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:

Step 1: 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 $P$

$$P = (v_1, v_2, \ldots, v_n).$$  \hspace{1cm} (1)

where $n$ is the number of evaluation factors for an assessment item, and $v_i (i=0,1,\ldots,n)$ 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

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

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

$$a_{ij} = F(b_{ij}) = F(v_i - v_j), \quad i, j = 1, 2, \ldots, n. \hspace{1cm} (3)$$
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.

| Judgment difference \( b_{ij} \) | Qualitative rating | Quantitative result \( a_{ij} \) |
|----------------------------------|--------------------|---------------------------------|
| \( 0 \leq b_{ij} < 10 \)         | Equally important  | 1                               |
| \( 20 \leq b_{ij} < 30 \)        | Slightly more important | 3                           |
| \( 40 \leq b_{ij} < 50 \)        | Clearly more important | 5                           |
| \( 60 \leq b_{ij} < 70 \)        | Strongly more important | 7                           |
| \( 85 \leq b_{ij} \leq 100 \)    | Extremely more important | 9                           |
| Intermediate difference          | Intermediate values | 2, 4, 6, 8                     |

\( b_{ij} \) is negative \( \rightarrow \) Be opposite to the above  
Reciprocal of the above

**Step 4**: Calculate the weight vector \( W_h \)

It has been proved theoretically that the weight vector \( W_h \) is the eigenvector corresponding to the maximum eigenvalue \( \lambda_{\text{max}} \) 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 \( A \)

\[
m_i = \prod_{j=1}^{n} a_{ij}.
\]

(4)

Then, calculate the \( n \)-th root of \( m_i \)

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

(5)

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

\[
s_i = \frac{\bar{s}_i}{\sum_{j=1}^{n} \bar{s}_j}, \quad i = 1, 2, \ldots, n.
\]

(6)

Further, calculate the maximum eigenvalue \( \lambda_{\text{max}} \) of \( A \) via \( s_i \)

\[
\lambda_{\text{max}} = \sum_{i=1}^{n} \frac{(A \circ W_h^T)_{ij}}{ns_i}.
\]

(7)

where \( (A \circ W_h^T)_{ij} \) means the element \( i \) of the vector \( A \circ W_h^T \).

**Step 5**: Consistency test

Calculate the consistency index \( I_C \) of \( A \)
\[ I_c = \frac{\lambda_{\text{max}} - n}{n - 1}. \]  

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

\[ R_c = \frac{I_c}{I_R} < 0.1. \]  

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 \( RIA \).

\[ \text{RIA} = [0.0, 0.52, 0.89, 1.12, 1.26, 1.36, 1.41, 1.46, 1.49, 1.52, 1.54, 1.56, 1.58, 1.59, 1.5943, 1.6064, 1.6133, 1.6207, 1.6292, 1.6385, 1.6403, 1.6462, 1.6497, 1.6556, 1.6587, 1.6631, 1.667, 1.6693, 1.6724] \]

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 \( p_{ij} \)

\[ p_{ij} = x_{ij} / \sum_{j=1}^{c} x_{ij}, \quad i = 1, 2, \ldots, n; j = 1, 2, \ldots, c. \]  

**Step 2:** Calculate the entropy value \( e_i \) of the evaluation factor \( i \)

\[ e_i = -k \sum_{j=1}^{c} p_{ij} \ln(p_{ij}). \]

\[ k = 1/\ln c. \]

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

**Step 3:** Calculate the entropy difference coefficient \( g_i \) of \( e_i \)

\[ g_i = 1 - e_i. \]

**Step 4:** Calculate the weight vector \( W_e \)

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

\[ t_i = g_i / \sum_{i=1}^{n} g_i. \]
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 \( W=(w_1,w_2,...,w_n) \) with both subjective and objective information features.

\[
\begin{align*}
    w_i &= s_i t_i / \sum_{i=1}^{n} s_i t_i , & i &= 1, 2, \ldots, n . \\
    w_i &= k_1 s_i + k_2 t_i , & i &= 1, 2, \ldots, n .
\end{align*}
\]  

(15)  

(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

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

(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).

\[
    w_i = (s_i + t_i) / \sum_{j=1}^{n} (s_j + t_j) .
\]

(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

\[
U=\{u_1,u_2,\ldots,u_n\}.
\]

(19)

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

**Step 2:** Determine the set of appraisal grades

\[
V=\{v_1,v_2,\ldots,v_m\}.
\]

(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).

