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Research on construction schedule risk management of power supply and distribution projects based on MCS-AHP model

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In order to manage the construction schedule risk of power supply and distribution engineering, a construction schedule risk evaluation model, namely the Monte Carlo simulation method - Analytic Hierarchy Process (MCS-AHP) model, is proposed. In this model, the Monte Carlo simulation method is adopted to improve the analytic Hierarchy Process (AHP), and the normal distribution interval is used to replace the specific value when constructing the fuzzy complementary judgment matrix, to reduce the risk of fuzzy thinking and incomplete information or scattered data in the process of investigation and judgment and improve the scientific evaluation. This paper takes a power supply and distribution project in Guangdong Province as an example uses the MCS-AHP model to measure the key factors limiting the project progress, and uses the AHP method for comparative analysis, to verify the feasibility of the MCS-AHP model. The analysis shows that the key influencing factors are material and equipment procurement, production and arrival, installation of 10 kv high voltage switchboard, electrical acceptance and single machine commissioning, installation of low-voltage switchboard and DC switchboard, and foundation construction of power station equipment, etc., which are consistent with the actual situation. Therefore, it is feasible to construct the MCS-AHP model, which can provide a new way of thinking for schedule risk management analysis.

KEYWORDS

power supply and distribution engineering, schedule risk management, MCS-AHP model, Monte Carlo simulation, normal distribution of fuzzy numbers

1 Introduction

1.1 Literature review

In recent years, with the rapid improvement of modernization and urbanization, the demand for electricity supply in the production and life of people in modern society has shown a trend of increasing year by year (Albogamy et al., 2022). The state is paying more and more attention to the investment and construction of electric power projects, and the scale and the voltage level of electric power projects have reached a historical peak (Venkatesh et al., 2022; Zhang and Kang, 2022). As the energy market transformation gradually unfolds, electric energy's supply and demand situation is also changing dramatically, which puts forward higher requirements for the construction of electric power projects (Sun et al., 2022). The power balance between power companies and consumers is crucial (Ali et al., 2022). Therefore, with the increase in power demand, the accelerated progress of power engineering construction will put great pressure on the different stages involved in power engineering construction projects. It also easy to causes the problem of delayed progress in power engineering construction (Sharma et al., 2022). Therefore, it is necessary to study the schedule risk management of power engineering projects.

Before the research on the schedule risk management of power engineering projects, we found that the research on the schedule risk of other construction project management has achieved many research results. In terms of identifying the risk factors of the project schedule, Cheng and Darsa, (2021) established the construction schedule risk assessment model (CSRAM) and identified 22 risk factors. Chen et al. (2020) identified construction schedule risks from the perspective of the dialectical systems at the industry level; Muneeswaran et al. (2020) Statistical analysis using relative importance index and fuzzy ranking was used to identify risks; Chen L et al. (2021) used the decomposition structure method (RBS) to classify the schedule risks of high arch dam concrete projects. In terms of the theory and method of project schedule risk management, Chen M et al. (2021) constructed a critical risk network, including key risks and links. Li X et al. (2020) used the BN-PERT risk assessment model to evaluate the project schedule risk. Cheng et al. (2019) developed a fuzzy Bayesian Network-Monte Carlo simulation (FBN-MCS) to determine the correlation between risk and project duration. In terms of risk management information management, Sami Ur Rehman et al. (2020) established a factor-characteristic matrix to discuss the role of BIM in providing effective solutions for progress management. Lin et al. (2021) uses critical chain technology and combine FMEA management tool with BIM technology to manage the risks in construction projects. Song et al. (2022) used the information to extend project control methods for resource-constrained projects. This paper studies the schedule risk management of construction projects based on previous research on the schedule risk management of power engineering projects.

In the process of research on schedule risk management of power engineering projects, it is found that the research in recent years mainly focuses on construction quality, safety and multi-dimensional risk management. For example, in the aspect of quality risk management of power engineering, Sami Ur Rehman et al. (2020) use the FUCOM method to determine the risk assessment standard. Sun (2020) uses case analysis to identify quality risk factors that significantly impact the quality of power engineering. In terms of power engineering safety risk management, Li (2021) analyzes and evaluates safety risk factors based on the fundamental theories of safety risk management. Bao et al. (2021) put forward a comprehensive risk assessment technique for digital instrumentation and control (DI&C for short) system (IRADIC technique) and put forward opinions and suggestions for risk management. In the aspect of risk analysis of power engineering construction, Shaktawat and Vadhera, (2021) take sensitivity analysis as the primary method to evaluate essential risk factors; Li Y. C et al. (2020) adopted the risk matrix method to assess the risks in the construction process of giant hydropower projects; Zheng et al. (2021) used an improved precise diffusion algorithm to solve the two-stage distributed optimization problem. In terms of multi-dimensional risk management; Liu and Xu, (2022) conducted power engineering risk management from the perspectives of economy, management, society and environmental coordination; Lotfi et al. (2022) studied the robust time-cost-quality-energy-environment trade-off with resource-constrained in project management. After consulting relevant data, it is found that the research results of various risk factors of power engineering are relatively wealthy, only schedule risk management is less studied, and schedule risk is one of the main threats to power engineering project management. Schedule risk control of power engineering construction is also vital to ensure the project objectives' realisation (Huang et al., 2018; Wu et al., 2022). Therefore, it is necessary to carry out relevant research.

Throughout the literature at home and abroad, it is found that the research methods of schedule risk management of power engineering are still in an earlier period, such as the interpretive structural model (ISM) method (Rao et al., 2014), AHP-RII combined method model (Hossen et al., 2015), PERT/CPM simulation model (Lee et al., 2018), etc. The research on the schedule risk of power projects often needs to solve the difficulties of establishing evaluation index systems and evaluation models. AHP is a multi-criteria decision-making tool (Dhingra et al., 2022; Raghav et al., 2022), and MCS can accurately predict through simulation (Khosravi et al., 2022; Ullah et al., 2022). Combining AHP (Li and Xu, 2021) with the MCS method (Koulinas et al., 2021) can well solve the problems of poor evaluation index system setting, complex set evaluation index standard weighting, and unquantifiable qualitative index evaluation. The main contribution of this paper is that the MCS-AHP model built can solve the above problems, and can effectively reduce the subjectivity so that the weight calculated and the relationship between them is more scientific. The MCS-AHP model is a mathematical method which is applicable to the research of power engineering schedule management and can be applied to the research of other projects and can be used for project location problems and project decision-making problems. The construction schedule risk evaluation index system of power supply and distribution engineering can also provide a reference for the research of schedule risk management of power engineering projects worldwide.

Based on the discussion, the rest of the organizational structure of this paper is as follows: In the second section, mainly introduces how to build the MCS-AHP model and its calculation steps. The third section is mainly about the model application. Based on the construction schedule risk assessment index system of power supply and distribution engineering, the MCS-AHP model is used to calculate the key influencing factors, and the traditional AHP model is used for comparative analysis to verify the feasibility of the MCS-AHP model. The fourth section summarizes the research results of this paper and the prospect for the future.

1.2 Problem statement

With the growing scale of power supply and distribution engineering construction projects, the construction period continues to extend, how to scientifically and effectively manage and control the progress of this long-term construction phase of power supply and distribution engineering project management has always been an enduring topic. The main reason is that power supply and distribution engineering is often restricted by various factors during construction, and this restriction factor often causes the actual progress of the project to deviate significantly from the expected progress. Once such tendency factors accumulate to a certain extent and exceed its risk pre-control ability, the project progress will be difficult to achieve its desired purpose. Thus it is easy to cause the project schedule the accident. Therefore, it is necessary to strengthen the dynamic tracking and monitoring of the

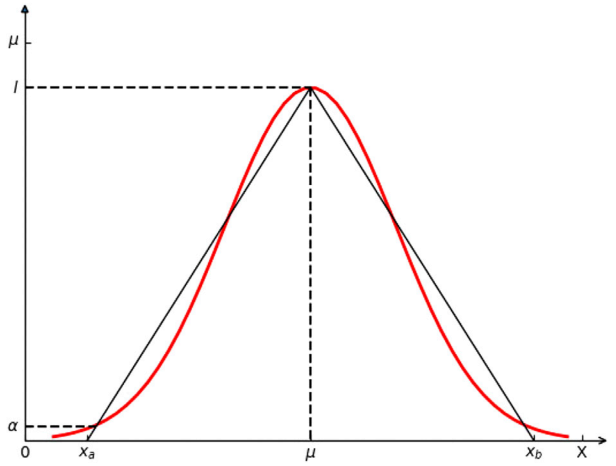

FIGURE 1
Normally distributed fuzzy numbers and triangular fuzzy numbers.

construction progress of the power supply and distribution projects to complete the project and obtain higher economic benefits.

In this section, we propose an MCS-AHP model to evaluate the construction schedule risk of power supply and distribution engineering, which has received little attention in previous studies. It is of great significance to determine, classify and measure the risk factors that bring adverse effects to the progress of the project, and to manage and monitor them effectively on this basis.

2 Model construction

2.1 Normally distributed fuzzy numbers

The standard distribution curve is high in the middle and low at the ends. μ is the centre of the normal distribution preference, and σ is the width, indicating the uncertainty present.

Define the average distribution affiliation function as:

$$f(x{:}\ \mu, \sigma) = \exp\left[\frac{-(x-\mu)^2}{\sigma^2}\right] \tag{1}$$

The method proposed in this paper will be compared with the triangular fuzzy number, as shown in Figure 1.

$$\alpha = \exp\left[\frac{-(x-\mu)^2}{\sigma^2}\right] \tag{2}$$

$$x_a = \mu - \sigma\sqrt{-\mathrm{Ln}(\alpha)} \tag{3}$$

$$x_b = \mu + \sigma\sqrt{-\mathrm{Ln}(\alpha)} \tag{4}$$

(The curve represents the normal distribution membership function, and the line represents the trigonometric function).

