Research on Comprehensive Evaluation of the Operation and Maintenance Status of Urban Deep Metro Station

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Abstract. With the rapid development of urban metro system, the operation and maintenance status of urban metro station has received increasing attention. The operation and maintenance status of urban subway stations involve various factors including structure, equipment, and environment, which are difficult to be accurately evaluated directly. On the other hand, as the burial depth of metro station increases, disaster-triggering factors become increasingly complex and diverse, which enhances the difficulty of evaluating the operation and maintenance status. A new method is proposed herein to realize the comprehensive evaluation of the operation and maintenance status of urban deep metro stations. Firstly, the evaluation indexes needed for evaluation are selected by referring to a large number of literatures, combined with many relevant specifications and standards, and based on some existing index selection principles. According to the selected indexes, an evaluation index system of operation and maintenance status of underground metro station is established. Then, based on the established evaluation index system, a comprehensive evaluation method for the operation and maintenance status of urban deep metro station is developed by combining the analytic hierarchy process (AHP) and relevant information aggregation methods. This method is characterized by considering the functions with prominent defects with the use of weighted geometric average (WGA) and variable weight methods. Finally, the proposed evaluation scheme is applied to guide the maintenance of China’s deepest metro station. The proposed comprehensive evaluation method will promote the in-time management and maintenance of urban deep metro station.

1. Introduction
With the acceleration of urbanization, there is an evitable trend for underground facilities, such as metro systems, to go increasingly deeper. With the gradual increase in the operating hours of urban metro stations, various operation and maintenance problems may emerge one after another. These include but are not limited to structural water leakage, large-scale power outages, equipment failures, and poor environmental quality, which may greatly disturb the normal operation of urban metro stations or even cause serious casualties. In Shanghai, water seepage is a common problem that needs to be faced during the operation and maintenance of subway stations due to shallow groundwater depth and high pressure [1]. In 2011, there were serious water leaks and stagnant water in many parts of the Shanghai subway, which greatly affected people's travel. Then, the relevant person in charge stated that there were water leaks in 11 Shanghai subway lines due to various reasons such as operation and maintenance measure, lack of experience, weather, and construction. In Beijing, the air quality in Beijing subway stations is poor due to the poor outside air quality and the large scale of operations where PM2.5, CO, TVOC and...
formaldehyde often exceed the standards. According to research [2], in the Beijing subway in winter, the highest rate of temperature exceeding the standard is 82.7%, the highest rate of relative humidity exceeding the standard is 64.8%, and the average concentration of PM2.5 in the subway line is 83.8%~98.7%. Dong-UK et al. [3] found that the PM2.5 concentration range of Seoul subway system in South Korea was 0.078–0.158mg/m3, and the PM10 concentration exceeded 83.3% of the air quality standards promulgated by the US-EPA. Compared with shallow metro stations, the operation and maintenance of deep metro station (usually deeper than 50 m) are more difficult in the following aspects: longer path for evacuation, higher structure and function complexity, more relying on artificial environment construction, etc. Hence, the deep metro station bears higher disaster risk and is more vulnerable to accidental damage in comparison to shallow metro station. Therefore, it is necessary to establish a comprehensive evaluation method for the operation and maintenance status of urban deep metro stations.

At present, a variety of specifications and requirements have been proposed in many countries and regions for the operation and maintenance management of metro stations, including those in Europe [4-6], the United States and China [7-9]. In addition, some researchers [10-12] also have also worked on the operation and maintenance management of metro stations. Wang [13] analyzed the functional types, passenger flow distribution and service capabilities of metro stations, and developed a metro station operation safety risk evaluation index system. Xiao et al. [14] established a set of evaluation system by analyzing and evaluating factors related to the vulnerability of metro station operation, considering personnel, environment and many other factors. However, the existing evaluation methods own the following common problems: 1) They only evaluate a single system or part of a metro station, and cannot reflect the real operational status comprehensively, i.e., the structure, equipment and environment are evaluated separately; 2) the indexes adopted by these evaluation methods lack feasibility and operability, and the data are difficult to be obtained and analyzed; 3) The traditional evaluation method lacks the outstanding ability for highlighting the existing defects of the station; 4) The index status grading standard is not clear. Therefore, it is necessary to propose a new evaluation index system and evaluation method.

In order to solve these problems, a new evaluation method is proposed to realize the comprehensive evaluation of the operation and maintenance status of urban deep metro stations.

2. The evaluation index system of operation and maintenance status of urban deep metro station

In order to be able to better evaluate the operation and maintenance status of urban deep metro stations, it is necessary to establish an evaluation index system which incorporates the various factors that need to be considered in the evaluation. Due to the limiting cases of deep urban metro station, the relevant factors influencing the operation and maintenance status are derived mostly from existing specifications and standards.

2.1 Influencing Factors of Operation and Maintenance Status of Urban Deep Metro Stations

For urban deep metro stations, the main reasons for sudden accidents during operation and maintenance are damage to structures, poor normal working capacity of equipment, and deterioration of environmental quality. Therefore, the influencing factors are divided into three subsystems accordingly: structural status, equipment status and environmental status.

2.1.1 Structure status. According to the existing research on underground facilities, the possible structural defects of metro stations include structural deformation, structural damage, water damage and material deterioration.

(1) structural deformation

The structural deformation of metro station includes lateral convergent deformation and vertical settlement deformation. For the lateral convergent deformation, we consider both the amount of lateral deformation and the speed of its development to prevent its possible deterioration. For settlement
deformation, the main concern is the amount of settlement, the difference in settlement and the speed of settlement development to prevent its possible deterioration.

