# A new hybrid approach to human error probability quantification - applications in maritime operations

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# Abstract

Human Reliability Analysis (HRA) has always been an essential research issue in safety critical systems. Cognitive Reliability Error Analysis Method (CREAM), as a well-known second generation HRA method is capable of conducting both retrospective and prospective analysis, thus being widely used in many sectors. However, the needs of addressing the use of a deterministic approach to configure common performance conditions (CPCs) and the assignment of the same importance to all the CPCs in a traditional CREAM method reveal a significant research gap to be fulfilled. This paper describes a modified CREAM methodology based on an Evidential Reasoning (ER) approach and a Decision Making Trial and Evaluation Laboratory (DEMATEL) technique for making human error probability quantification in CREAM rational. An illustrative case study associated with maritime operation is presented. The proposed method is validated by sensitivity analysis and the quantitative analysis result is verified through comparing the data and the benchmarking with the real data collected from Shanghai coastal waters. Its main contribution lies in that it for the first time addresses the data incompleteness in HEP, given that the previous relevant studies mainly focus on the fuzziness in data. The findings will provide useful insights for quantitative assessment of seafarers' errors to reduce maritime risks due to human errors.

Keywords: Human reliability analysis, CREAM, HEP quantification, maritime transport, maritime risk

# **1. Introduction**

Human error has caused many industrial accidents and disasters. Human Reliability Analysis (HRA) has therefore been an essential research issue. With the development of new technologies, the emerge of complex systems such as Nuclear Power Plant (NPP) and Very Large Crude Carrier (VLCC), makes the consequences of accidents more and more serious. Many approaches have been developed for facilitating human error quantification and human reliability analysis, such as Human Cognitive Reliability model (HCR) (Hannaman et al., 1984), Success Likelihood Index Method (SLIM) (Embrey et al., 1984), Technique for Human Error Rate Prediction (THERP) (Swain and Guttmann, 1983), Human Error Assessment and Reduction Technique (HEART) (Williams, 1988), A Technique for Human Error Analysis (ATHEANA) (Cooper et al., 1996), Cognitive Reliability and Error Analysis

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Method (CREAM) (Hollnagel, 1998), SPAR-H (Gertman et al., 2005) and Bayesian Network approach (Baraldi et al., 2015). There are also some specific methods developed in the literature for Human Error Probability (HEP) quantification (Sun et al., 2012). Such approaches have been widely applied to deal with human error and human factors in various sectors including nuclear (Alvarenga et al., 2014; Jang et al., 2013), spaceflight (Calhoun et al., 2013, 2014), marine and maritime (Akyuz and Celik, 2015a, 2015b, 2016; Yang et al., 2013; Akyuz, 2016; Chen et al., 2013; Wang et al., 2011), and civil infrastructure (Nan and Sansavini, 2016), etc.

# 1.1. CREAM

The well-known CREAM, established by Hollnagel in 1998 (Hollnagel, 1998), has been applied to human error quantification of safety-critical systems. Both retrospective and prospective analyses can be carried out for the diagnosis and prediction of industrial accidents and events. For the prospective analysis, two steps are designed for human error quantification which are a basic method and an extended method, respectively. The basic method is used for determination of control modes and corresponding error rate intervals at a screening stage, while the extended method is employed for error quantification of cognitive functions. However, the two inherently deterministic methods arguably lack capability of dealing with the uncertainties in common performance condition (CPC) configuration (Kim et al., 2006) and different weight assignments (He et al., 2008) to the CPCs in traditional CREAM. Recently, some studies have been conducted for the improvement of CREAM and HEP estimation by means of probabilistic techniques (Kim et al., 2006; Fujita and Hollnagel, 2004), fuzzy approaches (Konstandinidou et al., 2006; Marseguerra et al., 2006, 2007; Wang et al., 2001; Yang et al., 2013; Ung et al., 2015), simplification (Sun et al., 2012; He et al., 2008) and combination (Akyuz, 2015; Ribeiro, 2016). Fujita and Hollnagel (2004) designed a new version of basic method of CREAM and Kim et al. (2006) described a probabilistic approach for determining the control modes. Konstandinidou et al. (2006), Marseguerra et al. (2006, 2007 and Wang et al. (2001) presented fuzzy sets, fuzzy rules and fuzzy-clonal selection methods for contextual and reliability evaluation. However, the fuzzy model of CREAM brings on many redundant, self-contradictory rules, which would consume computational time, and lose the truth degree of the results (Wang et al., 2001). Sun et al. (2012) and He et al. (2008) simplified the CREAM for HEP point estimation while Lee et al. (2011) designed a CREAM-based communication error analysis method (CEAM) for communication error analysis. Akyuz (2015) constructed a risk-based CREAM model for HEP quantification towards the gas inerting process on-board crude oil tankers and Ribeiro et al (2016) presented a hybrid THERP-CREAM method to analysis the human reliability of Tokai-Mura accidents. Although showing attractiveness in terms of providing solutions to some of the inherent drawbacks of CREAM, such methods have not yet well addressed the incompleteness in subjective data from experts, revealing the need for further studies in the field.

# 1.2. Evidential Reasoning (ER) and DEMATEL technique

Dempster-Shafer Theory (DST) was developed by Dempster in 1967 (Dempster, 1967) and later refined by Shafer in 1976 (Shafer, 1976). Subsequently, DST is known as one of the most powerful tools to deal with uncertainty problems. The evidential reasoning (ER) approach (Yang and Singh, 1994; Yang et al., 2006; Xu et al., 2006), which was initially oriented to model multiple attribute decision analysis (MADA) problems is further developed for overcoming some weaknesses in DST. It is conducted by generating basic probability assignments (BPA) through the combination of degrees of belief (DoBs) and normalised

weights. It is because of the advantage of ER in modelling incompleteness that recently it has been widely applied in many domains such as safety assessment (Xi et al., 2008), environmental impact assessment (Wang et al., 2006) and software selection (Fu and Yang, 2010). In this paper, the ER approach is employed for evaluating the CPCs and combining the DoBs to generate the BPA of CPCs in the modified CREAM methodology. The DEMATEL technique was developed by the Geneva Research Centre of the Battelle Memorial Institute (Fontela and Gabus, 1976; Gabus and Fontela, 1973). It presents the cause and effect groups within a system or subsystem by applying matrices and digraphs to visualise the structure of complicated causal relationships. The advantages of DEMATEL lie in its capability of effectively modelling and quantifying the causal relationships among interdependent factors. The DEMATEL has therefore been successfully applied in many fields including business (Tseng, 2009; Wu and Lee, 2007), engineering (Seyed-Hosseini et al., 2008), education (Tzeng et al., 2007) and social studies (Tamura and Akazawa, 2005). In this paper, the technique is used to model the dependency among CPCs and further, together with the assigned weights of CPCs, to determine the values of adjusting indices. Given the strengths of ER and DEMATEL in modelling uncertainties, this paper proposes a new modified CREAM method to calculate HEP in a rational way.

Given their strengths in tackling different uncertainties exposed in traditional CREAM, ER and DEMATEL are combined to construct a new modified HEP quantification model of two stages, a general analysis stage and a quantification evaluation stage. The general analysis in Section 2 proposes an ER approach to model the incompleteness associated with CPC configuration and combination of DoBs, and to determine the corresponding control mode(s), probability intervals and the total state of context. The quantification evaluation in Section 3 describes a DEMATEL technique to simulate the interdependency of CPCs and to determine the different weights of CPCs and adjusting index values. Consequently, a rational error probability can be obtained at this stage. In Section 4, an illustrative case study in maritime operations is presented and real data has been recorded to benchmark and validate the modified method and research findings. Section 5 concludes this paper.

# 2. Modified CREAM: a general analysis

The core of CREAM is the Contextual Control Model (COCOM). COCOM focuses on a principle that human cognition is not only a response to a serious input but also a close loop process of continuous purposive adjustment for intension. Four kinds of control modes are defined according to the human cognition and the context, which are determined by nine Common Performance Conditions (CPCs). The four control modes are "Scrambled", "Opportunistic", "Tactical" and "Strategic" respectively (Fig.1) while the nine CPCs are "Adequacy of organisation (CPC1)", "Working conditions (CPC2)", "Adequacy of manmachine interface and operational support (CPC<sub>3</sub>)", "Availability of procedures and plans  $(CPC_4)$ ", "Number of simultaneous goals  $(CPC_5)$ ", "Available time  $(CPC_6)$ ", "Time of day (CPC<sub>7</sub>)", "Adequacy of training and experience (CPC<sub>8</sub>)" and "Crew collaboration quality (CPC<sub>9</sub>)", respectively (Table 1). Each CPC may be evaluated at different levels indicating an improved, not significant or reduced effect on human performance accordingly. The control mode and its wide failure interval are determined by the couple of  $(\Sigma_{Improved}, \Sigma_{Reduced})$ . For example, if an event is evaluated to have 5 CPCs of improved effects and 4 CPCs of reduced effects, then its corresponding COCOM will be "Tactical" according to Fig. 1 and failure probability interval will be  $1E-3 \le P \le 1E-1$  from Table 2.



