Team Collaboration Assessment Method in Marine Engine Room Simulator

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Abstract: Based on the fuzzy mathematics and set similarity theory an intelligent collaboration assessment method for engine room simulator was studied. First, an integrated weighting method using both subjective and objective information was designed to obtain the weight vector; second, the fuzzy comprehensive evaluation method was used to calculate the completion degree of team collaboration, then the Dice coefficient and the Tversky coefficient were adopted to quantify the sequence factor, interactivity factor, redundancy factor and unauthorized factor of team collaboration effectiveness; third, a comprehensive calculation was achieved by the completion degree and the four factors to get the team collaboration assessment result; finally, the influence of the collaboration factors on assessment result was analyzed by an example, and it was found that even if the team get a higher task completion degree, due to some factors, the score is still low. The research shows that the collaborative performance of a team can greatly influence the final assessment result, the quantitative analysis of team collaboration can more objectively reveal the impact on collaboration. It is an effective method to add the influence of team cooperation factors to the traditional individual evaluation.

Keywords: Marine engineering, team collaboration, intelligent assessment, engine room simulation.

1. Introduction

The traditional assessment mode of Marine Engine Room Simulator (ERS) mainly focuses on the task completion degree of individual operation. If a team is involved in the assessment, the assessment system also regards it as an operator. As a result, a blind spot of team collaborative assessment exists in the simulators. With the implementation of the new international conventions, a higher requirement has been put forward for the team collaborative ability of engine room crew and the implementation effect of engine room resource management. So, an effective team collaborative intelligent assessment method has become a research hotspot in the competency assessment of crew, and it is urgent to study an effective method in ERS.

1.1. Intelligent Assessment Methods

Intelligent assessment is an upgrade mode of electronic automated assessment. There are three types of research methods on intelligent assessment generally: the first is to adopt computer science to simulate the functions of human brain, such as the expert system method and the fuzzy comprehensive evaluation; the second is to research the evaluation activities of human brain from the perspective of physiology, and the typical example is the artificial neural network method; the third is based on the above two and associate with probability theory, genetic theory, etc., such as the machine learning method, the Monte Carlo simulation method and the genetic algorithm evaluation method [1].

1.2. Assessment Methods in ERS

Ikenishi et al. described the influence of learning method and learning group on learning outcomes, they found that group learning shows a better performance in occurrence number of operational errors than pair (two persons) learning and individual learning [2]. Panagiotis and Hikitas proposed an innovative behavioral assessment framework. This framework can be applied in combination with the technological achievement to measure the effectiveness of the course and the added skills of the participants [3]. Cao et al. apply the fuzzy comprehensive evaluation method to construct the fuzzy judgment matrix, and then use the fuzzy judgment matrix as objective evidence of intelligent assessment, combined with subjective weight factors, a comprehensive evaluation theory was established to achieve the marine engineering training and assessment of competence [4]. Hu et al. has studied some factors that affect operational capabilities. Through the method of quantitative evaluation factors, a mathematical model of combat capability evaluation factors was established [5]. Duan et al. proposed an intelligent evaluation method based on expert system and machine learning to improve the three-dimensional cabin collaborative training system, and made a comparative analysis of the intelligent assessment method based on expert system and machine learning [6]. Furthermore, Duan et al. proposed a man-ship-resource system model and an assessment method based on intelligent optimization [7]. In addition, to adapt to different training purposes, Shen et al. developed an educational virtual reality training system named DMS-VLCC3D, they designed three training modes: standalone, multi-user collaborative training and evaluation, and achieved a promising result through verification [8].

1.3. Assessment Methods in Other Sectors

According to the characteristics of flight simulator modification training, Fan et al. proposed to build an assessment model by using the simulation data of flight simulator and combining the scoring standards of training outline and piloting skills [9]. Yang selected the artificial neural networks comprehensive evaluation method, obtained the sample data by questionnaire method, established a management evaluation model based on BP artificial neural network architecture, and applied and tested the model to evaluate the actual construction management [10]. Chang et al. integrated the Important Performance Analysis (IPA) of the Analytic Hierarchy Process (AHP) and the 2-tuple fuzzy linguistic representation model to determine the benefits of the simulation training system [11]. Fang et al. proposed a new evaluating cloud similarity algorithm of the single ship track when inward/outward port based on the parameters vector of a two-dimensional cloud model, and verified the feasibility of the algorithm through simulation examples [12]. Sun et al. proposed a complete training effectiveness evaluation method based on virtual simulation. The key to this method is regarding the complex process as a discrete event activity flow system and establish an evaluation indicator system [13]. Ren et al. proposed an idea of establishing an evaluation model based on data-driven thinking, and used the extreme learning machine method in the field of machine learning as a tool for learning data, and performed data learning on the effectiveness evaluation model. Finally, the effectiveness of the method was verified by a computer simulation [14]. To improved the training programs for in maritime operations, Li et al. adopted three methods including questionnaire surveys, emphasizing visual focus, and visual switching between expert attention maps and Areas of Interest (AOI) to incorporate the experts' maritime operation knowledge and simulator experience into the training program [15].

