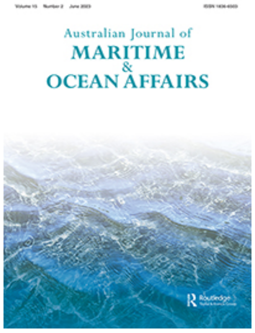

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An extended human reliability analysing under fuzzy logic environment for ship navigation

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ABSTRACT
Preparation for a sea voyage is one of the fundamental aspects of navigation. Several complexities are involved during the preparation of the ship for navigation due to the nature of maritime work. At this point, analysing human-related error is of paramount importance to ensure the safety of the ship and the crew. This paper describes the principles of a methodology, namely fuzzy-based shipboard operation human reliability analysis (SOHRA), to quantitatively perform human error assessment through procedures of preparing the ship for navigation. While the SOHRA (a marine-specific HRA approach) quantifies human error, the fuzzy logic deals with ambiguity and vagueness in the human error detection problem. The findings show that the total HEP (Human error probability) is found 1.49E-01 for preparing the ship for navigation. Consequently, the paper provides practical contributions to shore-based safety professionals, ship managers, and masters of the ship since it performs a systematic human reliability assessment and enhances safety control levels in the operational aspect.

1. Introduction

The human factor is of paramount significance in the maritime transportation industry due to the high risk involved (Yang et al. 2013). There is an inverse relationship between the concept of the human factor and human error. Thus, it is necessary to quantify the likelihood of human error to predict human reliability. Improved techniques require an understanding of human error concepts, in the particular maritime industry where various hazardous operations are being routinely performed. In this context, maritime regulatory authorities have been adopting a set of guidelines and circulars to reduce human error and enhance safety control levels in the operational aspect (Schröder-Hinrichs et al. 2013; Sezer, Akyuz, and Arslan 2021). However, human error-based incidents are still ongoing on-board ships (Gaonkar et al. 2011; Akyuz 2015; Kandemir et al. 2019;

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Kuroshi, Òlçer, and Kitada 2019). The annual report of marine causalities and incidents, which was documented by European Maritime Safety Agency (EMSA), shows that fatal incidents considerably continued in comparison with last year (EMSA 2020). Moreover, 54 per cent of those incidents were related to human error (EMSA 2020). Therefore, human reliability plays a crucial role in minimising human error-based incidents at sea.

Although a number of HRA techniques have been introduced for use in a wide range of industries, those adopted in the maritime industry have remained very limited. The shipboard operation human reliability analysis (SOHRA), for instance, has recently been introduced as a marine-specific technique to predict HEP (human error probability) for a particular type of task (Akyuz, Celik, and Cebi 2016). The method provides a practical tool to predict HEP systematically. This paper benefits from the aforementioned method to perform a sensitive human reliability assessment under a fuzzy logic environment in the maritime industry. While the SOHRA quantifies human error, the fuzzy logic deals with ambiguity and vagueness in the human error detection problem. In this context, the organisation of the paper is as follows. This part introduces the aim and scope of the study. Section 2 provides a brief literature review about HRA in the maritime transportation industry. Section 3 outlines the theoretical background of methods and how the methods are integrated. In Section 4, an extensive HRA through procedures of preparing the ship for navigation is performed to show the applicability of the proposed approach. Finally, Section 5 gives the conclusion and future studies.