Fig.1. Relation between CPCs and control modes (Hollnagel, 1998)

Table1. Description of CPCs and associated linguistic variables (Hollnagel, 1998)

| СРС   | Level   | Effect          |
|---|---|-----------------|
| CPC <sub>1</sub> Adequacy of organization             | L <sub>11</sub> Very efficient                      | Improved        |
| (AOO)   | L <sub>12</sub> Efficient                           | Not significant |
|   | L <sub>13</sub> Inefficient                         | Reduced         |
|   | L <sub>14</sub> Deficient                           | Reduced         |
| CPC <sub>2</sub> Working conditions                   | L <sub>21</sub> Advantageous                        | Improved        |
| (WCO)   | L <sub>22</sub> Compatible                          | Not significant |
|   | L <sub>23</sub> Incompatible                        | Reduced         |
| CPC3 Adequacy of MMI and operational support          | L <sub>31</sub> Supportive                          | Improved        |
| (MMI)   | L <sub>32</sub> Adequate                            | Not significant |
|   | L <sub>33</sub> Tolerable                           | Not significant |
|   | L <sub>34</sub> Inappropriate                       | Reduced         |
| CPC4 Availability of procedures/plans                 | L <sub>41</sub> Appropriate                         | Improved        |
| (AOP)   | L <sub>42</sub> Acceptable                          | Not significant |
|   | L <sub>43</sub> Inappropriate                       | Reduced         |
| CPC5 Number of simultaneous goals                     | L <sub>51</sub> Fewer than capacity                 | Not significant |
| (NOS)   | L <sub>52</sub> Matching current capacity           | Not significant |
|   | L <sub>53</sub> More than capacity                  | Reduced         |
| CPC <sub>6</sub> Available time                       | L <sub>61</sub> Adequate                            | Improved        |
| (ATI)   | L <sub>62</sub> Temporarily inadequate              | Not significant |
|   | L <sub>63</sub> Continuously inadequate             | Reduced         |
| CPC7 Time of day                                      | L <sub>71</sub> Day-time (0600-1800) (adjusted)     | Not significant |
| (TOD)   | L <sub>72</sub> Night-time (1700-2400) (unadjusted) | Reduced         |
|   | L <sub>73</sub> Night-time(0000-0700) (unadjusted)  | Reduced         |
| CPC <sub>8</sub> Adequacy of training and preparation | L <sub>81</sub> Adequate, high experience           | Improved        |
| (AOT)   | L <sub>82</sub> Adequate, limited experience        | Not significant |
|   | L <sub>83</sub> Inadequate                          | Reduced         |
| CPC9 Crew collaboration quality                       | L <sub>91</sub> Very efficient                      | Improved        |
| (CCQ)   | L92 Efficient                                       | Not significant |
|   | L93 Inefficient                                     | Not significant |
|   | L <sub>94</sub> Deficient                           | Reduced         |

## 2.1. Evaluating the CPCs using a DoB approach

The traditional method for evaluating the level and its effect to human reliability is easy and visible. However, it only shows a general principle (Kim et al., 2006) thus revealing some problems in its practical applications. It needs to be further improved and developed in determining the levels of CPCs and its effect to human reliability rationally. It is well known that an exact evaluation of CPCs is important but very difficult for the performance prediction. Nevertheless, it is not always easy to specify CPCs exclusively, due to the insufficiency of information and data of the context under investigation. There would be a great amount of uncertainties in the specification of CPCs. For tackling such uncertainties, a new approach which can model the DoBs distribution in the specification of CPCs is

proposed. For example, an expert can give DoBs such as {0.2 Very efficient, 0.5 Efficient, 0.3 Inefficient, 0 Deficient} instead of a "crisp" judgement when evaluating  $CPC_1$ . One of the advantages of the DoB approach (Yang and Singh, 1994) is that the uncertainty associated with a CPC can be expressed in a rational way as required in practice. Second, a number of  $(\Sigma_{Improved}, \Sigma_{Reduced})$  couples can be produced to indicate the possible contexts and to optimise the simulation of the associated operations. Third, the DoB approach allows the synthesis of CPCs specifications from multiple experts. It is noteworthy that the DoB approach for CPCs are clearly specified, the DoB can be set to be 1 for the corresponding CPCs levels. The algorithm of combining the DoB structures given by multiple experts on CPCs levels is represented in Section 2.2.

Although the rules of modelling the interdependence adjustment of CPCs in the traditional basic CREAM are presented, it was argued that the influence of such adjustment deems to be insignificant at a general analysis stage (Kim et al., 2006). The detailed consideration of modelling the CPC adjustment rules is therefore investigated in the detailed quantification analysis stage in Section 3.

## 2.2. Combining the evaluations by experts using ER algorithm

Let  $L_{in}$  denote the *n*th level of  $CPC_i$ , then  $L_i = \{L_{i1}, \dots, L_{in}, \dots, L_{iN}\}$  be the frame of discernment which represents the levels of  $CPC_i$   $(1 \le i \le 9; n=1,\dots,N)$  and it is required to be a collectively exhaustive and mutually exclusive set of hypotheses. If  $CPC_i$  is evaluated to a level  $L_{in}$  by the expert  $E_g$   $(1 \le g \le G)$  with a degree of belief  $\beta_{in}^g$ , we denote this evaluation by  $S(E_g) = \{(L_{in}, \beta_{in}^g)\}$ , which is a distributed evaluation and referred to as a belief structure (Yang et al., 2006), where  $\beta_{in}^g \ge 0$  and

$$\sum_{n=1}^{N} \beta_{in}^{g} \le 1 \tag{1}$$

If  $\sum_{n=1}^{N} \beta_{in}^{g} = 1$ , it is called a complete evaluation. If  $\sum_{n=1}^{N} \beta_{in}^{g} < 1$ , the evaluation is incomplete, the difference  $(1 - \sum_{n=1}^{N} \beta_{in}^{g})$  shows the degree of ignorance.

In the first step, a DoB given to an evaluation level  $L_{in}$  by  $E_g$  is transformed into a basic probability mass by multiplying the given DoB  $\beta_{in}^g$  by  $w_g^{\dagger}$  ( $\sum_{g=1}^G w_g = 1$ ) which is defined as the relative importance of  $E_g$ . The liner function which transformed the DoB given to an evaluation  $L_{in}$  by  $E_g$  into a basic probability mass can be established as follows

$$m_{in}^{g} = w_{g}\beta_{in}^{g}, n = 1, \dots, N; g = 1, \dots, G$$
<sup>(2)</sup>

If  $\beta_{in}^g$  satisfies Eq. (1), then  $\sum_{n=1}^N m_g^{in} \le 1$  and accordingly (Yang et al., 2006; Xu et al., 2006; Yang et al., 2009; Yang and Wang, 2015).

$$m_{L_i}^g = 1 - \sum_{n=1}^N m_{in}^g = 1 - w_g \sum_{n=1}^N \beta_{in}^g$$
(3)

<sup>&</sup>lt;sup>†</sup> Expert knowledge is influenced by individual perspectives and goals (Ford and Serman, 1998). Therefore, complete impartiality of expert knowledge is often difficult to achieve. An important consideration is the weighting factors of experts. In this study, the weighting factors of experts are determined according to their professional position, service time and education level.

$$\bar{m}_{L_i}^g = 1 - w_g \tag{4}$$

$$\widetilde{m}_{L_i}^g = w_g \left( 1 - \sum_{n=1}^N \beta_{in}^g \right) \tag{5}$$

where  $m_{in}^g$  is the basic probability mass which measures the belief exactly assigned to  $L_{in}$  and represents how strongly the expert  $E_g$  supports  $L_{in}$ .  $m_{L_i}^g = \overline{m}_{L_i}^g + \widetilde{m}_{L_i}^g$  for all g=1,2,...,G. The probability mass of  $E_g$  ( $m_{L_i}^g$ ) unassigned to any individual  $L_{in}$  is split into two parts, one caused by the relative importance of  $E_g$  ( $\overline{m}_{L_i}^g$ ), and the other due to the incompleteness of the belief degree assessment  $\beta_{in}^g$  ( $\widetilde{m}_{L_i}^g$ ).

