

Research on Digital-Intelligent Maintenance Capability Evaluation Method Based on Cloud Model

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Abstract: To evaluate the digital-intelligent maintenance capability, an evaluation index system is constructed based on cloud model theory from five dimensions: standard system development, technical foundation, production regulation and control, quality management and control, and digital-intelligent construction. A four-level evaluation criterion is proposed. The analytic hierarchy process (AHP) and correlation coefficient method are combined through game theory to determine the weights of evaluation indicators. The cloud model is adopted to calculate the correlation degree between evaluation indicators and evaluation grades, thereby establishing an evaluation model for digital-intelligent maintenance capability. Operational data from a maintenance institution are substituted into the proposed model to assess its digital-intelligent maintenance capability. The results verify that the proposed evaluation method is stable and reliable, and the research findings can provide effective technical support for the evaluation of digital-intelligent maintenance capability.

Keywords: Maintenance Capability; Digital-Intelligence; Evaluation; Cloud Model

1. Introduction

With the advent of the intelligent era, the digital-intelligent transformation of maintenance has become an irresistible general trend. Various intelligent maintenance scenarios are being continuously realized, including knowledge-driven fault prediction and preventive maintenance, intelligent fault diagnosis and maintenance scheme recommendation, dynamic intelligent scheduling and optimization based on real-time data, intelligent work order execution monitoring and quality inspection assisted by multimodal data, intelligent material demand forecasting and inventory optimization strategy generation, as well as maintenance support agents with auxiliary decision-making and collaborative capabilities^[1]. As a vital means to test the effectiveness of the digital-intelligent transformation of equipment repair institutions, the evaluation of digital-intelligent maintenance capability can effectively identify problems and deficiencies, practically promote the formation and improvement of their digital-intelligent maintenance capabilities, and thereby create greater benefits.

The evaluation models adopted in existing evaluation methods mainly include principal component analysis, fuzzy comprehensive evaluation, data envelopment analysis (DEA), ADC model, artificial neural network, etc.^[2]. Each of the above methods has its own characteristics; however, they fail to fully consider the randomness of evaluation indicator values and have relatively obvious limitations in handling indicator data with complex dimensions. The cloud model evaluation method can realize relevant model transformation by calculating algorithmic parameters such as expectation, entropy, variance and hyper-entropy of indicator values. It can well reveal the internal correlation between randomness and fuzziness, and achieve effective evaluation of the digital-intelligent maintenance capability of equipment repair institutions.

2. Design of Evaluation Method

An evaluation model for digital-intelligent maintenance capability is established. Centered on digital-intelligent maintenance capability, evaluation indicators are selected, and an evaluation index system is constructed from five dimensions: standard system development, technical foundation, production regulation and control, quality management and control, and digital-intelligent construction. The cloud model is adopted to carry out comprehensive evaluation, as illustrated in Figure 1.

