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Evaluation Model of Control System Quality Based on Multi-Level Gray Comprehensive Evaluation Method

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Abstract: In order to evaluate the quality service of control system operation, the control system quality evaluation index system is established and multi-level gray comprehensive evaluation method combined by AHP and gray comprehensive evaluation method is used to comprehensively evaluate. The analysis of the case shows that this method is feasible and maneuverable in practice.

Key words: Control system, quality evaluation, gray comprehensive evaluation method, AHP

INTRODUCTION

The civil aviation industry occupies an increasingly important position in today's transportation and one of the most important tasks is to protect the safety of civil aviation operations. Therefore, evaluating the quality of control system to improve the control system operation level can be a reference for the regulated sector.

Relating to the control system operation quality evaluation, there has been some research and application results. Domestic aspects, In order to evaluate the quality service of control system operation Zongping *et al.* (2012a) established the initial control system quality evaluation index system. Firstly, the principal component analysis was used to eliminate the index that exist correlation and information overlaps, again classification was used to iterative thought of clustering analysis, then the final control system quality evaluation index system was obtained. On that basis, comprehensive evaluation of the control quality system with matter-element was analyzed (Cheng *et al.*, 2009). And they established the quality evaluation indicator system of control system in terms of control system dynamic operation process, used the membership function of fuzzy mathematics to process each type of indicator and evaluated comprehensively. Then, the combination forecast model composed by exponential smoothing model and grey forecast method was used to predict the future trend of quality indicator (Dong and Shao, 2010). Jiangping *et al.* (2012a) proposed an evaluation method for operation performance of terminal control at a single-runway airport by integrating principal component analysis and K-means cluster analysis. The Chengdu terminal area with a single runway was taken as an example of application of the proposed method. According to expert questionnaires, a three-layer index system was prepared, from which 20 indexes as independent as possible were chosen as raw data for principal component analysis (Gao *et al.*, 2009). Jiangping *et al.* (2012a, b) presented that various factors involved in operation performance of air traffic control in terminal area and improvement of single aspect could make some impact on other aspects. Therefore, effective strategies for optimization of operation performance should be after integrated evaluation. To improve integrated evaluation for operation performance of air traffic control in terminal area, research on evaluation factors was fulfilled based on factorial analysis (He, 2011). In light of the incomplete previous air traffic control system, Jian *et al.* (2011) put forward an accurate evaluation, which was made from implicit and explicit aspects on the safety status of the air traffic control system. To solve the problem of uncertainty in air traffic management safety assessment, Songbing *et al.* introduced evidence theory to the assessment and model-based evidence theory was established to solve the uncertainty problem of the evaluation process (Jiangping *et al.*, 2012a). Establishing hazard severity evaluation indicator with full consideration of operation characteristics of ATM system, Yuan Le-ping *et al.* assessed the severity of identified hazard by using the fuzzy comprehensive evaluation theory (Jiangping *et al.*, 2012b). Nie *et al.* (2009) proposed that based on fuzzy mathematics, Multi-level fuzzy comprehensive evaluation model was established to evaluate the safety performance of Air

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Traffic Management (Jingfang *et al*., 2009). From the information economics perspective, the information asymmetry problems existing in the process of safety assessment were analyzed for ATM and the management patterns of higher education evaluation, quality certification and safety assessment in other industries were researched. Then, a third party assessment for ATM safety assessment was proposed by Yonggang and Shiwei (2011) based on the study of Jun and Zhiping (2003).

Vismari and Camargo Jr. (2005, 2008) presented a risk assessment methodology, preliminary proposed in, which is the fusion of the "absolute" and the "relative" risk assessment methods adopted by the International Civil Aviation Organization (Kai, 2010) and they also presented a method that permits the assessment of the impact of new technologies on the system safety levels (Nakamatsu *et al*., 2002). Nakamatsu *et al*. (2002) proposed a theoretical framework for logical safety verification for air traffic control based on a paraconsistent logic program called an Extended Vector Annotated Logic Program with Strong Negation (Nie *et al*., 2009).

Control system quality evaluation involves many factors, including qualitative factors and quantitative factors, which should comprehensively measure various factors, reduce the influence of artificial factors and establish a more objective and comprehensive evaluation method. At present, there are many about multi-objective evaluation method, such as Analytic Hierarchy Process (AHP) (Songbin *et al*., 2006), fuzzy comprehensive evaluation method (Tian *et al*., 2010; Vismari and Camargo Jr., 2005, 2008), Principal Component Analysis (PCA) (Vismari and Camargo Jr., 2005) and so on. But these methods all have their own deficiencies.