The second step is to obtain the total DoB ( $\beta_{in}$ ) by combining the basic probability masses  $(m_{in}^g)$  generated above. Suppose the evaluation levels are mutually exclusive and collectively exhaustive, Dempster's rule of combination (Yang et al., 2006) can be applied to combine the basic probability masses. Suppose  $m_{in}^{I(g)}$  is the combined belief degree  $L_{in}$  by aggregating all the basic probability masses from the *g* experts and  $m_{L_i}^{I(g)}$  is the remaining belief degree unassigned to any  $L_{in}$ . Let  $m_{in}^{I(1)} = m_{in}^1$  and  $m_{L_i}^{I(1)} = m_{L_i}^1$ . Then the overall combined belief degree in  $L_{in}$  can be generated as follows (Yang et al., 2006; Xu et al., 2006; Yang et al., 2009; Yang et al., 2014).

$$\{L_{in}\}: m_{in}^{I(g+1)} = K_{I(g+1)} \left[ m_{in}^{I(g)} m_{in}^{g+1} + m_{in}^{I(g)} m_{L_i}^{g+1} + m_{L_i}^{I(g)} m_{in}^{g+1} \right]$$
(6)

$$m_{L_i}^{I(g)} = \overline{m}_{L_i}^{I(g)} + \widetilde{m}_{L_i}^{I(g)} \quad g = 1, 2, \dots, G - 1$$
(7)

$$\{L_i\}: \ \widetilde{m}_{L_i}^{I(g+1)} = K_{I(g+1)} \left[ \widetilde{m}_{L_i}^{I(g)} \widetilde{m}_{L_i}^{g+1} + \widetilde{m}_{L_i}^{I(g)} \overline{m}_{L_i}^{g+1} + \overline{m}_{L_i}^{I(g)} \widetilde{m}_{L_i}^{g+1} \right]$$
(8)

$$\overline{m}_{L_{i}}^{l(g+1)} = K_{l(g+1)} \left[ \overline{m}_{L_{i}}^{l(g)} \overline{m}_{L_{i}}^{g+1} \right]$$
(9)

$$K_{I(g+1)} = \left[1 - \sum_{n=1}^{N} \sum_{\substack{h=1\\h \neq n}}^{N} m_{in}^{I(g)} m_{ih}^{g+1}\right]^{-1}, g = 1, 2, \dots, G-1$$
(10)

$$\{L_{in}\}: \beta_{in} = \frac{m_{in}^{I(G)}}{1 - \bar{m}_{L_i}^{I(G)}} \ (n = 1, 2, \dots, N)$$
(11)

$$\{L_i\}: \beta_{L_i} = \frac{\widetilde{m}_{L_i}^{I(G)}}{1 - \overline{m}_{L_i}^{I(G)}}$$
(12)

where  $\beta_{in}$  shows the combined DoB assigned to  $L_{in}$  in the levels of  $CPC_i$  ( $L_i$ ) and  $\beta_{L_i}$  indicates the normalised remaining DoB unassigned to any  $L_{in}$ .

1(0)

## 2.3. Calculating HEP of the whole task

In terms of the DoB approach for CPCs specification and the ER algorithm, the corresponding couple ( $\Sigma_{Improved}, \Sigma_{Reduced}$ ) can be obtained and presented by decimal figures instead of integer ones. It is therefore difficult to directly use Figure 1 and Table 2 to determine the probability intervals. For example, if a couple (1.5, 3.2) is obtained, the control

mode is at the boundary between Strategic and Tactical from Fig. 1, indicating that it belongs to both Strategic and Tactical control modes. Therefore, its probability interval can be determined by the intersection of the probability intervals of Strategic and Tactical modes. The probability intervals of the three boundaries between the four control modes are obtained through deriving the intersection between two neighbouring intervals. For example, the intersection between the probability intervals of Strategic and Tactical modes is 1E-3 < P < 1E-2. Consequently, all the probability intervals describing the original 4 control modes and the three boundaries between them are presented in Table 2.

Table 2. The control modes and probability intervals

| The control modes and probability intervals |                                |
|---|--------------------------------|
| Control mode                                | Probability interval           |
| Strategic                                   | 5E-5 <p<1e-2< td=""></p<1e-2<> |
| Boundary between St. and Ta.                | 1E-3 <p <1e-2<="" td=""></p>   |
| Tactical                                    | 1E-3 <p<1e-1< td=""></p<1e-1<> |
| Boundary between Ta. and Op.                | 1E-2 <p <1e-1<="" td=""></p>   |
| Opportunistic                               | 1E-2 <p<5e-1< td=""></p<5e-1<> |
| Boundary between Op. and Sc.                | 1E-1 <p <5e-1<="" td=""></p>   |
| Scrambled                                   | 1E-1 <p<1e-0< td=""></p<1e-0<> |

Although the above analysis can assist in narrowing the intervals, the failure probabilities obtained are still presented in a wide range interval and may not be sufficient for appropriate screening and control purposes. Further investigation at the general analysis stage is carried out based on a context variable which describes the total state of the nine CPCs. For better description of the context variable, the following assumptions are made (Sun et al., 2012; He et al., 2008; Apostolakis et al., 1988).

(1) The context variable is continuous.

(2) The HEP is also continuous.

(3) HEP exponentially increases or decreases with the context variations.

The above assumptions have been used in many HRA methods and the results are validated to be acceptable in practice (Sue et al., 2012). According to the assumptions above, the functional relation between the context variable (denoted as x) and HEP can be constructed as follows (He et al., 2008):

$$HEP = f(x) = \rho exp(\varphi x) \tag{13}$$

where  $x = \Sigma_{Improved} - \Sigma_{Reduced}$ ,  $\rho$  and  $\varphi$  are two constants to be determined.

Obviously, the maximum and minimum values of x are 7 and -9 (from Table 1) respectively as presented in Eq. (14).

$$HEP_{max} = \rho exp (-9\varphi),$$

$$HEP_{min} = \rho exp (7\varphi)$$
(14)

It can be found that  $HEP_{min}=0.00005$  and  $HEP_{max}=1$  from the failure probabilities in Table 2 (Hollnagel, 1998). Then, the values of  $\rho$  and  $\varphi$  could be calculated as 3.81E-3 and -0.619. When x=0, the context is in a neutral state. At this moment, the HEP indicates a value without any positive or negative effects received from the operational context where  $HEP_0 = \rho = 3.81E-3$ .

Thus for a certain value of x, Eq. (15) could be utilized for a general analysis:

$$HEP = HEP_0 \cdot exp(-0.619x) = 3.81 \times 10^{-3} exp(-0.619x)$$
(15)

Eq. (15) reflects the functional relation between the overall state of context and HEP. It can be used to determine the extent to which the context of the whole task is of positive, neutral or negative effect on human performance in the investigation of an event.

## 3. Modified CREAM: an extended quantification

#### 3.1. Identifying the weights $(v_i)$ of CPCs through DEMATEL

In the traditional CREAM, each CPC plays the same role on the influence to the operational context and HEP, though it is not a real case in practice. For example, it is often the case that the negative effect received from "night time" of  $CPC_7$  TOD may be less than the one from "continuously inadequate" (available time) associated with  $CPC_6$  ATI. Therefore, appropriate weights should be assigned to the CPCs to reflect their contribution towards HEP (Marseguerra et al., 2007).

The DEMATEL method is used to calculate the weights of CPCs in this section. The step of DEMATEL can be summarized as follows (Wu, 2008; Fontela and Gabus, 1976; Gabus and Fonela, 1973).

Firstly, each expert is asked to evaluate the direct influence between any two CPCs by using scores ranging from 0, 1, 2, and 3 which represent "no influence", "low influence", "medium influence" and "high influence" respectively in terms of synopsis of influence relationship among the CPCs in the traditional CREAM (Table 3). The notation of  $a_{ij}$  indicates the degree to which the expert believes  $CPC_i$  affects  $CPC_j$ . For i = j, the diagonal elements are set to zero. For each expert, a  $9 \times 9$  (there are 9 CPCs) matrix can be established as  $A^g = [a_{ij}^g]$ , where g is the number of experts with  $1 \le g \le G$ , and G is the total number of experts. Thus,  $A^1, A^2, \ldots, A^G$  are the metrics from G experts. The average matrix  $M = [m_{ij}]$  can be obtained as follows:

$$M = [m_{ij}] = \left[\sum_{g=1}^{G} a_{ij}^{g} w_{g}\right]$$
(16)

where  $w_g$  is the relative importance of  $E_g$  and  $\sum_{g=1}^{G} w_g = 1$ .

