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RESEARCH ON HUMAN RELIABILITY OF COALMINERS BASED ON FUZZY COMPREHENSIVE EVALUATION METHOD

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Abstract. *Based on the theory of fuzzy mathematics, fuzzy comprehensive evaluation method is introduced into human reliability evaluation for coalmine workers. According to actual situation of Wulong Coalmine of Fuxin Mining Group, based on analytic hierarchy process (AHP), a multi-level human reliability evaluation system of coalminers is established through analysis of various influencing factors for human reliability of the coalmine man-machine-environment-management system which consists of 9 second-level indices and 39 third-level indices. Finally, combining with safety grade table to deal with fuzzy comprehensive evaluation results can figure out coalminers' reliability level. The results prove that the evaluation is believable and practical of applying fuzzy comprehensive evaluation method to coalminers' human reliability evaluation and the method could be generalized to other coalmines.*

Keywords: Fuzzy comprehensive evaluation, Analytical hierarchy process (AHP), Human reliability evaluation, Coalminers, Indices system

1. **Introduction.** As a labor-intensive industrial system of production resources, natural disasters in coalmine, people's unsafe behavior, inadequate safety measures, deficient safety management and other factors may cause accidents in mine production system and pose a threat of injuries and deaths to workers. For a long time, people in the coal mining project produce more concerns about the safety and reliability of equipment and the importance of mining technology; however, when technology and equipment to improve reliability developed to a considerable extent, reliability of human who occupy a variety of roles like operators, watchers, and managers, highlights its importance. In recent years, a large number of domestic and international surveys show that accidents due to human caused by unsafe behaviors account for more than 70% to 90% of all accidents [1]. Similarly, more than 80% of coal industry accidents are due to imperfect site management and workers' violating regulations [2]. Therefore, research and discussion on the construction of human reliability intrinsically safe mine have important practical significance.

System reliability represents the capacity of system under specified conditions and predetermined period of time to complete a prescriptive function [3]. Generally speaking, reliability refers to the word "trusted". Human reliability (HRA) can be defined as the probability or ability of workers within predetermined time and specified conditions at any stage of the system operation to successfully complete the required job. The probability or ability also reflects degree of trust from others for error-free operational capability of workers to complete the required job [4].

There are few researches on human reliability evaluation for individuals; evaluation methods include fuzzy comprehensive evaluation [5], grey clustering analysis method [6], neural network prediction [7] and so on. Since human reliability evaluation method has some limitations, for example, human error can be identified when accident occurs, and it is helpless to check out potential human errors found, while it is rather difficult to obtain the probability or conditional probability of human error by counting "three-violation" behavior, rewards, punishments and attendance. In this paper, a fuzzy comprehensive evaluation method is introduced into human reliability evaluation, through the man-machine-environment-management production system due to various factors that influence people to analyze the reliability, which deals with various factors, strong fuzziness and other issues well. We use the analytic hierarchy process to assign weights of evaluation factors and invite many experts in the field of coalmine safety in scoring to weaken the influence of subjective judgment to make evaluation results objective and true. The using of the fuzzy comprehensive evaluation method combining AHP to evaluate the reliability of coalmine workers ensures the accuracy of evaluation results to maximum extent.

2. **Fuzzy Comprehensive Evaluation Method.**

2.1. **Basic steps of fuzzy comprehensive evaluation method.**

Fuzzy comprehensive evaluation method, is the application of fuzzy synthetic relationship principle, and can judge membership grade status things belong to from a number of factors; the basic steps are as follows [8-10].

(1) Establishment of factor set

Factor set is composed of various factors affecting the evaluation object, usually expressed: $U = (u_1, u_2, \ldots, u_m)$, the element u_i $(i = 1, 2, \ldots, m)$ represents the i-th factor which affects evaluation object. These factors usually have different degrees of fuzziness.

(2) Establishment of weight vector of factors

According to the different influence degrees of each factor in the evaluation system on evaluation object to determine the weight w_i $(i = 1, 2, \ldots, m)$ of each factor u_i $(i = 1, 2, \ldots, m)$. The fuzzy set consists of weights of each factor, represented by W: $W = (w_1, w_2, \ldots, w_m)$.

