Human Reliability Analysis in Ocean Voyages

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Abstract. There are various factors that can cause changes in human reliability during ocean voyages. By analyzing the ocean voyage scenario environment, seven factors including organizational planning, job competency level, personnel allocation, team collaboration level, physical and psychological state, ocean voyage time, and loading target scale were selected for fuzzy function processing. A time-varying function of human reliability in the ocean voyage scenario environment was constructed, and quantitative calculations of human error probability and reliability were carried out using examples to determine the variation law of human reliability under different days.

Keywords: human reliability; ocean voyages; human error probability

1 INTRODUCTION

Modern ships play an important role in the world economy and trade. Many ships need to perform ocean voyages for a long time, maintain navigation status, and have characteristics such as long navigation duration, complex technical processes, and harsh daily working environment. During ocean voyages, the personnel on duty are in a working state for a long time, and their mental state is highly tense. The daily operation time may accumulate to more than 18 hours. The longer the ocean voyage time, the higher the probability of human error in job operations, resulting in a decrease in human reliability over time.

In the field of human reliability analysis, the CREAM (Cognitive Reliability and Error Analysis Method) basic method is a widely used and relatively mature method, and its core idea is that the situational environment affects human cognition and behavior [1-4]. This basic law has strong practicality, but there are two problems: it believes that the 9 CPC (Common Performance Condition) factors representing the situational environment are equally important and have no difference in their impact on the probability of human error, but this is not the case; The CPC factor performance evaluation is generally completed through expert judgment, which makes the evaluation results susceptible to the influence of observational factors and reduces the accuracy of prediction results [1-5]. In view of this, the CPC factor of the traditional CREAM method is improved by introducing fuzzy membership degree to quantitatively evaluate the degree of fuzzy influence of each factor. The FAHP (Fuzzy Analytic Hierarchy

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Process) method is adopted to quantify the weight of each factor, and the trend of human error probability with the working time of ocean voyages is derived based on Markov correlation theory. The quantitative calculation function of human reliability under the scenario mode of ocean voyages is obtained, and verified with examples.

2 ANALYSIS OF THE ENVIRONMENT FOR OCEAN VOYAGES

During ocean voyages, personnel not only need to carry out established works, but also need to promptly and quickly deal with various unexpected situations, which puts high requirements on personnel's organizational command, job skills, team collaboration, physical and mental qualities, etc. In different ocean voyages scenarios, personnel's performance exhibits certain differences, which may lead to different human error issues. By analyzing the ocean voyages scenario environment, the key factors that affect human error can be identified.

2.1 Human Error Factor

Based on the actual work of ocean voyages, using the traditional 9 CPC factors as the basis, the staffing and ability level of job operators during the past few years of ocean navigation were carefully counted. Combined with the intuitive feelings of job operators, the ocean navigation scenario environment that affects human reliability was analyzed and summarized. Based on this, 7 CPC factors were selected, including organizational planning arrangement, job operation ability, personnel allocation, team cooperation and cooperation, physical and psychological state, ocean navigation time, and loading target scale, to compile the Ocean Navigation Scenario CPC Factor Table, as shown in Table 1.

Table 1. List of CPC factors for Ocean Voyages

Number	Name	Description	Related Factors
1	Organizational planning and arrangement	Whether the preparation work carried out according to the standard departure preparation time, and Whether it is an emergency preparation process	Preparation time Preparation deadline
2	Job competency level	Knowledge, operational skills, and experience level of job personnel	Having a certain level of knowledge and skills the number of personnel
3	Personnel allocation situation	Whether it meets the demand for the number of personnel in the position, reduces the part-time rate, and has a certain reserve rate	Number of personnel in positions with a certain level of ability
4	Team collaboration level	Can the collaboration quality of team members effectively exert supervision and constraints	Total number of personnel in the position Number of new horn players
5	Physical and psychological state	Physical, psychological, mental state, reaction speed, fatigue level, etc.	Navigation working hours

6	Ocean voyage time	Has the ocean voyage time reached its limit	Duration of navigation Extreme sailing time
7	Load target scale	Whether the loading of materials matches the tonnage of the ship and whether it is fully loaded	Target quantity Scale of loading materials

To describe the comprehensive impact of ocean voyages scenario environment on human error probability, the impact of CPC factor on human error probability is quantified, namely:

$$CPC_i = \begin{cases} N & \text{improve} \\ 0 & \text{not significant} \\ -N & \text{reduce} \end{cases} \tag{1}$$

In the formula: CPC_i represents the quantified value of the i impact of the CPC factor on the probability of human error, 0< N <1. The longer the duration of the ocean voyages, the stronger the reliability impact of the associated CPC factor.