This study attempts to start from the dynamic process of control system, establishes the indicator system of quality control system and plans to adopt the multi-level gray comprehensive evaluation method composed by AHP and gray comprehensive evaluation to assess control system operation quality. Firstly, index weight is determined by AHP, then evaluation gray class is determined by Gray comprehensive evaluation Method in accordance with the basis of sample matrix, again gray evaluation coefficient, weight vector and weight matrix are calculated. Finally, comprehensive evaluation of the indicators is made.

BASIC THEORY OF GRAY EVALUATION

In cybernetics, people use "black" to present information unknown, use "white" to present information known completely, use "gray" to present some information known and other information unknown. Accordingly, the system of information which is not fully known is called gray system. Through the development of ten years, gray system theory has been established to structural system of a new subject. Main contents include that theory system is based on gray hazy set, analysis system is relied on gray relational space, methodology system is based on gray sequence generated, technology system is on the subject of analysis, assessment, modeling, prediction, decision-making, control and optimize. The gray evaluation method is discussed following.

Grey evaluation is based on the theory and method of gray system. To a system or subordinate factors in a certain period of the state, against the predetermined goal, the evaluation and descriptions of a half qualitative and quantitative are made through system analysis. On a higher level, the comparison of the concepts and categories is formed to the comprehensive effect and the overall level of the system. In most cases, the state of the system is expressed by a number of indicators or a set of data. So, this method is called gray comprehensive evaluation.

Gray evaluation method (Yonggang and Shiwei, 2011) utilizes grey theory to make distributed information of experts processing as a description of the weight vector of different gray class level. On that basis, its single-value is processed. Comprehensive evaluation value of evaluation object is obtained. Then optimization selection between evaluation object is carried to improve the scientificalness and accuracy of evaluation. Among them, the characteristic value of whitening weight function reflects the characteristics of particular gray which is the core of gray class. Generally, grey comprehensive evaluation method includes evaluation object, evaluation index, evaluation category and evaluation target. Evaluation target is only one, which is called single-level gray comprehensive evaluation. Evaluation target is more than one, with higher level of assessment for evaluation target, which is called multi-level gray evaluation.

ESTABLISHING MULTI-LEVEL GRAY COMPREHENSIVE EVALUATION MODEL

The general method of evaluation system usually includes: construct the indicator system, use the appropriate way to deal with the indicator and based on these evaluate comprehensively.

Establishing control system quality evaluation indicator system structure: Through dynamic operation process of the control system, we decompose control system for four operation processes: Tower control, Approach control,

Table 1: Control system quality evaluation index system

Target layer	Primary indicator	Secondary indicator	Third indicator
Control system quality Comprehensive evaluation indicator U	Tower Control U_1	Traffic flow density index X_{11}	Total number of instructions of the controller command to the aircraft X_{111}
			Aircraft runway occupancy time X_{112}
		Control operation safety performance index X_{12}	Aircraft sorties of flight in the traffic pattern at the same time X_{121}
			Go around sorties of landing aircraft caused by ATC X_{122}
		Control operation efficiency performance X_{13}	Flight delay sorties rate X_{131}
			Flight average delay time X_{132}
	Approach Control U_2	Traffic flow density index X_{21}	The same time approach the aircraft sorties X_{211}
			The same time to leave the aircraft sorties X_{212}
		Control operation safety performance index X_{22}	The number of Aircraft conflicts with in the sector X_{221}
			Controller doesn't rectify incorrect aircraft to carry out the instructions X_{222}
		Control operation efficiency performance X_{23}	Control transfer efficiency X_{231}
			The time of Aircraft approach and departure X_{232}
	Area Control U_3	Traffic flow density index X_{31}	Busy time aircraft sorties in a area at the same time X_{311}
			Leisure time aircraft sorties in a area at the same time X_{312}
		Control operation safety performance index X_{32}	Mistakenly command Aircraft flying to artillery district, the prohibited area, dangerous area, the sorties of be corrected before entering yet X_{321}
			Controller doesn't rectify incorrect aircraft to carry out the instructions X_{322}
		Control operation efficiency performance X_{33}	Aircraft flight time in a area X_{331}
			Control transfer efficiency X_{332}
	Flight Service System U_4	Number of missing information X_{41}	Missing content X_{411}
			Missing address X_{412}
		Number of wrongly sending information X_{42}	Wrongly format X_{421}
			Wrongly content X_{422}
			Wrongly address X_{423}