(3) Establishment of comment set

Comment set is a set composed of all evaluation results, usually represented by V, $V = (v_1, v_2, \ldots, v_n)$, the element v_j $(j = 1, 2, \ldots, n)$ means the j-th evaluation result. According to actual need, evaluation result is in form of different numbers, remark grades or comment words.

(4) Obtaining evaluation matrix

Make fuzzy evaluation on single factor, in order to obtain the evaluation matrix. If the i-th element u_i in factor set belongs to the j-th element v_j in comment set V with a membership of r_{ij}, then single factor evaluation result on u_i, can be represented as fuzzy set $R_i = (r_{i1}, r_{i2}, \ldots, r_{in})$. All m single factor evaluation sets $R_i = (r_{i1}, r_{i2}, \ldots, r_{in})$ as row vector from fuzzy comprehensive evaluation matrix R.

(5) Establishment of comprehensive evaluation model

Through the fuzzy transformation, transfer factor weight vector W of U into fuzzy vector B:

$$B = W \cdot R = (b_1, b_2, \ldots, b_n) \tag{1}$$

Formula (1) is the fuzzy comprehensive evaluation model, "$\cdot$" for synthesis operator.

(6) Determining final evaluation score

Determine final evaluation score with formula $F = B \cdot S^T$, F as final evaluation score and S as corresponding factor grade score.

(7) Obtaining human reliability grade

According to the final evaluation score, by looking up the table of human reliability classification, we can obtain human reliability grade.

2.2. **Establishment of weight matrix of evaluation factors.**

In the fuzzy comprehensive evaluation model, weights account for their position of various factors in process of comprehensive decision. Analytic hierarchy process (AHP) method is an effective method to determine weights [11]. The structure model created by AHP has usually a hierarchical structure of target layer, factor layer, sub factor layer, and plan layer. The application of AHP judgment matrix, generally uses $1 \sim 9$ and their multiplicative inverse scaling method. The biggest eigenvalue and corresponding eigenvector can be obtained by calculating the judgment matrix, this eigenvector represents the importance of evaluation factors, namely the factor's weight. After determining the weight, it is necessary to carry out consistency test. The consistency index of CI is obtained by using Formula (2).

$$CI = (\lambda_{\max} - n)/(n - 1) \tag{2}$$

In the formula, $\lambda_{\max}$ is the biggest eigenvalue of the judgment matrix, and n as the order of the judgment matrix.

Check the table to determine the average random consistency index RI, and then calculate the consistency ratio CR:

$$CR = CI/RI \tag{3}$$

If CR is less than 0.1, there is no judgment matrix consistency problem, and judgment matrix is acceptable with reasonable assignment.

3. **Establishment of Human Reliability Evaluation Indices System of Coalmine Workers.** There are many factors due to human reliability of coal miners [12-17]. In view of the special environment for production of coalmine, using the idea of system engineering, and analytic hierarchy process (AHP), we construct the evaluation indices system of human reliability of coalminers (target layer). The factor layer of the indices system has nine factors, and sub factor layer is composed by 39 sub factors, as shown in Table 1 below.

Table 1. Evaluation indices system of human reliability of coalmine workers

Factor Level	Sub Factor Level
Biography Feature (B_1)	Job Seniority (C_{11}); Educational Background (C_{12}); Marriage (C_{13}); Annual Income (C_{14}); Annual Statistics of Violate Regulations (C_{15})
Character Feature (B_2)	Confidence (C_{21}); Pressure Endure (C_{22}); Impulse suppression (C_{23}); Responsibility (C_{24}); Earnest (C_{25}); Disciplined compliance (C_{26})
Physiological Feature (B_3)	Basic Physiological Feature (C_{31}); Pathology Feature (C_{32}); Fatigue (C_{33}); Attention Allocation (C_{34}); Response Capability (C_{35})
Social Life Pressure (B_4)	Economic Conditions (C_{41}); Interpersonal Relationship (C_{42}); Recent Incidents Affecting (C_{43})
Production Skill (B_5)	Notify Operation Rules (C_{51}); Operational Proficiency (C_{52}); Operating Accuracy (C_{53})
Safety Skill (B_6)	Latent Danger Cognition (C_{61}); Safety Regulations Grasp (C_{62}); Safety Operation and Adjustment (C_{63}); Safety Protection (C_{64}); Emergency Response Capabilities (C_{65})
Production Conditions (B_7)	Physical Environment (C_{71}); Operating Environment (C_{72}); Equipment Tools Condition (C_{73})
Work Conditions (B_8)	Task Scheduler (C_{81}); Work Property (C_{82})
Organization Management (B_9)	Rules & Regulations (C_{91}); Safety Training & Education (C_{92}); Safety Atmosphere (C_{93}); Organization Fairness (C_{94}); Organization Concern (C_{95}); Communication & Feedback (C_{96}); Labor Guarantee (C_{97})