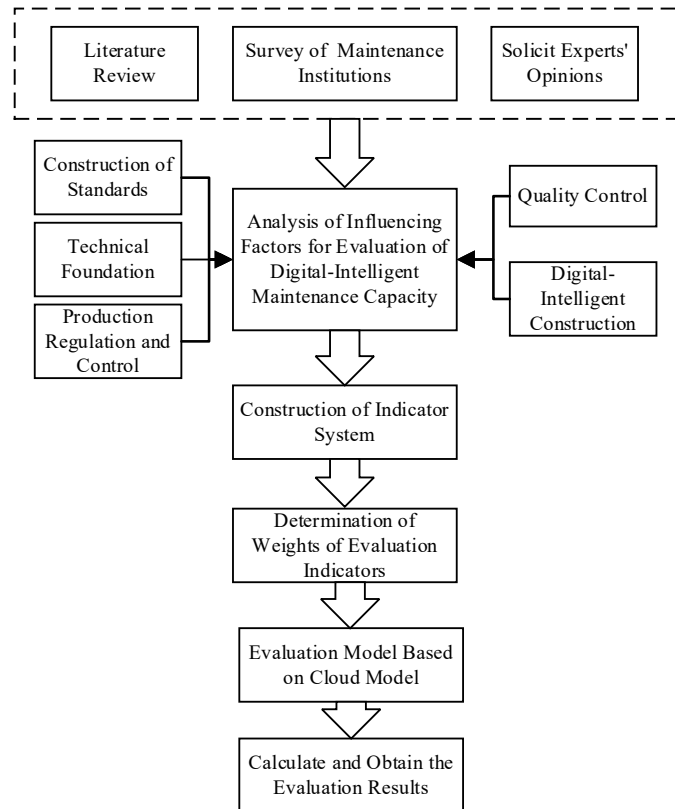


Fig.1 Evaluation process model of maintenance support capability of synthetic brigade

Figure 1 shows the process model for evaluating the digital-intelligent maintenance capability of equipment repair, whose procedures are divided into four steps: first, construct the evaluation index system by analyzing the influencing factors of digital-intelligent maintenance capability evaluation; second, calculate the weights of evaluation indicators with the combined weighting method integrating AHP and entropy weight method; third, establish an evaluation model based on the cloud model to implement assessment; fourth, compute the comprehensive evaluation results.

3. Construction of Evaluation Index System for Digital-Intelligent Maintenance Capability

The construction of the evaluation index system for digital-intelligent maintenance capability serves as the prerequisite and foundation for carrying out evaluation work^[3]. Constructing the index system is a sophisticated process that involves fully analyzing digital-intelligent maintenance activities, thoroughly dissecting the influencing factors of digital-intelligent maintenance capability, and complying with relevant construction principles. The scientificity and rationality of the evaluation index system directly determine the accuracy and objectivity of evaluation results. By referring to relevant literature and adhering to the principles of scientificity, completeness, systematicness and independence, the basic framework for constructing the evaluation index system of digital-intelligent maintenance capability is formulated, as shown in Figure 2.

Based on the above framework, this study draws on previous practical experience of maintenance capability evaluation, relevant regulations, maintenance capability evaluation guidelines and other documents. In-depth communications are conducted with relevant equipment repair institutions, and opinions from experts of research institutes and repair organizations are solicited. On this basis, evaluation indicators are selected from the following five dimensions^[3].

3.1 Standard System Development

It mainly refers to the development and implementation of full-process standards for maintenance businesses within equipment repair institutions, covering three categories of standards: technical standards such as coding of technical information for maintenance objects, technical indicator monitoring and maintenance data specifications; management standards including institutional

frameworks, responsibility division and approval procedures; operational standards like work procedures, tool usage specifications and staff conduct codes. The selected secondary indicators cover the status of technical standards, management standards and operational standards.

3.2 Basic Technical Level

It represents the fundamental technical capacity of equipment repair institutions to conduct maintenance in accordance with process task requirements, including structured, standardized and logically closed-loop management of maintenance technical documents; efficient application and optimization of maintenance technologies such as output of maintenance technical specifications, standard-compliant production and standardized quality inspection; as well as the effectiveness of inheritance, accumulation, research and innovation of maintenance technologies. The selected secondary indicators include technical management capability, technical application capability and technical innovation capability.

3.3 Production Regulation & Control Capability

It is the core execution capacity of equipment repair institutions to convert maintenance demands into maintenance deliverables, including overall planning of complex maintenance tasks, efficient adjustment of maintenance schemes and scientific production scheduling, as well as efficient control of material allocation, process connection and task execution throughout the whole maintenance process. The selected secondary indicators consist of overall task planning capability, dynamic scheduling capability and on-site control capability.

3.4 Quality Management & Control Capability

It refers to the capacity of equipment repair institutions to govern and control quality risks across the full maintenance workflow, including clear definition of quality responsibilities, traceability and accountability for all maintenance links, strict implementation of effective quality inspection and real-time monitoring throughout maintenance, and collaborative improvement of all elements in quality management. The selected secondary indicators include quality responsibility management capability, whole-process monitoring capability and quality collaborative improvement capability.