Table 3.

| Principal CPC (Influenced CPC)     | Component CPCs (Influencing CPCs)   |
|------------------------------------|---|
| Working Condition (WCO)            | Adequacy of Organisation (AOO), Adequacy of Man Machine Interface<br>and Shipboard Operational Support (MMI), Available Time (ATI), Time<br>of day/ Circadian Rhythm (TOD), Adequacy of Training and Preparation<br>(AOT) |
| Number of Simultaneous Goals (NOS) | WCO, MMI and Availability of Plans/Procedures (AOP)   |
| ATI                                | WCO, MMI, AOP, NOS and TOD  |
| Crew Collaboration Quality (CCQ)   | AOO and AOT   |
| MMI                                | AOO   |
| AOP                                | AOO   |
| AOT                                | AOO   |

Secondly, the normalized direct relation matrix X can be obtained by Eq. (17) (Wu, 2008; Shieh et al., 2010)

$$X = bM, \tag{17}$$

where  $b = \frac{1}{\max_{1 \le i \le 9} \sum_{j=1}^{9} m_{ij}}$ . Each element in matrix falls between zero and one.

Thirdly, the total matrix can be obtained by Eq. (18)

$$T = X(I - X)^{-1}$$
(18)

where *I* is the identity matrix. *R* and *C* are defined to represent the sum of rows and sum of columns of T, respectively.  $R_i$ , which is the sum of the *i*th row in matrix *T*, summarizes both direct and indirect effects given by  $CPC_i$  to other CPCs.  $C_i$ , which is the sum of *i*th column in matrix T, shows both direct and indirect effects received by  $CPC_i$  from the other CPCs. The sum  $(R_i+C_i)$  indicates the total effects given and received by  $CPC_i$ . That is, the value of  $(R_i+C_i)$  stands for the degree of importance that  $CPC_i$  plays in the entire system. On the contrary, the value of  $(R_i-C_i)$  shows the net effect that  $CPC_i$  contributes to the system. Specifically, if  $(R_i-C_i)$  is positive,  $CPC_i$  is a cause factor, while  $CPC_i$  is a result factor if  $(R_i-C_i)$  is negative.

Lastly, the weights of CPCs can be obtained. The value of  $(R_i+C_i)$  stands for the degree of importance of  $CPC_i$ . The normalized weights of CPCs can therefore be calculated by

$$v_i = \frac{R_i + C_i}{\sum_{i=1}^{9} (R_i + C_i)} \times 9$$
(19)

where  $v_i$  is the weight of  $CPC_i$ .

## 3.2. Obtaining the adjusting index ( $\delta_{in}$ ) of CPC levels

The value of adjusting index is based on the weights of CPCs and fine-tuned in proportion. The adjusting indices of the  $CPC_i$ 's levels, which have *improved*, not significant and reduced effects, are assigned to  $+v_i$ , zero and  $-v_i$  respectively. This is a general principle to convert weights to adjusting indices. However, if there are two levels being assigned the same effect, then the corresponding  $v_i$  value should be fine-tuned in proportion. For example, for "crew collaboration quality", the four levels "very efficient", "efficient", "inefficient" and "deficient" have "improved", "not significant", "not significant" and "reduced" effects on performance reliability, respectively. According to the above general principle, the adjusting indices of both "efficient" and "inefficient" are zero, which does not well reflect the reality in measuring human reliability. Given the fact that the effect of "inefficient" on human reliability should be slightly "reduced" rather than "not significant", its adjusting index  $\delta_{in}$  of the *n*th level of  $CPC_i$  will be determined by proportion using a linear distribution.

#### 3.3. Calculating the CFP of sub-tasks

In the general analysis, the context variable is defined as the overall state of context whose value is  $\Sigma_{Improved} - \Sigma_{Reduced}$ . When  $\Sigma_{Improved} - \Sigma_{Reduced} = 0$ , the context would be the nominal state and HEP would be HEP<sub>0</sub>. However such a simple analysis may not be well suited to modelling the scenarios in the extended quantification, because a CPC has its specific effect role on human reliability. Therefore, the value of the functional relation x should be recalculated in a specific task context.

A new calculation approach, which can disclose the specific quantitative influence of a CPC on human reliability, is developed and described as follows:

$$x_i = \sum_{n=1}^{N} \delta_{in} \beta_{in} \tag{20}$$

where,  $x_i$  is the specific influence of  $CPC_i$  on human reliability;  $\delta_{in}$  is the adjusting index of *n*th level of  $CPC_i$ ;  $\beta_{in}$  is the combined DoB of *n*th level of  $CPC_i$  as mentioned in Section 2.2.2. N=3 when *i* belongs to the set of (2, 4, 5, 6, 7 or 8) while N=4 when *i* is equal to 1, 3 or 9.

Therefore, the overall quantitative influence of context can be indicated as follows:

$$x = \sum_{i=1}^{9} x_i \tag{21}$$

Consequently, the quantitative evaluation of Cognitive Failure Probability (CFP) of each subtask is

$$CFP = CFP_0 \cdot exp(-0.619x) \tag{22}$$

where exp(-0.619x) keeps consistence with its counterpart in Eq. (15) while CFP<sub>0</sub> varies with respect to the cognitive function and generic failure type of sub-tasks. According to the extended CREAM method, CFP<sub>0</sub> representing the basic values of generic cognitive function failure types will change as listed in Table 4 (Hollnagel, 1998). In the general analysis stage,  $HEP_0=3.81E-3$  is a holistic consideration of the whole task, while the cognitive function failure probability estimation should be carried out with respect to the adjusted CFP<sub>0</sub>.

Table 4

| Basic values for generic cognitive failure types |                           |             |  |  |  |  |  |
|--|---------------------------|-------------|--|--|--|--|--|
| Cognitive function                               | Generic failure type      | Basic value |  |  |  |  |  |
|  | Generie failure type      | $(CFP_0)$   |  |  |  |  |  |
| Observation                                      | O1 Wrong object observed  | 1.0E-3      |  |  |  |  |  |
|  | O2 Wrong identification   | 7.0E-2      |  |  |  |  |  |
|  | O3 Observation not made   | 7.0E-2      |  |  |  |  |  |
| Interpretation                                   | I1 Faulty diagnosis       | 2.0E-1      |  |  |  |  |  |
|  | I2 Decision error         | 1.0E-2      |  |  |  |  |  |
|  | I3 Delayed interpretation | 1.0E-2      |  |  |  |  |  |
| Planning   | P1 Priority error         | 1.0E-2      |  |  |  |  |  |
|  | P2 Inadequate plan        | 1.0E-2      |  |  |  |  |  |
| Execution  | E1 Action of wrong type   | 3.0E-3      |  |  |  |  |  |
|  | E2 Action at wrong time   | 3.0E-3      |  |  |  |  |  |
|  | E3 Action on wrong object | 5.0E-4      |  |  |  |  |  |
|  | E4 Action out of sequence | 3.0E-3      |  |  |  |  |  |
|  | E5 Missed action          | 3.0E-2      |  |  |  |  |  |
|  |                           |             |  |  |  |  |  |

Basic values for generic cognitive failure type

Source: Adopted from Hollnagel, (1998).

## 4. Case study

The statistics of marine accidents show that ship collision is the upmost hazard and could cause serious damage to the properties, environment and human lives. Previous studies have shown that human error is the main contributor of ship collision accidents (P&I Club, 1992; Pennie et al., 2007; Graziano et al., 2016) and attempts to reduce the marine accidents caused by human errors. In this section, a case investigating the collision avoidance of a particular scenario in Shanghai coastal waters is presented (See Table 6) to demonstrate the use of the modified methodology. Keeping sharp lookout, judgment of the risk of collision, and taking

anti-collision actions are key sub-tasks in collision avoidance for the involved officer on watch (OOW). Once errors or failures happened in these sub-tasks, a collision accident could occur. The question as to how the probability of the errors is obtained in a quantitative form needs to be answered.

# 4.1. General analysis

# 4.1.1. Evaluation of CPCs by experts

First of all, two experts were invited to analyse the investigated case through a collaborative research project between Shanghai Maritime University and Shanghai Pilot Station. Therefore, they both well knew the above defined investigation context and were selected to evaluate the CPCs and provide their DoBs with respect to each CPC level. Their professional positions, service time and education backgrounds are described in Table 5. Table 6 shows the evaluations of each CPC given by the two selected experts.