2. Literature review

Few studies have been conducted over the last several decades to enhance HRA methods, resulting in two entire generations of HRA. HRA techniques such as first-generation, a technique for human error rate prediction (THERP), human error assessment and reduction technique (HEART) (Swain and Guttmann 1983), the success-likelihood index method (SLIM) (Embrey et al. 1984) as well as human cognition reliability (Hannaman, Spurgin, and Lukic 1985) focus specifically on work properties in HEP estimations and less with the effects of environment and situation (Abrishami et al. 2020). The second-generation approaches, including such cognitive reliability and error analysis methods (Hollnagel 1993) and A Technique for Human Error Analysis (Barriere et al. 2000), were developed to improve on the design of the first generation. In second-generation methods, operator cognition and context are seen as important contributors to HEP. However, both generations have certain limitations, such as being extremely contextual, missing a causal framework to link performance shaping factors (PSFs) to operator performance (Ekanem, Mosleh, and Shen 2016), and is difficult to incorporate with system safety evaluation techniques (Groth and Swiler 2013). Third-generation nuclear action reliability assessment (Kirwan et al. 2004) and standardised plant analysis risk-human reliability analysis method (Gertman et al. 2005) have indeed been presented to classify potential human errors and quantify their likelihood of occurrence in the task of complex processes and systems. Third-generation methods now have certain restrictions, and their progress is still in its early stages.

The maritime transportation industry is composed of a set of elements such as ship, crew, ownership, management, and administration authority, classification and insurance society, etc. which have a different effect on the overall performance. One of the most important elements of those is ship crew since a wide range of technical or operational processes have been undertaken by them. Therefore, crew (human) reliability plays a critical role since the statistics show that most marine accidents are occurred due to human errors (Fotland 2004; Aydin et al. 2021).

Maritime transportation involves various hazardous operations which pose serious risks to crew, commodity, and environment. In order to enhance safety of the ship, deck and engine ratings must be ready in advance. Specifically, if the ship is carrying dangerous cargo on-board such as chemical substances, liquefied gas, crude oil, and solid cargoes, particular care must be taken by the ship crew. At this point, the expectation from the crew is to complete tasks without any failure. Shore-based safety professionals, ship managers, or safety practitioners have been adopting different techniques to systematically measure crew error during critical shipboard operations. Human reliability measurement methods for various areas may be found in the literature. The majority of these approaches use HEP calculations to determine a possible failing level for a specific process (Kirwan 1994).

However, the techniques are broadly adopted from different disciplines such as nuclear (Kirwan et al. 2004; Gibson et al. 2012; Chen, Zhang, and Qing 2021), aviation (Kirwan and Gibson 2008; Guo and Sun 2020), and railway (Martins and Maturana 2013; Jin et al. 2019; Samima and Sarma 2021) since the high risk involved. In maritime literature, there is a tendency to seek a creative solution to minimise human error and enhance reliability. Particularly, a growing concern has risen with regard to collision (Pourzanjani and Zheng 2001; Montewka et al. 2010; Martins and Maturana 2013; Abaei, Hekkenberg, and BahooToroody 2021), grounding (Amrozowicz, Brown, and Golay 1997; Akhtar and Utne 2014; Ung 2018) emergency situations (El-Ladan and Turan 2012; Musharraf et al. 2013; Omorodion et al. 2021), navigation (Sulaiman, Saharuddin, and Kader 2012; de Abreu et al. 2020), shipboard operations (Arslan 2009; Yang et al. 2013; Akyuz and Celik 2015b; Gaspar et al. 2019; Kandemir et al. 2019; Kuroshi, Òlçer, and Kitada 2019; Wang, Liu, and Liu 2021), and operating emergency fire pump (Akyuz, Celik, and Celik 2018). Since these researches have considerable contributions in theoretical and practical aspects to the maritime transportation industry, most of them mainly suffer one major limitation: not to use a marine-specific method. There are also some studies related to human error prediction to monitoring human reliability performance in off-shore operations (Konstandinidou et al. 2006; Turan et al. 2011; Taber et al. 2013; Zhang and Tan 2018) and a study of the current generation of quantitative risk analysis in the off-shore petroleum industry (Zhen et al. 2020). In the context of maritime HRA, there is a lack of research in the literature to adopt marine-specific PSF in evaluating the performance of human reliability. To remedy the gap, this paper benefits from the SOHRA (a marine-specific HRA technique) approach under the fuzzy logic environment to perform extensive human reliability analysis.

3. Methodology

This paper provides a methodological extension through the integration of the fuzzy logic into the SOHRA approach to perform a comprehensive human reliability assessment.