(2) structural damage
Structural damage includes cracks, holes behind walls, and structural damage. For cracks, sufficient attention should be paid to the size, number and shape of cracks. For holes behind walls, the main concern is the size. The damage of the structure will cause damage to the concrete structure, such as the damage of the concrete protective layer, accelerated steel corrosion and other undesirable phenomena, so sufficient attention needs to be paid.

(3) water damage
The metro station may be eroded and affected by the surrounding groundwater. The amount of water leakage, the area of wet stains and the water seepage speed are the most intuitive indexes for evaluating water damage. At the same time, the pH of the seepage water reflects the corrosive degree of the seepage water on the structure, which also needs to be considered.

(4) material deterioration
For concrete, the main deteriorations include the carbonization of the concrete, the decrease in strength of the concrete, and the decrease in thickness of the concrete due to damage. For steel materials such as steel bars, the deterioration resides in steel corrosion. The aging of the gasket is also a key factor that needs to be considered as it will also lead to a decline in its waterproof performance.

2.1.2 equipment status. In order to maintain the normal operation of the urban deep metro station, a large amount of equipment is needed to support its normal operation. Regarding the equipment status, it is necessary to pay attention to the equipment operation status and the equipment maintenance status respectively.

(1) the equipment operation status
The normal operation of metro station depends on the coordination of many systems, including the power supply system, environment and equipment monitoring system, automatic fire alarm system, platform screen door system, communication system, ventilation and air conditioning system, water supply and drainage system, escalator system, automatic fare collection system, etc. The equipment operation status is evaluated according to the working ability of these systems.

(2) the equipment maintenance status
The equipment maintenance status is evaluated according to the qualified rate of equipment maintenance, the number of faults and the completeness of protective equipment.

2.1.3 environmental status. The environmental status of urban deep metro station includes environmental comfort and environmental quality.

(1) environmental comfort
The requirements for environmental comfort mainly come from the protection of the good environment for the staff and passengers in the metro station. In the metro station, low noise, good lighting, appropriate wind speed and comfortable temperature and humidity are conducive to employees and passengers to maintain a comfortable state, which has a considerable impact on the normal operation of the metro station.

(2) environmental quality
As a public space, the metro station has a huge people flow. Therefore, it has certain requirements for the environmental quality, mainly including the appropriate ventilation volume, the content of harmful gases and particles in the air, electromagnetic radiation, radioactive pollution, etc.

2.2 Principle of index selection
As described in Section 2.1, there are a variety of disasters that may deteriorate the operation and maintenance status of urban deep metro stations. Some of them are interrelated and have different influences on the operation and maintenance status. The number of evaluation indexes should neither be too small nor too large. The former may cause the lack of information, which may reduce the
evaluation accuracy, while the latter may cause information duplication and interference. Therefore, it is recommended that the selection of evaluation should adhere to the following four principles:

(1) completeness principle.

The selected evaluation indexes should reflect the real operation and maintenance status of the deep urban metro station comprehensively and completely, without information shortage.

(2) key principles.

The selected evaluation index needs to be representative and decisive. The capabilities of evaluation indexes reflecting the operation and maintenance status are different. Therefore, there is no need to blindly pursue the number of indicators.

(3) operability principle.

Those data indexes that cannot be obtained by the existing monitoring equipment or strategies are only of theoretical significance for the comprehensive evaluation of operation and maintenance status. Therefore, the selection of evaluation indexes should be combined with the specific conditions, which conforms to the principle of operability.

(4) hierarchy principle.

The comprehensive evaluation of operation and maintenance status of deep urban metro station is complex. Different disaster factors with typical characteristics can be divided into different categories. In the process of index selection, the classification of different subsystems should be firstly carried out, then the specific indicators in the subsystem should be determined, and finally the evaluation indexes that affects different indicators shall be determined.

2.3 Establish the evaluation index system

The architecture of the evaluation index system is shown in Figure 1. The disaster-triggering factors described in Section 2.1 can be divided into three subsystems: structural status, equipment status and environmental status. A multi-level evaluation index system of deep urban metro station is obtained accordingly, i.e., operation and maintenance status (target layer) → subsystem (criterion layer) → disaster causing factor (index layer 1) → evaluation index (index layer 2). The evaluation index system of operation and maintenance status of urban deep metro station is distributed hierarchically, and the model is a multi-ladder structure which can be described as following:

**Target layer:** operation and maintenance status of urban deep metro station, referred as station status.

**Criterion layer:** it represents three subsystems of the index system, including structure status, equipment status and environment status.

**Index layer:** it represents the first level index related to each subsystem and the second level index related to each first level index.

![Figure 1. The structure of the index system.](image-url)
to the size of the foundation. The cracking depth is the ratio of crack depth to wall thickness. The crack density is the ratio of the total area of all cracks to the total area inside the station. The depth and radius of structure damage refer to the depth and radius of the voids caused by the surface spalling or falling blocks due to external loading or other reasons during the operation period. The proportion of wet stain area is the ratio of the total wet area to the total waterproof area in the station. The carbonization of the concrete is the ratio between the carbonation depth of concrete and the design thickness of protective layer at corresponding position. The strength degradation of the concrete is the ratio of the effective strength of testing concrete to the design strength of concrete. The decrease in thickness of the concrete is the ratio of the effective thickness of testing concrete to the designed thickness of concrete.

The power supply system status is scored according to the implementation of safety measures and some other standards, including main substation, traction substation, step-down substation, catenary (contact rail), power cable and maintenance parts reparation. The specific scoring standard is obtained by referring to Appendix D of ‘Standard for the operation safety assessment of existing metro’ [8]. The other second level indexes related to the equipment operation status represent the operation status of each system according to its reliability:

\[
K_{sys}(T_i) = \frac{T_{sys, r} - T_b}{T_{sys, r}}
\]

where \(K_{sys}(T_i)\) is the system reliability corresponding to ’sys’ system in the statistical period \(T_i\), ’sys’ system refers to the system corresponding to the required reliability, including the communication system, FAS (automatic fire alarm system), BAS (Building Automation System), platform screen door system, ventilation and air conditioning system, water supply and drainage system, escalator system, ticket vending (vending machine system), storage (recharging machine system), inspection (ticket gate system), \(T_{sys, r}\) is the scheduled service hours of ’sys’ system, \(T_b\) is the breakdown time of ’sys’ system.