Figure 1 explains the description of the alpha value. Eqs. 5, 6 explain the definition of a customarily distributed fuzzy number as a transformed form of a triangular fuzzy number. It is assumed that Ti is the triangular fuzzy number and Gi is the element of the preference matrix after performing the triangular approximation.

$$S_i = \frac{\sum_j G_{ij}}{\sum_i \sum_j G_{ij}} = \frac{\sum_j \left(l_i^j, m_i^j, u_i^j\right)}{\sum_i \sum_j \left(l_i^j, m_i^j, u_i^j\right)} \tag{5}$$

where, $l_i^j \cong m_i^j - \sigma_i^j \sqrt{-\mathrm{Ln}(\alpha)}$, $u_i^j \cong m_i^j + \sigma_i^j \sqrt{-\mathrm{Ln}(\alpha)}$

To obtain a representative approximation of the triangle, the value of α is set to 0.01. This means that a normal distribution funtion approximates 99% of the values:

$$S_i = \frac{\left(\sum_j l_i^j, \sum_j m_i^j, \sum_j u_i^j\right)}{\left(\sum_i \sum_j l_i^j, \sum_i \sum_j m_i^j, \sum_i \sum_j u_i^j\right)} = \left(\frac{\sum_j l_i^j,}{\sum_i \sum_j u_i^j}, \frac{\sum_j m_i^j,}{\sum_i \sum_j m_i^j}, \frac{\sum_j u_i^j,}{\sum_i \sum_j l_i^j}\right) \tag{6}$$

where,

$$\sum_j l_i^j = \sum_j m_i^j - \sum_j \sigma_i^j \left(\sqrt{-\mathrm{Ln}(\alpha)}\right) \tag{7}$$

$$\sum_j u_i^j = \sum_j m_i^j + \sum_j \sigma_i^j \left(\sqrt{-\mathrm{Ln}(\alpha)}\right) \tag{8}$$

$$\sum_i \sum_j l_i^j = \sum_i \sum_j m_i^j - \sum_i \sum_j \sigma_i^j \left(\sqrt{-\mathrm{Ln}(\alpha)}\right) \tag{9}$$

$$\sum_i \sum_j u_i^j = \sum_i \sum_j m_i^j + \sum_i \sum_j \sigma_i^j \left(\sqrt{-\mathrm{Ln}(\alpha)}\right) \tag{10}$$

$$\text{and, } m_{S_i} = \frac{\sum_j m_i^j}{\sum_i \sum_j m_i^j}, X_{S_i}^L = \frac{\sum_j l_i^j}{\sum_i \sum_j u_i^j}, X_{S_i}^R = \frac{\sum_j u_i^j}{\sum_i \sum_j l_i^j}$$

Will be transformed into an asymmetric normal distribution of fuzzy numbers as follows:

$$\sigma_{S_i}^L = \frac{m_{S_i} - X_{S_i}^L}{\sqrt{-\mathrm{Ln}(\alpha)}} \tag{11}$$

$$\sigma_{S_i}^R = \frac{X_{S_i}^R - m_{S_i}}{\sqrt{-\mathrm{Ln}(\alpha)}} \tag{12}$$

$\sigma_{S_i}^L$ A denotes the width of the left branch of the fuzzy number of the normal distribution and $\sigma_{S_i}^R$ denotes the width of the right branch of the fuzzy number of the normal distribution. The affiliation function of the asymmetric standard distribution number is:

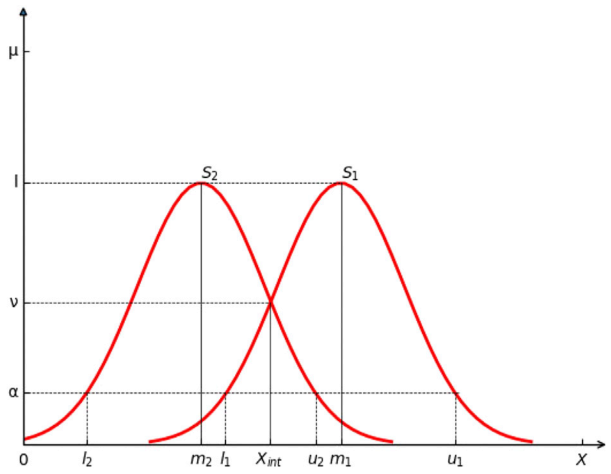

FIGURE 2
The intersection of two normally distributed membership functions.

$$\mu_{S_i(X)} = \begin{cases} \exp\left[-\left(\dfrac{x - m_{S_i}}{\sigma^L_{S_i}}\right)^2\right], x \le m_{S_i} \\ \exp\left[-\left(\dfrac{x - m_{S_i}}{\sigma^R_{S_i}}\right)^2\right], x > m_{S_i} \end{cases} \tag{13}$$

Let $\mu_{S_1}(x)$ and $\mu_{S_2}(x)$ be two normally distributed fuzzy numbers, as in Figure 2 below:

$$\mu_{S_1(X)} = \begin{cases} \exp\left[-\left(\dfrac{x - m_{S_1}}{\sigma^L_{S_1}}\right)^2\right], x \le m_{S_1} \\ \exp\left[-\left(\dfrac{x - m_{S_1}}{\sigma^R_{S_1}}\right)^2\right], x > m_{S_1} \end{cases} \tag{14}$$

$$\mu_{S_2(X)} = \begin{cases} \exp\left[-\left(\dfrac{x - m_{S_2}}{\sigma^L_{S_2}}\right)^2\right], x \le m_{S_2} \\ \exp\left[-\left(\dfrac{x - m_{S_2}}{\sigma^R_{S_2}}\right)^2\right], x > m_{S_2} \end{cases} \tag{15}$$

$$v = \begin{cases} \exp\left[-\left(\dfrac{m_{S_2} - m_{S_1}}{\sigma^L_{S_1} + \sigma^R_{S_2}}\right)^2\right], m_{S_1} > m_{S_2} \\ \exp\left[-\left(\dfrac{m_{S_2} - m_{S_1}}{\sigma^R_{S_1} + \sigma^L_{S_2}}\right)^2\right], m_{S_1} < m_{S_2} \end{cases} \tag{16}$$

The degree of probability of $S_2 = \mu_{S_2}(x) \ge S_1 = \mu_{S_1}(x)$ is defined as:

$$\begin{aligned} V(S_2 \ge S_1) &= \mathrm{hgt}(S_1 \cap S_2) = \mu_{S_2}(X_{int}) \\ &= \begin{cases} 1, & m_{S_2} \ge m_{S_1} \\ \exp\left[-\left(\dfrac{m_{S_2} - m_{S_1}}{\sigma^R_{S_1} + \sigma^L_{S_2}}\right)^2\right], & m_{S_1} < m_{S_2} \end{cases} \end{aligned} \tag{17}$$

Where X_{int} denotes the vertical coordinate of the inner intersection between $\mu_{S_1}(x)$ and $\mu_{S_2}(x)$. Both values of $V(S_2 \ge S_1)$ and $V(S_1 \ge S_2)$ need to be compared S_1 and S_2.

2.2 AHP model

The Analytic hierarchy process is one of the multi-criteria decision-making methods that simplify the decision-making process and enables the evaluation of qualitative and quantitative criteria (Alelaiwi, 2019). The calculation steps of the hierarchical analysis method are as follows:

2.2.1 Construct the evaluation index system

In-depth analysis of practical problems, top-down hierarchical analysis of relevant factors, the construction of index layer, factor layer and other index systems.

2.2.2 Construct a fuzzy judgment matrix

The two factors of the same layer are compared and analyzed, and the fuzzy judgment matrix is constructed according to the scale of the fuzzy judgment matrix. The relative importance of each factor is judged within the range of the set judgment scale, and the fuzzy judgment matrix is obtained.

2.2.3 Calculate the index weight

Calculate the weight value of all factors in the fuzzy judgment matrix, Method 1: Root value method

The first step, the matrix R_{ij} is obtained by multiplying each row of elements, namely:

$$R_{ij} = \prod\nolimits_{j=1}^{n} a_{ij} \tag{18}$$

The second step, the matrix R_i is obtained by taking the square root of the combined result, namely:

$$R_i = \sqrt[n]{R_{ij}} \tag{19}$$

The third step, the weight vector is obtained by normalization processing, namely:

$$W_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \tag{20}$$

Method two: Sum method.

The first step is to normalize the column vectors to obtain the matrix R_{ij}, namely:

$$R_{ij} = \begin{bmatrix} \dfrac{a11}{\sum_{i=1}^{n} ai1} & \dfrac{a12}{\sum_{i=1}^{n} ai2} & \cdots & \dfrac{a1n}{\sum_{i=1}^{n} ain} \\ \dfrac{a21}{\sum_{i=1}^{n} ai1} & \dfrac{a22}{\sum_{i=1}^{n} ai2} & \cdots & \dfrac{a2n}{\sum_{i=1}^{n} ain} \\ \cdots & \cdots & \cdots & \cdots \\ \dfrac{an1}{\sum_{i=1}^{n} ai1} & \dfrac{an2}{\sum_{i=1}^{n} ai2} & \cdots & \dfrac{ann}{\sum_{i=1}^{n} ain} \end{bmatrix} \tag{21}$$

The second step, add the lines of the normalized matrix R_{ij} to get matrix R^*_{ij}, namely:

$$R^*_{ij} = \begin{bmatrix} \dfrac{a11}{\sum_{i=1}^{n} ai1} + \dfrac{a12}{\sum_{i=1}^{n} ai2} + \cdots + \dfrac{a1n}{\sum_{i=1}^{n} ain} \\ \dfrac{a21}{\sum_{i=1}^{n} ai1} + \dfrac{a22}{\sum_{i=1}^{n} ai2} + \cdots + \dfrac{a2n}{\sum_{i=1}^{n} ain} \\ \cdots \quad \cdots \quad \cdots \quad \cdots \\ \dfrac{an1}{\sum_{i=1}^{n} ai1} + \dfrac{an2}{\sum_{i=1}^{n} ai2} + \cdots + \dfrac{ann}{\sum_{i=1}^{n} ain} \end{bmatrix} \tag{22}$$

The third step, the row sum of the added matrix R^*_{ij} is normalized to obtain the weight vector w_{ij}.