4. The Weight Determination Based on AHP.

4.1. Weight distribution of factor level relative to target level. First of all, according to research of human reliability theory, mine production experience and scoring by experts to determine the factors importance degree [12,14,16,17], and obtain factor level judgment matrix as Table 2 shows.

TABLE 2. Judgment matrix of factor level

A	B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9	W
B_1	1	1/4	1/4	1/7	1/8	1/8	1/2	1/2	1/4	0.0196
B_2	4	1	2	1/4	1/6	1/6	4	4	1/2	0.0665
B_3	4	1/2	1	1/5	1/7	1/7	3	3	1/3	0.0485
B_4	7	4	5	1	1/3	1/3	6	6	3	0.1634
B_5	8	6	7	3	1	1/2	6	6	3	0.2468
B_6	8	6	7	3	2	1	7	7	5	0.3112
B_7	2	1/4	1/3	1/6	1/7	1/8	1/2	1/2	1/4	0.0241
B_8	2	1/4	1/3	1/6	1/6	1/7	1	1	1/3	0.0342
B_9	4	2	3	1/3	1/3	1/5	3	3	1	0.0857
$\lambda_{\max} = 3.0340$, $CI = 0.1002$, $RI = 1.4616$, $CR = 0.0686 < 0.10$										

Calculate the maximum eigenvalue and eigenvector of judgment matrix using Matlab software:

$\lambda_{\max} = 3.0340$, $W = (0.0196, 0.0665, 0.0485, 0.1634, 0.2468, 0.3112, 0.0241, 0.0342, 0.0857)$

Then $CI = 0.1002$ calculated from Formula (2), $RI = 1.4616$ by table lookup, $CR = 0.0686 < 0.10$ calculated from Formula (3), meet the consistency check.

4.2. Weight distribution of sub factor level relative to factor level. In the same way, we can get judgment matrix of sub factor level relative to factor level, and then calculate the eigenvector related to its maximum eigenvalue:

(1) Biography feature eigenvectors: $W_1 = (0.2552, 0.0463, 0.1055, 0.1290, 0.4640)$
(2) Character feature eigenvectors:
$W_2 = (0.0391, 0.0643, 0.1045, 0.2244, 0.1740, 0.3937)$
(3) Physiological feature eigenvectors: $W_3 = (0.0464, 0.0827, 0.2954, 0.1589, 0.4166)$
(4) Social life pressure eigenvectors: $W_4 = (0.2706, 0.0852, 0.6442)$
(5) Production skill eigenvectors: $W_5 = (0.0719, 0.2790, 0.6491)$
(6) Safety skill eigenvectors: $W_6 = (0.4138, 0.2747, 0.1857, 0.0555, 0.0703)$
(7) Production conditions eigenvectors: $W_7 = (0.6370, 0.1047, 0.2583)$
(8) Work conditions eigenvectors: $W_8 = (0.8000, 0.2000)$
(9) Organization management eigenvectors:
$W_9 = (0.0903, 0.2530, 0.0977, 0.3835, 0.0303, 0.0405, 0.1047)$