In addition to the above systems, the reliability calculation method of the automatic fare collection system is as follows:

\[
K_{AFS}(T_i) = 0.4 \times K_{vending}(T_i) + 0.2 \times K_{storage}(T_i) + 0.4 \times K_{inspecting}(T_i)
\]

where \(K_{AFS}(T_i)\) is the system reliability of the automatic fare collection system in the statistical period \(T_i\).

The other second level indexes related to the equipment maintenance status are obtained according to the counting method given in [13]. As the regulation of ‘Hygienic Indicators and Limits for Public Places’ [14], the qualified range of humidity is 40%-80% and the qualified range of temperature is 16°C-28°C. The qualified rate is the qualified duration divided by the total duration. Note that not all indexes are needed to build up the evaluation index system. The selection of indexes should consider the specific situation of the evaluation object and the different monitoring schemes.

3. A comprehensive evaluation method for the operation and maintenance status of urban deep metro station

After the establishment of the evaluation index system of operation and maintenance status of urban deep metro station, the comprehensive evaluation method for the operation and maintenance status of urban deep metro station need to be used to comprehensively evaluate the operation and maintenance status of urban deep metro station. The data of the second level index of the evaluation index system will be collected for comprehensive evaluation of operation and maintenance status of urban deep metro station.

A comprehensive evaluation method needs to process, analyze and information aggregate all kinds of data collected according to the evaluation index system. It should be able to highlight the defects in the operation and maintenance status, and make the status of all indexes performed intuitively. Therefore, it is necessary to firstly convert all kinds of collected data according to the second level index of the evaluation index system into a specific percentage score. The higher the score is, the better the status will be. This kind of score will be used in the entire process of later analysis, processing and information aggregation. Then, the weight of each index needs to be calculated according to the relative...
importance of different evaluation indexes. Finally, according to the hierarchically distribution of the evaluation index system, the information is aggregated layer by layer, so as to calculate the operation and maintenance status of urban deep metro station. The algorithms for each step are given below:

3.1 Data converting method

The collected data for the second level index of the evaluation index system need to be converted into percentage score so that the status of each index can be performed intuitively, simultaneously and conveniently.

In the process of data conversion, the concept of membership degree in fuzzy comprehensive evaluation [16,17] is applied. In this case, the status of each index will be divided into several levels and the membership degrees are proportion of status of different levels which can describe the status in a more accurate way.

According to the reference norms and documents, the status of each index will be divided into four levels: Ⅰ, Ⅱ, Ⅲ and Ⅳ (where Ⅰ represents the best status, Ⅳ indicates the worst status). According to nature of data collected for each second level index, the second level index will be divided into two kinds: continuous indexes and discrete indexes. The membership degree of different indexes will be calculated in different ways.

After the membership degree of different index has been calculated, the membership degree will be converted into percentage score by the single-value method. Through the average processing, it can be found that Ⅰ represents the score range of 75-100, Ⅱ represents the score range of 50-75, Ⅲ covers the score range of 25-50, Ⅳ covers the score range of 0-25. The four ranges have average values of 87.5, 62.5, 37.5 and 12.5, respectively as the parameter of the single valued method. Hence, Eq. (3) can be used for converting the membership degree into percentage score:

\[ s = \frac{87.5 \times \mu_1 + 62.5 \times \mu_2 + 37.5 \times \mu_3 + 12.5 \times \mu_4}{\mu_1 + \mu_2 + \mu_3 + \mu_4} \]  

where \( \mu_1 \) present the membership degree of Ⅰ level, \( \mu_2 \) present the membership degree of Ⅱ level, \( \mu_3 \) present the membership degree of Ⅲ level and \( \mu_4 \) present the membership degree of Ⅳ level.

3.1.1 Discrete indexes. Discrete index is the index whose data is expressed by specific description, including cracks morphology, the water seepage speed, the aging of the gasket. Their different level descriptions can be referred to Table 1. As for discrete index, the calculation method of the membership degree is on the basis of triangular distribution, and the membership degree of different levels and corresponding scores are shown in Table 2.

| Table 1. The different level descriptions of discrete indexes |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                            | Ⅰ                           | Ⅱ                           | Ⅲ                           | Ⅳ                           |
| cracks morphology           | There are no cracks or few  | There are cracks, and certain | The cracks are dense, and there | The cracks are dense, with shear |
|                             | cracks in the structure, and no sign | development trend. | are shear cracks and the | cracks and rapid development |
|                             | of development.             |                            | development speed is fast     | speed, showing massive cracks, |
| the water seepage speed     | Wet stain                   | Dripping water              | Gushing water                | and falling risk             |
| the aging of the gasket     | Normal                      | Degradation                 | Deterioration                |                              |
### Table 2. The membership degree and score of different levels

| level | I     | II    | III   | IV    | score  |
|-------|-------|-------|-------|-------|--------|
| I     | 0.875 | 0.125 | 0     | 0     | 84.375 |
| II    | 0.125 | 0.75  | 0.125 | 0     | 62.5   |
| III   | 0     | 0.125 | 0.75  | 0.125 | 37.5   |
| IV    | 0     | 0     | 0.125 | 0.875 | 15.625 |

3.1.2 Continuous indexes. The data of continuous indexes can be collected in forms of continuous numerical values. As for continuous index, the calculation method of the membership degree is on the basis of Cauchy distribution. There are two kinds of continuous indexes:

1. Small excellent index. A smaller data indicates a better status.
2. Large excellent index. A larger data corresponds to a better status.