3.1. SOHRA

The SOHRA technique is based on tailoring the main principles of the HEART to quantify the probability of human error in the maritime transportation industry (Akyuz and Celik 2015a). It has been developed as a marine-specific HRA tool since the other techniques adopted from different disciplines are not always appropriate for maritime industry-related tasks (Konstandinidou et al. 2006). The technique provides marine-specific error-producing condition (m-EPC), which addresses to PSF affecting human performance. The SOHRA has been statically validated by analysing a hundred real-marine accident cases as it was adopted for usage by the maritime transportation industry in a wide range of probabilistic safety assessment (PSA).

Due to the nature of maritime works, it is very challenging to obtain human error data in the maritime transportation industry. Therefore, it is very difficult to predict HEP. However, the SOHRA presents a consistent approach to conduct HRA by calculating the HEP for a particular type of task since the relevance of PSFs completely meets the requirements of maritime industry. The technique consists of two fundamental parameters to quantify HEP: generic task type (GTT) and m-EPC values. The GTT identifies a specific task associated with the generic error probability (GEP). While GEP can be defined as a probability of human error where initial quantification for the task being assessed (Kirwan and Gibson 2008), m-EPC is factor which is influencing human performance negatively and increasing GEP value. The technique has capable of calculating HEP by combining GEP and m-EPC values.

3.2. Fuzzy-AHP

Analytic hierarchy process (AHP) is a well-known multi-criterion decision-making method to prioritise the relative weight of criteria (Saaty 1980). The method is widely used in decision-making to a solve complex problem. One of the fundamental limitations of the method is not to deal with uncertainty and vagueness. To overcome aforementioned problem, the method was extended with fuzzy sets where vagueness or imprecision in human judgements in the decision-making process is solved (Zadeh 1965). Hence, it represents interval judgements rather than fixed—values. In the method, linguistic values are used to transform decision-maker's assessment into meaningful information. Triangular fuzzy numbers (TFNs), in this context, are used to quantify the judgement values of linguistic data as TFNs are relatively easy to use. The TFNs can be illustrated as (l|m, m|u) or (l, m, u). In the notation, parameters 'l' states the smallest possible value, parameter 'm' denotes the most promising value, and parameter 'u' gives the most significant possible value that describes a fuzzy event (Gumus et al. 2013). Accordingly, the membership function can be defined as follows (Zimmermann 2001):

$$\mu(x/\tilde{M}) = \begin{cases} 0, & x < l \\ (x-1)/(m-l), & 1 \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & x > u \end{cases}. \quad (1)$$

Since there are various fuzzy comparison matrices such as the geometric mean method (Buckley 1985), a fuzzy logarithmic least squares method (van Laarhoven and Pedrycz 1983), a fuzzy least squares priority method (LSM) (Xu 2000), a fuzzy preference programming method(Xu 2000) undertaken in different disciplines, Buckley's fuzzy-based AHP algorithms become prominent in the literature to prioritise criteria weight (Buckley 1985). In this paper, Buckley's fuzzy-AHP is employed due to its simplicity as well as providing a unique solution to the reciprocal comparison matrix (Gumus et al. 2013).

3.3. Proposed approach: fuzzy-SOHRA

This section describes the implementation steps of the proposed approach (Fuzzy-SOHRA). Accordingly, Figure 1 illustrates the framework of the proposed approach.

Step 1. Task analysis: A task analysis is exercised on the basis of hierarchical task analysis (HTA) to perform a detailed human error prediction. In the HTA, a high-level of main tasks is decomposed to a sub-task. Thus, a systematic description of each main task can be clarified to calculate the probability of human error in the system.

