater treatment plant. The establishment of objective and quantitative method for sewage treatment plants evaluation, and the improvement measures proposed will help the improvement of the inefficient sewage treatment plants.

### 3.2. Establishment of evaluation index system for operational performance of municipal wastewater treatment plant in China

The evaluation index of the municipal wastewater treatment system were selected by fully considering the importance, representativeness and certainty. Therefore, selection principle of the evaluation index was specified with LCA thought, and the overall index system framework was determined along the whole process of pollutant removal, adjustment, operation, maintenance and management in the municipal wastewater treatment plant. The energy saving and environmental protection features were focused, whilst the quality, safety and economy index were also considered. The selection of indicators should be considered comprehensive and exercisable, adopting the principle of the combination of qualitative and quantitative evaluation indicators. Quantitative indicators should be measurable and qualitative indicators should be easy to verify.

To fully reflect the comprehensive profit of the municipal wastewater treatment plant, by LCA theory was integrated into the comprehensive evaluation of the sewage treatment plant. Meanwhile, combined with its own characteristics, the environmental protection attributes, resources and energy attributes, economic attributes, management and process attributes of the sewage plant were analyzed. The specific index of the evaluation system was selected by combining a variety of methods, taking the theoretical analysis as the basis. With the standard comparison, the factors that are frequently found in national, industry and local standards related to sewage treatment products, monitoring, maintenance and operation were selected as evaluation index. Based on the failure analysis of the failure process in the engineering case and the main concerns in the post-project evaluation, several representative indicators were comprehensively selected, and on this basis, industry surveys, expert guidance, and index classification have been continuously applied. The selected indexes were adjusted and modified to get the preliminary comprehensive evaluation index system of municipal wastewater treatment plant. The environmental protection performance, resources and energy consumption, technical and economic performance, production management as well as main facility and equipment
condition were selected as Class A indexes. The environmental protection performance index was to reflect the waste gas, sewage, solid waste and other environmental affects generated in the municipal wastewater treatment system operation; the energy and resources consumption index was to reflect the water, electricity and drug consumption in the municipal wastewater treatment system operation; the technical and economic performance index was to reflect the main technical and economic performance of the municipal wastewater treatment system operation; the production management index was to evaluate the management system and practical operation management level of municipal wastewater treatment system; the main facility and equipment condition index was to evaluate the operation and equipment efficiency of the main facilities and equipments of municipal wastewater treatment process. Refer to Table 1 for specific levels of the operation evaluation index system of municipal wastewater treatment.

Table 1. Evaluation index system for municipal wastewater treatment plant

| Target level | Class A index                                                                 | Class B index                                                                 |
|--------------|-------------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| Environmental protection performance B1 | Average annual water quality standard-reaching rate C1 | Electricity consumption for water treatment per unit C6                      |
|             | Average annual exhaust emissions C2                                          | Electricity consumption for pollutant consuming oxygen reduction per unit C7 |
|             | Average annual sludge quality standard-reaching rate C3                      | Drug consumption for water treatment per unit C8                            |
|             | Average annual pollutant comprehensive reduction rate C4                    | Drug consumption of dry sludge dewatering per unit C9                       |
|             | Microbial activity C5                                                       | Fresh water consumption for water treatment per unit C10                   |
| Resource and energy consumption B2 | ...                                                                           | ...                                                                           |
| Technical and economic performance B3 | Technical requirement C11*                                                   | Technical requirement C11*                                                   |
|             | Water operation cost per unit C12                                           | Water operation cost per unit C12                                           |
|             | Operation cost intact rate C13                                               | Operation cost intact rate C13                                               |
|             | Pollutant consuming oxygen reduction cost per unit C14                      | Pollutant consuming oxygen reduction cost per unit C14                      |
|             | COD reduction cost per unit C15                                              | COD reduction cost per unit C15                                              |
|             | Annual maintenance cost C16                                                  | Annual maintenance cost C16                                                  |
|             | Annual labor cost C17                                                       | Annual labor cost C17                                                       |
|             | Occupation area C18                                                         | Occupation area C18                                                         |
|             | ...                                                                           | ...                                                                           |
| Production management B4 | System and procedure C19*                                                      | System and procedure C19*                                                      |
|             | Organization C20*                                                           | Organization C20*                                                           |
|             | Staff training C21*                                                         | Staff training C21*                                                         |
|             | Emergence plan C22*                                                         | Emergence plan C22*                                                         |
|             | Operation, inspection account                                                | Operation, inspection account                                                |
and record C23*
Monitoring analysis record C24*
Equipment account C25*
Technical documents C26*

... Annual operation rate C27
Operation hydraulic load C28
Operation COD load C29
Building intact rate C30
Key equipment intact rate C31
Key equipment efficiency C32

Main facility and equipment condition B5

Note: * indicates the qualitative evaluation index

As shown in Table 1, there are 5 Class A indexes for the effect evaluation of municipal wastewater treatment system operation, and they are further refined into 32 Class B indexes, including:

- The Class B indexes of environmental protection performance includes 5 items: average annual water quality standard-reaching rate, average annual exhaust emission, average annual sludge standard-reaching rate, average annual pollutant comprehensive reduction rate and microbial activity. The environmental impact of the sewage plant can be evaluate more comprehensively from the air, water and solid waste aspects;

- Class B indexes of resources and energy consumption includes 5 items: electricity consumption for water treatment per unit, electricity consumption for pollutant consuming oxygen reduction per unit, drug consumption for water treatment per unit, drug consumption of dry sludge dewatering per unit, fresh water consumption for water treatment per unit. The indexes evaluate the utilization of resources and energy in municipal wastewater treatment plant from the view of clean production, which will help realize the virtuous cycle of the whole system;

- The Class B indexes of technical and economic performance include 8 items: technical requirements, water operation cost per unit, operation cost intact rate, pollutant consuming oxygen cost reduction per unit, COD reduction cost per unit, annual maintenance cost, annual labor cost and occupation area. The indexes reflect the investment and development level of sewage plants and the possible financial and technological problems during operation. The overall operation level of sewage treatment plants can be improved by cost and processes adjustment;

- Class B indexes of production management include 8 items: system and procedure, organization, staff training, emergency plan, operation and inspection account and records, monitoring analysis of records, equipment account, technical documents, which will improve the operation performance of the municipal wastewater treatment plant by the quality and environmental management means;

- Class B indexes of main facility and equipment status include 6 items: annual operation rate, operation hydraulic load, operation COD load, structure integrity rate, key equipment intact rate, key equipment energy efficiency. The index specifically reflects the operation stability, hardware, the advancement of equipment of the sewage treatment plant, so as to improve the overall operation of sewage treatment plant by adjusting facilities and equipment performance parameters.

4. Conclusion
- Although China has preliminarily established the framework of municipal wastewater treatment system standard system, the scientificalness, integrity, systematicness, coordination and operability of the system should be improved; the standard number is small with
unbalance distribution; the evaluation index system of operation effect has not been established, lacking of unified evaluation standard.

- Based on the industry research and expert guidance, via analyzing the relevant national, industry and local standards of municipal wastewater treatment plants and referring the focus content of project cases and project, the evaluation method applicable to municipal wastewater treatment plant operation is proposed. 5 Class A indexes and 32 Class B indexes about the environmental performance, resources and energy consumption, technical economic performance, production management and main facility and equipment are available to evaluate the operation effect of municipal wastewater treatment plant.

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