1.4. Aim of This Paper

Based on the above analysis, the assessment method of team collaboration with quantifying the degree of teamwork in ERS was rarely researched and proposed. Therefore, on the basis of the existing research results, this paper aims to present an intelligent assessment method of team collaboration in ERS. The key research objectives include the determination of weight set, the calculation of collaboration completion degree, the quantification of collaboration capability, and the verification of the proposed method by a typical example.

2. Proposed Methodology

2.1. Integrated Weight Calculation

There are two kinds of weight calculation methods in an assessment, one is function-driven subjective weighting method, and the other is difference-driven objective weighting method. In this paper, two kinds of weighting methods using both subjective and objective information are logically integrated to obtain the weight vector.

2.1.1. Subjective weighting method

The Delphi method, also known as the expert consultation method, is a qualitative research method that is widely used in the establishment of the evaluation index system [16], and the AHP is a widely used and verified subjective weighting method that can quantify the qualitative analysis by the differences between judgment elements [17], as a combination of quantitative and qualitative research methods [18], it is often used to establish evaluation index weights in comprehensive evaluation [19]. It combines the empirical knowledge of experts with rational analysis, thereby improving the scientific nature of the weights. In this paper, the judgments generated by the Delphi method are used as the original input of AHP to quantitatively describe the target weights. The calculation steps are as follows:

Step1: Collect the experts independent judgments

Using the Delphi method, the expert opinions are sorted by mathematical statistics and fed back to the experts again, a new round of consultation and opinions are collected, so repeatedly, the group decision-making behavior of the experts with more consistent prediction results is finally obtained [20], and generate the judgment vector *P*

$$P=(v_1,v_2,\cdots,v_n). \tag{1}$$

where *n* is the number of evaluation factors for an assessment item, and v_i (i=0,1,…,n) is the expert judgment result of *i* evaluation factor.

Step 2: Establish the hierarchical structure mode

First, through analysis, the factors are decomposed into different levels of elements to form a hierarchical structure, that is, the overall goal is decomposed level by level to form different levels, such as the first index level, the second index level, and so on to the lowest index level [21].

Step 3: Construct the judgment matrix *A*

Let *A* be the judgment matrix, then

$$A=(a_{ij}),\quad a_{ij}>0,\quad a_{ji}=\frac{1}{a_{ij}}. \tag{2}$$

where a_{ij} is the comparison result of the importance of factor *i* and factor *j*, the calculation formula is

$$a_{ij}=F(b_{ij})=F(v_i-v_j),\qquad i,j=1,\ 2,\cdots,\ n. \tag{3}$$

where n is the number of evaluation factors, v_i is the expert judgment value of the element i obtained by Delphi method, and the mapping relationship of function F is shown in Table 1.

Table 1. Element Scale Table of Judgment Matrix

Judgment difference b_{ij}	Qualitative rating	Quantitative result a_{ij}
$0 \le b_{ij} < 10$	Equally important	1
$20 \le b_{ij} < 30$	Slightly more important	3
$40 \le b_{ij} < 50$	Clearly more important	5
$60 \le b_{ij} < 70$	Strongly more important	7
$85 \le b_{ij} \le 100$	Extremely more important	9
Intermediate difference	Intermediate values	2, 4, 6, 8
b_{ij} is negative	Be opposite to the above	Reciprocal of the above

Step 4: Calculat the weight vector W_h

It has been proved theoretically that the weight vector W_h is the eigenvector corresponding to the maximum eigenvalue λ_{max} of the judgment matrix A [22]. To simplify the calculation, the square root method is used to obtain W_h as:

Calculate the product m_i of each row elements of A

$$m_i = \prod_{j=1}^{n} a_{ij} . \tag{4}$$

Then, calculate the n-th root of m_i

$$\bar{s}_i = \sqrt[n]{m_i} . \tag{5}$$

Normalize the vector $\overline{W}_h = (\bar{s}_1, \bar{s}_2, \cdots, \bar{s}_n)$ to get the feature vector $W_h=(s_1,s_2,\ldots,s_n)$, where

$$s_i = \frac{\bar{s}_i}{\sum_{j=1}^{n} \bar{s}_j}, \qquad i = 1,\ 2, \cdots,\ n . \tag{6}$$

Further, calculate the maximum eigenvalue λ_{max} of A via s_i

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{(A \circ W_h^{\mathrm{T}})_i}{n s_i} . \tag{7}$$

where $(A \circ W_h^{\mathrm{T}})_i$ means the element i of the vector $A \circ W_h^{\mathrm{T}}$.

Step 5: Consistency test

Calculate the consistency index I_C of A

$$I_C = \frac{\lambda_{max} - n}{n-1}. \tag{8}$$

When I_C=0, the judgment matrix A has complete consistency, and the greater I_C, the greater the inconsistency. To determine the acceptable range of the degree of inconsistency, the consistency ratio R_C needs to be calculated, and if

$$R_C = \frac{I_C}{I_R} < 0.1. \tag{9}$$

The judgment matrix A can be considered to have satisfactory consistency, where I_R is the average random consistency index, which can be obtained by the index array RIA.

RIA=[0,0,0.52,0.89,1.12,1.26,1.36,1.41,1.46,1.49,1.52,1.54,1.56,1.58,1.59,1.5943,1.6064,1.6133,1.6207,1.6292,1.6385,1.6403,1.6462,1.6497,1.6556,1.6587,1.6631,1.667,1.6693,1.6724]

2.1.2. Objective weighting method

The Entropy Weight Method (EWM) can determine the index weight according to the amount of information provided by the observation value of each index. Because ERS has a good observation convenience for the operation information, the EWM can be well adopted to realize the objective weighting calculation of evaluation factors [23].