2.2.4 Consistency test

In the risk assessment of the power supply and distribution project construction schedule, in addition to the index weight calculated according to expert scores, consistency index CI and consistency ratio CR should also be investigated. The matrix's maximum characteristic roots λ_{max}, CI and CR can be calculated by Eqs. 23, 24. When CI = 0, it indicates that the results have complete consistency; when CI approaches 0, it indicates good consistency; the more significant the consistency index CI is, the greater the degree of inconsistency deviation.

$$\lambda_{max} = \sum\nolimits_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{23}$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{24}$$

Since the fuzzy judgment matrix presents inconsistency in most cases, in order to measure the consistency index CI value, we need to introduce the random consistency index RI value, which depends on the matrix order:

$$CR = \frac{CI}{RI} \tag{25}$$

When $CR < 0.1$ indicates that the fuzzy judgment matrix has a good consistency, it passes the consistency test; otherwise, it fails.

2.3 MCS-AHP model

Monte Carlo simulation (Qazi et al., 2021) is used to improve on the fuzzy hierarchical analysis method to quantify the degree of influence of schedule risk factors for power supply and distribution projects. In Monte Carlo simulation, the normal distribution is used as the most appropriate distribution model to approximate the probability distribution functions of the criteria and factors. The method is mainly based on fuzzy hierarchical analysis, using fuzzy hierarchical analysis as the general framework and using regular distribution intervals instead of specific values when constructing fuzzy complementary judgement matrices to reduce the risk of probabilistic uncertainty, as well as to reduce the risk of people's fuzzy thinking and incomplete information or scattered data in the process of investigation and judgement, to avoid the results. The specific steps are as follows.

2.3.1 Establish an evaluation indicator system

Establish a hierarchical decision structure for construction schedule risk management for power supply and distribution projects, using objective layer A, criterion layer B, and factor layer C to complete the structure. This paper describes that objective layer A is the most essential factor in determining criterion layer B and factor layer C. The attributes of the decision target layer A, criterion layer B and factor layer C should be developed based on the actual project.

2.3.2 Expert scoring

The expert interview method and other statistical methods can produce the results of expert scoring and obtain the vital information of each criterion level and factor level, respectively, then use Saaty's scale method for preliminary assessment and then decide the normal distribution range according to the expert scoring results.

2.3.3 Preliminary determination of the regular distribution interval

The results of each expert's score are listed to make a reasonable judgement on the construction schedule of the power supply and distribution project. In general, the total standard deviation σ is uncertain, and we can use the sampling standard deviation s as the point estimate of the total standard deviation to predict the overall parameters, using the sampling standard deviation s as the total standard deviation σ. The sampling means as the total mean μ. A normal distribution is evaluated by sorting the data in a spreadsheet to determine the normal distribution curve's lowest, most likely and highest values. Eq. 28 gives the probability distribution function for a standard distribution curve, and Eqs. 29, 30 determine the independent typical distribution properties. The interval estimates under large samples when σ and μ are unknown are,

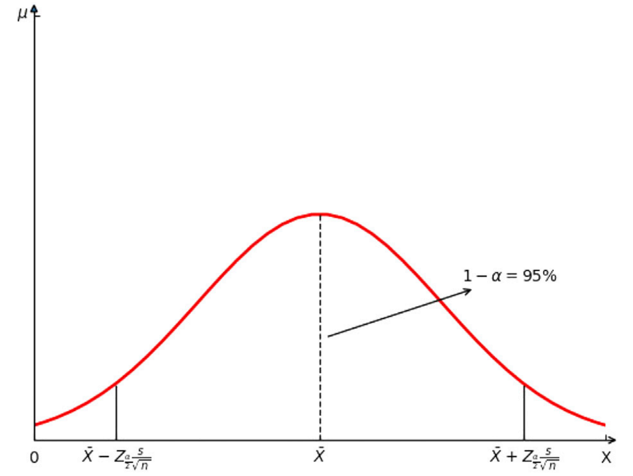

FIGURE 3
Normal distribution curve interval when confidence degree 1-α = 95%.

$$\mu \pm Z_{\alpha/2} \cdot \frac{\sigma}{\sqrt{n}} \tag{26}$$

When s is used instead of σ, the interval estimate at the time of substitution is,

$$\bar{x} \pm Z_{\alpha/2} \cdot \frac{s}{\sqrt{n}} \tag{27}$$

$$f\left(x|\mu,\sigma\right) = \frac{1}{s\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2s^2}} \tag{28}$$

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} = \frac{x_1 + x_2 + \cdots + x_n}{n} \tag{29}$$

$$s = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \tag{30}$$

$$\hat{a} = \bar{x} - Z_{\alpha/2} \cdot \frac{s}{\sqrt{n}} \tag{31}$$

$$\hat{b} = \bar{x} \tag{32}$$

$$\hat{c} = \bar{x} + Z_{\alpha/2} \cdot \frac{s}{\sqrt{n}} \tag{33}$$

Where: $\bar{x}$ is the mean of the normal distribution, s is the standard deviation of the normal distribution, $\hat{a}$ is the lowest value, $\hat{b}$ is the most likely value, $\hat{c}$ is the highest value, n is the number of data, α is the confidence rate, confidence level, reflecting the credibility of the prediction conclusion. If the confidence level is given in advance, we can look up its corresponding statistical variables through the standard normal distribution $Z_{\alpha/2}$. The typical confidence levels are 90%, 95%, 95.45% and 99.73%. In this paper, we choose 1-α = 95%, and the confidence level is 1.96. Figure 3 below illustrates the a normal distribution curve with a 95% confidence period.

2.3.4 Monte Carlo simulation of a normal distribution interval

A standard distance fuzzy number is generated by generating a random variable for $\bar{x}$, $\bar{x} - Z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}$, $\bar{x} + Z_{\alpha/2} \cdot \frac{s}{\sqrt{n}}$, and applying Monte Carlo to simulate a normal distribution 100 normal random variables are used in this paper and Eqs. 34, 37 describe how the random numbers are generated.

$$F\left(X\middle|\mu,\sigma\right)=\frac{1}{\sigma\sqrt{2\pi}}\int_{-\infty}^{x}e^{-\frac{(x-\mu)^2}{2\sigma^2}}\approx\frac{1}{2}\left(1+\mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right)\tag{34}$$

Random Monte Carlo numbers can be generated by plotting input variables (X) ranging from 0 to 100, generating random variables from i = 1 to 100 times, and storing the results as columns of random variables. Eqs. 38–40 are then used to determine the Monte Carlo normal distribution mean and standard deviation to account for the values of a, b and c.

$$a=\mu-Z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}}\tag{35}$$

$$b=\mu\tag{36}$$

$$c=\mu+Z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}}\tag{37}$$

$$\mu=\frac{\sum_{i=1}^{n}x_i}{n}=\frac{x_1+x_2+\ldots+x_n}{n}\tag{38}$$

$$\sigma=\sqrt{\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n-1}}\tag{39}$$

Where $F(X|\mu,\sigma)$ is the cumulative distribution function of the normal distribution,μ and σ are the mean and standard deviation of the Monte Carlo normal distribution, and a, b and c are the lower, most likely and higher values for which the mutual inverse fuzzy set values are applicable.

$$(a,b,c)^{-1}=\left(\frac{1}{\mu+Z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}}},\frac{1}{\mu},\frac{1}{\mu-Z_{\alpha/2}\cdot\frac{\sigma}{\sqrt{n}}}\right)\tag{40}$$

2.3.5 Normality test

This paper used P-P plots and the Kolmogorov-Smirnov test to test the normality of all judgement data.

For the P-P plot, the actual data cumulative rate of the data distribution, when assumed to be normally distributed, must first be calculated; this is then represented as a split scatter plot, with the X-axis representing the actual cumulative percentage and the Y-axis representing the cumulative percentage of the assumed normal distribution. Because of the normal distribution assumed for the figures, the cumulative percentage of the hypothetical normal distribution is the same as the cumulative percentage of the accurate figures.

The KS test was used to test the normality of the statistics, using the upper exact bound (the maximum value of the difference) between the cumulative distribution function $f_x(x)$ of the sample and the cumulative distribution function $F_n(x)$ of the normal distribution to determine whether the Kolmogorov distribution was met. The KS test significantly indicates normality when the maximum difference in D_n is less than the value in the Kolmogorov-Smirnov table. The mathematical equations for the KS test are Eqs. 41–43.

$$D_n=\sup|f_x(x)-F_n(x)|\tag{41}$$

$$f_x(x)=\int_{-\infty}^{x}f_x(k)dk=\int_{-\infty}^{x}\frac{1}{\sigma\sqrt{2\pi}}e\left(-\frac{(k-\mu)^2}{2\sigma^2}\right)dk\tag{42}$$

$$F_n(x)=\frac{1}{n}\sum_{i=1}^{n}1_{xi\le t}\tag{43}$$

Where D_n is the highest difference between statistics $f_x(x)$ and $F_n(x)$, sup is the exact upper boundary of the distance (supremum), $f_x(x)$ is the cumulative distribution function of the sample, and $F_n(x)$ is the cumulative distribution function of the normal distribution. To simplify the calculation, this paper uses IBM SPSS software to plot P-P plots and perform KS tests to determine whether the data conform to normality. When the data > 0.05, it means that the data form a normal distribution, while when the data ≤ 0.05, it means that the data do not form a normal distribution.