For continuous indexes, it is necessary to determine their three state classification criteria and indicator types, and calculate their membership degrees by combining Eqs. 4-11, after which their percentage scores can be calculated using Eq. 3. It should be noted that if it is a large excellent index, the score calculation should use Eq. 12.

\[
\mu_1 = \begin{cases} 
1 & x \leq a_1 \\
\frac{1}{1+\alpha_1 (x-a_1)} & x > a_1 
\end{cases} 
\]

\[
\mu_2 = \frac{1}{1+\alpha_2 (x-a_2)} 
\]

\[
\mu_3 = \frac{1}{1+\alpha_3 (x-a_3)} 
\]

\[
\mu_4 = \begin{cases} 
0 & x \leq a_4 \\
\frac{1}{1+\alpha_4 (a_4-x)} & x > a_4 
\end{cases} 
\]

\[
\mu_i(k_1) = \mu_2(k_1) = 0.5 
\]

\[
\mu_2(k_2) = \mu_3(k_2) = 0.5 
\]

\[
\mu_3(k_3) = 0.5 
\]

\[
\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \end{bmatrix} = \begin{bmatrix} 0.8 & 0 & 0 &\left| k_1 \right| \\ 0.5 & 0.5 & 0 &\left| k_2 \right| \\ 0 & 0.5 & 0.5 &\left| k_3 \right| \\ 0 & 0.25 & 0.75 &\left| k_4 \right| \end{bmatrix} 
\]

\[
S = \frac{12.5 \times \mu_1 + 37.5 \times \mu_2 + 62.5 \times \mu_3 + 87.5 \times \mu_4}{\mu_1 + \mu_2 + \mu_3 + \mu_4} 
\]

where \( k_1, k_2, k_3 \) are the three state classification criteria which divide the status of the index into four parts and \( k_1 < k_2 < k_3 \). \( \alpha_1, \alpha_2, \alpha_3, \alpha_4 \) are the calculation parameters, and \( x \) is the index value. The three state classification criteria, indicator types and the reference of each index are shown in Appendix B.

3.2 Weight calculation method

The weight of each index can be calculated by the method of analytic hierarchy process (AHP). Suppose there is a certain index, which has \( m \) subordinate indexes. Firstly, we can use expert scoring method to determine the relative importance of different indexes, and get the comparison matrix \( A = (a_{ij})_{m \times m} \).

Then, the initial weight of each index can be calculated by combining Eqs. 13-15.

\[
\bar{a}_{ij} = \frac{a_{ij}}{\sum_{j=1}^{m} a_{ij}} \quad i,j = 1,2,\ldots, m 
\]

\[
\bar{a}_i = \sum_{j=1}^{m} \bar{a}_{ij} \quad i,j = 1,2,\ldots, m 
\]

\[
\omega_i = \frac{\bar{a}_i}{\sum_{i=1}^{m} \bar{a}_i} \quad i = 1,2,\ldots, m 
\]
where \( \omega_0_i \) is the initial weight of the \( i \)-th subordinate index. And \( \omega = (\omega_0_1, \omega_0_2, ... , \omega_0_m)^T \) is the weight vector which is composed of the weight of each index.

At the same time, the consistency test should be carried out using Eqs. (16)-(18).

\[
\lambda_{\text{max}} = \frac{1}{m} \sum_{i=1}^{m} \frac{\omega_i}{\omega_0_i} \\
\text{CI} = (\lambda_{\text{max}} - m)/(m - 1) \quad (17) \\
\text{CR} = \text{CI}/\text{RI} \quad (18)
\]

where \( \lambda_{\text{max}} \) is the maximum eigenvalue of the comparison matrix \( A \), CI is consistency index, CR is consistency ratio and RI is random consistency index, and the RI values for different \( m \) are provided in Table 3.

**Table 3. Value table of RI**

| \( m \) | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RI | 0 | 0.515 | 0.893 | 1.119 | 1.250 | 1.345 | 1.420 | 1.462 | 1.487 | 1.516 | 1.541 |

If CR>0.1, the comparison matrix A can be considered to have acceptable consistency; otherwise, the comparison matrix A needs to be adjusted.

Finally, the weight of the selected indexes for evaluating the operation and maintenance status as introduced at the end of Section 2.3 can be calculated according to Eq. 19.

\[
\omega_i = \frac{\omega_0_i}{\sum_{j=1}^{n} \omega_0_j} \quad i = 1,2, ..., n
\]

where \( n \) means the total number of indexes selected from the \( m \) subordinate indexes, \( \omega_0_i \) is the initial weight of the \( i \)-th selected index, and \( \omega_i \) is the adjust weight of the \( i \)-th selected index. The calculated initial weights of each indexes are shown in Appendix C.

### 3.3 Information aggregation method

In the process of information aggregation, the defects in the operation and maintenance status should be highlighted. Through information aggregation layer by layer, the operation and maintenance status of urban deep metro stations can be obtained.

Suppose there is an index having \( n \) subordinate indexes, the \( j \)-th subordinate index has a score of \( s_j \) and a weight (adjusted) of \( \omega_j \). In order to highlight the defects in the operation and maintenance status, weighted geometric average (WGA) method and variable weight method are adopted.

#### 3.3.1 Variable weight method

The variable weight method aims to adjusting the weight of index according to the statue of the index. A poorer status will have a larger weight. Thereby, the defects can be more highlighted. The variable weight method can be realized by Eqs. 20 and 21:

\[
d(s) = \frac{4s - 4s^2}{4s^2 - 4s} \quad (20) \\
w_j = \frac{w_j^s d(s)}{\sum_{j=1}^{m} w_j^s d(s)} \quad (21)
\]

where \( v \) is the speed of state change, generally taken as \((n+1)/2\), \( w_j^s \) is the weight of the \( j \)-th index and \( d(s) \) is the variable weight status parameter.