3.5 Digital-Intelligent Construction Level

It denotes the capacity of equipment repair institutions to advance digital-intelligent upgrading of the entire maintenance workflow and realize intelligent transformation of maintenance businesses driven by maintenance knowledge, covering integration between maintenance businesses and information systems, data-driven maintenance processes, and the application of intelligent maintenance scenarios. The selected secondary indicators involve informatization level, digitalization level and intellectualization level.

The complete evaluation index system for digital-intelligent maintenance capability is illustrated in Figure 3.

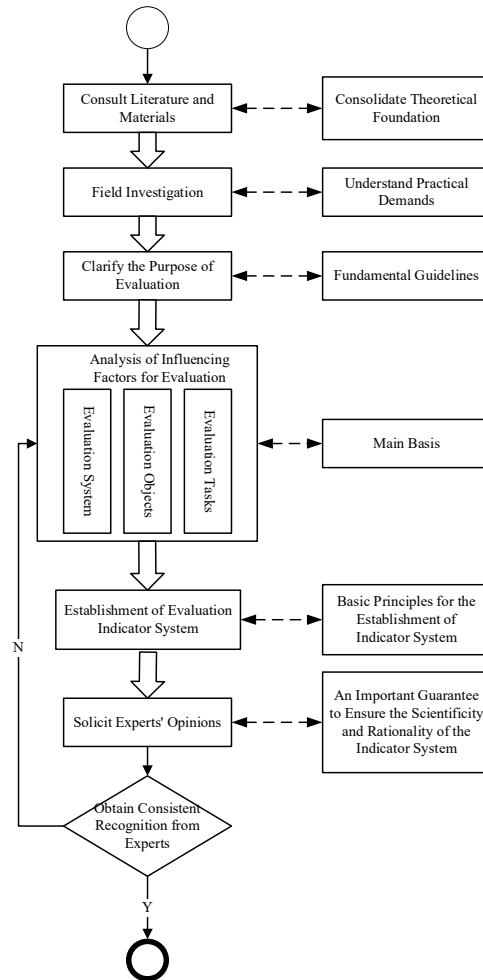


Fig.2 Thoughts on the construction of evaluation index system

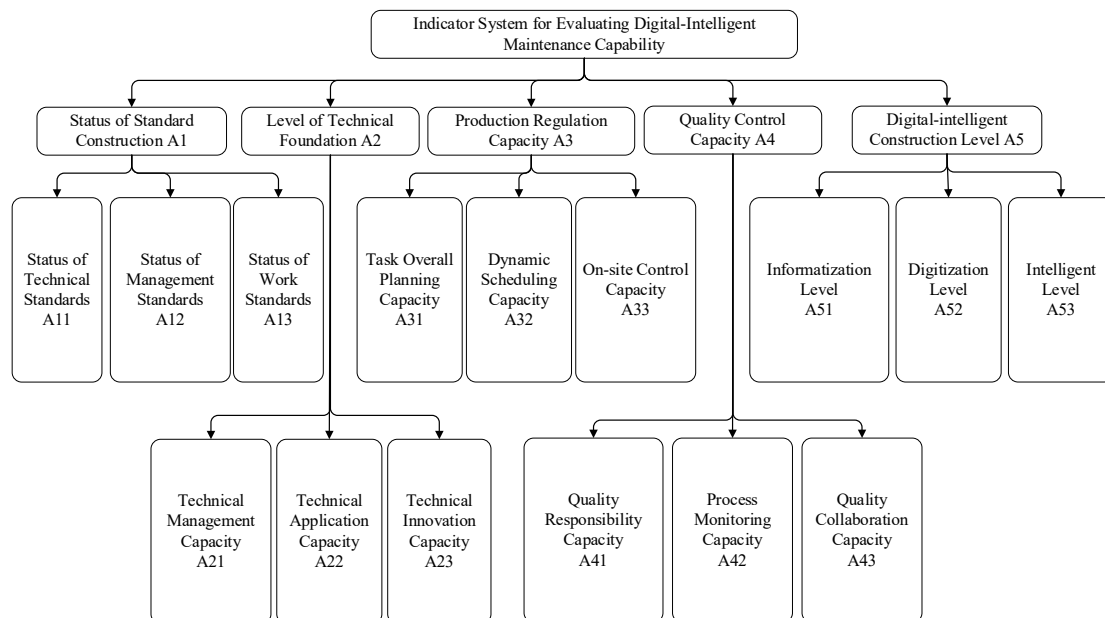


Fig.3 Evaluation Index System of Digital-Intelligent Maintenance Capacity

4. Weight Calculation for Evaluation Indexes

In view of the subjectivity of influencing factors, this paper adopts the Analytic Hierarchy Process

(AHP) to calculate subjective weights. In accordance with the numerical relationships among indicators, the entropy weight method is used to obtain objective weights. Afterwards, taking minimum deviation as the objective, a game theory algorithm is introduced for combined weighting^[4], so as to improve the scientificity and reliability of indicator weights.

4.1 Calculation of Subjective Weights via AHP

The AHP method is the most classic, convenient and practical subjective weighting method. It generally adopts the 1–9 scaling method to construct a relational matrix of pairwise evaluation indicators. The indicator weights are determined by calculating the maximum eigenvector, and the rationality of the values is verified through the consistency test of the judgment matrix. The square root method or summation method can be used to calculate the maximum eigenvalue and eigenvector of the judgment matrix; this paper selects the summation method^[5]. The brief calculation steps of the normalized summation method are as follows:

(1) Normalize each column of the judgment matrix, i.e.,

$$\bar{a}_{ij} = a_{ij} / \sum_{k=1}^n a_{kj}, i, j = 1, 2, \dots, n \quad (1)$$

(2) Sum the elements of the newly generated judgment matrix row by row, i.e.,