$$f : U \rightarrow F(V) \quad u_i \mapsto (r_{i1}, r_{i2}, \ldots, r_{im}).$$ (21)

where $R=(r_{i1}, r_{i2}, \ldots, r_{im})$ is the single factor appraisal vector, which is a fuzzy mapping from $u_i (i=0, \ldots, n)$ to the appraisal vector $V$, so the fuzzy mapping matrix $R$ is shown as

$$R = \begin{bmatrix}
    r_{i1} & r_{i2} & \cdots & r_{im} \\
    r_{21} & r_{22} & \cdots & r_{2m} \\
    \vdots & \vdots & \ddots & \vdots \\
    r_{n1} & r_{n2} & \cdots & r_{nm}
\end{bmatrix}. $$ (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 $w_b$ as shown in formula (23), to get the appraisal vector $B$.

$$B = W \circ R = (w_1 r_{11}, w_2 r_{21}, \ldots, w_n r_{n1}) \circ R. $$ (23)

$$B = (b_1, b_2, \ldots, b_m) \quad B \in F(V).$$

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

$$E = B \circ V^T = \sum_{j=1}^{m} b_j v_j. $$ (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).

$$I_D = \frac{2 |D_1 \cap D_2|}{D_1 + D_2}, \quad S_D \in [0,1]. $$ (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).

$$I_S = \frac{2 \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij}}{k + l} \quad \text{if } p_{ij} = 1, j^* = j.$$  (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).

$$I_A = \frac{2 \sum_{i=1}^{k} \sum_{j=1}^{l} p_{ij}}{k + l}.$$  (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).

$$I_T = \frac{|T_1 \cap T_2|}{|T_1 \cap T_2| + \alpha (T_1 - T_2) + \beta (T_2 - T_1)} \quad I_T \in [0,1].$$  (29)

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

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 $\alpha, \beta$ are called depth coefficients.

The introduction of $\alpha, \beta$ 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.

\[
I_R = \frac{\sum_{i=1}^{k} \sum_{j=1}^{l} P_{0ij}}{\sum_{i=1}^{k} \sum_{j=1}^{l} P_{0ij} + 0.4 \sum_{i=1}^{k} \sum_{j=1}^{l} P_{1ij} + 0.6 \sum_{j=1}^{l} \sum_{i=1}^{k} P_{2ij}}.
\]

(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; \( \alpha, \beta \) 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.

\[
I_N = \frac{\sum_{i=1}^{k} \sum_{j=1}^{l} P_{0ij}}{\sum_{i=1}^{k} \sum_{j=1}^{l} P_{0ij} + 0.2 \sum_{i=1}^{k} \sum_{j=1}^{l} P_{1ij} + 0.8 \sum_{j=1}^{l} \sum_{i=1}^{k} P_{2ij}}.
\]

(31)

where \( P_{0ij}, P_{1ij}, P_{2ij} \) are same as in formula (30), and \( \alpha, \beta \) 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).

\[
C = \frac{\lambda_S I_S + \lambda_A I_A + \lambda_R I_R + \lambda_N I_N}{\lambda_S + \lambda_A + \lambda_R + \lambda_N} \cdot E.
\]

(32)

where \( \lambda_S, \lambda_A, \lambda_R, \lambda_N \) 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.

| 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).