Let x_{ij} be the observation value of trainee j for the evaluation factor i, the EWM calculation steps are as follows:

Step 1: Calculate the characteristic proportion p_{ij}

$$p_{ij} = x_{ij} \Big/ \sum_{j=1}^{c} x_{ij}, \quad i = 1, 2, \cdots, n; j = 1, 2, \cdots, c. \tag{10}$$

Step 2: Calculate the entropy value e_i of the evaluation factor i

$$e_i = -k \sum_{j=1}^{c} p_{ij} \ln(p_{ij}). \tag{11}$$

$$k = 1/\ln c. \tag{12}$$

where e_i>0, k>0, and if x_{ij} are equal to a given k, then p_{ij}=1/c, and e_i=e_{max}=1 means entropy is maximum.

Step 3: Calculate the entropy difference coefficient g_i of e_i

$$g_i = 1 - e_i. \tag{13}$$

Step 4: Calculate the weight vector W_e

Let W_e=(t_1,t_2,…,t_n) be the weight vector, then

$$t_i = g_i \Big/ \sum_{i=1}^{n} g_i. \tag{14}$$

where t_i is the normalized weight coefficient.

2.1.3. Weight integration

Use multiplicative integration formula (15) or additive integration formula (16) to generate the integrated weight vector $W=(w_1,w_2,\ldots,w_n)$ with both subjective and objective information features.

$$w_i = s_i t_i \Big/ \sum_{i=1}^{n} s_i t_i , \qquad i=1,\ 2,\cdots,\ n. \tag{15}$$

$$w_i = k_1 s_i + k_2 t_i , \qquad i=1,\ 2,\cdots,\ n. \tag{16}$$

where $k_1>0$, $k_2>0$ are undetermined constants, and $k_1+k_2=1$.

Let y_j be the evaluation result of object j, and the sum of c evaluation objects is

$$\sum_{j=1}^{c} y_j = \sum_{j=1}^{c}\sum_{i=1}^{n} w_i x_{ij} = \sum_{j=1}^{c}\sum_{i=1}^{n} (k_1 s_i + k_2 t_i) x_{ij}. \tag{17}$$

where k_1 and k_2 can be determined via maximize the sum with the constraints of k_1 and k_2 by Lagrange multiplier method.

In addition, k_1 and k_2 can also be determined by the preference of decision makers. If $k_1=k_2$, the weight w_i can be calculated via the following formula (18).

$$w_i = (s_i + t_i) \Big/ \sum_{i=1}^{n} (s_i + t_i). \tag{18}$$

2.2. Completion Degree Calculation

The completion degree of team collaborate tasks is a key factor of the assessment method focuses on. Combined the integrated weight vector, the fuzzy comprehensive evaluation method can be used to calculate the completion degree. The steps are as follows:

Step 1: Make the set of evaluation factors

$$U=\{u_1,u_2,\ldots,u_n\}. \tag{19}$$

where u_i ($i=0,\ldots,n$) is evaluation factor i with varying degrees of fuzziness.

Step 2: Determine the set of appraisal grades

$$V=\{v_1,v_2,\ldots,v_m\}. \tag{20}$$

where v_j ($j=0,\ldots,m$) presents one of the appraisal grades, V is appraisal set.

Step 3: Determine the fuzzy membership functions

According to the variable type and the changing trend of each evaluation factor, the fuzzy membership functions could be defined separately, which are shown in the methodology application section for details.

Step 4: Set the fuzzy mapping matrix *R*

The function of the mapping matrix *R* is to provide a mapping from *U* to *V* according to the corresponding membership function [24], as formula (21).

$$f: U \to F(V) \qquad u_i \mapsto (r_{i1}, r_{i2}, \cdots, r_{im}). \tag{21}$$

where $R_i=(r_{i1},\ldots,r_{im})$ is the single factor appraisal vector, which is a fuzzy mapping from u_i (i=0,…,n) to the appraisal vector *V*, so the fuzzy mapping matrix *R* is shown as

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{1m} \\ \vdots & \vdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix}. \tag{22}$$

Step 5: Calculate the weight vector *W*

According to the previous comprehensive weight calculation, the weight vector $W=(w_1,w_2,\ldots,w_n)$ corresponding to each evaluation factor can be obtained.

Step 6: Get the appraisal vector *B*

Considering the importance of each factor, the single factor evaluation vector R_i needs to be assigned a corresponding weight w_i, as shown in formula (23), to get the appraisal vector *B*.

$$B = W \circ R = (w_1, w_2, \cdots, w_n) \circ R. \tag{23}$$

$$B = (b_1, b_2, \cdots, b_m) \qquad B \in F(V).$$

$$b_j = \sum_{i=1}^{n} w_i r_{ij} \quad (j = 1, 2, \cdots, m). \tag{24}$$

where b_j is the normalized appraisal index.