Area control and Flight Service System and establish control system quality indicator system, such as Table 1. The comprehensive evaluation indicator of control system is the comprehensive reflection of control system operation quality. The process of tower control, approach control, area control also consider traffic flow density index, control operation safety performance index and control operation efficiency performance. The three elements can affect control system quality. Therefore, traffic flow density index, control operation safety performance index and control operation efficiency performance are the secondary indicators. Each secondary indicators have several evaluation factors, according to the track data of the automation system, data of radiotelephony communications between controllers and pilots and the keyboard operation data of controllers, extracting the factors that effect on the quality in secondary indicators, as well as decomposing and refining the higher level of indicator, namely third indicators.

Determining indicator weight and evaluation criteria: In order to minimize the influence of subjective factors, the combination of the weighting method, Delphi method and AHP, is used to determine the weight vector of the evaluation indicator.

Making ω_i* be the important degree of indicator i, ω_j* be the important degree of indicator j and r_j be the comparison value of important degree of indicator i relative to indicator j, namely:

$$r_j = \omega_i^* / \omega_j^*$$

Then:

$$\omega_j^* = \begin{cases} \left(1+\sum_{j=2}^{n}\left(\prod_{k=j}^{n} r_k\right)\right)^{-1} & j=n \\ \omega_{j+1}^* r_{j+1} & j=1,2,\ldots,n-1 \end{cases}, \quad \sum_{i=1}^{n}\omega_i = 1$$

Thus, according to the important degree of indicator and proportional to the dimension of ω_i*, the weight of ω_i will be determined.

Scoring criteria of each of indicator can be divided into five grades of excellent, good, medium, poor and worse, which score is also divided into five levels: 5, 4, 3, 2 and 1. Between two adjacent level, the score is 4.5, 3.5, 2.5 and 1.5. Finally, the evaluation score is also divided into five grades: excellent (4.25-5), good (3.5-4.25), medium (2.75-3.5), poor (2-2.75) and worse (1-2).

Establishing evaluation sample matrix and evaluation gray: The evaluation job is carried out by expert group composed by several experts. Set there are p experts participate in the evaluation. The score of evaluation index U_{ijk} given by the number k expert is d_{ijk}. Therefore, evaluation sample matrix is following (Yuan *et al*., 2006):

$$D=\begin{pmatrix} d_{111} & d_{112} & \cdots & d_{11p} \\ \vdots & \vdots & \vdots & \vdots \\ d_{1n_1 1} & d_{1n_1 2} & \cdots & d_{1n_1 p} \\ d_{211} & d_{212} & \cdots & d_{21p} \\ \vdots & \vdots & \vdots & \vdots \\ d_{2n_2 1} & d_{2n_2 2} & \cdots & d_{2n_2 p} \\ \vdots & \vdots & \vdots & \vdots \\ d_{m11} & d_{m12} & \cdots & d_{m1p} \\ \vdots & \vdots & \vdots & \vdots \\ d_{mn1} & d_{mn2} & \cdots & d_{mnp} \end{pmatrix}$$

The number of gray class is e, with its gray number and whitenization weight function as Table 2 (Zhang, 2011).

Calculating grey evaluation coefficient, gray evaluation weight vector and weight matrix: To evaluation index U_{ijk}, the gray evaluation coefficient of the number e evaluation gray class for belongs is as follow (Zongping *et al*., 2012b):

$$X_{ije}=\sum_{i=1}^{p} f_e(d_{ijt})(t=1,2,..,t)$$

The summary gray evaluation coefficient of each evaluation gray class for belongs is:

$$X_{ij}=\sum_{e=1}^{g}(d_{ije})(e=1,2,..,g)$$

To evaluation index U_{ijk}, the gray evaluation weight of the number e evaluation gray class for belongs is r_{ije}:

$$r_{ije}=\frac{X_{ije}}{X_{ij}}, e=1,2,...,g$$

Then gray evaluation weight vector is: $r_{ij}=(r_{ij1}, r_{ij2},\ldots, r_{ijg})$.