Table 5

| Description of the selected experts           |  |  |  |  |  |  |
|---|--|--|--|--|--|--|
| The expert Description of the expert selected |  |  |  |  |  |  |
| Eı  | A professor with a PhD degree who<br>has been engaged in marine risk<br>research for over 20 years and has a<br>good understanding of organization of<br>shipping and marine operations. He<br>has also served as a chief mate on<br>board ship continuously for 1 year<br>during his professional career. |  |  |  |  |  |
| $E_2$   | A captain with a bachelor degree who<br>has worked on board ship for 18 years<br>(2 years of being a captain) and has a<br>good safety record.   |  |  |  |  |  |

Table 6

The states of 9 CPCs and the evaluation from two experts

| CPC     | Description of situations  | Level           | $\beta_{in}^1$ | $\beta_{in}^2$ |
|---------|--|-----------------|----------------|----------------|
| $CPC_1$ | The seafarers are organized as a framework of management-operational-support level.  | L <sub>11</sub> | 0.6            | 0.5            |
| AOO     | There is a validated Safety Management System and clear responsibilities to the crew   | L <sub>12</sub> | 0.4            | 0.3            |
|         | members. The shipping company has a complete organizational structure and is able to   | L <sub>13</sub> | 0              | 0.2            |
|         | provide the powerful shore-based support for the ships.  | $L_{14}$        | 0              | 0              |
| $CPC_2$ | The bridge is small. The temperature is $30^{\circ}$ C due to that the air conditioner is  | L <sub>21</sub> | 0              | 0              |
| WCO     | temporarily not working. Wind is SE 10-12m/s. The vessel is slightly pitching and  | L22             | 0.4            | 0.7            |
|         | rolling. Environmental noise caused by VHF communications is serious.  | L <sub>23</sub> | 0.6            | 0.3            |
| CPC3    | The interface of the control panel including the monitors, knobs and buttons of the  | L31             | 0              | 0              |
| MMI     | navigational aids (Radar, ARPA, AIS, GPS, engine telegraph, automatic helm, and so   | L32             | 0.8            | 0.6            |
|         | on) is relatively friendly.  | L33             | 0.2            | 0.3            |
|         |  | L34             | 0              | 0.1            |
| $CPC_4$ | The checklists and procedures for navigation in heavy weather, restricted visibility,  | L41             | 0.8            | 0.7            |
| AOP     | narrow channels and coast waters in SMS are well-defined, however the planning of  | L42             | 0.2            | 0.2            |
|         | sailing in harbour areas is slightly insufficient, particularly the awareness and preparation  | L43             | 0              | 0.1            |
| CDC-    | There are multiple simultaneous cools due to the beauty traffic density. The duty officer  | T               | 0              | 0              |
| CPC5    | I here are multiple simultaneous goals due to the neavy traffic density. The duty officer  | L51<br>I        | 1              | 0              |
| NOS     | sometimes must contact with other vessels and take an action to avoid consion with   | L52             | 1              | 1              |
| CDC     | Shin an addition of the second s | L53             | 0              | 0              |
|         | Ship speed is reduced according to the speed limitation of trainc regulation, so the   | L <sub>61</sub> | 0.0            | 0.7            |
| AII     | captain of officer has enough time to change the speed of after the course for anti-   | L62             | 0.4            | 0.3            |
| CDC     | avoidance. But sometimes the operator is under a fittle fight time pressure.   | L <sub>63</sub> | 0              | 0              |
| CPC7    | The time of the operation is from 1600 to 1900. The officer feel a little tired due to the   | L71             | 0.4            | 0.6            |
| TOD     | preparation for sea at last midnight after discharging and loading.  | L <sub>72</sub> | 0.6            | 0.4            |
|         |  | L73             | 0              | 0              |
| $CPC_8$ | The crew members with competence certifications have been trained at a maritime  | $L_{81}$        | 0              | 0.2            |
| AOT     | university and on-board. They familiar with the responsibilities. It is the 2 <sup>nd</sup> time for the   | L82             | 0.8            | 0.8            |

|                  | officer on watch (C/O) navigating in Shanghai waterways and coaster waters.          | L83 | 0.2 | 0   |
|------------------|--|-----|-----|-----|
| CPC <sub>9</sub> | The captain, duty officer and helmsman have worked for the same shipping company for | L91 | 0.1 | 0   |
| CCQ              | several years. They have been on board this ship and worked together for 2 months.   | L92 | 0.8 | 0.6 |
|                  |  | L93 | 0.1 | 0.4 |
|                  |  | L94 | 0   | 0   |

#### 4.1.2. Combination of the evaluations

The weights of the two experts are assigned as (agreed among them)  $w_{1=0.6}$  and  $w_{2=0.4}$  according to their background information in Table 5. The basic probability masses for  $E_1$  and  $E_2$  can be modelled using Eqs. (2) - (5). Taking  $CPC_1$  as an example, the basic probability masses are computed as Eqs. (23) and (24).

$$E_{2}: \begin{cases} m_{11}^{11} = w_{1}\beta_{11}^{11} = 0.6 \times 0.6 = 0.36 \\ m_{12}^{11} = w_{1}\beta_{12}^{11} = 0.6 \times 0.4 = 0.24 \\ m_{13}^{11} = w_{1}\beta_{13}^{11} = 0.6 \times 0 = 0 \\ m_{14}^{11} = w_{1}\beta_{14}^{11} = 0.6 \times 0 = 0 \\ m_{L_{1}}^{11} = 1 - \sum_{n=1}^{N} m_{1n}^{1n} = 1 - (0.36 + 0.24 + 0 + 0) = 0.4 \\ \overline{m}_{L_{1}}^{1} = 1 - w_{1} = 1 - 0.6 = 0.4 \\ \widetilde{m}_{L_{1}}^{1} = w_{1}(1 - \sum_{n=1}^{N}\beta_{1n}^{1}) = 0.6 \times (1 - (0.6 + 0.4 + 0 + 0)) = 0 \end{cases}$$

$$E_{2}: \begin{cases} m_{12}^{21} = w_{2}\beta_{12}^{2} = 0.4 \times 0.5 = 0.20 \\ m_{13}^{22} = w_{2}\beta_{12}^{2} = 0.4 \times 0.3 = 0.12 \\ m_{13}^{2} = w_{2}\beta_{13}^{2} = 0.4 \times 0.2 = 0.08 \\ m_{14}^{21} = w_{2}\beta_{14}^{21} = 0.4 \times 0 = 0 \\ m_{L_{1}}^{21} = 1 - \sum_{n=1}^{N} m_{1n}^{21} = 1 - (0.20 + 0.12 + 0.08 + 0) = 0.6 \\ \overline{m}_{L_{1}}^{2} = 1 - w_{2} = 1 - 0.4 = 0.6 \\ \overline{m}_{L_{1}}^{2} = w_{2}(1 - \sum_{n=1}^{N}\beta_{1n}^{2}) = 0.4 \times (1 - (0.6 + 0.4 + 0 + 0)) = 0 \end{cases}$$

$$(24)$$

The basic probability masses  $m_{11}^1$ ,  $m_{12}^1$ ,  $m_{13}^1$  and  $m_{14}^1$  in Eq. (23), measure the DoBs exactly assigned to  $L_{11}$ ,  $L_{12}$ ,  $L_{13}$  and  $L_{14}$  by  $E_1$ . The probability mass of  $E_1$  ( $m_{L_1}^1 = 0.4$ ) unassigned to any individual  $L_{1n}$  is split into two parts, one caused by the relative importance of  $E_1$  ( $\overline{m}_{L_1}^1 =$ 0.4), and the other due to the incompleteness of the belief degree assessment  $\beta_{1n}^1$  ( $\widetilde{m}_{L_1}^g = 0$ ). Similarly, the basic probability masses from  $E_2$  can be modelled in Eq. (24). Using the same approach, the basic probability masses for the levels of other CPCs from  $E_1$  and  $E_2$  can be obtained.