#### 3.3.2 Weighted geometric average (WGA) method

The WGA method can be expressed through Eq. 23:

\[
y = \prod_{i=1}^{m} w_i^{s_i} \quad (22)
\]

The WGA method can reflect not only the different importance of subordinate indexes, but also the defects of each index.

Combining the weighted geometric average (WGA) and variable weight methods, the operation and maintenance status of urban deep metro station can be obtained through layer-by-layer calculations. The operation and maintenance status of urban deep metro station can be reflected from its score by Table 4.
Table 4. The grading table of the operation and maintenance status of urban deep metro station

| The operation and maintenance status of urban deep metro station | score |
|---------------------------------------------------------------|-------|
| Excellent                                                     | [75,100] |
| normal                                                        | [50,75) |
| bad                                                           | [25,50) |
| dangerous                                                     | [0,25) |

3.4 Case study

Hongtudi Station located in Chongqing is the deepest metro station in China. The platform of Metro Line 6 is more than 60 meters underground, while the buried depth of the Metro Line 10 station even reaches 94.467m.

The FAS system of the metro station recorded the data of temperature, humidity and carbon dioxide concentration. These are the base data for the corresponding second level indexes, which can be used to evaluate the operation and maintenance status of urban deep metro station according to the methods described above. The calculated parameter and data of the corresponding second level indexes are shown in Table 5. It should be noted that Hongtudi station is a newly operating station, and there are very few equipment and structure monitoring data. Therefore, evaluation of the maintenance status is performed merely based on the environmental data.

Table 5. The calculated parameters and data of the corresponding second level indexes

| Criterion layer | First level index | w | Second level index | w | k1 | k2 | k3 | data |
|-----------------|-------------------|---|--------------------|---|----|----|----|------|
| environmental status | environmental comfort | 0.3774 | qualified rate of temperature (%) | 0.1368 | 50 | 60 | 80 | 100 |
| environmental quality | environmental comfort | 0.6226 | qualification rate of relative humidity (%) | 0.1368 | 50 | 60 | 80 | 100 |
| environmental quality | carbon dioxide content (%) | 0.0385 | 0.1 | 0.15 | 0.2 | 0.04 |

All of the selected second level indexes are continuous index. The carbon dioxide content is a small excellent index, while the others are large excellent indexes. “qualified rate of temperature” and “qualification rate of relative humidity” are the two subordinate indexes of the first level index “environmental comfort”, and “carbon dioxide content” is the only subordinate index of the first level index “environmental quality”. Combined with the data converting method, the score and the adjusted weight (not through variable weight method) of the selected second level indexes can be obtained:

Table 6. The score and adjusted weight of the selected second level indexes

| Second level index | score | weight |
|--------------------|-------|--------|
| qualified rate of temperature | 82.83 | 0.5 |
| qualification rate of relative humidity | 82.83 | 0.5 |
| carbon dioxide content | 84.22 | 1 |

Firstly, the information aggregation of the first level index “environmental comfort” is carried out using the variable weight method by Eqs. 20-21. In this process, n is equal to 2 and v is equal to 1.5 of (n+1)/2. The corresponding variable weight status parameter $d(s)$ and the weight $w'$ adjusted by variable weight method are given in Table 7:

Table 7. The parameters of information aggregation for the second level indexes

| Second level index | $d(s)$ | $w'$ |
|--------------------|--------|------|
| qualified rate of temperature | 1.32 | 0.5 |
| qualification rate of relative humidity | 1.32 | 0.5 |

And the score of the index “environmental comfort” can be gotten by Form (24). The result and process has been shown in Form (24):

$$s = 82.83^{0.5} \times 82.83^{0.5} = 82.83$$

(23)

The index “environmental quality” has only one subordinate index, so the score is equal to the score of “carbon dioxide content”, i.e., 84.22.
Then, the information aggregation of the first level index “environmental status”, which has two subordinate indexes of “environmental comfort” and “environmental quality”, is carried out. The parameter through the process of information aggregation, including the adjusted weight \( w \) (not through variable weight method), the variable weight status parameter \( d(s) \), the weight \( w' \) adjusted by variable weight method, are given in Table 8:

| First level index                  | \( w \)    | \( d(s) \) | \( w' \) |
|-----------------------------------|------------|------------|----------|
| environmental comfort             | 0.3774     | 1.32       | 0.383    |
| environmental quality             | 0.6226     | 1.29       | 0.617    |

And the score of the index “environmental status” can be obtained by Eq. 25.

\[
s = 82.83^{0.383} \times 84.22^{0.617} = 83.68
\]  

(24)

Since the target index “station status” has only one subordinate index, the score is equal to the score of “environmental status”, i.e., 83.68. According to Table 4, it can be inferred that the operation and maintenance status of this urban deep metro station is excellent.

4. Conclusion
A comprehensive analysis on the influencing factors of operation and maintenance status for urban deep metro station was firstly conducted. Then, based on some index selection principles, the evaluation indexes of the operation and maintenance status of the urban deep metro stations were determined from which the evaluation index system of operation and maintenance status of urban deep metro station was established, which consisted of three subsystems: structure status, equipment status and environmental status.

On the basis of the evaluation index system, a comprehensive evaluation method for the operation and maintenance status of urban deep metro station is developed. In this method, firstly, the data of the index is converted into percentage score based on the concept of membership degree in the fuzzy comprehensive evaluation theory; then, the weight of the index is calculated by the analytic hierarchy process (AHP); then, the information aggregation is carried out combining the weighted geometric average (WGA) method and the variable weight method in order to highlight the defects of the operation and maintenance status, from which the operation and maintenance status of urban deep metro station can be obtained.