$$A = \begin{bmatrix}
1 & 1/8 & 1/4 & 1/3 & 1/3 & 1/6 & 1/3 & 1/4 & 1/4 & 1/3 & 1/7 & 1/8 & 1/9 & 1/5 & 1/6 & 1/2 & 1/2 \\
8 & 1 & 4 & 5 & 6 & 5 & 3 & 5 & 4 & 4 & 6 & 1 & 1 & 1/2 & 3 & 2 & 7 & 7 \\
4 & 1/4 & 1 & 2 & 2 & 1/2 & 2 & 1 & 1 & 2 & 1/3 & 1/4 & 1/6 & 1/2 & 1/2 & 3 & 3 & I01 \\
3 & 1/5 & 1 & 1 & 1 & 1/3 & 1 & 1 & 1 & 1 & 1/4 & 1/5 & 1/6 & 1/2 & 1/3 & 2 & 2 & I02 \\
3 & 1/6 & 1/2 & 1 & 1 & 1/4 & 1 & 1/2 & 1/2 & 1 & 1/5 & 1/6 & 1/7 & 1/3 & 1 & 1 & 1 & 2 & 2 & I03 \\
3 & 1/5 & 1/2 & 1 & 1 & 1/3 & 1 & 1 & 1/2 & 1 & 1/5 & 1/5 & 1/7 & 1/3 & 1/4 & 2 & 2 & I04 \\
6 & 1/3 & 2 & 3 & 4 & 3 & 1 & 3 & 2 & 2 & 4 & 1/2 & 1/2 & 1/4 & 1 & 1 & 5 & 5 & I05 \\
3 & 1/5 & 1/2 & 1 & 1 & 1/3 & 1 & 1 & 1/2 & 1 & 1/4 & 1/5 & 1/7 & 1/3 & 1/3 & 2 & 2 & I06 \\
4 & 1/4 & 1 & 1 & 2 & 1/2 & 1 & 1 & 1 & 2 & 1/4 & 1/4 & 1/6 & 1/2 & 1/3 & 3 & 3 & I07 \\
3 & 1/6 & 1/2 & 1 & 1 & 1/4 & 1 & 1/2 & 1/2 & 1 & 1/5 & 1/5 & 1/7 & 1/3 & 1/4 & 2 & 2 & I08 \\
7 & 1 & 3 & 4 & 5 & 5 & 2 & 4 & 4 & 3 & 5 & 1 & 1 & 1/3 & 2 & 1 & 6 & 6 & I09 \\
8 & 1 & 4 & 5 & 6 & 5 & 2 & 5 & 4 & 4 & 5 & 1 & 1 & 1/2 & 3 & 2 & 6 & 7 & I10 \\
9 & 2 & 6 & 6 & 7 & 7 & 4 & 7 & 6 & 6 & 7 & 3 & 2 & 1 & 5 & 4 & 8 & 8 & I11 \\
5 & 1/3 & 2 & 2 & 3 & 3 & 1 & 3 & 2 & 2 & 3 & 1/2 & 1/3 & 1/5 & 1 & 1 & 4 & 4 & I12 \\
6 & 1/2 & 2 & 3 & 4 & 4 & 1 & 3 & 3 & 2 & 4 & 1 & 1/2 & 1/4 & 1 & 1 & 5 & 5 & I13 \\
2 & 1/7 & 1/3 & 1/2 & 1/2 & 1/5 & 1/2 & 1/3 & 1/3 & 1/2 & 1/6 & 1/6 & 1/8 & 1/4 & 1/5 & 1 & 1 & I14 \\
2 & 1/7 & 1/3 & 1/2 & 1/2 & 1/5 & 1/2 & 1/3 & 1/3 & 1/2 & 1/6 & 1/7 & 1/8 & 1/4 & 1/5 & 1 & 1 & I15 \\
\end{bmatrix}$$
Get the weight vector $W_h$ via formulas (4) to (6).

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

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

$$\hat{\lambda}_{\text{max}} = 18.4162.$$  

$$I_C = 0.0245.$$  

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).

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

### 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.

| ID | Standard status/value       | Membership type |
|----|-----------------------------|-----------------|
| 01 | -40 mmWC to 0 mmWC          | A               |
| 02 | True                        | D               |
| 03 | 20% to 95%                  | A               |
| 04 | 40% to 95%                  | A               |
| 05 | Above 50%                   | B               |
| 06 | Above 20V                   | B               |
| 07 | Less than 1800 rpm          | C               |
| 08 | Above 0.6 bar               | B               |
| 09 | Above 1.4 bar               | B               |
| 10 | Less than 90°C              | C               |
| 11 | True                        | D               |
| 12 | 440V, ±1%                   | A               |
| 13 | 60HZ, ±10%                  | A               |
| 14 | True                        | D               |
| 15 | True                        | D               |
| 16 | More than 7                 | B               |
| 17 | True                        | D               |
| 18 | True                        | D               |
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.

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

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

$$B = (0.0691, 0.0035, 0.1619, 0.1605, 0.5734).$$

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:

$$ D_s = \{I_{s01}, I_{s02}, \ldots, I_{s15}\} \ \text{(See the first column of Table 4 for details).} $$

$$ D_A = \{I_{101}, I_{102}, \ldots, I_{108}\} \ \text{(See the first column of Table 5 for details).} $$

$$ T_R = \{I_{r01}, I_{r02}, \ldots, I_{r18}\} \ \text{(See the first column of Table 6 for details).} $$

$$ T_N = \{I_{n01}, I_{n02}, \ldots, I_{n18}\} \ \text{(See the first column of Table 7 for details).} $$