Table 2: Gray class, gray number and whitenization weight function

Gray class	Gray number	Whitenization weight function
Excellent (e = 1)	$\otimes_1 \in [5, +\infty]$	$f_1(d_{ijk})=\begin{cases} d_{ijk}/5, & d_{ijk}\in[0,5] \\ 1, & d_{ijk}\in[5,+\infty] \\ 0, & d_{ijk}\notin[0,+\infty] \end{cases}$
Good (e = 2)	$\otimes_2 \in [0, 4, 8]$	$f_2(d_{ijk})=\begin{cases} d_{ijk}/4, & d_{ijk}\in[0,4] \\ 8-d_{ijk}/4, & d_{ijk}\in[4,8] \\ 0, & d_{ijk}\notin[0,8] \end{cases}$
Medium (e = 3)	$\otimes_3 \in [0, 3, 6]$	$f_3(d_{ijk})=\begin{cases} d_{ijk}/3, & d_{ijk}\in[0,3] \\ 6-d_{ijk}/3, & d_{ijk}\in[3,6] \\ 0, & d_{ijk}\notin[0,6] \end{cases}$
Poor (e = 4)	$\otimes_4 \in [0, 2, 4]$	$f_4(d_{ijk})=\begin{cases} d_{ijk}/2, & d_{ijk}\in[0,2] \\ 4-d_{ijk}/2, & d_{ijk}\in[2,4] \\ 0, & d_{ijk}\notin[0,4] \end{cases}$
Worse (e = 5)	$\otimes_5 \in [0, 1, 2]$	$f_5(d_{ijk})=\begin{cases} d_{ijk}, & d_{ijk}\in[0,1] \\ 2-d_{ijk}, & d_{ijk}\in[1,2] \\ 0, & d_{ijk}\notin[0,2] \end{cases}$

Thus, the gray evaluation weight matrix R_{ij} of third evaluation index U_{ijk} is following:

$$R_{ij}=\begin{pmatrix} r_{i1} \\ r_{i2} \\ \vdots \\ r_{ij} \end{pmatrix}=\begin{pmatrix} r_{i11} & r_{i12} & \cdots & r_{i1g} \\ r_{i21} & r_{i22} & \cdots & r_{i2g} \\ \vdots & \vdots & \ddots & \vdots \\ r_{ij1} & r_{ij2} & \cdots & r_{ijg} \end{pmatrix}$$

Comprehensive evaluation: Third indicator U_{ijk} is first evaluated and the evaluation gray class level is assigned in according with high and low level. Each evaluation gray class level numerical value vector I_i is obtained. The evaluation result is $M_{ij} = R_{ij}I_i^T$. Then, secondary index U_{ij} would be evaluated. Each evaluation gray class level numerical value vector I is obtained. Then, Primary index U_{ij} would be evaluated. The result is $N_i = A_iM_i$, $N = (N_1, N_2,\ldots, N_m)^T$. Among them, A_{ij} is the weight vector of third evaluation indicator, A_i is the weight vector of secondary evaluation indicator. Finally the comprehensive evaluation value of evaluation object comes to S = AN. Among them, A is the weight vector of primary evaluation indicator.

Multi-level gray comprehensive evaluation process: The flow chart of Multi-level gray comprehensive evaluation is shown in Fig. 1.

Example analysis: Radiotelephony communications data of air traffic management bureau from January to December in 2010 is used to comprehensively evaluate. The control system quality evaluation index system is as Table 1.