2.3.6 Construct a normal distribution fuzzy two-by-two comparison matrix

Using a two-by-two comparison matrix of normally distributed fuzzy numbers instead of the fuzzy complementary judgment matrix of the traditional hierarchical analysis method, construct a comparison matrix E=(e_{ij})nxn based on the lowest value a, the most probable value b and the highest value c obtained in step 4, and set the random normally distributed values of E_{11} and E_{12} as (a_{11},b_{11},c_{11}) and (a_{12},b_{12},c_{12}) respectively.

$$E=\begin{bmatrix}(1,1,1) & (a_{12},b_{12},c_{12}) & \cdots & (a_{1n},b_{1n},c_{1n})\\ (1/c_{12},1/b_{12},1/a_{12}) & (1,1,1) & \cdots & (a_{2n},b_{2n},c_{2n})\\ \cdots & \cdots & \ddots & \cdots\\ (1/c_{1n},1/b_{1n},1/a_{1n}) & (1/c_{2n},1/b_{2n},1/a_{2n}) & \cdots & (1,1,1)\end{bmatrix}\tag{44}$$

2.3.7 Test of consistency

Like the traditional fuzzy analytic hierarchy process, consistency analysis is required for each fuzzy judgment matrix to ensure that the fuzzy pairwise comparison matrix is adequate for evaluation. Once it is inconsistent, the relevant fuzzy pairwise comparison matrix needs to be adjusted. Since the interval scale is used to replace the point scale, uing the traditional consistency analysis. Some scholars (Ramík and Korviny, 2010) proposed a new consistency index (NI) to measure the consistency of pairwise comparison matrix with fuzzy ternary interval.

$$NI_n^{\sigma}(A)=\gamma_n^{\sigma}\cdot\max_{i,j}\left\{\max\left\{\left|\frac{U_i^L}{U_j^U}-a_{ij}\right|,\left|\frac{U_i^M}{U_j^M}-b_{ij}\right|,\left|\frac{U_i^U}{U_j^L}-c_{ij}\right|\right\}\right\}\tag{45}$$

$$\gamma_n^{\sigma}=\frac{1}{\max\left\{\sigma-\sigma^{(2-2n)/n},\sigma^2\left(\left(\frac{2}{n}\right)^{2/(n-2)}-\left(\frac{2}{n}\right)^{n/(n-2)}\right)\right\}},\sigma<\left(\frac{n}{2}\right)^{n/(n-2)}\tag{46}$$

$$\gamma_n^{\sigma}=\frac{1}{\max\{\sigma-\sigma^{(2-2n)/n},\sigma^{(2n-2)/n}-\sigma\}},\sigma\ge\left(\frac{n}{2}\right)^{n/(n-2)}\tag{47}$$

Where,

$$U_k^L=C_{\min}\cdot\frac{\left(\prod_{j=1}^{n}a_{kj}^L\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n}a_{ij}^M\right)^{1/n}}\tag{48}$$

$$C_{\min}=\min_{i=1,\ldots,n}\left\{\frac{\left(\prod_{j=1}^{n}a_{ij}^M\right)^{1/n}}{\left(\prod_{j=1}^{n}a_{ij}^L\right)^{1/n}}\right\}\tag{49}$$

$$U_k^M=\frac{\left(\prod_{j=1}^{n}a_{kj}^M\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n}a_{ij}^M\right)^{1/n}}\tag{50}$$

$$U_k^U=C_{\max}\cdot\frac{\left(\prod_{j=1}^{n}a_{kj}^u\right)^{1/n}}{\sum_{i=1}^{n}\left(\prod_{j=1}^{n}a_{ij}^M\right)^{1/n}}\tag{51}$$

$$C_{\max}=\max_{i=1,\ldots,n}\left\{\frac{\left(\prod_{j=1}^{n}a_{ij}^M\right)^{1/n}}{\left(\prod_{j=1}^{n}a_{ij}^u\right)^{1/n}}\right\}\tag{52}$$

TABLE 1 Construction schedule risk evaluation system for power supply and distribution.

Target level	Guideline level	Factor layer
Construction schedule risk for power supply and distribution	Construction preparation A	Construction personnel, materials and equipment approach A1
		Construction plan preparation review stage A2
		Project Department set up A3
		Site temporary facility set up A4
	Civil construction B	Power piping construction B1
		Electric pipe jacking construction B2
		Cable well construction B3
		High and low pressure indoor construction B4
		Power station equipment foundation construction B5
	Installation construction C	Procurement, production and arrival of materials and equipment C1
		Installation of 10 KV high voltage Distribution cabinet C2
		Dry type transformer installation C3
		Install low-voltage PDC and DC panel C4
		High voltage protection, metering system installation C5
		Cable tray installation and cable laying C6
	Commissioning and acceptance by the electricity supply department D	Electrical acceptance and monomer commissioning D1
		System setup and whole group start debugging D2
		Preliminary inspection, elimination, final inspection and handover by Power supply department D3
		Power transmission D4

Where, σ is the pairwise comparison scale (for example, when the expert scores the result of 1/9 and 9, the pairwise comparison scale is 9), γ_n^σ is the regular constant, and $\mathrm{NI}_n^\sigma(\mathrm{A})$ is the consistency index of the fuzzy pairwise comparison matrix. When the value of $\mathrm{NI}_n^\sigma(\mathrm{A})$ is between 0 and 0.1, the fuzzy pairwise comparison matrix passes the consistency test. When the value of $\mathrm{NI}_n^\sigma(\mathrm{A})$ is closer to 0, the consistency test of the fuzzy pairwise comparison matrix is more consistent.

2.3.8 Calculation of weights and ranking

Normalize the two-by-two comparison matrix to obtain the matrix $R = (\mathrm{r_{ij}})$ nxn, Method 1: Root value method

$$\mathrm{r_{ij}} = \left(\frac{\mathrm{a_{ij}}}{\sum_{i=1}^{n}\mathrm{a_{ij}}}, \frac{\mathrm{b_{ij}}}{\sum_{i=1}^{n}\mathrm{b_{ij}}}, \frac{\mathrm{c_{ij}}}{\sum_{i=1}^{n}\mathrm{c_{ij}}}\right), \mathrm{i} = 1, 2, 3, \ldots., \mathrm{n} \tag{53}$$

The fuzzy weight values were obtained using Buckley's geometric averaging method FAHP to calculate the fuzzy weights of each fuzzy matrix. The fuzzy weight values were calculated by geometric averaging for each row using Eq. 54.

$$\mathrm{w_{ij}} = \left(\prod\nolimits_{j=1}^{n}\mathrm{r_{ij}}\right)^{\frac{1}{n}} \tag{54}$$

Method two: Sum method

It is consistent with the calculation steps of the analytic hierarchy process

The fuzzy final value is calculated by computing the total hierarchical ranking.

$$\mathrm{w_i} = \sum_{j=1}^{n}\mathrm{w_{ij}}{}^{*}\mathrm{w_j} \tag{55}$$

3 Case study

3.1 Project overview

The power supply and distribution project selected in this paper is XX Power Supporting Phase II Project, and the construction site is XX Road, XX District, XX City, Guangdong Province. The construction scope of this project is 2# plant construction, 3# plant construction and power station construction.

3.2 Establishment of risk indicator system

The essential step in the risk analysis of power supply and distribution project construction is to set up the risk assessment index system of progress. Progress risk assessment index system should be scientific and accurate, include all factors that may affect the construction progress of power supply and distribution projects,

TABLE 2 Monte Carlo random generation number of criterion layer.

Indicator	B than A	C than A	D than A	C than B	D than B	D than C
x̄	3.875	7.625	3.563	3.813	0.604	0.184
s	0.927	0.992	0.864	1.014	0.460	0.025
Monte Carlo number randomly generated numbers						
1	3.047	7.241	3.478	4.577	1.219	0.213
2	2.897	7.585	2.673	3.729	0.375	0.170
3	2.836	9.096	2.328	2.111	1.050	0.186
...	...	...	...	...	...	...
98	2.833	7.660	4.511	3.158	0.617	0.209
99	5.459	8.837	2.667	1.891	-0.384	0.169
100	4.942	6.393	5.199	4.180	0.964	0.202
μ	3.812	7.597	3.596	3.760	0.620	0.183
σ	0.910	1.022	0.876	1.021	0.459	0.024

and pay attention to redundancy and contradiction among all factors while eliminating human interference factors. Combined with the actual power supply and distribution project situation, this paper summarizes the construction progress evaluation index system of the power supply and distribution project. As shown in Table 1 below.

3.3 MCS-AHP determines the weight of indicators

3.3.1 Expert questionnaire situation

Sixteen experts were invited to evaluate the evaluation index system, including the project leader, deputy project manager, technical person, safety person and full-time safety officer to evaluate all the index factors. In order to construct A fuzzy pairwise comparison matrix, the two factors are compared. For example, the civil construction criterion B is compared with the construction preparation criterion A, and the importance between the two is compared according to the 1-9 scale method proposed by Professor Saaty (Kieu et al., 2021). Details of the expert scores for the guideline and factor tiers are detailed in Supplementary Appendices S1–S5.