The established comprehensive evaluation method was applied to China’s current deepest metro station, i.e., Hongtudi Station, which shows that the operation and maintenance status of Hongtudi station is excellent.

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### Appendix A

| Target layer | Criterion layer | First level index | Second level index |
|--------------|-----------------|-------------------|--------------------|
|              | criterion layer | structure deformation | the speed of lateral convergent deformation(mm/year) |
|              |                 |                    | the lateral convergent deformation rate(%) |
|              |                  |                    | the lateral convergent deformation(mm) |
|              |                   |                    | the settlement(mm) |
|              |                    |                    | the maximum settlement difference (%) |
|              | structure damage  | settling velocity(mm/year) | |
|              |                    | the length of cracks(m) | |
|              | station status     | the width of cracks(mm) | |
|              |                    | the depth of cracks | |
|              |                    | cracks morphology | |
|              |                    | the density of cracks (%) | |
|              | material deterioration | the depth of cavities(mm) | |
|              |                    | the length of cavities(m) | |
|              |                    | the depth of structure damage(mm) | |
|              |                    | the radius of structure damage(mm) | |
|              | water damage       | the amount of water leakage (L/d) | |
|              |                    | the pH of water seepage | |
|              |                    | the water seepage speed | |
|              |                    | the area of wet stains (m²) | |
|              |                    | the proportion of wet stain area | |
|              |                    | the single wet stain area(m²) | |
|              |                    | the carbonization of the concrete | |
|              |                    | the decrease in strength of the concrete | |
|              |                    | the decrease in thickness of the concrete | |
|              |                    | Steel bars section loss rate (%) | |
|              |                    | Steel material section loss rate (%) | |
|              |                    | the aging of the gasket | |
|              | equipment operation status | power supply system status | |
|              |                    | environment and equipment monitoring system status | |
|              |                    | automatic fire alarm system status | |
|              |                    | platform screen door system status | |
|              |                    | communication system status | |
|              |                    | ventilation and air conditioning system status | |
|              |                    | water supply and drainage system status | |
|              |                    | escalator system status | |
|              |                    | automatic fare collection system status | |
|              | equipment maintenance status | the qualified rate of equipment maintenance (%) | |
|              |                    | the number of faults(time/month) | |
|              |                    | equipment updating rate (%) | |
|              |                    | rate of equipment to be repaired (%) | |
|              |                    | running equipment failure rate (%) | |
|              |                    | the completeness of protective equipment (%) | |
|              | environmental status | qualified rate of temperature (%) | |
|              | environmental comfort | qualification rate of relative humidity (%) | |
|              |                    | indoor wind speed(m/s) | |
|              |                    | station brightness(lx) | |
|              |                    | station noise(dB) | |
|              |                    | noise of train entering and leaving station (dB) | |
| Environmental Quality | fresh air volume (m³/h*people)) |
|-----------------------|---------------------------------|
|                       | carbon dioxide content (%)      |
|                       | radon content (Bq/m³)           |
|                       | inhalable particulate matter content (mg/m³) |
|                       | carbon monoxide content (mg/m³) |
|                       | formaldehyde content (mg/m³)    |
|                       | nitrogen oxide content (mg/m³)  |
|                       | sulfur dioxide content (mg/m³)  |
|                       | ammonia content (mg/m³)         |
|                       | ozone content (mg/m³)           |
|                       | benzene content (mg/m³)         |
|                       | toluene content (mg/m³)         |
|                       | xylene content (mg/m³)          |
|                       | benzopyrene content (ng/m³)     |
|                       | total volatile organic compounds (mg/m³) |
|                       | radioactivity of building materials |
|                       | electric field intensity(V/m)   |
|                       | magnetic induction (μT)          |
Appendix B