$$\bar{w}_i = \sum_{j=1}^n \bar{a}_{ij}, j = 1, 2, \dots, n \quad (2)$$

(3) Normalize vector $\bar{w}_i = (\bar{w}_1, \bar{w}_2, \dots, \bar{w}_n)^T$, i.e.,

$$w'_i = \bar{w}_i / \sum_{j=1}^n \bar{w}_j, i = 1, 2, \dots, n \quad (3)$$

The obtained vector $w' = (w'_1, w'_2, \dots, w'_n)^T$ is the required eigenvector.

(4) The maximum eigenvalue is

$$l_{max} = \sum \frac{(Bw')_i}{nw'_i} \quad (4)$$

where: $(Bw')_i$ represents the i-th element of vector Bw' .

The construction of judgment matrix and consistency test method have been elaborated in relevant literatures, so they will not be repeated in this paper.

4.2 Calculation of Objective Weights

The entropy weight method determines indicator weights based on indicator entropy values, and its specific steps are as follows:

Let the set of evaluation objects be $\{A_i\} (i=1, 2, \dots, m)$, the set of indicators be $\{X_j\} (j=1, 2, \dots, n)$, and x_{ij} denote the raw value of the J-th indicator for the I-th evaluation object.

(1) Calculate the standardized value of the I-th evaluation object under the J-th indicator:

$$P_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (5)$$

(2) Calculate the entropy value e_j of the J-th indicator:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln p_{ij} \quad (6)$$

(3) Calculate weight α_j of the J-th indicator:

$$\alpha_j = \frac{1 - e_j}{\sum_{j=1}^n (1 - e_j)} \quad (7)$$

4.3 Combined Weighting Based on Game Theory

At present, common methods for combined weighting include the multiplicative synthesis method and the linear weighting method. The multiplicative synthesis method multiplies the corresponding values of multiple obtained weights and then normalizes the results to acquire combined weights. However, this method has certain drawbacks: it widens the gaps among evaluation objects with low performance while narrowing the gaps among those with high performance, which may fail to conform to reality. The linear weighting method assigns artificial combination coefficients to multiple weights for weighting combination, and the determination of combination coefficients is highly subjective. Therefore, this paper adopts the idea of game theory and introduces a game model. With the goal of minimizing deviations, the two types of obtained weights are optimally combined to generate the combined weights^[5].