Step 7: Calculate the evaluation result

The result *E* of fuzzy comprehensive evaluation can be obtained via formula (25), which will represent the completion degree of team cooperation.

$$E = B \circ V^{\mathrm{T}} = \sum_{j=1}^{m} b_j v_j. \tag{25}$$

2.3. Sequence Factor Calculation

The sequence factor is an objective description of the team operation in the form of time flow according to standards and objective conditions.

The Dice coefficient I_{D} can be used to measure the similarity of two sets D_1 and D_2 via formula (26).

$$I_{\mathrm{D}} = \frac{2|D_1 \cap D_2|}{D_1 + D_2} \qquad S_{\mathrm{D}} \in [0,1]. \tag{26}$$

where the numerator $D_1 \cap D_2$ is the number of the same elements in two sets, which represents the degree of similarity between two sets affected by common elements, and the denominator $(D_1+D_2)/2$ is the arithmetic mean of the number of elements in two sets, which maintains the integrity of information [25].

If D_1 is a standard sequence set with k elements, D_2 is an actual sequence set with l elements generated in team collaboration, then based on formula (26), the quantitative index I_S representing the sequence factor can be calculated through set traversal via formula (27).

$$I_{\mathrm{S}} = \frac{2\sum_{i=1}^{k}\sum_{j^*=1}^{l} p_{ij}}{k+l} \Bigg|_{\text{if } p_{ij}=1,\, j^*=j} . \tag{27}$$

where p_{ij} is the probability that the i-th element in D_1 is the same as the j-th element in D_2, and be simplified to 0 or 1; j^* means that whenever p_{ij}=1, let $j^*=j$, and jump out of the loop for the next round of calculation until $i=k$ ends.

2.4. Interactivity Factor Calculation

The interactivity factor is an objective description of the alternating and interactive operations, so the factor focuses on information exchange and coordination between operators.

Based on formula (26), If D_1 is a standard interactivity set with k elements, D_2 is an actual interactivity set with l elements generated in team collaboration, and then the quantitative index I_A representing the interactivity factor can be calculated through set traversal via formula (28).

$$I_{\mathrm{A}} = \frac{2\sum_{i=1}^{k}\sum_{j=1}^{l} p_{ij}}{k+l} . \tag{28}$$

where p_{ij} is the same as the parameter in formula (27). Unlike formula (27), the interactivity factor has no sequence requirement, so formula (28) will traverse all elements of the two sets.

2.5. Redundancy Factor Calculation

The redundancy factor is an objective description of irrelevant operations in the process of team collaboration.

Similar to the Dice coefficient, the Tversky coefficient I_T is also an index to measure the similarity of two sets T_1 and T_2 , and it can be obtained via formula (29).

$$I_{\mathrm{T}} = \frac{|T_1 \cap T_2|}{|T_1 \cap T_2| + \alpha(T_1 - T_2) + \beta(T_2 - T_1)} \qquad I_{\mathrm{T}} \in [0,1] . \tag{29}$$

$$\alpha + \beta = 1 \qquad \alpha, \beta \in [0,1] .$$

where $T_1 \cap T_2$ is the number of the same elements in two sets, $T_1 - T_2$ or $T_2 - T_1$ is the number of elements in the relative complement of the both sets, and α, β are called depth coefficients.

The introduction of α, β, $T_1 - T_2$ and $T_2 - T_1$ can make the Tversky coefficient more emphasize the positive correlation between the similarity of two sets and their common attributes, so it can be used for the quantitative analysis of the redundant operation factor and the unauthorized operation factor in collaboration.

If T_1 is an standard non-redundancy set with k elements, T_2 is a actual operation set with l elements generated in team collaboration, then based on formula (29) to get $T_1 \cap T_2, T_1 - T_2, T_2 - T_1$ by traversing and comparing the sets, and to calculate the quantitative redundancy index I_R via formula (30). The $T_1 - T_2$ represents the number of operations not implemented according to the standard operations, and the $T_2 - T_1$ represents the number of redundant operations beyond the standard operations.

$$I_{\mathrm{R}} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{l} p_{0ij}}{\sum_{i=1}^{k}\sum_{j=1}^{l} p_{0ij} + 0.4\sum_{i=1}^{k}\sum_{j=1}^{l} p_{1ij} + 0.6\sum_{j=1}^{l}\sum_{i=1}^{k} p_{2ij}}. \tag{30}$$

where p_{0ij} is the probability that the i-th element in T_1 is the same as the j-th element in T_2, p_{1ij} is the probability that the i-th element in T_1 is different from the j-th element in T_2, p_{2ij} is the probability that the j-th element in T_2 is different from the i-th element in T_1, and $p_{0ij}, p_{1ij}, p_{2ij}$ can be simplified to 0 or 1; α, β can be set according to the emphasis on item $T_1 - T_2$ and $T_2 - T_1$, and generally be set to 0.4 or 0.6.

2.6. Unauthorized Factors Calculation

The unauthorized factor is an objective description of the team member to perform beyond the personal duty and authority according to the engine room specifications.