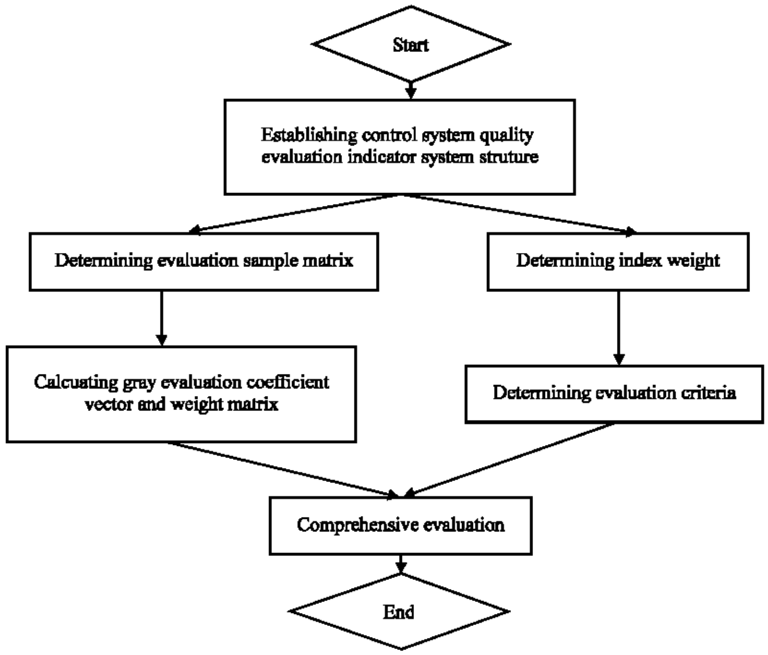

Fig. 1: Flow chart of multi-level gray comprehensive evaluation flow chart

Control system quality evaluation index weight: The primary evaluation indicator of control system quality evaluation is U_1, U_2, U_3, U_4, the analyses of experts consider that U_1, U_2, U_3 and U_4 are in the following order relations:

$$U_2 > U_3 > U_1 > U_4 \Rightarrow \omega_1^* > \omega_2^* > \omega_3^* > \omega_4^*$$

Make $r_2 = \omega_1^*/\omega_2^* = 1.2$, $r_3 = \omega_2^*/\omega_3^* = 1.4$, $r_4 = \omega_3^*/\omega_4^* = 1.4$

So, $\omega_4^* = (1+5.712)^{-1} = 0.1490; \omega_3^* = \omega_4^*\ r_4 = 0.1490 * 1.4 = 0.2086$; $\omega_2^* = 0.2920$; $\omega_1^* = 0.3504$.

Therefore, the weight vector of primary evaluation indicator is A = (0.3504, 0.2920, 0.2086, 0.1490). The weight vector of secondary evaluation indicator can be determined similarly:

$A_1 = (0.4350, 0.3632, 0.2018)$, $A_2 = (0.4382, 0.2247, 0.3371)$, $A_3 = (0.4588, 0.3059, 0.2353)$, $A_4 = (0.5454, 0.4546)$

The weight vector of third evaluation indicator is following:

$$A_{11} = (0.4762, 0.5238),\ A_{12} = (0.4348, 0.5652),\ A_{13} = (0.4000, 0.6000);$$
$$A_{21} = (0.5000, 0.5000),\ A_{22} = (0.6296, 0.3704),\ A_{23} = (0.4167, 0.5833);$$
$$A_{31} = (0.6154, 0.3846),\ A_{32} = (0.6429, 0.3571),\ A_{33} = (0.5263, 0.4737)$$
$$A_{41} = (0.5556, 0.4444),\ A_{42} = (0.2841, 0.3182, 0.3977)$$

Establish evaluation sample matrix: According to the grade standard, control system quality evaluation index should be scored by 5 experts. The evaluation sample matrix D is as follows:

$$D = \begin{pmatrix}
3.5 & 3.0 & 3.5 & 3.0 & 3.0 \\
3.5 & 2.5 & 3.5 & 2.5 & 3.5 \\
3.0 & 3.0 & 3.5 & 3.0 & 2.5 \\
3.5 & 2.5 & 3.0 & 3.5 & 3.0 \\
3.0 & 2.5 & 3.5 & 3.5 & 3.5 \\
3.0 & 3.0 & 3.5 & 3.0 & 3.5 \\
3.5 & 4.0 & 3.5 & 3.5 & 3.5 \\
3.5 & 4.0 & 3.0 & 3.5 & 3.5 \\
3.5 & 3.0 & 2.5 & 2.5 & 3.0 \\
3.5 & 4.0 & 3.0 & 3.5 & 3.0 \\
3.0 & 3.0 & 2.5 & 3.0 & 3.5 \\
3.5 & 3.0 & 2.5 & 3.0 & 3.5 \\
3.0 & 3.5 & 4.0 & 3.5 & 2.5 \\
3.0 & 3.0 & 4.0 & 3.5 & 3.5 \\
3.5 & 3.5 & 3.5 & 3.0 & 4.0 \\
4.0 & 3.5 & 3.0 & 2.5 & 2.0 \\
3.0 & 3.0 & 4.0 & 3.5 & 3.5 \\
3.5 & 3.5 & 3.0 & 4.0 & 4.0 \\
3.0 & 3.0 & 3.5 & 3.5 & 3.5 \\
2.5 & 3.0 & 3.0 & 3.5 & 3.5 \\
3.5 & 3.5 & 3.5 & 3.5 & 3.0 \\
4.0 & 3.0 & 2.5 & 3.5 & 3.5 \\
3.0 & 3.5 & 3.5 & 3.5 & 4.0
\end{pmatrix}$$