The AHP method and entropy weight method are used to calculate the subjective weight w_i' and objective weight w_i'' respectively, and then the game theory game model algorithm is adopted to compute the combined weight.

(1) L weighting methods are adopted to calculate the weights of evaluation indicators, and the resulting weight vectors are denoted as $w_k = (w_{k1}, w_{k2}, \dots, w_{kl})$. Any linear combination of the L vectors is defined as $w = \sum_{k=1}^L a_k w_k^T$. To obtain the optimal combined weight w^* , optimization of the linear combination is required, for which a game model is introduced as follows:

$$\min \left\| \sum_{k=1}^L a_k w_k^T - w_k \right\| \quad (8)$$

(2) Based on the differential properties of matrices, the system of linear equations for the optimized derivative condition is derived as follows:

$$\begin{bmatrix} w_1 w_1^T & \cdots & w_1 w_L^T \\ \vdots & \vdots & \vdots \\ w_L w_1^T & \cdots & w_L w_L^T \end{bmatrix} \begin{bmatrix} a_1 \\ \vdots \\ a_L \end{bmatrix} = \begin{bmatrix} w_1 w_1^T \\ \vdots \\ w_L w_L^T \end{bmatrix} \quad (9)$$

(3) Normalize the coefficient a obtained from the above formula to solve for a^* , and the final combined weight w^* is expressed as:

$$w^* = \sum_{k=1}^L a_k^* w_k^T \quad (10)$$

5. Construction of Evaluation Model for Digital-Intelligent Maintenance Capacity

5.1 Cloud Model

The cloud model converts qualitative descriptions into quantitative ones via mathematical expressions, which can effectively address the fuzziness and randomness of evaluated objects. A normal cloud is represented by a triple (Ex, En, He) . The expectation Ex stands for the central value of the membership cloud; entropy En describes the uncertainty of attribute concepts and reflects both fuzziness and randomness; hyper-entropy He measures the uncertainty of entropy and characterizes the randomness of samples^[6].

Calculation steps of the cloud model:

- (1) Construct the standard cloud and determine the cloud model parameters E_x , E_n , H_e , as well as the required number of cloud droplets N ;
- (2) Generate the normal random number x_i according to the indicator values;
- (3) Calculate the cloud correlation membership degree, as shown in Equation (11).

$$k_i = \exp\left[-\frac{(x_i - Ex)^2}{2(E_n')^2}\right] \quad (11)$$

- (4) After determining the digital characteristic parameters of the cloud model, its cloud graph can be generated in accordance with the cloud model algorithm.

5.2 Construction of Standard Cloud

The grade boundaries of each evaluation indicator are treated as a dual-constraint interval $[c_{\min}, c_{\max}]$. Taking full account of the fuzziness and randomness of constrained indicator values, the interval is moderately extended to calculate the characteristic parameters of the normal cloud model.

$$E_x = \frac{c_{\max} + c_{\min}}{2} \quad (12)$$

$$E_n = \frac{c_{\max} - c_{\min}}{6} \quad (13)$$

$$H_e = S \quad (14)$$

Where: S is a constant adjustable according to the specific conditions of evaluation indicators, and $S = 1.0$ is adopted in this paper.

5.3 Construction of Clouds for Evaluation Indicators

After normalizing the indicator values, the cloud characteristic parameters of evaluation indicators are calculated by Formulas (15)–(18).

$$E_{x,j} = \frac{1}{n} \sum_{i=1}^n x_{ij} \quad (15)$$

$$E_{n,j} = \frac{1}{n} \sqrt{\frac{\pi}{2}} \sum_{i=1}^n |x_{i,j} - E_{x,j}| \quad (16)$$

$$S_j^2 = \frac{1}{n-1} \sum_{i=1}^n (x_{i,j} - E_{x,j})^2 \quad (17)$$

$$H_{e,j} = \sqrt{S_j^2 - E_n^2} \quad (18)$$

Where: $E_{x,j}$, S_j^2 , $E_{n,j}$, $H_{e,j}$ respectively represent the sample expectation, entropy, variance and hyper-entropy of the J-th indicator; x_{ij} denotes the I-th value of the J-th indicator.