3.3.2 Determining Monte Carlo random generation numbers

The mean and standard deviation can be calculated based on the experts' ratings of the two comparison factors. In order to reduce the bias caused by subjective factors, this paper selects a large sample of data to evaluate the construction risk of power supply and distribution projects. However, if the questionnaire method is used to calculate the extensive sample data, there may be a significant error. On this basis, 100 random variables were generated by applying the Monte Carlo random generation number principle. For this purpose, the standard deviation s of the sample was used as the point estimate of the total standard deviation for the prediction of the overall parameters, using the sample standard deviation s as the total standard deviation σ and the sample mean x̄ as the total mean μ. The Monte Carlo random generation numbers of the criterion layer are sorted out as shown in Table 2, and the Monte Carlo random generation numbers of other factor layers are shown in Supplementary Appendices S6–S9.

3.3.3 Normality test

After generating Monte Carlo random numbers, it is also necessary to test the normality of the data. There are many methods to test for normality, and this paper takes P-P plots and K-S test tables for verification, the basic principles of which are referred to in Eqs. 41–43. To simplify the calculation and improve the calculation efficiency, this paper mainly uses the software spss for testing. According to the criterion layer, K-S test, Table 3 shows that when all values of asymptotic significance are more excellent than 0.05, so the criterion layer data conforms to a normal distribution. According to Figures 4–7 and Supplementary Appendix S10, the hypothesised cumulative ratios of the normal distribution are consistent with the cumulative ratios of the actual data, so the criterion layer data are consistent with a normal distribution. The data in each factor layer also conform to normal distribution. Due to space limitations, the K-S test and P-P plot for each factor layer will not be developed in detail here.

3.3.4 Construct fuzzy pairwise comparison matrix and consistency test

The population mean μ and the population standard deviation σ of the sample can be determined according to the random numbers generated by the pair comparison of factors. Eqs. 35–37 are used to determine the lower limit a, the most probable value b, and the upper limit c of the fuzzy pair-to-pair comparison matrix. The fuzzy pair-to-pair comparison matrix can be constructed by using Eq. 44, and the constructed pair-to-pair comparison matrix is shown in Tables 4–Tables 8 (In order to distinguish the results calculated by using AHP model, MCS-AHP is added to the table, representing the results calculated by using MCS-AHP model):

According to Eqs. 45–52, a consistency test can be performed on the pair-to-pair comparison matrix of the criterion layer. Combined with Table 4, it can be calculated as follows:

TABLE 3 K-S test of criterion layer.

Kolmogorov-Sminov test								
Number of cases			B than A	C than A	D than A	C than B	D than B	D than C
			100	100	100	100	100	100
Normal parameters[a,b]	Average		3.812	7.597	3.596	3.760	0.620	0.183
	Standard Deviation		0.910	1.022	0.876	1.021	0.459	0.024
Most extreme difference	Absolute values		.027	.033	.025	.018	.027	.032
	positive values		.027	.033	.019	.016	.026	.032
	negative values		−.022	−.024	−.025	−.018	−.027	−.024
Test statistics			.027	.033	.025	.018	.027	.032
Asymptotic saliency (two-tailed)[c]			.200[d]	.200[d]	.200[d]	.200[d]	.200[d]	.200[d]
Monte Carlo significance (two-tailed)[e]	significance		.483	.211	.674	.972	.489	.258
	99% confidence interval	lower limit	.470	.200	.662	.968	.476	.247
		upper limit	.496	.221	.686	.976	.502	.269

[a] The test distribution is normal.

[b] Calculated from data.

[c] Riley's significance correction.

[d] This is the lower limit of true saliency.

[e] Rielly's method based on 10,000 Monte Carlo samples with 2 million starting seeds.

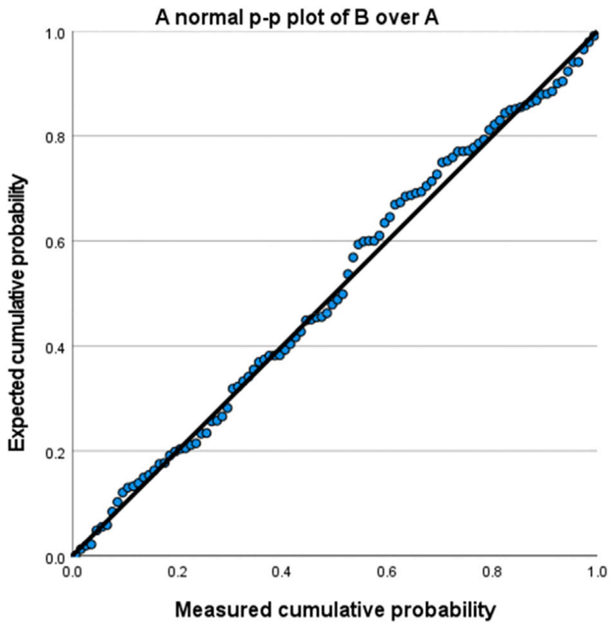

FIGURE 4
A normal p-p plot of B over A.

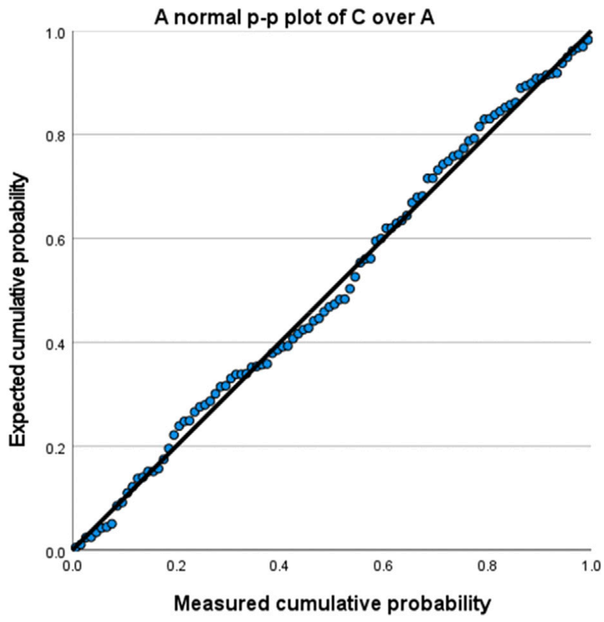

FIGURE 5
A normal p-p plot of C over A.

$$\sigma = \left[\frac{1}{9}.9\right] = 9, \mathrm{n} = 4$$

$$9 > \left(\frac{4}{2}\right)^{4/(4-2)} = 4$$

$$\gamma_4^9 = \frac{1}{\max\left(9 - 9^{(-6/4)}, 9^{(6/4)} - 9\right)} = \frac{1}{\max\left(8.963, 18\right)} = 0.056$$

$$\mathrm{C}_{\min} = 1.008$$

$$\mathrm{C}_{\max} = 0.992$$

$$\tilde{\mathrm{u}}_1 = \left(\mathrm{u}_1^{\mathrm{L}}, \mathrm{u}_1^{\mathrm{M}}, \mathrm{u}_1^{\mathrm{U}}\right) = (0.054, 0.054, 0.054)$$

$$\tilde{\mathrm{u}}_2 = \left(\mathrm{u}_2^{\mathrm{L}}, \mathrm{u}_2^{\mathrm{M}}, \mathrm{u}_2^{\mathrm{U}}\right) = (0.194, 0.196, 0.198)$$

$$\tilde{\mathrm{u}}_3 = \left(\mathrm{u}_3^{\mathrm{L}}, \mathrm{u}_3^{\mathrm{M}}, \mathrm{u}_3^{\mathrm{U}}\right) = (0.612, 0.612, 0.612)$$

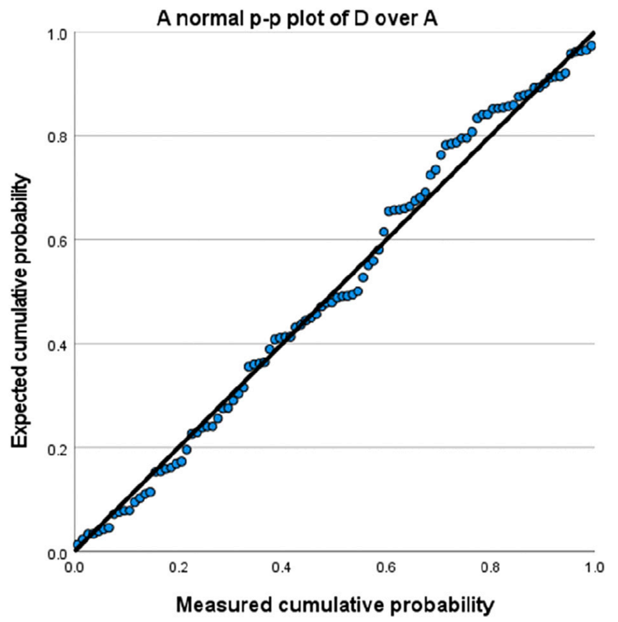

FIGURE 6
A normal p-p plot of D over A.