Considering the weights of each factor, it is necessary to take into account the degree of influence of the above aspects. Due to the fact that the CREAM basic method did not consider the weight differences of CPC factors in different environments, treating all factors equally is not in line with the reality of ocean voyages. The FAHP method can more accurately measure the impact of various CPC factors on the overall performance of ocean navigation scenarios. To characterize the comprehensive impact of the ocean navigation scenario environment, the CPC factor impact comprehensive index R (referred to as the scenario index) is defined, which is:

$$R = \sum_{i=1}^{7} 7\omega_i CPC_i \tag{2}$$

In the formula, ω_I is the weight of the CPC factor obtained by applying the FAHP method. According to the correspondence between the CPC scenario index R and the control mode [1-4], as shown in Table 2, it can be seen that the maximum and minimum values of R are 7 and -7.

Table 2. R Correspondence to Control Mode

Number	Scenario Index *R*	Control Mode	Error Probability Interval
1	4≤R≤7	Strategic	（0.00005，0.01）
2	0≤R<4	Tactical type	（0.001，0.1）
3	-4≤R<0	Opportunity oriented	（0.001，0.5）
4	-7≤R<-4	Chaotic type	（0.1，1）

2.2 Fuzzy Membership Function

In practical work, the boundary between scenario index and control mode is not clear, and the human error factor cannot be determined by a clear value of 1 or -1 in practice. Therefore, membership functions are used to fuzzily process the CPC factor [6-9].

The Factors of Organizational Planning and Arrangement. The more flexible the time limit of the organization plan arrangement factor for ocean voyages, the longer the preparation time for the organization plan, the more opportunities for various preparation work, and the lower the probability of human error. Describe the fuzzy impact relationship between organizational planning and human error probability using the following membership functions:

$$CPC_1 = \begin{cases} 1, & t_E - t_0 < t_{SX} - t_0 \\ 0, & t_E - t_0 = t_{SX} - t_0 \\ -1, & t_E - t_0 > t_{SX} - t_0 \end{cases} \tag{3}$$

In the formula: t_0 is the start loading time for ocean voyages, t_E is the time limit for preparing everything according to standard workflow, and t_{SX} is the time limit for completing actual preparation work.

The Factors of Job Competency Level. The impact of competency on the probability of human error is directly related to job settings, personnel occupancy rate, and training level. Describe the fuzzy impact relationship between job competency and human error probability using the following membership function:

$$CPC_2 = \begin{cases} \dfrac{g_{sy} - g_{xq}}{g_{xq}}, & g_{sy} - g_{xq} > 0 \\ 0, & g_{sy} - g_{xq} = 0 \\ -1, & g_{sy} - g_{xq} < 0 \end{cases} \tag{4}$$

In the formula, g_{xq} is the total number of qualified personnel required for completing ocean voyages, g_{sy} is the current total number of qualified personnel for training positions.

The Factors of Personnel Allocation Situation. During ocean voyages, personnel in each position must be assigned and positioned, and backup positions should be appropriately increased to cope with unexpected situations. Describe the fuzzy function relationship between personnel allocation and human error probability using the following membership functions:

$$CPC_3 = \begin{cases} \dfrac{p_{sy} - p_o}{p_{sy}}, & p_{sy} - p_o > 0 \\ 0, & p_{sy} - p_o = 0 \\ -1, & p_{sy} - p_o < 0 \end{cases} \tag{5}$$

In the formula: $p_o = (1+b) * p_{sy}$ is the number of personnel required for ocean voyages and p_{sy} is represents the current total number of personnel. If $p_{sy} - p_o > 0$, It indicates that the personnel are adequately equipped, otherwise it indicates that there is a certain vacancy, and it is necessary to arrange part-time work or rotate work at a certain time.The standby coefficient is based on the experience of ocean voyages data. The general value is $b = (0.01 \sim 0.03) * D$, and D is the number of days for ocean voyages.