5.4 Construction of Comprehensive Evaluation Cloud

The comprehensive evaluation cloud can be calculated by combining the combined weight values and cloud characteristic parameters of evaluation indicators via Formula (19). The final evaluation result cloud is obtained by comparison with the standard cloud.

$$\begin{cases} E_x = \sum_{i=1}^n E_{x,j} w_j \\ E_n = \sqrt{\sum_{i=1}^n (E_{n,j}^2 w_j)} \\ H_e = \sum_{i=1}^n H_{e,j} w_j \end{cases} \quad (19)$$

6. Case Analysis

Taking an maintenance institution as the evaluation object, this paper evaluates the practical operation of its digital-intelligent maintenance business in 2025. After collecting specific full-year operational data, standardization processing is carried out. Meanwhile, 10 experts are invited to score each evaluation indicator in combination with relevant standards, and the values of indicators are shown in Table 1.

Tab.1 Evaluation index score

Index	Expert1	2	3	4	5	6	7	8	9	10
W_{11}	94	89	84	95	75	83	81	73	88	77
W_{12}	73	88	80	71	71	88	76	77	85	77
W_{13}	73	74	71	73	72	90	81	75	87	83
W_{21}	90	82	86	85	89	89	83	85	87	86
W_{22}	93	92	85	89	92	97	86	88	85	86
W_{23}	75	83	75	76	75	77	81	77	75	84
W_{31}	83	81	85	86	79	79	89	85	78	87
W_{32}	79	72	90	87	70	90	80	73	74	82
W_{33}	90	80	91	93	80	88	82	82	81	90
W_{41}	94	80	84	88	85	94	87	85	82	87
W_{42}	69	74	84	81	64	70	73	80	83	80
W_{43}	82	86	72	86	71	81	87	80	80	76
W_{51}	86	87	92	89	90	83	83	85	87	89
W_{52}	89	84	94	92	84	91	84	83	86	87
W_{53}	70	79	74	72	74	90	78	85	86	77

6.1 Calculation of Combined Weights

Based on the established evaluation indicator system, ten experts in the field of maintenance are invited to score the pairwise importance of indicators, and the Analytic Hierarchy Process (AHP) is adopted to calculate the subjective weight w' of evaluation indicators. The entropy weight method is used to compute the objective weight w'' based on the scores of evaluation indicators provided by the ten experts. Afterwards, game theory is applied to obtain the combined weight w , and the detailed results are listed in Table 2. The weight distribution is illustrated in Figure 4. It can be seen from Figure 4 that there exists a certain discrepancy between subjective weights and objective weights, while the

game-based combined weights reconcile the differences between subjective and objective weights.

Tab.2 Evaluation index weight value

Index	w'	w''	w
W_{11}	0.2272	0.0510	0.1127
W_{12}	0.0601	0.0739	0.0691
W_{13}	0.1431	0.0860	0.1060
W_{21}	0.0112	0.0419	0.0312
W_{22}	0.0513	0.0868	0.0744
W_{23}	0.0196	0.1418	0.0990
W_{31}	0.0687	0.0567	0.0609
W_{32}	0.0113	0.0591	0.0424
W_{33}	0.0287	0.0858	0.0658
W_{41}	0.1280	0.0464	0.0750
W_{42}	0.0538	0.0369	0.0428
W_{43}	0.033	0.0448	0.0407
W_{51}	0.0178	0.0589	0.0445
W_{52}	0.0898	0.0736	0.0793
W_{53}	0.0565	0.0565	0.0565