Calculate gray evaluation coefficient: For index U_{111}, the evaluation coefficient of evaluation object belongs to the number e gray class is as follow:

When e = 1, $x_{111} = f_1(3.5)+f_1(3.0)+f_1(3.5)+f_1(3.0)+f_1(3.0) = 3.2$
When e = 2, $x_{112} = f_2(3.5)+f_2(3.0)+f_2(3.5)+f_2(3.0)+f_2(3.0) = 4$
When e=3, $x_{113} = f_3(3.5)+f_3(3.0)+f_3(3.5)+f_3(3.0)+f_3(3.0) = 4.667$
When e = 4, $x_{114} = f_4(3.5)+f_4(3.0)+f_4(3.5)+f_4(3.0)+f_4(3.0) = 2$
When e = 5, $x_{115} = f_5(3.5)+f_5(3.0)+f_5(3.5)+f_5(3.0)+f_5(3.0) = 0$

The summary evaluation coefficient of index U_{111} is:

$$x_{11} = \sum_{e=1}^{5} x_{11e} = 13.867$$

Calculate gray evaluation weight vector and weight matrix: Gray evaluation weight vector of index U_{111} is: r_{11}= (0.232, 0.288, 0.337, 0.144, 0).

Similarly, we can calculate: r_{12}= (0.231, 0.289, 0.311, 0.168, 0).

Gray evaluation weight matrix R_{11} of index U_{11} is as follows. R_{12} and R_{13} are obtained similarly.

$$R_{11} = \begin{pmatrix} 0.232 & 0.288 & 0.337 & 0.144 & 0 \\ 0.231 & 0.289 & 0.311 & 0.168 & 0 \end{pmatrix}$$

Comprehensive evaluation: Firstly, U_{111} is comprehensively evaluated and the result is M_{11}. Other evaluation results of third evaluation index can be obtained similarly:

$$M_{11} = R_{11} I_1^T = \begin{pmatrix} 0.232 & 0.288 & 0.337 & 0.144 & 0 \\ 0.231 & 0.289 & 0.311 & 0.168 & 0 \end{pmatrix} (5 \quad 4 \quad 3 \quad 2 \quad 1)^T = \begin{pmatrix} 3.611 \\ 3.580 \end{pmatrix}$$

Similarly:

$$M_{12} = \begin{pmatrix} 3.521 \\ 3.626 \end{pmatrix} M_{13} = \begin{pmatrix} 3.627 \\ 3.550 \end{pmatrix}$$

Then, the index U_{11} is evaluated:

$$N_{11} = A_{11} M_{11} = (0.4762, 0.5238)(3.611, 3.580)^T = 3.594$$

Other evaluation results can be obtained similarly.

$$N_{12} = 3.580, N_{13} = 3.581$$
$$N_{21} = 3.789, N_{22} = 4.065, N_{23} = 3.550$$
$$N_{31} = 4.425, N_{32} = 3.685, N_{33} = 3.759$$
$$N_{41} = 3.618, N_{42} = 3.711$$

Then, the index U_1 is evaluated:

$$N_1 = (3.594, 3.580, 3.581)(0.435, 0.363, 0.202)^T = 3.586$$

Other evaluation results can be obtained similarly:

$$N_2 = 3.770, N_3 = 4.042, N_4 = 3.660$$

The comprehensive evaluation result S is as follows:

$$S = AN = (3.586, 3.770, 4.042, 3.660)(0.3504, 0.2920, 0.2086, 0.1490)^T = 3.745$$

Results analysis: The results shows that the comprehensive evaluation value of control system quality is 3.745, which obtains level "good", conforming to the actual situation.

CONCLUSION

This study starts from the dynamic operational process of control system, establishes control system quality evaluation indicator system. Firstly, index weight is determined by AHP, then evaluation gray class is determined by gray comprehensive evaluation method in accordance with the basis of sample matrix and gray evaluation coefficient, weight vector and weight matrix are calculated. Finally, comprehensive evaluation of the indicators is made. Through the analysis and verification of the example, satisfactory results are achieved.

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