5. Example Application.

5.1. Establishment of evaluation matrix. We determine the comment sets $V = (v_1, v_2, v_3, v_4, v_5)$ = (excellent, good, medium, not good, bad) and consult ten experts engaged in coalmine safety behavior research. Experts vote to scores of sub factors of evaluation object, according to personal experience, access to results of a questionnaire survey, test scores, physical examination, archives and other information. Based on the statistics of ten experts vote, ultimately form sub factors evaluation matrix [16,17]. For example, ten experts vote for "confidence" sub factor C_{21}, voting result is: six for excellent, three for good, one for medium, no one think not good or bad, then the fuzzy evaluation vector of $C_{21} = (0.6, 0.3, 0.1, 0, 0)$. According to the method above, we select three staffs in excavation team in Wulong Coalmine of Fuxin Mining Group, and conclude

Table 3. Human reliability judgment matrix of staff A

Factor Level	Sub Factor Level	Membership Grade: Excellent	Good	Medium	Not Good	Bad	Factor Level	Sub Factor Level	Membership Grade: Excellent	Good	Medium	Not Good	Bad
B_1	C_{11}	0.8	0.2	0	0	0	B_5	C_{51}	0.3	0.7	0	0	0
	C_{12}	0.7	0.3	0	0	0		C_{52}	0.9	0.1	0	0	0
	C_{13}	0.6	0.4	0	0	0		C_{53}	0.8	0.1	0.1	0	0
	C_{14}	0.1	0.7	0.2	0	0	B_6	C_{61}	0.2	0.7	0.1	0	0
	C_{15}	0.9	0.1	0	0	0		C_{62}	0.3	0.7	0	0	0
B_2	C_{21}	0.6	0.3	0.1	0	0		C_{63}	0.3	0.6	0.1	0	0
	C_{22}	0.3	0.5	0.2	0	0		C_{64}	0.1	0.8	0.1	0	0
	C_{23}	0.8	0.2	0	0	0		C_{65}	0.1	0.9	0	0	0
	C_{24}	0	0.3	0.5	0.2	0	B_7	C_{71}	0.6	0.2	0.2	0	0
	C_{25}	0	0.1	0.6	0.3	0		C_{72}	0.8	0.1	0.1	0	0
	C_{26}	0.8	0.2	0	0	0		C_{73}	0.9	0.1	0	0	0
B_3	C_{31}	0	0.1	0.5	0.3	0.1	B_8	C_{81}	0.5	0.3	0.2	0	0
	C_{32}	0.3	0.6	0.1	0	0		C_{82}	0.7	0.3	0	0	0
	C_{33}	0.7	0.3	0	0	0	B_9	C_{91}	0.6	0.2	0.2	0	0
	C_{34}	0.6	0.3	0.1	0	0		C_{92}	0.8	0.1	0.1	0	0
	C_{35}	0	0.3	0.5	0.2	0		C_{93}	0.7	0.3	0	0	0
B_4	C_{41}	0	0.3	0.5	0.2	0		C_{94}	0.9	0.1	0	0	0
	C_{42}	0	0.5	0.4	0.1	0		C_{95}	0.8	0.2	0	0	0
	C_{43}	0	0.3	0.5	0.2	0		C_{96}	0.7	0.2	0.1	0	0
								C_{97}	0.9	0.1	0	0	0

reliability evaluation matrices of staffs A, B, C. Evaluation matrix of staff A is shown in Table 3.

5.2. **Establishment of comprehensive evaluation matrix of each factor.** Synthesize fuzzy subset W_i and R_i $(i = 1, 2, 3, 4, 5, 6, 7, 8, 9)$ to corresponding factor evaluation matrix by synthesis operator:

(1) Biography feature evaluation matrix: $B_1 = W_1 \cdot R_1 = (0.7304, 0.2438, 0.0258, 0, 0)$
(2) Character feature evaluation matrix: $B_2 = W_2 \cdot R_2 = (0.5260, 0.3601, 0.1139, 0, 0)$
(3) Physiological feature evaluation matrix:
$B_3 = W_3 \cdot R_3 = (0.3269, 0.3155, 0.2557, 0.0972, 0.0046)$
(4) Social life pressure evaluation matrix:
$B_4 = W_4 \cdot R_4 = (0.1933, 0.4459, 0.2982, 0.0626, 0)$
(5) Production skill evaluation matrix: $B_5 = W_5 \cdot R_5 = (0.7920, 0.1431, 0.0649, 0, 0)$
(6) Safety skill evaluation matrix: $B_6 = W_6 \cdot R_6 = (0.2335, 0.7010, 0.0655, 0, 0)$
(7) Production conditions evaluation matrix: $B_7 = W_7 \cdot R_7 = (0.6984, 0.1637, 0.1379, 0, 0)$
(8) Work conditions evaluation matrix: $B_8 = W_8 \cdot R_8 = (0.5400, 0.3000, 0.1600, 0, 0)$
(9) Organization management evaluation matrix:
$B_9 = W_9 \cdot R_9 = (0.8169, 0.1357, 0.0474, 0, 0)$