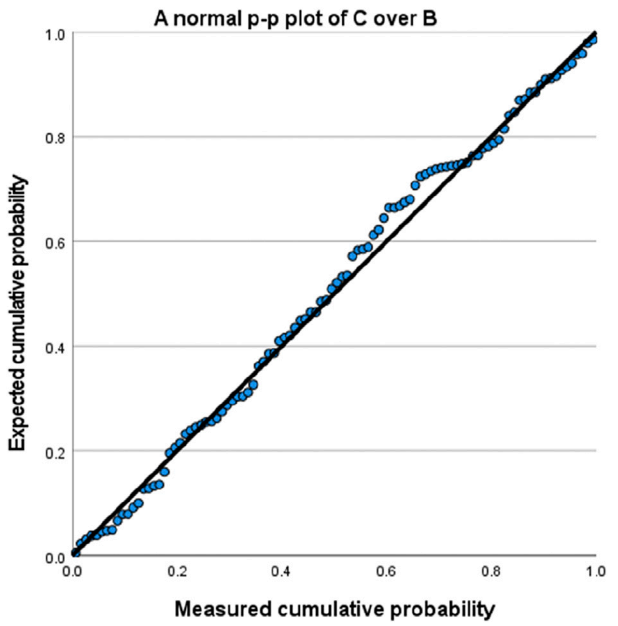

FIGURE 7
A normal p-p plot of C over B.

$$\widetilde{u}_4 = \left(u_4^L, u_4^M, u_4^U\right) = (0.137, 0.138, 0.139)$$

$$\max\left\{\left|\frac{U_i^L}{U_j^U} - a_{ij}\right|, \left|\frac{U_i^M}{U_j^M} - b_{ij}\right|, \left|\frac{U_i^U}{U_j^L} - c_{ij}\right|\right\} = \max\{1.032, 1.029, 1.028\}$$
$$= 1.032$$

$$NI_4^9(A) = \gamma_4^9 \cdot \max_{i,j}\left\{\max\left\{\left|\frac{U_i^L}{U_j^U} - a_{ij}\right|, \left|\frac{U_i^M}{U_j^M} - b_{ij}\right|, \left|\frac{U_i^U}{U_j^L} - c_{ij}\right|\right\}\right\}$$
$$= 0.056 \cdot 1.032 = 0.058$$

Because $NI_4^9(A) = 0.058 < 0.1$, it passes the consistency test. The consistency test of other factor layers is the same. Due to space limitations, the calculation will not be carried out in detail.

3.3.5 Determine the relative weight and ranking of each index

Based on the fuzzy pair-to-pair comparison matrix and Eqs. 53–55, the normalized matrix and standard weight of the criterion layer and factor layer can be calculated to determine the objects that should be paid the most attention to, as shown in Tables 9, 14 below (In order to distinguish the results calculated by using AHP model, MCS-AHP is added to the table, representing the results calculated by using MCS-AHP model):

As seen from Table 9, installation construction has the most significant weight. Civil construction, commissioning and acceptance of the power supply department has the third weight, and construction preparation has the least weight. Therefore, installation construction and civil construction should be the critical criteria layer. According to the standard weight and ranking Table 10 of the construction preparation factor layer, it can be seen that the construction of temporary facilities on site has the most significant weight, followed by the construction personnel, materials and equipment entering the site, the construction plan preparation and review stage has the third weight. The construction department has the least weight. Therefore, the critical factors in the criterion layer of construction preparation are the establishment of temporary facilities on site and the entry of construction personnel, materials and equipment. It can be seen from the standard weight and ranking Table 11 of the civil construction factor layer that the weight of power station equipment foundation construction is the first, the weight of high and low-pressure indoor foundation construction is the second, the weight of cable well construction is the third, the weight of power pipe jack construction is the fourth, and the weight of power pipe row construction is the fifth. Therefore, power station equipment foundation construction and high and low-pressure indoor foundation construction are the key factors in the criteria of civil construction. As can be seen from the standard weight and ranking Table 12 of the installation and construction factor layer, the purchase of materials and equipment, production and arrival of goods have the most significant weight. The installation of a 10 kv high voltage distribution cabinet has the second weight, the installation of low voltage distribution cabinet and DC panel has the third weight, and the installation of high voltage protection and the metering system has the fourth weight. The weight of cable tray installation and cable laying ranks fifth, and the weight of dry transformer installation is the least. Therefore, in the criterion layer of installation and construction, we should focus on the procurement, production and arrival of materials and equipment, installing a 10 kv high-voltage distribution cabinet, low-voltage distribution cabinet and DC screen installation. According to the standard weight and ranking Table 13 of the acceptance factor layer of the commissioning and power supply department, the weight of electrical test and single commissioning are the highest, followed by the weight of acceptance and handover of the power supply department, the weight of system commissioning. The whole group starting commissioning is the third, and the weight of power transmission is the least. Therefore, in the criterion layer of

TABLE 4 Pairwise comparison matrix of criterion layer (MCS-AHP).

Indicator	A	B	C	D
A	(1,1,1)	(0.259,0.262, 0.266)	(0.131,0.132, 0.133)	(0.274,0.278, 0.282)
B	(3.756,3.812, 3.868)	(1,1,1)	(0.262,0.266, 0.270)	(1.543,1.613, 1.689)
C	(7.534,7.597, 7.660)	(3.697,3.760, 3.823)	(1,1,1)	(5.435,5.464, 5.495)
D	(3.542,3.596, 3.650)	(0.592,0.620, 0.648)	(0.182,0.183, 0.184)	(1,1,1)
$NI_4^9(A) = 0.058 < 0.1$				

TABLE 5 Pairwise comparison matrix of construction preparation factor layer (MCS-AHP).

Indicator	A_1	A_2	A_3	A_4
A_1	(1,1,1)	(1.482,1.541, 1.600)	(2.559,2.613, 2.667)	(0.734,0.790, 0.846)
A_2	(0.625,0.649, 0.675)	(1,1,1)	(2.231,2.295, 2.359)	(0.787,0.839, 0.891)
A_3	(0.375,0.383, 0.391)	(0.424,0.436, 0.448)	(1,1,1)	(0.314,0.318, 0.322)
A_{14}	(1.182,1.266, 1.362)	(1.122,1.192, 1.271)	(3.106,3.145, 3.185)	(1,1,1)
$NI_4^9(A) = 0.017 < 0.1$				

TABLE 6 Pairwise comparison matrix of civil construction factor layer (MCS-AHP).

Indicator	B_1	B_2	B_3	B_4	B_5
B_1	(1,1,1)	(0.245,0.248,0.252)	(0.256,0.260,0.265)	(0.180,0.182,0.184)	(0.176,0.178,0.180)
B_2	(3.963,4.023, 4.083)	(1,1,1)	(0.609,0.630,0.653)	(0.284,0.288,0.292)	(0.258,0.263,0.268)
B_3	(3.790,3.849, 3.908)	(1.531,1.587, 1.643)	(1,1,1)	(0.303,0.307,0.311)	(0.276,0.280,0.284)
B_4	(5.417,5.481, 5.545)	(3.427,3.474, 3.521)	(3.215,3.260, 3.305)	(1,1,1)	(0.597,0.620,0.643)
B_5	(5.531,5.603, 5.675)	(3.732,3.806, 3.880)	(3.522,3.573, 3.624)	(1.556,1.615, 1.674)	(1,1,1)
$NI_4^9(A) = 0.081 < 0.1$					

TABLE 7 Pairwise comparison matrix of installation and construction factor layer (MCS-AHP).

Indicator	C1	C2	C3	C4	C5	C6
C_1	(1,1,1)	(3.878,3.941, 4.004)	(5.629,5.691,5.753)	(3.718,3.771,3.824)	(3.936,3.992,4.048)	(4.330,4.394,4.458)
C_2	(0.250,0.254,0.258)	(1,1,1)	(3.524,3.577,3.630)	(1.600,1.658,1.716)	(1.223,1.266, 1.309)	(1.880,1.940,1.999)
C_3	(0.174,0.176,0.178)	(0.275,0.280,0.284)	(1,1,1)	(0.269,0.273,0.277)	(0.263,0.267,0.271)	(0.306,0.310,0.314)
C_4	(0.262,0.265,0.268)	(0.583,0.603,0.625)	(3.610,3.663,3.717)	(1,1,1)	(1.748,1.808,1.868)	(1.940,2.000,2.060)
C_5	(0.247,0.251,0.254)	(0.764,0.790,0.818)	(3.690,3.745,3.802)	(0.535,0.553,0.572)	(1,1,1)	(1.390,1.435, 1.480)
C_6	(0.224,0.228,0.231)	(0.500,0.515,0.532)	(3.185,3.226,3.268)	(0.485,0.500,0.515)	(0.676,0.697,0.719)	(1,1,1)
$NI_4^9(A) = 0.042 < 0.1$						

commissioning and acceptance of the power supply department, emphasis should be placed on the two factors of electrical test, unit commissioning and acceptance and handover of the power supply department.

Based on Tables 9–Tables 14 can be obtained. Based on the comprehensive analysis of the standard weights and the overall ranking of all factors, it can be concluded that the purchase of materials and equipment, production and arrival of goods take the first place, the installation of 10 kv high-voltage power distribution cabinet takes the second place, electrical acceptance and single commissioning takes the third place, and the installation of low-voltage power distribution cabinet and DC panel takes the fourth

TABLE 8 Pairwise comparison matrix of factor layer of commissioning and acceptance of power supply department (MCS-AHP).

Indicator	D_1	D_2	D_3	D_4
D_1	(1,1,1)	(6.554,6.618, 6.682)	(5.978,6.036, 6.094)	(7.442,7.509, 7.576)
D_2	(0.150,0.151, 0.152)	(1,1,1)	(0.297,0.300, 0.303)	(1.699,1.756, 1.812)
D_3	(0.164,0.166, 0.167)	(3.300,3.333, 3.367)	(1,1,1)	(3.539,3.593, 3.647)
D_4	(0.132,0.133, 0.134)	(0.552,0.569, 0.588)	(0.274,0.278, 0.283)	(1,1,1)
$NI_4^9(A) = 0.071 < 0.1$				

TABLE 9 Standard weight and ranking of criteria layer (MCS-AHP).