The Factors of Team Collaboration Level. The level of team collaboration has a shortcoming effect, and the level of collaboration of newly added horn operators is crucial. The newly hired personnel have a relatively short operating time and low proficiency in equipment, and their efficiency and quality in cooperating and completing work with other trumpeters in a short period of time are not high, which seriously restricts the team's level of collaborative operation. Describe the fuzzy relationship between team collaboration level and human error probability using the following membership function:

$$CPC_4 = \left(1 - \frac{g_n}{g_{sy}}\right)^{D/D_{\max}} \tag{6}$$

In the formula: g_n represents the total number of trained and qualified personnel in the current position, g_{sy} represents the number of new operators added in the past two years, D is the number of days for ocean voyages, $D_{\max}$ is the extreme time for ocean voyages.

Generally speaking, the more new trumpeters there are, the more job rotations they participate in, the more cumulative errors they make during work handovers or intersections, and the lower the level of team collaboration, which will lead to a higher probability of human error.

The Factors of Physical and Psychological State. The growth theory curve is applicable to the growth laws of animal organisms and is commonly used to analyze life cycle problems with growth limits. The reliability level of personnel in the ocean voyages environment also shows this trend [5]. Describe the fuzzy relationship between physical and psychological states and human error probability using the following membership functions:

$$CPC_5 = \frac{K}{1 + ae^{-b\gamma}} \tag{7}$$

In the formula: γ represents the fuzzy correlation index, which is used to measure the fuzzy correlation degree caused by changes in the physical condition of job personnel under the workload of ocean voyages. The value can be taken as $\gamma = D\times 10^{-2}$, and D is the number of days of ocean voyages, K=1.004, $\alpha = 15.412$ [5].

The Factors of Ocean Voyage Time. Ocean voyages generally require long periods of navigation, transportation, and loading. The longer the time, the personnel gradually enter a fatigue period, resulting in an increased probability of human error. Describe the fuzzy relationship between the execution time factor of ocean voyages and the probability of human error using the following membership functions:

$$CPC_6 = \frac{D_{\max} - D}{D_{\max}} \tag{8}$$

In the formula, $D_{\max}$ is the number of days the ship has sailed to its limit, and D is the number of days it has completed the ocean voyages. Generally speaking, the duration of a ocean voyages cannot exceed the maximum duration of the voyage.

The Factors of Load Target Scale. The more materials are loaded, the stronger the ship's ability to navigate long distances, but the probability of human error will also increase. Describe the fuzzy relationship between the loading target scale and the probability of human error using the following membership functions:

$$CPC_7 = \frac{M_{\max} - M}{M_{\max}} \tag{9}$$

In the formula: $M_{\max}$ represents the maximum quantity of materials loaded for the ship's ocean voyage, and M represents the quantity of materials loaded for this ocean voyage.

3 QUANTITATIVE CALCULATION OF HUMAN RELIABILITY

3.1 Calculation of Human Error Probability

The relationship between ocean voyages scenario environment and human reliability is shown in Figure 1. Human reliability will increase with the improvement of ocean voyages scenario environment, and the probability of human error P_{HEP} will decrease.

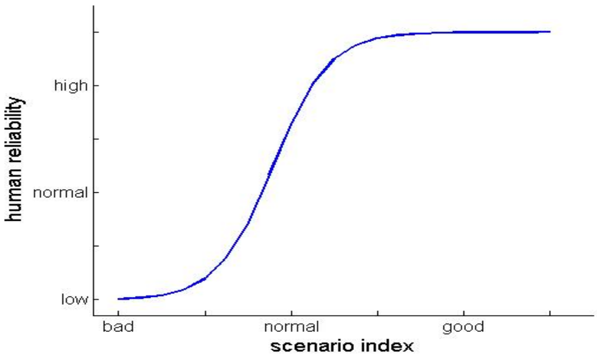

Fig. 1. Relationship Diagram between Ocean Voyages Situation Pattern and Human Factor Reliability