| Second level index                                                                 | k₁      | k₂      | k₃      | Type            | Reference |
|----------------------------------------------------------------------------------|---------|---------|---------|-----------------|-----------|
| the speed of lateral convergent deformation(mm/year)                             | 1       | 2       | 10      | Small excellent index | [25]      |
| the lateral convergent deformation rate(%)                                       | 0.25    | 0.4     | 1.5     | Small excellent index | [19]      |
| the depth of structure damage(mm)                                                | 20      | 60      | 120     | Small excellent index | [19]      |
| the settlement(mm)                                                               | 40      | 75      | 150     | Small excellent index | [19]      |
| the maximum settlement difference (%)                                            | 0.35    | 0.6     | 2       | Small excellent index | [19]      |
| settling velocity(mm/year)                                                       | 5       | 10      | 15      | Small excellent index | [21]      |
| the length of cracks(m)                                                          | 3       | 5       | 10      | Small excellent index | [22]      |
| the width of cracks(mm)                                                          | 1       | 3       | 5       | Small excellent index | [22]      |
| the depth of cracks                                                               | 1/3     | 0.5     | 2/3     | Small excellent index | [23]      |
| the density of cracks (%)                                                         | 0.01    | 0.02    | 0.03    | Small excellent index | [18]      |
| the depth of cavities(mm)                                                         | 100     | 300     | 500     | Small excellent index | [23]      |
| the length of cavities(m)                                                         | 1       | 3       | 5       | Small excellent index | [24]      |
| the depth of structure damage(mm)                                                | 5       | 10      | 20      | Small excellent index | [25]      |
| the radius of structure damage(mm)                                               | 50      | 100     | 200     | Small excellent index | [25]      |
| the amount of water leakage (L/d)                                                | 1.25    | 2.5     | 4       | Small excellent index | [18]      |
| the pH of water seepage                                                          | 4.0     | 5.0     | 6.0     | Large excellent index | [20]      |
| the area of wet stains (m²)                                                       | 0.1     | 0.2     | 0.3     | Small excellent index | [18]      |
| the proportion of wet stain area                                                   | 0.1%    | 0.6%    | 1%      | Small excellent index | [18]      |
| the single wet stain area(m²)                                                     | 0.2     | 0.3     | 0.4     | Small excellent index | [18]      |
| the carbonization of the concrete                                                | 1/10    | ½       | 2/3     | Small excellent index | [23]      |
| the decrease in strength of the concrete                                          | 0.65    | 0.75    | 0.85    | Large excellent index | [22]      |
| the decrease in thickness of the concrete                                         | 0.6     | 0.75    | 0.9     | Large excellent index | [22]      |
| Steel bars section loss rate (%)                                                 | 3       | 10      | 25      | Small excellent index | [26]      |
| Steel material section loss rate (%)                                             | 5       | 10      | 25      | Small excellent index | [23]      |
| power supply system status                                                        | 88      | 91.5    | 95      | Large excellent index | [8]       |
| environment and equipment monitoring system status                                | 0.9     | 0.933   | 0.966   | Large excellent index |          |
| automatic fire alarm system status                                                |          |         |         |                  | [27]      |
| platform screen door system status                                                |          |         |         |                  |          |
| communication system status                                                      |          |         |         |                  |          |
| ventilation and air conditioning system status                                     | 0.8     | 0.866   | 0.933   | Large excellent index |          |
| water supply and drainage system status                                          |          |         |         |                  |          |
| escalator system status                                                          |          |         |         |                  |          |
| automatic fare collection system status                                          | 0.98    | 0.9866  | 0.9933  | Large excellent index |          |
| the qualified rate of equipment maintenance (%)                                   | 60      | 80      | 90      | Large excellent index | [13]      |
| the number of faults(time/month)                                                 | 15      | 30      | 40      | Small excellent index |          |
| equipment updating rate (%)                                                       | 3       | 5       | 7       | Large excellent index |          |
| rate of equipment to be repaired (%)                                             | 5       | 10      | 20      | Small excellent index |          |
| Parameter                                           | 10  | 20  | 30  | Small excellent index | 50  | 80  | 95  | Large excellent index | 50  | 60  | 80  | Large excellent index |
|-----------------------------------------------------|-----|-----|-----|-----------------------|-----|-----|-----|-----------------------|-----|-----|-----|-----------------------|
| running equipment failure rate (%)                 |     |     |     |                       |     |     |     |                       |     |     |     |                       |
| the completeness of protective equipment (%)       | 50  | 80  | 95  | Large excellent index |     |     |     |                       |     |     |     |                       |
| qualified rate of temperature (%)                 | 50  | 60  | 80  | Large excellent index |     |     |     |                       |     |     |     |                       |
| qualification rate of relative humidity (%)       | 50  | 60  | 80  | Large excellent index |     |     |     |                       |     |     |     |                       |
| indoor wind speed (m/s)                           | 0.2 | 0.3 | 0.5 | Small excellent index | [30, 34] |     |     |                       |     |     |     |                       |
| station brightness (lx)                           | 75  | 100 | 150 | Large excellent index | [39] |     |     |                       |     |     |     |                       |
| station noise (dB)                                 | 60  | 65  | 70  | Small excellent index | [32] |     |     |                       |     |     |     |                       |
| noise of train entering and leaving station (dB)  | 65  | 70  | 80  | Small excellent index | [32.33] |     |     |                       |     |     |     |                       |
| fresh air volume (m³/(h*people))                  | 10  | 20  | 30  | Large excellent index | [30, 31] |     |     |                       |     |     |     |                       |
| carbon dioxide content (%)                         | 0.1 | 0.15| 0.2 | Small excellent index | [30, 31] |     |     |                       |     |     |     |                       |
| radon content (Bq/m³)                              | 100 | 200 | 400 | Small excellent index | [30, 36] |     |     |                       |     |     |     |                       |
| inhalable particulate matter content (mg/m³)      | 0.04| 0.07| 0.15| Small excellent index | [28] |     |     |                       |     |     |     |                       |
| carbon monoxide content (mg/m³)                    | 4   | 10  | 30  | Small excellent index | [28.29] |     |     |                       |     |     |     |                       |
| formaldehyde content (mg/m³)                       | 0.05| 0.1 | 0.12| Small excellent index | [30, 34] |     |     |                       |     |     |     |                       |
| nitrogen oxide content (mg/m³)                     | 0.05| 0.1 | 0.25| Small excellent index | [28] |     |     |                       |     |     |     |                       |
| sulfur dioxide content (mg/m³)                     | 0.06| 0.15| 0.5 | Small excellent index | [28] |     |     |                       |     |     |     |                       |
| ammonia content (mg/m³)                            | 0.1 | 0.2 | 0.5 | Small excellent index | [30] |     |     |                       |     |     |     |                       |
| ozone content (mg/m³)                              | 0.1 | 0.16| 0.2 | Small excellent index | [28] |     |     |                       |     |     |     |                       |
| benzene content (mg/m³)                            | 0.037| 0.037| 0.11 | Small excellent index | [30] |     |     |                       |     |     |     |                       |
| toluene content (mg/m³)                            | 0.067| 0.067| 0.2 | Small excellent index | [30] |     |     |                       |     |     |     |                       |
| xylene content (mg/m³)                             | 0.067| 0.133| 0.2 | Small excellent index | [30] |     |     |                       |     |     |     |                       |
| benzopyrene content (ng/m³)                        | 1   | 1.75| 2.5 | Small excellent index | [28] |     |     |                       |     |     |     |                       |
| total volatile organic compounds (mg/m³)           | 0.2 | 0.4 | 0.6 | Small excellent index | [30] |     |     |                       |     |     |     |                       |
| radioactivity of building materials                 | 1.3 | 1.9 | 2.8 | Small excellent index | [37] |     |     |                       |     |     |     |                       |
| electric field intensity (V/m)                     | 13  | 27  | 40  | Small excellent index | [38] |     |     |                       |     |     |     |                       |
| magnetic induction (μT)                             | 0.04| 0.08| 0.12| Small excellent index | [28] |     |     |                       |     |     |     |                       |
## Appendix C