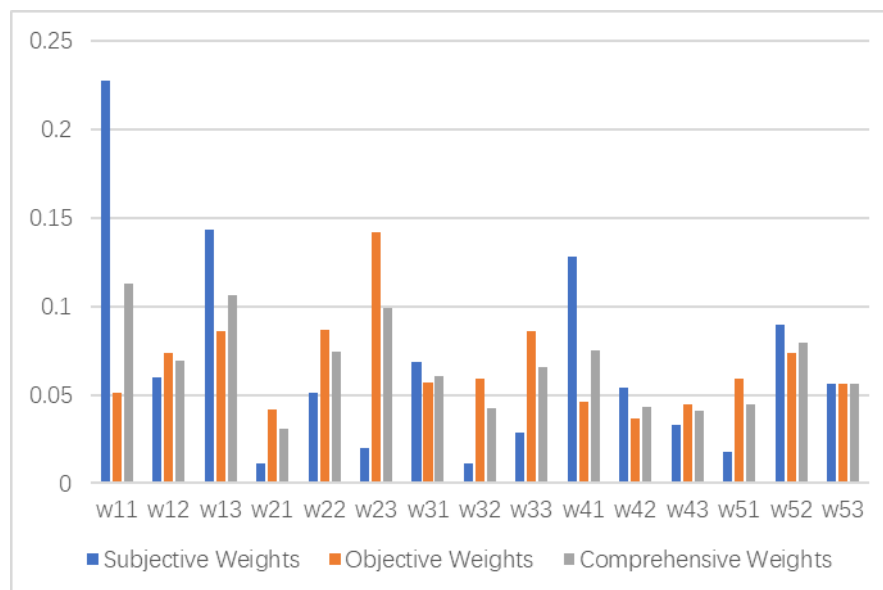


Fig.4 Weight Distribution of Evaluation Indicators for Digital-Intelligent Maintenance Capability

6.2 Determination of Standard Evaluation Clouds

The evaluation grades of digital-intelligent maintenance capacity are divided into four levels: Grade I, II, III and IV, corresponding to Excellent, Good, Medium and Poor. The value intervals of each grade are set as (80,100], (60,80], (40,60] and [0,40] respectively. The standard normal cloud model of each evaluation indicator (i.e., the grade standard cloud model of evaluation indicators) can be obtained through Formulas (10)–(12). The evaluation grades and corresponding standard clouds are presented in Table 3.

Tab.3 Evaluation levels and standard clouds

Grade	Value Range	Standard Cloud
I	(80,100]	(90,3.33,1.0)
II	(60,80]	(70,3.33,1.0)
III	(40,60]	(50,3.33,1.0)
IV	[0,40]	(20,6.67,1.0)

With the normal cloud generator, the parameters of the standard cloud models in Table 3 are imported and the number of cloud droplets is set to 3000 to generate the standard cloud diagram, as shown in Figure 5. In Figure 5, red, blue, yellow and green represent the standard clouds of Grade I to Grade IV respectively.

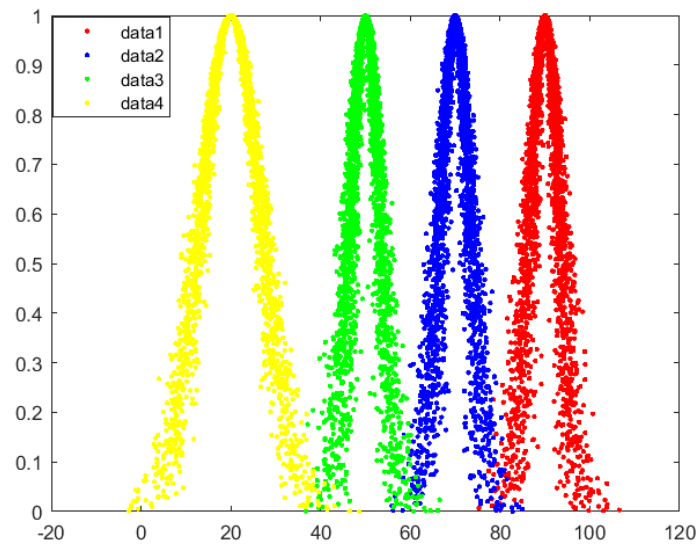


Fig.5 Standard Cloud Diagram for Evaluation Grades of Digital-Intelligent Maintenance Capacity

6.3 Determination of Evaluation Indicator Clouds

The cloud parameters of each evaluation indicator are calculated according to Formula (11) and Formulas (15)–(18), and the calculation results are shown in Table 4.