5.3. **Determining human reliability grade of evaluation object.**

5.3.1. *Establishment of evaluation vector.* Human reliability evaluation matrix of coal-miner: $C = W \cdot B$, normalized evaluation vector of staff A:
$C = W \cdot B = (0.4329, 0.3664, 0.1580, 0.0425, 0.0002)$
Staff B evaluation vector: $(0.1031, 0.2502, 0.4049, 0.2261, 0.0157)$
Staff C evaluation vector: $(0.1566, 0.2589, 0.3698, 0.1662, 0.0485)$

5.3.2. *Determining final evaluation score.* Converting reliability score to percentile points according to grade score shown in Table 4, we can obtain the final human reliability score.

Table 4. Evaluation of human reliability grade

Reliability Grade	Excellent	Good	Medium	Not Good	Bad
Grade Score	100	85	70	55	40

Final score of staff A:
$F = C \cdot S^T = (0.4329, 0.3664, 0.1580, 0.0425, 0.0002) \cdot (100, 85, 70, 55, 40)^T = 87.8402$
Final score of staff B is 75.4805 while staff C is 75.2651.

5.3.3. *Determining human reliability grade.* Checking up Table 5 – Classification of human reliability grade, we can switch final evaluation to reliability grade. The result shows that staff A obtains excellent, while staffs B and C receive good.

Table 5. Classification of human reliability grade

Reliability Grade	Excellent	Good	Medium	Not Good	Bad
Reliability Score	> 80	70-79	60-69	40-59	< 40

5.4. **Evaluation results test.** Staff A is a middle-aged energetic tunneling worker, who has a harmonious family with little family economic pressure. He is cheerful optimism, serious and responsible with steady production skills, for five consecutive years without three-violation behavior, and is elected as labor model of the team. The evaluation result of reliability is excellent.

Staff B is a tunneling worker close to fifty with long job seniority. He has experienced many accidents and is able to withstand pressure. Though rich security experience, he is in poor health and has a little life stress, recent minor injuries, no three-violation behavior, and works a little slack. The evaluation result of reliability of staff B is good.

Staff C is a young tunneling worker with only three years job seniority, unmarried, physically fit, positive, self-confident, serious responsible, and has little family burden. However, due to the inadequate working hours, lack of work experience, easy-impulsive, he sometimes does not work in accordance with regulations, insufficient capacity responding to emergencies event, and recently had a three-violation behavior, so the evaluation result of reliability of staff C is good.

In summary, the results of this evaluation which are accurate and reliable can truly reflect the safety conditions of employees. Through total of 142 persons of two teams of Wulong Coal Excavation of Fuxin Mining Group, we make the evaluation of the human reliability. The average score of final results of the evaluation is 69.76, reflecting the reliability grade of most coalminers is good or moderate, which shows safety situation is not optimistic.

6. **Conclusion.** Human reliability evaluation of coalmine workers is aimed at providing scientific basis for coalmine enterprises on reliability evaluation of production safety of on duty personnel. The indices system determines weight by using analytic hierarchy process and evaluates by applying fuzzy comprehensive evaluation method on the basis of covering as much factors as possible which affects coalmine workers' operating reliability. In this way, supervisors can comprehend behavior rules of employees more accurate, detect employees' psychological problem in time, then take measures without delay on behavior and psychological intervention, retraining and job-transfer for workers who have particular accident tendency to minimize workers' unsafe behavior and thereby reduce the occurrence of accidents. The evaluation method is verified to highly conform to actual situation and considerably practical, while the indices and weights can be directly applied within the same profession. Therefore, it is worth application and popularization in coalmine enterprises.

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