If T_1 is a standard duty-perform set with k elements, T_2 is a actual operation set with l elements generated in team collaboration, then based on formula (29) to get $T_1 \cap T_2, T_1 - T_2, T_2 - T_1$ by traversing and comparing the sets, and to calculate the quantitative unauthorized index I_N via formula (31). The $T_1 - T_2$ represents the number of operations not implemented according to the standard duty-perform operations, and the $T_2 - T_1$ represents the number of unauthorized operations beyond the standard operations.

$$I_{\mathrm{N}} = \frac{\sum_{i=1}^{k}\sum_{j=1}^{l} p_{0ij}}{\sum_{i=1}^{k}\sum_{j=1}^{l} p_{0ij} + 0.2\sum_{i=1}^{k}\sum_{j=1}^{l} p_{1ij} + 0.8\sum_{j=1}^{l}\sum_{i=1}^{k} p_{2ij}}. \tag{31}$$

where p_{0ij}, p_{1ij}, p_{2ij} are ame as in formula (30), and α, β generally can be set to 0.2 or 0.8.

2.7. Assessment Result Calculation

The final collaboration assessment result C can be achieved via the combination of E, I_S, I_A, I_R, I_N. The calculation process is shown as formula (32).

$$C = \frac{(\lambda_{\mathrm{S}} I_{\mathrm{S}} + \lambda_{\mathrm{A}} I_{\mathrm{A}} + \lambda_{\mathrm{R}} I_{\mathrm{R}} + \lambda_{\mathrm{N}} I_{\mathrm{N}})}{\lambda_{\mathrm{S}} + \lambda_{\mathrm{A}} + \lambda_{\mathrm{R}} + \lambda_{\mathrm{N}}} \bullet E. \tag{32}$$

$$\lambda_{\mathrm{S}}, \lambda_{\mathrm{A}}, \lambda_{\mathrm{R}}, \lambda_{\mathrm{N}} \in [0,1].$$

where λ_S, λ_A, λ_R, λ_N corresponding to four indexes are undetermined constants, and can be set according to the emphasis on each collaboration factor, generally all be set 0.25.

3. Methodology Application

To verify the method proposed, the evaluation item of "Emergency Power Plant Start" was selected as an example for application verification, and then, the results were analyzed. In this example, some evaluation factors and criteria have been partially adjusted, and the actual factors and criteria will depend on the specific vessel.

3.1. Completion Degree of Collaboration

The evaluation factors and the Delphi judgment values of the evaluation item are shown in Table 2.

Table 2. Evaluation Factors and Judgment Table

ID	Evaluation factor	Delphi judgment
I01	Engine room ventilation	8
I02	Power supply of local control box	80
I03	DO tank level	45
I04	LO sump level	36
I05	Cooling water tank level	28
I06	Start battery voltage	32
I07	Emergency generator speed	60
I08	DO inlet pressure	35
I09	LO inlet pressure	41
I10	Cylinder water outlet temperature	45
I11	Prime mover control mode	30
I12	Emergency generator voltage	72
I13	Emergency generator frequency	78
I14	Circuit breaker status	95
I15	Emergency lighting power supply	55
I16	Other loads power supply	63
I17	Generator control mode	20
I18	Tie switch control mode	18

3.1.1. Subjective weight calculation

Get the judgment matrix A via formula (2) and (3).

$$
A=\begin{bmatrix}
1 & 1/8 & 1/4 & 1/3 & 1/3 & 1/3 & 1/6 & 1/3 & 1/4 & 1/4 & 1/3 & 1/7 & 1/8 & 1/9 & 1/5 & 1/6 & 1/2 & 1/2 \\
8 & 1 & 4 & 5 & 6 & 5 & 3 & 5 & 4 & 4 & 6 & 1 & 1 & 1/2 & 3 & 2 & 7 & 7 \\
4 & 1/4 & 1 & 1 & 2 & 2 & 1/2 & 2 & 1 & 1 & 2 & 1/3 & 1/4 & 1/6 & 1/2 & 1/2 & 3 & 3 \\
3 & 1/5 & 1 & 1 & 1 & 1 & 1/3 & 1 & 1 & 1 & 1 & 1/4 & 1/5 & 1/6 & 1/2 & 1/3 & 2 & 2 \\
3 & 1/6 & 1/2 & 1 & 1 & 1 & 1/4 & 1 & 1/2 & 1/2 & 1 & 1/5 & 1/6 & 1/7 & 1/3 & 1/4 & 1 & 2 \\
3 & 1/5 & 1/2 & 1 & 1 & 1 & 1/3 & 1 & 1 & 1/2 & 1 & 1/5 & 1/5 & 1/7 & 1/3 & 1/4 & 2 & 2 \\
6 & 1/3 & 2 & 3 & 4 & 3 & 1 & 3 & 2 & 2 & 4 & 1/2 & 1/2 & 1/4 & 1 & 1 & 5 & 5 \\
3 & 1/5 & 1/2 & 1 & 1 & 1 & 1/3 & 1 & 1 & 1/2 & 1 & 1/4 & 1/5 & 1/7 & 1/3 & 1/3 & 2 & 2 \\
4 & 1/4 & 1 & 1 & 2 & 1 & 1/2 & 1 & 1 & 1 & 2 & 1/4 & 1/4 & 1/6 & 1/2 & 1/3 & 3 & 3 \\
4 & 1/4 & 1 & 1 & 2 & 2 & 1/2 & 2 & 1 & 1 & 2 & 1/3 & 1/4 & 1/6 & 1/2 & 1/2 & 3 & 3 \\
3 & 1/6 & 1/2 & 1 & 1 & 1 & 1/4 & 1 & 1/2 & 1/2 & 1 & 1/5 & 1/5 & 1/7 & 1/3 & 1/4 & 2 & 2 \\
7 & 1 & 3 & 4 & 5 & 5 & 2 & 4 & 4 & 3 & 5 & 1 & 1 & 1/3 & 2 & 1 & 6 & 6 \\
8 & 1 & 4 & 5 & 6 & 5 & 2 & 5 & 4 & 4 & 5 & 1 & 1 & 1/2 & 3 & 2 & 6 & 7 \\
9 & 2 & 6 & 6 & 7 & 7 & 4 & 7 & 6 & 6 & 7 & 3 & 2 & 1 & 5 & 4 & 8 & 8 \\
5 & 1/3 & 2 & 2 & 3 & 3 & 1 & 3 & 2 & 2 & 3 & 1/2 & 1/3 & 1/5 & 1 & 1 & 4 & 4 \\
6 & 1/2 & 2 & 3 & 4 & 4 & 1 & 3 & 3 & 2 & 4 & 1 & 1/2 & 1/4 & 1 & 1 & 5 & 5 \\
2 & 1/7 & 1/3 & 1/2 & 1 & 1/2 & 1/5 & 1/2 & 1/3 & 1/3 & 1/2 & 1/6 & 1/6 & 1/8 & 1/4 & 1/5 & 1 & 1 \\
2 & 1/7 & 1/3 & 1/2 & 1/2 & 1/2 & 1/5 & 1/2 & 1/3 & 1/3 & 1/2 & 1/6 & 1/7 & 1/8 & 1/4 & 1/5 & 1 & 1
\end{bmatrix}
\Leftarrow
\begin{array}{l}
\mathrm{I01}\\ \mathrm{I02}\\ \mathrm{I03}\\ \mathrm{I04}\\ \mathrm{I05}\\ \mathrm{I06}\\ \mathrm{I07}\\ \mathrm{I08}\\ \mathrm{I09}\\ \mathrm{I10}\\ \mathrm{I11}\\ \mathrm{I12}\\ \mathrm{I13}\\ \mathrm{I14}\\ \mathrm{I15}\\ \mathrm{I16}\\ \mathrm{I17}\\ \mathrm{I18}
\end{array}
$$