Indicator	A	B	C	D	wj	Rank
A	(0.063,0.062,0.062)	(0.045,0.046,0.047)	(0.083,0.083,0.084)	(0.033,0.034,0.033)	(0.055,0.056,0.057)	4
B	(0.237,0.238,0.239)	(0.180,0.177,0.174)	(0.166,0.168,0.170)	(0.186,0.193,0.199)	(0.192,0.194,0.196)	2
C	(0.475,0.475,0.473)	(0.667,0.667,0.667)	(0.634,0.633,0.633)	(0.658,0.654,0.649)	(0.605,0.607,0.609)	1
D	(0.223,0.225,0.226)	(0.106,0.110,0.113)	(0.115,0.116,0.116)	(0.121,0.120,0.118)	(0.141,0.142,0.143)	3

TABLE 10 Standard weight and ranking of construction preparation factor layer (MCS-AHP).

Indicator	A_1	A_2	A_3	A_4	wj	Rank
A_1	(0.314,0.303,0.292)	(0.368,0.370,0.371)	(0.287,0.289,0.290)	(0.258,0.268.0.278)	(0.306,0.307,0.308)	2
A_2	(0.196,0.197,0.197)	(0.248,0.240,0.232)	(0.251,0.254,0.256)	(0.277,0.284,0.291)	(0.243,0.244,0.245)	3
A_3	(0.118,0.116,0.114)	(0.105,0.105,0.104)	(0.112,0.110,0.109)	(0.111,0.108,0.105)	(0.108,0.110,0.112)	4
A_4	(0.371,0.384,0.397)	(0.278,0.285,0.294)	(0.349,0.347,0.346)	(0.353,0.339,0.327)	(0.337,0.339,0.341)	1

TABLE 11 Standard weight and ranking of civil construction factor layer (MCS-AHP).

Indicator	B_1	B_2	B_3	B_4	B_5	wj	Rank
B_1	(0.051,0.050,0.049)	(0.024,0.025,0.026)	(0.029,0.030,0.031)	(0.054,0.054,0.053)	(0.076,0.076,0.076)	(0.046,0.047.0.048)	5
B_2	(0.201,0.202,0.202)	(0.101,0.099,0.097)	(0.071,0.072,0.074)	(0.085,0.085,0.085)	(0.112,0.112,0.113)	(0.113,0.114,0.115)	4
B_3	(0.192,0.193,0.193)	(0.154,0.157,0.159)	(0.116,0.115,0.113)	(0.091,0.091,0.090)	(0.119,0.120,0.120)	(0.134,0.135,0.136)	3
B_4	(0.274,0.275,0.275)	(0.345,0.343,0.342)	(0.374,0.374,0.374)	(0.300,0.295,0.289)	(0.259,0.265,0.271)	(0.309,0.310,0.311)	2
B_5	(0.281,0.281,0.282)	(0.376,0.376,0.377)	(0.409,0.410,0.410)	(0.468,0.476,0.484)	(0.433,0.427,0.421)	(0.393,0.394.0.395)	1

TABLE 12 Standard weight and ranking of installation and construction factor layers (MCS-AHP).

Indicator	C_1	C_2	C_3	C_4	C_5	C_6	wj	Rank
C_1	(0.463,0.459,0.456)	(0.554,0.552,0.551)	(0.272,0.272,0.272)	(0.488,0.486,0.484)	(0.445,0.442,0.439)	(0.399,0.397,0.394)	(0.433,0.435,0.436)	1
C_2	(0.116,0.117,0.118)	(0.142,0.140,0.138)	(0.171,0.171,0.172)	(0.210,0.214,0.217)	(0.138,0.140,0.142)	(0.173,0.175,0.177)	(0.158,0.160,0.161)	2
C_3	(0.080,0.081,0.081)	(0.039,0.039,0.039)	(0.048,0.048,0.047)	(0.035,0.035,0.035)	(0.030,0.030,0.029)	(0.028,0.028,0.027)	(0.042,0.043,0.044)	6
C_4	(0.121,0.122,0.123)	(0.083,0.084,0.086)	(0.175,0.175,0.176)	(0.131,0.129,0.127)	(0.197,0.200,0.203)	(0.179,0.180,0.182)	(0.147,0.148,0.150)	3
C_5	(0.114,0.115,0.116)	(0.109,0.110,0.112)	(0.178,0.179,0.180)	(0.070,0.071,0.072)	(0.113,0.110,0.108)	(0.128,0.130,0.131)	(0.118,0.119,0.120)	4
C_6	(0.103,0.104,0.105)	(0.071,0.072,0.073)	(0.154,0.154,0.154)	(0.063,0.064,0.065)	(0.076,0.077,0.078)	(0.092,0.090,0.088)	(0.093,0.094,0.095)	5

TABLE 13 Standard weight and ranking of factor layer for commissioning and acceptance of power supply department (MCS-AHP).

Indicator	D_1	D_2	D_3	D_4	wj	Rank
D_1	(0.692,0.689,0.688)	(0.574,0.575,0.575)	(0.792,0.793,0.793)	(0.544,0.542,0.540)	(0.649,0.650,0.651)	1
D_2	(0.104,0.104,0.105)	(0.088,0.087,0.086)	(0.039,0.039,0.040)	(0.124,0.127,0.129)	(0.088,0.089,0.090)	3
D_3	(0.113,0.114,0.115)	(0.288,0.289,0.289)	(0.132,0.131,0.130)	(0.259,0.259,0.260)	(0.197,0.198,0.199)	2
D_4	(0.091,0.092,0.092)	(0.048,0.049,0.051)	(0.036,0.037,0.037)	(0.073,0.072,0.071)	(0.062,0.063,0.064)	4

TABLE 14 Standard weight and total ranking of target layer (MCS-AHP).

Guideline level	w_{ij}	Factor layer	w_j	w_i	NI_n^σ (A)	Rank
A	(0.055,0.056,0.057)	A_1	(0.306,0.307,0.308)	(0.0168,0.0172,0.0176)	$0.017 < 0.1$	14
		A_2	(0.243,0.244,0.245)	(0.0134,0.0137,0.0140)		15
		A_3	(0.108,0.110,0.112)	(0.0059,0.0062,0.0064)		19
		A_4	(0.337,0.339,0.341)	(0.0185,0.0190,0.0194)		13
B	(0.192,0.194,0.196)	B_1	(0.046,0.047.0.048)	(0.0088,0.0091,0.0094)	$0.081 < 0.1$	17
		B_2	(0.113,0.114,0.115)	(0.0217,0.0221,0.0225)		12
		B_3	(0.134,0.135,0.136)	(0.0257,0.0262,0.0267)		10
		B_4	(0.309,0.310,0.311)	(0.0593,0.0601,0.0609)		7
		B_5	(0.393,0.394.0.395)	(0.0755,0.0764,0.0774)		5
C	(0.605,0.607,0.609)	C_1	(0.433,0.435,0.436)	(0.2620,0.2640,0.2655)	$0.04 < 0.1$	1
		C_2	(0.158,0.160,0.161)	(0.0956,0.0971,0.0980)		2
		C_3	(0.042,0.043,0.044)	(0.0254,0.0261,0.0268)		11
		C_4	(0.147,0.148,0.150)	(0.0889,0.0898,0.0913)		4
		C_5	(0.118,0.119,0.120)	(0.0714,0.0722,0.0731)		6
		C_6	(0.093,0.094,0.095)	(0.0563,0.0571,0.0579)		8
D	(0.141,0.142,0.143)	D_1	(0.649,0.650,0.651)	(0.0915,0.0923,0.0931)	$0.071 < 0.1$	3
		D_2	(0.088,0.089,0.090)	(0.0124,0.0126,0.0129)		16
		D_3	(0.197,0.198,0.199)	(0.0278,0.0281,0.0284)		9
		D_4	(0.062,0.063,0.064)	(0.0087,0.0089,0.0091)		18

TABLE 15 Pairwise comparison matrix of criterion layer (AHP).

Indicator	A	B	B	D	wj	Rank
A	1	0.258	0.131	0.281	0.056	4
B	3.875	1	0.262	1.656	0.195	2
C	7.625	3.813	1	5.435	0.608	1
D	3.563	0.604	0.184	1	0.141	3

place. The weight of power station equipment foundation construction is the fifth, and the weight of high-pressure protection and metering system installation is the sixth. Therefore, in the risk management of the entire construction schedule of the power supply and distribution project, the most important factors should be the control of materials and equipment procurement, production and arrival, installation of 10 kv high-voltage distribution cabinet, electrical acceptance and single commissioning, installation of low-voltage distribution cabinet and DC panel, equipment foundation construction of power station and installation of high-voltage protection metering system.

3.4 AHP determines the index weight

3.4.1 Construct a pairwise matrix and calculate the relative weights of each indicator

Based on the results of the expert questionnaire, fuzzy two-by-two comparison matrices were constructed for the guideline layer, the

TABLE 16 Pairwise comparison matrix of construction preparation factor layer (AHP).

Indicator	A_1	A_2	A_3	A_4	wj	Rank
A_1	1	1.479	2.583	0.750	0.300	2
A_2	0.676	1	2.250	0.844	0.246	3
A_3	0.387	0.444	1	0.316	0.110	4
A_4	1.333	1.184	3.165	1	0.345	1

TABLE 17 Pairwise comparison matrix of civil construction factor layer (AHP).

Indicator	B_1	B_2	B_3	B_4	B_5	wj	Rank
B_1	1	0.250	0.258	0.182	0.178	0.047	5
B_2	4.000	1	0.615	0.291	0.262	0.113	4
B_3	3.875	1.625	1	0.302	0.281	0.135	3
B_4	5.500	3.438	3.313	1	0.640	0.313	2
B_5	5.625	3.813	3.563	1.563	1	0.391	1

TABLE 18 Pairwise comparison matrix of installation construction factor layer (AHP).