Next, the combination of the basic probability masses from the two experts can be conducted using Eqs. (6) - (10).

$$\{L_{1n}\}: \begin{cases} \{L_{11}\}: m_{11}^{l(2)} = K_{l(1+1)} \left[ m_{11}^{l(1)} m_{11}^{2} + m_{11}^{l(1)} m_{L_{1}}^{2} + m_{L_{1}}^{l(1)} m_{11}^{2} \right] \\ = 1.1617 [0.36 \times 0.20 + 0.36 \times 0.6 + 0.4 \times 0.20] = 0.4275 \\ \{L_{12}\}: m_{12}^{l(2)} = K_{l(1+1)} \left[ m_{12}^{l(1)} m_{12}^{2} + m_{12}^{l(1)} m_{L_{1}}^{2} + m_{L_{1}}^{l(1)} m_{12}^{2} \right] \\ = 1.1617 [0.24 \times 0.12 + 0.24 \times 0.6 + 0.4 \times 0.12] = 0.2565 \\ \{L_{13}\}: m_{13}^{l(2)} = K_{l(1+1)} \left[ m_{13}^{l(1)} m_{13}^{2} + m_{13}^{l(1)} m_{L_{1}}^{2} + m_{L_{1}}^{l(1)} m_{13}^{2} \right] \\ = 1.1617 [0 \times 0.08 + 0 \times 0.6 + 0.4 \times 0.08] = 0.0372 \\ \{L_{14}\}: m_{14}^{l(2)} = K_{l(1+1)} \left[ m_{14}^{l(1)} m_{14}^{2} + m_{14}^{l(1)} m_{L_{1}}^{2} + m_{L_{1}}^{l(1)} m_{14}^{2} \right] \\ = 1.1617 [0 \times 0 + 0 \times 0.6 + 0.4 \times 0] = 0 \end{cases}$$

$$\overline{m}_{L_1}^{I(2)} = K_{I(2)} \left[ \overline{m}_{L_i}^{I(1)} \overline{m}_{L_i}^2 \right] = 1.1617 [0.4 \times 0.6] = 0.2788$$
<sup>(26)</sup>

$$\{L_1\}: \ \widetilde{m}_{L_1}^{I(2)} = K_{I(2)} \left[ \widetilde{m}_{L_1}^{I(1)} \widetilde{m}_{L_1}^2 + \widetilde{m}_{L_1}^{I(1)} \overline{m}_{L_1}^2 + \overline{m}_{L_1}^{I(1)} \widetilde{m}_{L_1}^2 \right] = 1.1617[0 \times 0 + 0 \times 0.6 + 0.4 \times 0]$$
  
= 0 (27)

$$K_{I(2)} = \left[1 - \sum_{n=1}^{N} \sum_{\substack{h=1\\h \neq n}}^{N} m_{1n}^{I(1)} m_{1h}^{2}\right]^{-1}$$

 $= [1 - 0.36 \times 0.12 + 0.36 \times 0.08 + 0.36 \times 0 + 0.24 \times 0.20 + 0.24 \times 0.08 + 0.24 \times 0 + 0 \times 0.20 + 0 \times 0.12 + 0 \times 0 + 0 \times 0.20 + 0 \times 0.12 + 0 \times 0.08]^{-1}$ = 1.1617 (28)

$$\{L_{1n}\}: \beta_{11} = \frac{m_{11}^{I(2)}}{1 - \bar{m}_{L_{1}}^{I(2)}} = \frac{0.4275}{1 - 0.2788} = 0.5928 \approx 0.59$$

$$\{L_{11}\}: \beta_{12} = \frac{m_{12}^{I(2)}}{1 - \bar{m}_{L_{1}}^{I(2)}} = \frac{0.2565}{1 - 0.2788} = 0.3557 \approx 0.36$$

$$\{L_{13}\}: \beta_{13} = \frac{m_{13}^{I(2)}}{1 - \bar{m}_{L_{1}}^{I(2)}} = \frac{0.0372}{1 - 0.2788} = 0.0516 \approx 0.05$$

$$\{L_{14}\}: \beta_{14} = \frac{m_{14}^{I(2)}}{1 - \bar{m}_{L_{1}}^{I(2)}} = \frac{0}{1 - 0.2788} = 0$$

$$\{L_{1}\}: \beta_{L_{1}} = \frac{\tilde{m}_{L_{1}}^{I(2)}}{1 - \bar{m}_{L_{1}}^{I(2)}} = \frac{0}{1 - 0.2788} = 0$$

$$(30)$$

As a result, the combined DoBs of  $L_{11}$ ,  $L_{12}$ ,  $L_{13}$  and  $L_{14}$  of  $CPC_1$  are calculated as 0.5928, 0.3557, 0.0516 and 0 respectively. Similarly, the combined DoBs associated with other CPCs can be obtained and presented in Table 7.

Table 7

The combined DoBs of each level of 9 CPCs

| CPCs    | DoBs  |
|---------|---|
| $CPC_1$ | $(L_{11}, 0.59); (L_{12}, 0.36); (L_{13}, 0.05); (L_{14}, 0)$ |
| $CPC_2$ | $(L_{21}, 0); (L_{22}, 0.51); (L_{23}, 0.49)$                 |
| СРС3    | $(L_{31}, 0); (L_{32}, 0.77); (L_{33}, 0.21); (L_{34}, 0.02)$ |
| $CPC_4$ | $(L_{41}, 0.80); (L_{42}, 0.17); (L_{43}, 0.03)$              |
| $CPC_5$ | $(L_{51}, 0); (L_{52}, 1); (L_{53}, 0)$                       |
| $CPC_6$ | $(L_{61}, 0.66); (L_{62}, 0.34); (L_{63}, 0)$                 |
| $CPC_7$ | $(L_{71}, 0.47); (L_{72}, 0.53); (L_{73}, 0)$                 |
| $CPC_8$ | $(L_{81}, 0.05); (L_{82}, 0.84); (L_{83}, 0.11)$              |
| $CPC_9$ | $(L_{91}, 0.06); (L_{92}, 0.77); (L_{93}, 0.17); (L_{94}, 0)$ |

#### 4.1.3. HEP of the whole task

Next, the couple ( $\sum_{Improved}, \sum_{Reduced}$ ) can be calculated by summing up the DoBs of the improved and reduced effects.  $\sum_{Improved}=0.59+0+0+0.80+0.66+0.05+0.06=2.16$  and  $\sum_{Reduced}=0.05+0+0.49+0.02+0.03+0+0+0.53+0+0.11+0=1.23$ . ( $\sum_{Improved}, \sum_{Reduced}$ ) are obtained as (2.16, 1.23). For the specific anti-collision task in Shanghai coastal waters, the control mode is estimated as tactical and the corresponding probability interval is (0.001, 0.1). Furthermore, the value of context variable x is 2.16-1.23=0.93 in a general analysis.

Consequently, the associated error probability (per anti-collision operation under the proposed context is computed as follows using Eq. (15).

 $HEP = 3.81 \times 10^{-3} exp(-0.619x) = 0.00381 exp(-0.619 \times 0.93) = 2.14 \times 10^{-3}$ 

This point value is located in the probability interval (0.001, 0.1) of the tactical control mode in CREAM.

## 4.2. Extended quantification of HEP

### 4.2.1. The weights of CPCs

The two experts were also invited to evaluate the relationship among CPCs in the defined context under investigation. The two  $9 \times 9$  matrices containing the two experts' judgements on CPCs dependency are presented as follows.

|         | г0 | 2 | 2.5 | 2 | 0   | 0   | 0 | 2 | 1.5 |                    | г0 | 1.5 | 2 | 2 | 0   | 0   | 0 | 1.5 | 21 |  |
|---------|----|---|-----|---|-----|-----|---|---|-----|--------------------|----|-----|---|---|-----|-----|---|-----|----|--|
|         | 0  | 0 | 0   | 0 | 2   | 2   | 0 | 0 | 0   |                    | 0  | 0   | 0 | 0 | 2.8 | 3   | 0 | 0   | 0  |  |
|         | 0  | 1 | 0   | 0 | 1.5 | 2   | 0 | 0 | 0   |                    | 0  | 2   | 0 | 0 | 1   | 1.5 | 0 | 0   | 0  |  |
|         | 0  | 0 | 0   | 0 | 1   | 1.5 | 0 | 0 | 0   |                    | 0  | 0   | 0 | 0 | 1   | 1.5 | 0 | 0   | 0  |  |
| $A_1 =$ | 0  | 0 | 0   | 0 | 0   | 2.5 | 0 | 0 | 0   | , A <sub>2</sub> = | 0  | 0   | 0 | 0 | 0   | 2   | 0 | 0   | 0  |  |
| -       | 0  | 1 | 0   | 0 | 0   | 0   | 0 | 0 | 0   |                    | 0  | 0.5 | 0 | 0 | 0   | 0   | 0 | 0   | 0  |  |
|         | 0  | 1 | 0   | 0 | 0   | 2   | 0 | 0 | 0   |                    | 0  | 1.5 | 0 | 0 | 0   | 1   | 0 | 0   | 0  |  |
|         | 0  | 1 | 0   | 0 | 0   | 0   | 0 | 0 | 2   |                    | 0  | 0.5 | 0 | 0 | 0   | 0   | 0 | 0   | 2  |  |
|         | L0 | 0 | 0   | 0 | 0   | 0   | 0 | 0 | 0   |                    | LO | 0   | 0 | 0 | 0   | 0   | 0 | 0   | 01 |  |

The value of 2 in the first row and second column of matrix  $A_1$  indicates that expert  $E_1$  believes  $CPC_1$  has "medium" influence on  $CPC_2$  under the given scenario. This evaluation is also made by refereeing the influence relationship defined in CREAM (in Table 3). The numerical values at the diagonal of each matrix are 0 because a CPC cannot affect itself.