Get the weight vector W_h via formulas (4) to (6).

W_h=(0.010,0.126,0.037,0.027,0.021,0.024,0.066,0.024,0.033,0.037,0.022,0.102,0.120,0.190,0.059,0.073,0.015,0.014)

Calculate the maximum eigenvalue λ_{max} of A and the consistency index I_C via formulas (7) and (8).

$$\lambda_{\max} = 18.4162.$$

$$I_C = 0.0245.$$

Calculate the consistency ratio R_C via formula (9) and the array RIA.

$$R_C = \frac{I_C}{I_R} = 0.0152.$$

The consistency ratio $R_C<0.1$ means the matrix A has a satisfactory consistency, so the subjective weight W_h can be adopted.

3.1.2. Objective weight calculation

For each evaluation factor, 30 trainees were selected for original data collection, and the objective weight vector W_e was calculated via formulas (10) to (14).

W_e=(0.074,0.026,0.038,0.055,0.083,0.016,0.028,0.069,0.054,0.107,0.081,0.017,0.028,0.042,0.076,0.089,0.063,0.054)

3.1.3. Integrated weight calculation

In this example, the additive integration method was adopted, and set k_1=0.7 and k_2=0.3, so the integrated weight W was achieved via formula (16).

W=(0.029,0.096,0.037,0.035,0.039,0.022,0.055,0.038,0.039,0.058,0.040,0.077,0.092,0.146,0.064,0.078,0.029,0.026)

3.1.4. Completion degree calculation

The defined membership function is shown in Fig. 1, and the specific parameter standard and membership type of each evaluation factor are shown in Table 3.

Table 3. Parameter Standard and Membership Type

ID	Standard status/value	Membership type
I01	−40 mmWC to 0mmWC	A
I02	True	D
I03	20% to 95%	A
I04	40% to 95%	A
I05	Above 50%	B
I06	Above 20V	B
I07	Less than 1800rpm	C
I08	Above 0.6bar	B
I09	Above 1.4bar	B
I10	Less than 90°C	C
I11	True	D
I12	440V，±1%	A
I13	60HZ，±10%	A
I14	True	D
I15	True	D
I16	More than 7	B
I17	True	D
I18	True	D

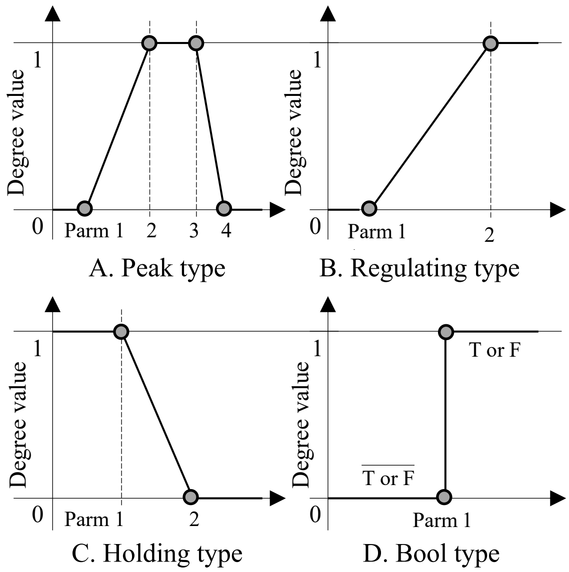

Fig. 1. Membership function types.