### 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.

| $D_s$                                           | $D_{SC}$ | Remark |
|-------------------------------------------------|----------|--------|
| I$_{s01}$: Battery mode adjustment               | I$_{s01}$| Valid  |
| I$_{s02}$: Local control box power on            | I$_{s02}$| Valid  |
| I$_{s03}$: Ventilation adjustment                | I$_{s05}$| Invalid|
| I$_{s04}$: FO tank drainage                      | -        | -      |
| I$_{s05}$: DO tank level adjustment              | I$_{s06}$| Invalid|
| I$_{s06}$: LO tank level adjustment              | I$_{s10}$| Valid  |
| I$_{s07}$: CW tank level adjustment              | I$_{s09}$| 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$_{s12}$| Invalid|
| I$_{s12}$: Circuit breaker connected             | I$_{s13}$| Invalid|
| I$_{s13}$: Power supply to loads                 | I$_{s11}$| Valid  |
| I$_{s14}$: Generator in AUTO mode                | I$_{s15}$| Valid  |
| 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.

| $D_A$                                           | $D_{AC}$ | Remark |
|-------------------------------------------------|----------|--------|
| I$_{a01}$: P2/I$_{a02}$→P1/I$_{a03}$             | I$_{a01}$| Valid  |
| I$_{a02}$: P3/I$_{a05}$→P5/I$_{a06}$             | I$_{a02}$| Valid  |
| I$_{a03}$: P5/I$_{a06}$→P4/I$_{a07}$             | P5/I$_{a06}$→P3/I$_{a07}$ Invalid |
| I$_{a04}$: P3/I$_{a08}$→P5/I$_{a09}$             | P3/I$_{a08}$→P3/I$_{a09}$ Invalid |
| I$_{a05}$: P5/I$_{a09}$→P6/I$_{a10}$             | I$_{a05}$| Valid  |
| I$_{a06}$: P6/I$_{a11}$→P2/I$_{a12}$             | I$_{a06}$| Valid  |
| I$_{a07}$: P2/I$_{a13}$→P6/I$_{a14}$             | -        | -      |
| I$_{a08}$: P6/I$_{a14}$→P2/I$_{a15}$             | -        | -      |
Note: “P#1/I5*1→P#2/I5*2” means that the “P#1” transfers the information to “P#2” after completing the “I5*1” operation, and then “P#2” completes the “I5*2” operation.

Put $D_A, D_{RC}$ 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 $T_N$ is shown in Table 6.

| $T_R$       | $T_{RC}$ | Remark |
|-------------|----------|--------|
| Is01: Is01  | Is01     | Valid  |
| Is02: Is02  | Is02     | Valid  |
| Is03: Is03  | Is03     | Valid  |
| Is04: Is04  | -        | -      |
| Is05: Is05  | Is05     | Valid  |
| Is06: Is06  | Is06     | Valid  |
| Is07: Is07  | Is07     | Valid  |
| Is08: Is08  | Is08     | Valid  |
| Is09: Is09  | Is09     | Valid  |
| Is10: Is10  | Is10     | Valid  |
| Is11: Is11  | Is11     | Valid  |
| Is12: Is12  | Is12     | Valid  |
| Is13: Is13  | Is13     | Valid  |
| Is14: Is14  | -        | -      |
| Is15: Is15  | Is15     | Valid  |
| Is16: Voltage regulate | Is16 | Valid |
| Is17: Frequency regulate | Is17 | Valid |
| Is18: CW valve operate | Is18 | Valid |

- Redundant invalid operation 1
- Redundant invalid operation 2
- Redundant invalid operation 3
- Redundant invalid operation 4

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.

| $T_N$       | $T_{NC}$ | Remark |
|-------------|----------|--------|
| Is01: P2/Is01 | Is01   | Valid  |
| Is02: P2/Is02 | Is02   | Valid  |
| Is03: P1/Is03 | Is03   | Valid  |
| Is04: P3/Is04 | -      | -      |
| Is05: P3/Is05 | Is05   | Valid  |
| Is06: P5/Is06 | Is06   | Valid  |
| Is07: P4/Is07 | P3/Is07 | Invalid |
| Is08: P3/Is08 | Is08   | Valid  |
| Is09: P5/Is09 | P3/Is09 | Invalid |
| Is10: P6/Is10 | Is10   | Valid  |
| Is11: P6/Is11 | Is11   | Valid  |
| Is12: P2/Is12 | Is12   | Valid  |
| Is13: P2/Is13 | Is13   | Valid  |
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 $\lambda_S$, $\lambda_A$, $\lambda_R$, $\lambda_N$ 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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