| Criterion layer | W | First level index | W | Second level index | W |
|-----------------|---|-------------------|---|-------------------|---|
| structure status | 0.5568 | structure deformation | 0.2625 | the speed of lateral convergent deformation (mm/year) | 0.1784 |
| | | | | the lateral convergent deformation rate (%) | 0.1784 |
| | | | | the lateral convergent deformation (mm) | 0.1784 |
| | | | | the settlement (mm) | 0.1784 |
| | | | | the maximum settlement difference (%) | 0.1081 |
| | | | | settling velocity (mm/year) | 0.1784 |
| | | | | the length of cracks (m) | 0.0493 |
| | | | | the width of cracks (mm) | 0.1201 |
| | | | | the depth of cracks | 0.125 |
| | | | | cracks morphology | 0.1191 |
| | | | | the density of cracks (%) | 0.0864 |
| | | | | the depth of cavities (mm) | 0.125 |
| | | | | the length of cavities (m) | 0.125 |
| | | | | the depth of structure damage (mm) | 0.125 |
| | | | | the radius of structure damage (mm) | 0.125 |
| | | structure damage | 0.3207 | the amount of water leakage (L/d) | 0.1768 |
| | | | | the pH of water seepage | 0.0588 |
| | | | | the water seepage speed | 0.2316 |
| | | | | the area of wet stains (m²) | 0.1709 |
| | | | | the proportion of wet stain area | 0.1958 |
| | | | | the single wet stain area (m²) | 0.1661 |
| | | water damage | 0.2172 | the carbonization of the concrete | 0.0824 |
| | | | | the decrease in strength of the concrete | 0.1804 |
| | | | | the decrease in thickness of the concrete | 0.2002 |
| | | | | Steel bars section loss rate (%) | 0.1629 |
| | | | | Steel material section loss rate (%) | 0.1565 |
| | | | | the aging of the gasket | 0.2175 |
| | | | | power supply system status | 0.2147 |
| | | material deterioration | 0.1996 | environment and equipment monitoring system status | 0.0637 |
| | | | | automatic fire alarm system status | 0.0732 |
| | | | | platform screen door system status | 0.1144 |
| | | | | communication system status | 0.1477 |
| | | | | ventilation and air conditioning system status | 0.1144 |
| | | | | water supply and drainage system status | 0.1144 |
| | | | | escalator system status | 0.1144 |
| | | | | automatic fare collection system status | 0.0433 |
| | | equipment operation status | 0.5 | the qualified rate of equipment maintenance (%) | 0.1994 |
| | | | | the number of faults (time/month) | 0.3345 |
| | | equipment maintenance status | 0.5 | the qualified rate of equipment maintenance (%) | 0.1994 |
| | | | | the number of faults (time/month) | 0.3345 |
| Environmental Status | Environmental Quality | Parameter                                      | Value  |
|----------------------|-----------------------|------------------------------------------------|--------|
|                      | environmental comfort | equipment updating rate (%)                    | 0.0702 |
|                      | environmental comfort | rate of equipment to be repaired (%)           | 0.1196 |
|                      | environmental comfort | running equipment failure rate (%)             | 0.1846 |
|                      | environmental comfort | the completeness of protective equipment (%)   | 0.0917 |
|                      | environmental comfort | qualified rate of temperature (%)             | 0.1368 |
|                      | environmental comfort | qualification rate of relative humidity (%)    | 0.1368 |
|                      | environmental comfort | indoor wind speed (m/s)                        | 0.0731 |
|                      | environmental comfort | station brightness (lx)                       | 0.0731 |
|                      | environmental comfort | station noise (dB)                            | 0.0731 |
|                      | environmental comfort | noise of train entering and leaving station (dB)| 0.5072 |
|                      | environmental quality | fresh air volume (m³/h*people)                | 0.3462 |
|                      | environmental quality | carbon dioxide content (%)                    | 0.0385 |
|                      | environmental quality | radon content (Bq/m³)                         | 0.0385 |
|                      | environmental quality | inhalable particulate matter content (mg/m³)  | 0.0385 |
|                      | environmental quality | carbon monoxide content (mg/m³)               | 0.0385 |
|                      | environmental quality | formaldehyde content (mg/m³)                  | 0.0385 |
|                      | environmental quality | nitrogen oxide content (mg/m³)                | 0.0385 |
|                      | environmental quality | sulfur dioxide content (mg/m³)                | 0.0385 |
|                      | environmental quality | ammonia content (mg/m³)                       | 0.0385 |
|                      | environmental quality | ozone content (mg/m³)                         | 0.0385 |
|                      | environmental quality | benzene content (mg/m³)                       | 0.0385 |
|                      | environmental quality | toluene content (mg/m³)                       | 0.0385 |
|                      | environmental quality | xylene content (mg/m³)                        | 0.0385 |
|                      | environmental quality | benzopyrene content (ng/m³)                  | 0.0385 |
|                      | environmental quality | total volatile organic compounds (mg/m³)       | 0.0385 |
|                      | environmental quality | radioactivity of building materials            | 0.0385 |
|                      | environmental quality | electric field intensity (V/m)                | 0.0385 |
|                      | environmental quality | magnetic induction (μT)                       | 0.0385 |