Set the appraisal set V as

$$V=\{0,20,40,60,80,100\}.$$

and the fuzzy mapping matrix R can be obtained via formula (21) and (22) associated with the defined membership functions.

$$R=\begin{bmatrix} 0 & 0 & 0 & 0 & 0.2 & 0.8 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0.1 & 0.9 \\ 0 & 0 & 0 & 0.2 & 0.8 & 0 \\ 0 & 0 & 0.1 & 0.9 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0.3 & 0.7 \\ 0 & 0 & 0 & 0.2 & 0.8 & 0 \\ 0 & 0 & 0 & 0 & 0.9 & 0.1 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0.7 & 0.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0.4 & 0.6 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Get the appraisal vector B by putting W, R into formula (23).

$$B = (0.0691,0,0.0351,0.1619,0.1605,0.5734).$$

Get the completion degree E via formula (25).

$$E = 81.298.$$

3.2. Four Indexes of Team Collaboration

In this example, the involved team P consisted of 6 members, marked with P1 to P6.

$$P=\{P1,P2,P3,P4,P5,P6\}.$$

The standard set D_S, interactivity set D_A, non-redundancy set T_R and duty-perform set T_N are shown as follows:

$D_S=\{I_S01,I_S02,\ldots,I_S15\}$ (See the first column of Table 4 for details).

$D_A=\{I_A01,I_A02,\ldots,I_A08\}$ (See the first column of Table 5 for details).

$T_R=\{I_R01,I_R02,\ldots,I_R18\}$ (See the first column of Table 6 for details).

$T_N=\{I_N01,I_N02,\ldots,I_N18\}$ (See the first column of Table 7 for details).

3.2.1. Sequence index calculation

D_{SC} is the actual set generated in the collaboration of team P, and the element comparison with the standard Sequence set D_S is shown in Table 4.

Table 4. Element comparison table of D_S and D_{SC}

D_S	D_{SC}	Remark
I_S01: Battery mode adjustment	I_S01	Valid
I_S02: Local control box power on	I_S02	Valid
I_S03: Ventilation adjustment	I_S05	I_S03|Invalid
I_S04: FO tank drainage	-	-
I_S05: DO tank level adjustment	I_S06	I_S03|Invalid
I_S06: LO tank level adjustment	I_S03	Valid
I_S07: CW tank level adjustment	I_S07	Valid
I_S08: DO inlet pressure adjustment	I_S08	Valid
I_S09: LO inlet pressure adjustment	I_S09	Valid
I_S10: Emergency generator start	I_S10	Valid
I_S11: Prime mover in AUTO mode	I_S12	I_S11|Invalid
I_S12: Circuit breaker connected	I_S13	I_S11|Invalid
I_S13: Power supply to loads	I_S11	Valid
I_S14: Generator in AUTO mode	-	-
I_S15: Tie switch control mode	I_S15	Valid

Note: "-" indicates no element, and "I_S*| Invalid" means the current item is counted as invalid due to the element "I_S*" in D_{SC}.

Put D_S, D_{SC} into formula (27) and get the quantitative sequence index I_S

$$I_S=0.643.$$

3.2.2. Interactivity index calculation

D_{AC} is the actual set generated in the collaboration of team P, and the element comparison with the standard interactivity set D_A is shown in Table 5.

Table 5. Element comparison table of D_A and D_{AC}

D_A	D_{AC}	Remark
I_A01: $P2/I_S02 \rightarrow P1/I_S03$	I_A01	Valid
I_A02: $P3/I_S05 \rightarrow P5/I_S06$	I_A02	Valid
I_A03: $P5/I_S06 \rightarrow P4/I_S07$	$P5/I_S06 \rightarrow P3/I_S07$	Invalid
I_A04: $P3/I_S08 \rightarrow P5/I_S09$	$P3/I_S08 \rightarrow P3/I_S09$	Invalid
I_A05: $P5/I_S09 \rightarrow P6/I_S10$	I_A05	Valid
I_A06: $P6/I_S11 \rightarrow P2/I_S12$	I_A06	Valid
I_A07: $P2/I_S13 \rightarrow P6/I_S14$	-	-
I_A08: $P6/I_S14 \rightarrow P2/I_S15$	-	-

Note: "P#1/I_S*1→P#2/I_S*2" means that the "P#1" transfers the information to "P#2" after completing the "I_S*1" operation, and then "P#2" completes the "I_S*2" operation.

Put D_A, D_{AC} into formula (28) and get the quantitative interactivity index I_A

$$I_A=0.571.$$

3.2.3. Redundancy index calculation

T_{RC} is the actual set with redundant information generated in the collaboration of team P, and the element comparison with the standard set T_R is shown in Table 6.