Using Eq. (16), the average matrix of  $A_1$  and  $A_2$  ( $w_{1=0.6}$ ,  $w_{2=0.4}$ ) is obtained as follows.

|     | г0 | 1.80 | 2.30 | 2.00 | 0    | 0    | 0 | 1.80 | 1.70 |
|-----|----|------|------|------|------|------|---|------|------|
|     | 0  | 0    | 0    | 0    | 2.32 | 2.40 | 0 | 0    | 0    |
|     | 0  | 1.40 | 0    | 0    | 1.30 | 1.80 | 0 | 0    | 0    |
|     | 0  | 0    | 0    | 0    | 1    | 1.50 | 0 | 0    | 0    |
| M = | 0  | 0    | 0    | 0    | 0    | 2.30 | 0 | 0    | 0    |
|     | 0  | 0.80 | 0    | 0    | 0    | 0    | 0 | 0    | 0    |
|     | 0  | 1.20 | 0    | 0    | 0    | 1.60 | 0 | 0    | 0    |
|     | 0  | 0.80 | 0    | 0    | 0    | 0    | 0 | 0    | 2.00 |
|     | L0 | 0    | 0    | 0    | 0    | 0    | 0 | 0    | 0    |

Next the normalized direct matrix is calculated by Eq. (17).

|     | г0 | 0.1875 | 0.2396 | 0.2083 | 0      | 0      | 0 | 0.1875 | 0.17711 |  |
|-----|----|--------|--------|--------|--------|--------|---|--------|---------|--|
|     | 0  | 0      | 0      | 0      | 0.2417 | 0.2500 | Õ | 0      | 0       |  |
|     | 0  | 0.1458 | 0      | 0      | 0.1354 | 0.1875 | 0 | 0      | 0       |  |
|     | 0  | 0      | 0      | 0      | 0.1042 | 0.1563 | 0 | 0      | 0       |  |
| X = | 0  | 0      | 0      | 0      | 0      | 0.2396 | 0 | 0      | 0       |  |
|     | 0  | 0.0833 | 0      | 0      | 0      | 0      | 0 | 0      | 0       |  |
|     | 0  | 0.1250 | 0      | 0      | 0      | 0.1667 | 0 | 0      | 0       |  |
|     | 0  | 0.0833 | 0      | 0      | 0      | 0      | 0 | 0      | 0.2083  |  |
|     | L0 | 0      | 0      | 0      | 0      | 0      | 0 | 0      | 0 ]     |  |

Consequently, the total relation matrix T is obtained as follows:

|     | г0 | 0.2521 | 0.2396 | 0.2083 | 0.1151 | 0.1681 | 0 | 0.1875 | 0.2161 |  |
|-----|----|--------|--------|--------|--------|--------|---|--------|--------|--|
|     | 0  | 0.0263 | 0      | 0      | 0.2480 | 0.3160 | 0 | 0      | 0      |  |
|     | 0  | 0.1685 | 0      | 0      | 0.1761 | 0.2718 | 0 | 0      | 0      |  |
|     | 0  | 0.0155 | 0      | 0      | 0.1079 | 0.1860 | 0 | 0      | 0      |  |
| Г = | 0  | 0.0205 | 0      | 0      | 0.0050 | 0.2459 | 0 | 0      | 0      |  |
|     | 0  | 0.0855 | 0      | 0      | 0.0207 | 0.0263 | 0 | 0      | 0      |  |
|     | 0  | 0.1425 | 0      | 0      | 0.0344 | 0.2106 | 0 | 0      | 0      |  |
|     | 0  | 0.0855 | 0      | 0      | 0.0207 | 0.0263 | 0 | 0      | 0.2083 |  |
|     | L0 | 0      | 0      | 0      | 0      | 0      | 0 | 0      | 0 ]    |  |

According to Section 3.1.3,  $R_i$  is the sum of the *i*th row of matrix T and  $C_i$  is the sum of *i*th column of matrix T. Values of  $R_i$ ,  $C_i$ ,  $(R_i+C_i)$  and  $(R_i-C_i)$  are obtained and presented in Table 8 according to Eq. (18)

Table 8 The  $R_i$ ,  $C_i$ ,  $(R_i+C_i)$  and  $(R_i-C_i)$  values of CPCs

| CPCs          | $CPC_1$ | $CPC_2$ | CPC3   | $CPC_4$ | CPC5    | CPC <sub>6</sub> | CPC7   | $CPC_8$ | CPC9    |
|---------------|---------|---------|--------|---------|---------|------------------|--------|---------|---------|
| $R_i$         | 1.3868  | 0.5904  | 0.6164 | 0.3094  | 0.2713  | 0.1325           | 0.3876 | 0.3409  | 0       |
| $C_i$         | 0       | 0.7965  | 0.2396 | 0.2083  | 0.7279  | 1.4510           | 0      | 0.1875  | 0.4245  |
| $R_i+C_i$     | 1.3868  | 1.3869  | 0.8560 | 0.5177  | 0.9992  | 1.5835           | 0.3876 | 0.5284  | 0.4245  |
| $R_i$ - $C_i$ | 1.3868  | -0.2061 | 0.3769 | 0.1011  | -0.4565 | -1.3185          | 0.3876 | 0.1534  | -0.4245 |

In the second column of Table 8, the value of 1.3868 in the second row indicates both the direct and indirect effects given by  $CPC_1$ . The value of 0 in the third row represents both direct and indirect effects received by  $CPC_1$  from the other CPCs. The value of 1.3868 in the fourth row shows the total effects produced by  $CPC_1$ . The value of 1.3868 in the fifth row means the net effect that  $CPC_1$  contributes to the system. Thus, the importance of the nine CPCs can be prioritized as C6>C2>C1>C5>C3>C8>C4>C9>C7 based on their individual (R+C) values. The weights  $(v_i)$  of CPCs (Table 9) can also be calculated using Eq. (19).

# 4.2.2. The adjusting index of CPC levels

Next the adjusting index (denoted as  $\delta_{in}$ ) of CPCs' levels can be determined according to the rules described in Section 3.2. For example, the weight of *CPC*<sub>1</sub> *AOO* is 1.55. The adjusting index of "very efficient", "efficient" and "deficient" can therefore be 1.55, 0 and -1.55 due to their individual most positive effect, neutral effect and most negative effect. For the level of "inefficient", its effect on human reliability is negative, but the degree of effect is less than "deficient". Its adjusting index is thus calculated as 0.78 using a linear distribution. In a similar way, all adjusting indices (Table 9) of the 9 CPCs' levels can be determined.

| Table 9 | 9 |
|---------|---|
|---------|---|

| The weights of Cr Cs and adjusting index of Cr Cs revers |         |         |         |         |         |         |         |         |                  |  |
|--|---------|---------|---------|---------|---------|---------|---------|---------|------------------|--|
| CPCs   | $CPC_1$ | $CPC_2$ | $CPC_3$ | $CPC_4$ | $CPC_5$ | $CPC_6$ | $CPC_7$ | $CPC_8$ | CPC <sub>9</sub> |  |
| $v_i$  | 1.55    | 1.55    | 0.95    | 0.58    | 1.11    | 1.77    | 0.43    | 0.59    | 0.47             |  |
| $\delta_{i1}$  | 1.55    | 1.55    | 0.95    | 0.58    | 0       | 1.77    | 0       | 0.59    | 0.47             |  |
| $\delta_{i2}$  | 0       | 0       | 0       | 0       | -0.56   | 0       | -0.22   | 0       | 0                |  |
| $\delta_{i3}$  | -0.78   | -1.55   | 0       | -0.58   | -1.11   | -1.77   | -0.43   | -0.59   | -0.24            |  |
| $\delta_{i4}$  | -1.55   |         | -0.95   |         |         |         |         |         | -0.47            |  |

The weights of CPCs and adjusting index of CPCs' levels

# 4.2.3. CFP of sub-tasks of ship collision avoidance

The specific effects of CPCs can be quantified using Eq. (20). For example,

 $x_1 = \sum_{n=1}^N \delta_{1n} \beta_{1n} = (1.55 \times 0.59) + (0 \times 0.36) + (-0.78 \times 0.05) + (-1.55 \times 0) = 0.8755.$ 

Similarly, the specific effects of all 9 CPCs are obtained as

 $[x_i] = [0.8755, -0.7595, -0.0190, 0.4466, -0.5600, 1.1682, -0.1166, -0.0354, -0.0126].$ 

Consequently, the total context influence on CFP is obtained using Eq. (21).