For the convenience of CPC weight processing and comprehensive score calculation, it is assumed that there is an approximate correspondence between the ocean voyages scenario environment and human error probability [5-7]. The logarithmic relationship between changes in common performance conditions and improvements or decreases in human error probability can be described as follows:

$$\ln(P_{HEP} / P_{HEP.0}) = K\mathrm{I} \tag{10}$$

Based on this, a natural logarithm model is used to fit the relationship between human error probability P_{HEP} and scenario index R:

$$\ln(P_{HEP} / P_{HEP.0}) = KR \tag{11}$$

In the formula: K is a constant, which can be derived from the following formula:

$$\begin{aligned} \ln(P_{HEP.\max} / P_{HEP.0}) &= KR_{\min} \\ \ln(P_{HEP.\min} / P_{HEP.0}) &= KR_{\max} \end{aligned} \tag{12}$$

Therefore, there are:

$$K = \ln(P_{HEP.\max} / P_{HEP.\min}) / (R_{\min} - R_{\max}) \tag{13}$$

$$P_{HEP.0} = P_{HEP.\max} / e^{KR_{\min}} \tag{14}$$

According to Table 2, the extreme value of human error probability can be taken $P_{HEP.\max} = 1.0$, $P_{HEP.\min} = 0.00005$. The CPC factor is set to an extreme value according to their respective settings.

Table 3. Extreme Table of CPC Factor

Factor	1	2	3	4	5	6	7	Scenario index
Maximum value	1	1	1	1	1	1	1	7
minimum value	-1	-1	-1	0	0	0	0	-3

After improvement $R_{\max} = 7$, After lowering $R_{\min} = -3$. From this, it can be concluded that: K=-0.9903, $P_{HEP.0} = 0.0513$. and: $P_{HEP} = P_{HEP.0}e^{K \cdot R} = 0.0513e^{-0.9903 \cdot R}$.

The above equation can be used to measure the degree to which the probability of human error P_{HEP} is affected by changes in ocean navigation scenarios. The curve shown in Figure 2 shows that when the scenario index is low, meaning that various factors are not suitable for work, the probability of human error is higher; When the scenario index increases, meaning that various factors are beneficial for carrying out work, the probability of human error gradually decreases.

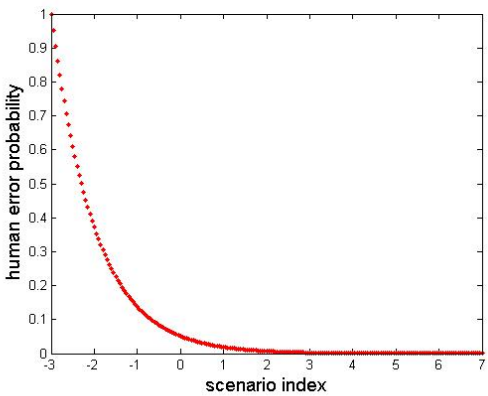

Fig. 2. Human Error Probability Curve

3.2 Calculation of Human Reliability

For job operators, the variation pattern of reliability during continuous working hours can be used to analyze their error probability [10]. The probability of a job operator correctly executing a work at any given time is:

$$P(X(t) = 0) = e^{-\alpha t} \tag{15}$$

The probability of operational errors by personnel at the given t times is:

$$F(t) = 1 - P(X(t) = 0) = 1 - e^{-\alpha t} \tag{16}$$

The P_{HEP} calculated from the previous text can be considered to be approximately equal to the average human error probability during the working time of ocean voyages, as $\alpha = P_{HEP}$.

In summary, the calculation formula for human reliability R_H can be obtained as follows:

$$R_H = e^{-P_{HEP} \cdot t} = e^{-[0.0513\exp(-0.9903*R)]\cdot t} \tag{17}$$

Based on the above equation, the variation curve of human reliability R_H with work time and scenario index can be generated, as shown in Figure 3. The trend of human reliability under 8 and 16 hour working modes is shown by the green, yellow, and red curves, respectively. This indicates that the heavier ocean voyages, the longer the working time, the heavier the psychological pressure and workload of personnel, and the poorer the reliability of human factors. Under the same scenario index, human reliability shows a decreasing trend with prolonged working hours.