Table 6. Element Comparison Table of T_R and T_{RC}

T_R	T_{RC}	Remark
I_R01: I_S01	I_R01	Valid
I_R02: I_S02	I_R02	Valid
I_R03: I_S03	I_R03	Valid
I_R04: I_S04	-	-
I_R05: I_S05	I_R05	Valid
I_R06: I_S06	I_R06	Valid
I_R07: I_S07	I_R07	Valid
I_R08: I_S08	I_R08	Valid
I_R09: I_S09	I_R09	Valid
I_R10: I_S10	I_R10	Valid
I_R11: I_S11	I_R11	Valid
I_R12: I_S12	I_R12	Valid
I_R13: I_S13	I_R13	Valid
I_R14: I_S14	-	-
I_R15: I_S15	I_R15	Valid
I_R16: Voltage regulate	I_R16	Valid
I_R17: Frequency regulate	I_R17	Valid
I_R18: CW valve operate	I_R18	Valid
-	Redundant operation 1	Invalid
-	Redundant operation 2	Invalid
-	Redundant operation 3	Invalid
-	Redundant operation 4	Invalid

Put the T_R, T_{RC} into formula (30) and get the quantitative redundancy index I_R

$$I_R=0.833.$$

3.2.4. Unauthorized index calculation

T_{NC} is the actual set with unauthorized information generated in the collaboration of team P, and the element comparison with the standard set T_N is shown in Table 7.

Table 7. Element Comparison Table of T_N and T_{NC}

T_N	T_{NC}	Remark
I_N01: P2/I_R01	I_N01	Valid
I_N02: P2/I_R02	I_N02	Valid
I_N03: P1/I_R03	I_N03	Valid
I_N04: P3/I_R04	-	-
I_N05: P3/I_R05	I_N05	Valid
I_N06: P5/I_R06	I_N06	Valid
I_N07: P4/I_R07	P3/I_R07	Invalid
I_N08: P3/I_R08	I_N08	Valid
I_N09: P5/I_S09	P3/I_R09	Invalid
I_N10: P6/I_R10	I_N10	Valid
I_N11: P6/I_R11	I_N11	Valid
I_N12: P2/I_R12	I_N12	Valid
I_N13: P2/I_R13	I_N13	Valid

I_N14: P6/I_R14	-	-
I_N15: P2/I_R15	P6/I_R15	Invalid
I_N16: P6/I_R16	P1/I_R16	Invalid
I_N17: P6/I_R17	P1/I_R17	Invalid
I_N18: P4/I_R18	P1/I_R18	Invalid

Put the T_N, T_{NC} into formula (31) and get the quantitative unauthorized index I_N

$$I_N = 0.656.$$

3.3. Comprehensive Calculation

According to formula (32), set λ_S, λ_A, λ_R, λ_N are all 0.25 and associate the values of completion degree 81.298, sequence index 0.643, interactivity index 0.571, redundancy index 0.833 and unauthorized index 0.656 to get the collaboration assessment result C of the team P as

$$C=54.94.$$

3.4. Results

The result of the fuzzy comprehensive evaluation in group P was 81.298, which indicated that the task of this group was completed to a high degree. Except for the redundancy index of 0.833, the sequence index of 0.643, the interaction index of 0.571, and the unauthorized index of 0.656 were all far lower than 1, indicating that the team cooperation performance was not good. Therefore, the impact of team collaboration performance eventually led to an assessment result of 57.76.

Through the comparison between the actual operation set and the standard operation set, the three main reasons for the lack of team cooperation can be concluded: First, the team members did not know enough about the operation process and were not proficient enough; Second, the information sharing between the team members was not smooth and timely, and the interaction effect was not good; Finally, the team members did not have a good understanding of the personal responsibilities and authorities specified. So, the effectiveness of the collaboration assessment method can be verified by the example.

4. Conclusions

To study an intelligent collaboration assessment method in ERS for training can promote the development of engine room resource management in the competency assessment of crew and provide technical and program support for further implementation of new international conventions. In traditional non-collaborative assessment mode, it is difficult for team members to effectively perceive the impact of personal factors on the team collaboration, nor can they make a positive reflection on various their behaviors after the assessment. The application of the collaboration assessment method can effectively find the problems that arise in collaboration and carry out targeted training.

The multi-factor quantification of team collaboration can analyze the impact factors of team collaboration in general, reflect the work effect of each member in detail, and ensure the objectivity and accuracy of collaboration assessment. Based on more details of evaluation rules, the multi-factor quantitative analysis method proposed in this paper can be further expanded on other performances of team collaboration. In the future, the motivation factor, the concentration factor, the decision-making factor, etc. will be focused on to achieve the supplement and improvement of the methods proposed.

In the maritime field, the assessment methods of crew competence from manual judgment to machine automation and intelligent assessment is an inevitable development trend. However, the collaboration assessment method for collaboration effectiveness is still in the initial stage, and the related research and application are not deep and extensive enough. It is necessary to deeply combine the characteristics and needs of ERS to explore reasonable and effective assessment methods, and the follow-up research will be further carried out from two aspects: intelligent mechanism and collaboration quantification.

Conflict of Interest

As the author of the paper, I declare that this paper has no conflicts of interest.

Author Contributions

Hui Cao and Jundong Zhang studied the methods used in the paper; Hui Cao and Youbing Cao extracted the data needed for the paper and analyzed the data, and finally wrote the paper; all authors had approved the final version.

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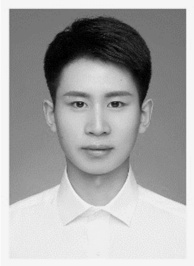

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