 $x = \sum_{i=1}^{9} x_i = 0.99.$ 

Compared to the context variable value of 0.93 in the general analysis, 0.99 in extended quantification analysis is slightly larger. The difference between two values is caused by the introduction of the different weights of CPCs and adjusting indices of their ranking levels when considering their dependency in specific task context.

In Table 10, the whole task of ship anti-collision is divided into sub-tasks and possible errors are identified. Cognitive functions of sub-tasks and generic failure types of possible errors are analyzed to determine the basic value of each possible error. Then the adjusted probabilities of possible errors can be calculated using Eq.22.

| Sub-ta           | ask i | n ship collision avoidance              | Possible errors                                 | Cognitive<br>function | Generic failure type      | CFP <sub>0</sub> | Adjusted<br>CFP |
|------------------|-------|---|---|-----------------------|---------------------------|------------------|-----------------|
| 1<br>Observation | 1.1   | Visual observation                      | Not maintaining<br>Continuous visual<br>lookout | Observation           | O3 Observation not made   | 7.00E-02         | 3.79E-02        |
|                  | 1.2   | Observation via navigational aids       | Inadequate use of aids                          | Observation           | O2 Wrong identification   | 7.00E-02         | 3.79E-02        |
|                  | 1.3   | Communication with other ship           | Communication<br>interrupt                      | Execution             | E5 Missed action          | 3.00E-02         | 1.63E-02        |
|                  | 1.4   | Comparison of information               | Comparison error                                | Interpretation        | I3 Delayed interpretation | 1.00E-02         | 5.42E-03        |
| 2<br>Judgment    | 2.1   | Judgment of Risk of collision           | Wrong judgment                                  | Interpretation        | I1 Faulty diagnosis       | 2.00E-01         | 1.08E-01        |
|                  | 2.2   | Evaluation of situation                 | Wrong judgment                                  | Interpretation        | I1 Faulty diagnosis       | 2.00E-01         | 1.08E-01        |
|                  | 2.3   | Choice of applicable items in COLREG 72 | Select wrong items                              | Planning              | P2 Inadequate plan        | 1.00E-02         | 5.42E-03        |
| 3<br>Decision-   | 3.1   | Decision of action to avoid collision   | Wrong action                                    | Interpretation        | I2 Decision error         | 1.00E-02         | 5.42E-03        |
| making           | 3.2   | Decision of time of action              | Wrong time                                      | Planning              | P1 Priority error         | 1.00E-02         | 5.42E-03        |
| 4<br>Action      | 4.1   | Alter course or/and speed               | Improper implementation                         | Execution             | E1 Action of wrong type   | 3.00E-03         | 1.63E-03        |

Table 10 Extended analysis and quantification for ship collision avoidance

# 4.3. Model validation and result comparison

# 4.3.1. Validation using sensitivity analysis

Sensitivity analysis is a study on how the uncertainty in the output of a model can be apportioned to different sources of uncertainty in the model input. It is a method for testing the degree of sensitivity of a model's variables. The sensitivity analysis was carried out by changing the evaluation of  $CPC_1$  by  $E_1$ . The original expert evaluation values associated with  $L_{11}$  were decreased from 0.6 to 0.1 at a step of 0.1. The assumption made is that the trend line of certain CFPs should increase steadily. The trend lines of selective CFPs are illustrated in Fig.2.



Fig.2 The trend lines of selective CFPs

A similar proposed approach is applied to determine if small changes of input variables will induce the corresponding changes in the output results of CFPs. It can be observed from the

trend lines in Figure 2 that four selective CFPs have increased correspondingly with increment of evaluation values. Additionally, no abrupt large changes of CFPs were generated in the sensitivity analysis. Therefore, the model is able to illustrate the differences and has partially validated the model developed.

# 4.3.2. Result comparison

The cognitive model and framework of CREAM could be used in retrospective and prospective analysis. However, the quantification results provided are mainly based on the expert specification on CPCs. Lack of data, which makes it inevitable to adopt expert judgment, is the most important source of the uncertainty for many HRA methods (He et al., 2008) including the proposed method. The knowledge and experience imparity of experts leads to evaluation differences on CPCs and further on HRA analysis results. Therefore, the ER algorithm is used to deal with the differential judgments of experts. The quantification results derived from  $E_1$ ,  $E_2$  and ER algorithm are compared respectively. From Table 11, we can find that the CFP values derived from ER algorithm fall between the values resulted from two experts. It shows the strength of ER algorithm in the proposed method on dealing with the uncertainties from experts' judgments.

| Sub-tasks |     | CED      | By E <sub>1</sub> | By E <sub>2</sub> | Combined |
|-----------|-----|----------|-------------------|-------------------|----------|
|           |     | CFP0     | CFP <sub>1</sub>  | CFP <sub>2</sub>  | CFP      |
|           | 1.1 | 7.00E-02 | 4.43E-02          | 3.72E-02          | 3.79E-02 |
| 1         | 1.2 | 7.00E-02 | 4.43E-02          | 3.72E-02          | 3.79E-02 |
| 1         | 1.3 | 3.00E-02 | 1.90E-02          | 1.60E-02          | 1.63E-02 |
|           | 1.4 | 1.00E-02 | 6.33E-03          | 5.32E-03          | 5.42E-03 |
|           | 2.1 | 2.00E-01 | 1.27E-01          | 1.06E-01          | 1.08E-01 |
| 2         | 2.2 | 2.00E-01 | 1.27E-01          | 1.06E-01          | 1.08E-01 |
|           | 2.3 | 1.00E-02 | 6.33E-03          | 5.32E-03          | 5.42E-03 |
| 3         | 3.1 | 1.00E-02 | 6.33E-03          | 5.32E-03          | 5.42E-03 |
|           | 3.2 | 1.00E-02 | 6.33E-03          | 5.32E-03          | 5.42E-03 |
| 4         | 4.1 | 3.00E-03 | 1.90E-03          | 1.60E-03          | 1.63E-03 |

Table 11 Comparison of results

Additionally, real data has been collected to validate the above result. Since Sep. 30<sup>th</sup> 2011 until Oct. 1<sup>st</sup> 2012, the operational data under the same context in Shanghai coastal waters has been collected and recorded. From the recorded data, it is revealed that from 2688 events that could lead to the error of "not maintaining continuous visual lookout or/and inadequate use of aids", 81 errors actually occurred (Fang et al., 2012). The error rate is 0.0301. The closeness of 0.0379 and 0.0301 shows a fairly good consistency between the estimated value and the real error rate, thus also provide evidence to support the research findings and proposed quantification method in this paper.

# 5. Conclusion

A new HEP quantification methodology is proposed based on the ER approach, DEMATEL and CREAM. It can be used for not only a general analysis but also the quantitative evaluation of HRA in maritime operations. The procedure of quantification is described and

an illustrative case study is produced. A sensitivity analysis and comparison of quantification results is carried out for the validation of the newly proposed model.

The belief degree approach, instead of the deterministic one-or-zero way in specification of CPCs, can well model the uncertainty and be more practical when adopting experts' judgments. The ER algorithm can combine the different evaluations to improve the limitations of knowledge and experience of every expert in CPCs specification. The weights generated by DEMATEL and adjusted indices derived from the weights express the various influences of CPCs in a practical operation. Therefore, compared to the previous CREAM based HEP quantification studies, the new method has shown its superiority due to the fact that (1) the ER approach with the belief degree manner can deal with the uncertainties caused by insufficient information and data in the evaluation of CPCs and be capable of combining the DoBs from different sources; (2) setting of the adjusting indices based on the DEMATEL technique allows different importance of CPCs and more sensitive estimation of HEP.

This paper focuses on the development of the new modified CREAM method and its application in the maritime industry. The propagation of an event is made through the representation of a scenario of maritime operation. It is believed that the method provides useful insights on a systemic and structural cognitive task analysis of complex systems and hence will facilitate cognitive HRA in other sectors to enhance incorporation of human element in the safety management of critical systems. However, it only focuses on how seafarers' actions can fail, and concerns the human element in seafarers' reliability analysis. It has therefore revealed its applicability and limits in practice, with respect to Prof Eric Hollnagel's disclaimers on CREAM in his personal website.

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