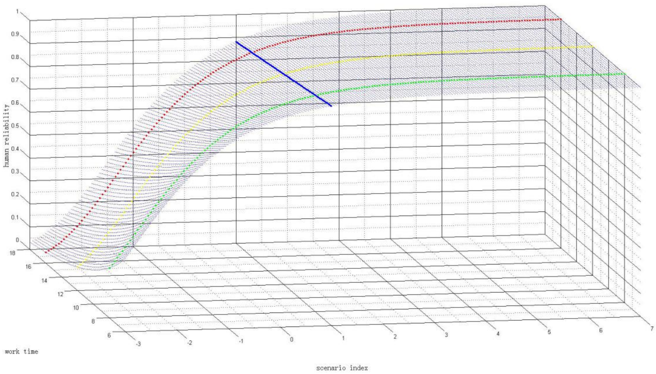

Fig. 3. Variation diagram of human factor reliability for ocean voyages

4 EXAMPLE

Assuming that a certain ship is about to carry out ocean voyages, its loading capacity is set to 3/4 of its full load, and the maximum time for ocean voyages is 200 days. According to general practice, personnel are assigned and their ocean voyage days are set to 30, 60, 90, 120, 150, and 180, respectively. Based on assumed data, the fuzzy membership degree quantification method was used to obtain the reliability impact of CPC factors, and the fuzzy membership degree is shown in Table 4.

Table 4. Quantitative Results of CPC Factor

Days of ocean voyages	CPC_1	CPC_2	CPC_3	CPC_4	CPC_5	CPC_6	CPC_7
30	1	0.441860465	0.399864529	0.768817204	0.965041005	0.85	0.25
60	1	0.441860465	0.360245722	0.768817204	0.713351761	0.7	0.25
90	1	0.441860465	0.322807766	0.768817204	0.196395957	0.55	0.25

120	1	0.441860465	0.287375415	0.768817204	0.023622476	0.4	0.25
150	1	0.441860465	0.253791709	0.768817204	0.002391268	0.25	0.25
180	1	0.441860465	0.221915648	0.768817204	0.000237443	0.1	0.25

Using the technical expert questionnaire scoring method, 7 CPC factor weights were scored and a fuzzy judgment matrix was established. The CPC factor weights were calculated based on the FAHP method, as shown in Table 5. The human reliability data of ocean voyages scenario index corresponding to different days and working hours calculated based on Tables 4 and 5 are shown in Table 6.

Table 5. Weight Value of CPC Factor

CPC Factor	CPC_1	CPC_2	CPC_3	CPC_4	CPC_5	CPC_6	CPC_7
Weight Value	0.1286	0.1500	0.1500	0.1429	0.1382	0.1595	0.1286

Table 6. Reliability Data for People on Ocean Voyages

Days of ocean voyages	Scenario index	Human error probability	human reliability(16h)	human reliability(12h)	human reliability(8h)
30	4.89300142	0.000402899	0.993574346	0.995176878	0.996781995
60	4.44060207	0.00063063	0.989960652	0.992461	0.994967664
90	3.734068272	0.001269571	0.979891784	0.98488061	0.989894835
120	3.362349939	0.00183457	0.971073504	0.978225722	0.985430618
150	3.139063546	0.002288602	0.964044678	0.972910457	0.981857769
180	2.936011652	0.00279836	0.956213791	0.966977241	0.977861847

The results indicate that the length of working hours and the number of ocean voyages days have a significant impact on human reliability. As the duration of ocean voyages increases, the scenario index gradually decreases and tends to be unfavorable, with a higher probability of human error and a significant decrease in human reliability. Taking 16 hours of daily work as an example, the probability of human error during a 30 day ocean voyage is 0.000402899. As the number of days spent on ocean voyages increases, the probability of human error also gradually increases. When conducting a 180-day ocean voyage, the probability of human error is 0.00279836, which is several times higher than the 30-day ocean voyage.

5 CONCLUSION

Based on the improved human reliability model in this article, it can evaluate the probability of human error in ocean voyages, with high discrimination and relatively objective accuracy. It is used to estimate the potential risk points of human error probability in ocean voyages, take targeted measures to improve human reliability in ocean voyages, and can be used as a quantitative tool for safety risk assessment in ocean voyages. It is helpful for scientific organization, rigorous deployment, and reasonable planning, and provides scientific guidance for the development of ocean voyages.

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