Indicator	C_1	C_2	C_3	C_4	C_5	C_6	wj	Rank
C_1	1	3.938	5.688	3.750	4.000	4.375	0.435	1
C_2	0.254	1	3.625	1.688	1.313	1.875	0.161	2
C_3	0.176	0.276	1	0.278	0.270	0.305	0.044	6
C_4	0.267	0.592	3.597	1	1.813	1.938	0.147	3
C_5	0.250	0.762	3.704	0.552	1	1.375	0.118	4
C_6	0.229	0.533	3.279	0.516	0.727	1	0.096	5

construction preparation factor layer, the civil construction factor layer, the installation construction factor layer and the commissioning and power supply department acceptance factor layer, and the weights were calculated and ranked as shown in Tables 15–Tables 19 (to distinguish the results calculated by the MCS-AHP model, AHP was added to the table to indicate the results calculated by the AHP model):

3.4.2 Test of consistency

Since experts may have a large subjective deviation when scoring the schedule risk of power supply and distribution engineering, it is necessary to conduct a consistency test on all pairwise mutual judgment matrices. Firstly, the consistency test is carried out on the pairwise mutual judgment matrix of the criterion layer. The specific steps are as follows:

Consistency test of the pairwise matrix of criterion layer

Step 1. Eq. 23 can be used to calculate the maximum characteristic root $\lambda_{\max}$ of the matrix. of which,

TABLE 19 Pairwise comparison matrix of acceptance factor layer of commissioning and power supply department (AHP).

Indicator	D_1	D_2	D_3	D_4	wj	Rank
D_1	1	6.625	6.000	7.438	0.650	1
D_2	0.151	1	0.303	1.688	0.089	3
D_3	0.167	3.300	1	3.563	0.199	2
D_4	0.134	0.592	0.281	1	0.064	4

$$AW = \begin{bmatrix} 1 & 0.258 & 0.131 & 0.281 \\ 3.875 & 1 & 0.262 & 1.656 \\ 7.625 & 3.813 & 1 & 5.435 \\ 3.563 & 0.604 & 0.184 & 1 \end{bmatrix} \cdot \begin{bmatrix} 0.056 \\ 0.195 \\ 0.608 \\ 0.141 \end{bmatrix} = \begin{bmatrix} 0.226 \\ 0.805 \\ 2.545 \\ 0.570 \end{bmatrix}$$

$$= (0.226,\ 0.805, 2.545, 0.570)^T$$

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} = \frac{1}{4}\left(\frac{0.226}{0.056} + \frac{0.805}{0.195} + \frac{2.545}{0.608} + \frac{0.570}{0.141}\right) = 4.098$$

Step 2. the consistency index can be calculated using Eq. 24.

$$CI = \frac{\lambda_{\max} - n}{n-1} = \frac{4.098 - 4}{4-1} = 0.033$$

Step 3. the consistency ratio is calculated using Eq. 25, where the value of RI depends on the order of the matrix, and the pairwise matrix of the criterion layer has an order of 4. Checking the RI value (Chen, 2018) shows that when $n = 4$, RI = 0.89

$$CR = \frac{CI}{RI} = \frac{0.033}{0.89} = 0.037 < 0.1$$

Therefore, the pairwise matrix of the criterion layer passes the consistency test, and the weight calculated meets the requirements. The calculation steps of consistency test for each factor layer are the same. Due to space limitation, the calculation will not be carried out in detail.

According to the weights of each indicator calculated from Tables 15, 19 and the consistency ratios, the final weights can be calculated as shown in Table 20 below:

3.5 Discussion

From the target layer standard weight and Total Ranking (AHP) Table 20, it can be seen that the results calculated by the AHP model are as follows: C_1 ranks first in the weight of material and equipment purchased, production and arrival, C_2 ranks second in the weight of installation of 10 KV high voltage switchboard, and D_1 ranks the third in the weight of electrical acceptance and mono commissioning. C_4 installation of low-voltage PDC and DC panel ranks fourth, B_5 installation of power station equipment foundation ranks fifth, and C_5 installation of high-voltage protection and metering system ranks sixth. In preventing risks in the construction schedule of power supply and distribution engineering, these factors should be paid the most attention to.

According to the standard Weight and Total Ranking (MCS-AHP) Table 14 of the target layer, C_1 has the highest weight of material equipment purchase, production and arrival, which has the greatest

TABLE 20 Standard weight and total ranking of target layer (AHP).

Guideline level	w_{ij}	Factor layer	w_j	w_i	λ_{max}	CR	Rank
A	0.056	A_1	0.300	0.0168	4.021	$0.008 < 0.1$	14
		A_2	0.246	0.0138			15
		A_3	0.110	0.0062			19
		A_4	0.345	0.0193			13
B	0.195	B_1	0.047	0.0092	5.186	$0.042 < 0.1$	17
		B_2	0.113	0.0220			12
		B_3	0.135	0.0263			11
		B_4	0.313	0.0610			7
		B_5	0.391	0.0762			5
C	0.608	C_1	0.435	0.2645	6.204	$0.033 < 0.1$	1
		C_2	0.161	0.0979			2
		C_3	0.044	0.0268			10
		C_4	0.147	0.0894			4
		C_5	0.118	0.0717			6
		C_6	0.096	0.0584			8
D	0.141	D_1	0.650	0.0917	4.174	$0.065 < 0.1$	3
		D_2	0.089	0.0125			16
		D_3	0.199	0.0281			9
		D_4	0.064	0.0090			18

impact on the construction progress of power supply and distribution project and is the absolute factor that should be paid the most attention to. C_2 10 kv high voltage switchboard installation takes the second place, D_1 electrical acceptance and single commissioning takes the third place, and C_4 low voltage switchboard and DC panel installation take the fourth place, but these three have more overlapping weights and have a similar impact on the progress. They are all factors that should be paid attention to. The emphasis on electrical acceptance, unit commissioning and installation of low-voltage PDC and DC panel should not be lower than that of installation of 10 kv high-voltage PDC. The weight of B_5 power station equipment foundation construction is the fifth, and the weight of C_5 high-voltage protection and metering system installation is the sixth. There are many overlapping parts between the two, which should have the same impact on the schedule. Therefore, in the risk management of the entire construction schedule of the power supply and distribution project, the most important factors should be the control of materials and equipment procurement, production and arrival, installation of 10 kv high-voltage distribution cabinet, electrical acceptance and single commissioning, installation of low-voltage distribution cabinet and DC panel, equipment foundation construction of power station and installation of high-voltage protection metering system. There are many overlapping parts of weight between some factors, so it is not simple to sort a single process, which should be dealt with comprehensively.

In short, according to the final calculation results of the MCS-AHP model and the AHP model, the following conclusions can be drawn:

(1) The results calculated using the traditional AHP are consistent with those calculated by MCS-AHP, so the effectiveness of the improved AHP can be verified.
(2) The difference between the two methods is that the result calculated by traditional AHP is a specific value, while the result calculated by MCS-AHP is an interval. It can be concluded that risk factors are not simply ranked to judge the degree of impact on the schedule risk of power supply and distribution projects, and there may be much overlap between some factors. Therefore, the influence relationship between the two factors on the schedule should be considered comprehensively. If the traditional AHP is only used to single rank the schedule risk of power supply and distribution projects, It may ignore the degree of influence of some factors on the construction schedule. Therefore, the improved MCS-AHP is adopted to study the construction schedule risk of power supply and distribution engineering, which can effectively reduce the subjectivity and make the calculated weights and the relationship between them more scientific.

4 Conclusion

4.1 Conclusion

The following conclusions were drawn from a study of construction schedule risk factors for power supply and distribution projects.

(1) A complete evaluation index system for schedule risk management of power supply and distribution projects is constructed by determining 4 criterion layers and 19-factor layers to manage the schedule risk of this project in multiple dimensions and levels. With the fuzzy hierarchical analysis method as the general framework, the average distribution interval is used instead of specific values when constructing the two-two comparison matrix to reduce the subjective probability as well as to reduce the risk of people's fuzzy thinking during investigation and evaluation, which effectively solves the problem of greater subjectivity in the traditional fuzzy hierarchical analysis method, thus avoiding the influence on the results of the construction schedule risk evaluation index system of power supply and distribution projects and making the schedule The risk management is more scientific and reasonable.
(2) Taking a power-supporting Phase II project (construction) in Guangdong Province as an example, the results show that we should focus on controlling the procurement of materials and equipment, production and arrival of goods, installation of 10 kv high voltage distribution cabinet, electrical acceptance and single commissioning, installation of low voltage distribution cabinet and DC screen, equipment foundation construction of power station and installation of high voltage protection metering system. The results of schedule risk analysis are consistent with reality. The MCS-AHP model constructed has great significance for the risk analysis of power engineering and provides a reference for the risk analysis of other projects.

4.2 Limitations and prospects

Although this paper has made certain research results on the research of construction schedule risk management of power supply and distribution engineering, due to its own theoretical knowledge is not perfect. Therefore, there are limitations and shortcomings in the research results, which are manifested in the following aspects.

(1) Since the actual construction process of power supply and distribution engineering projects is more complex and changeable than the theoretical construction process, and there are certain other risk factors, the construction schedule evaluation index system of power supply and distribution engineering constructed is relatively rough and not comprehensive enough. In the future, we can consider adding some other dynamic risk factors to make the evaluation index system more perfect.
(2) This paper mainly adopts the Monte Carlo simulation method to improve the traditional AHP, using intervals instead of specific values to reduce the subjectivity of the evaluation, but does not consider that certain risk factors may affect each other in connection with each other, so in the future, we should adopt some quantitative methods to study the coupling relationship between risk factors to optimize the evaluation model, and can also adopt some newer research methods for power engineering projects.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding authors.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

HX was employed by the company of State Grid Jiangxi Electric Power Co., Ltd.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenrg.2022.1104007/full#supplementary-material

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