Tab.4 Evaluation index cloud digital characteristic parameters

Index	$E_{x,j}$	$E_{n,j}$	$H_{e,j}$
W_{11}	83.9	7.44	4.96
W_{12}	78.6	2.37	4.11
W_{13}	77.9	2.50	5.96
W_{21}	86.2	0.96	2.57
W_{22}	89.3	1.48	2.44
W_{23}	77.8	1.29	0.78
W_{31}	83.2	1.39	1.84
W_{32}	79.7	2.73	1.40
W_{33}	85.7	1.88	0.82
W_{41}	86.6	1.67	3.93
W_{42}	75.8	2.48	2.52
W_{43}	80.1	2.07	1.90
W_{51}	87.1	1.08	1.25
W_{52}	87.4	1.42	0.97
W_{53}	78.5	2.40	2.78

6.4 Determination of Comprehensive Evaluation Cloud

Substitute each indicator cloud and combined weights into Formula (19), and the comprehensive cloud parameters $E_x = 82.52$, $E_n = 6.62$, $H_e = 2.58$ for maintenance support capacity evaluation can be obtained, based on which the cloud diagram is drawn as shown in Figure 6. It can be seen from Figure 6 that the black cloud represents the comprehensive evaluation cloud of maintenance support capacity of the brigade. By comparing it with the standard clouds, the evaluation grade of its digital-intelligent maintenance capacity is Grade I.

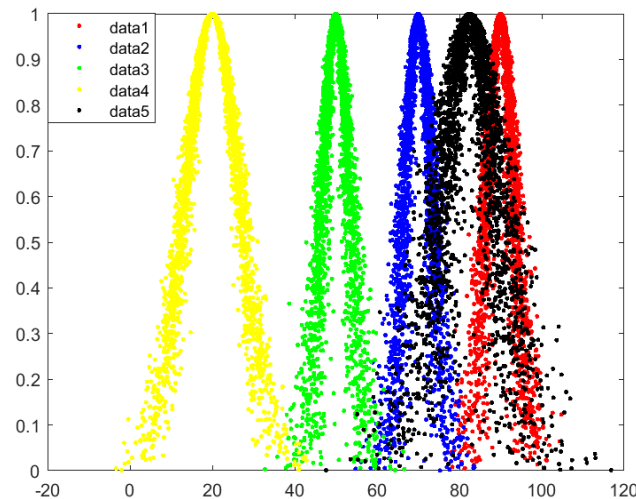


Fig.6 Comprehensive Evaluation Cloud Diagram of Digital-Intelligent Maintenance Support Capacity

7. Conclusion

In response to the development demand for the digital-intelligent transformation of current maintenance, this paper constructs a complete evaluation system for digital-intelligent maintenance capacity. It integrates the Analytic Hierarchy Process (AHP) and entropy weight method, and adopts game theory for optimization to obtain combined weights that balance experts' subjective experience and objective data information. The normal cloud model is introduced to quantify the fuzziness and randomness in the evaluation process. By establishing graded standard clouds, indicator clouds and a comprehensive evaluation cloud, visual and accurate assessment of digital-intelligent maintenance support capacity is realized.

Case analysis results demonstrate that the proposed evaluation method can effectively distinguish different evaluation grades and objectively reflect the actual operation level of digital-intelligent maintenance businesses in equipment repair institutions. It can provide a feasible technical approach and reference basis for maintenance organizations to conduct self-assessment of their capacity and higher authorities to carry out inspection and evaluation.

Future research can further expand evaluation samples, improve the dynamic update mechanism of indicators, optimize cloud model parameters combined with real-time operation and maintenance big data, and continuously enhance the applicability and reliability of the evaluation system for digital-intelligent maintenance capacity.

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