Step 2. Scenario definition: A large number of shipboard scenarios are defined to select GTT and m-EPC that best matches sub-task needed to quantify. The scenario includes a

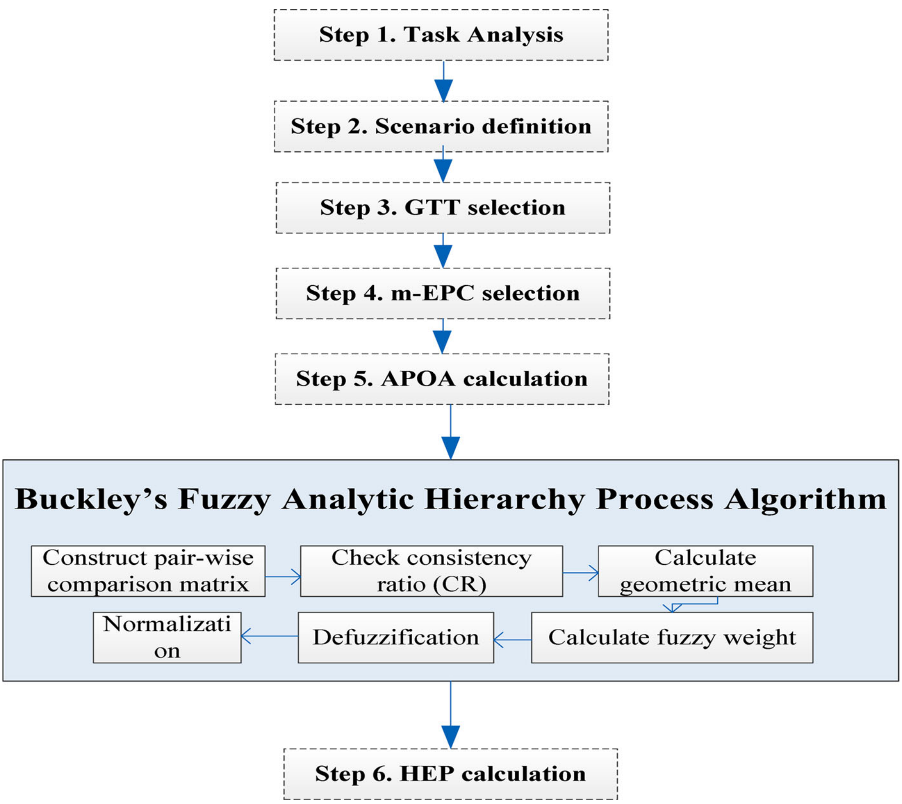

Figure 1. A flow chart diagram of proposed approach.

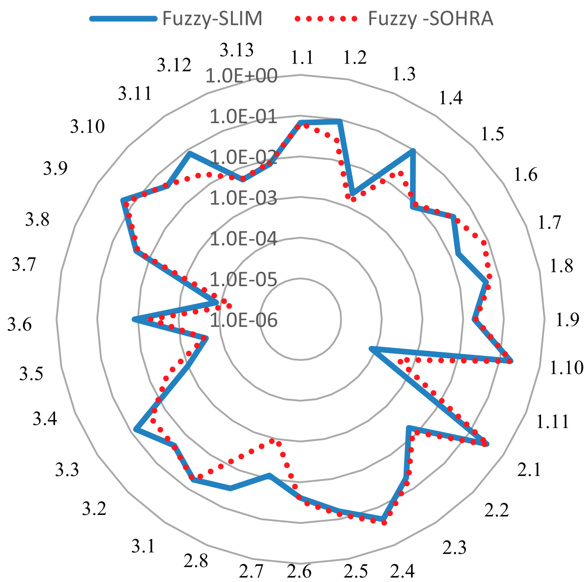

Figure 2. Comparative representation of HEP values for fuzzy-SOHRA and fuzzy-SLIM.

wide range of different conditions such as weather, sea state, time of day, fatigue, working condition, stress, and the experience of the crew.

Step 3. GTT selection: Since the aim of GTT is to provide a generic description of a sub-task, a GEP value is determined on the basis of relevant GTT. Each GTT is selected from the list of tables on the basis of sub-task (Williams 1988; Akyuz and Celik 2015a). Then, the GEP value is ascertained for each sub-task in accordance with relevant GTT.

Step 4. m-EPC selection: As the m-EPC is a PSF and effects GEP negatively, the selection of m-EPC is of paramount importance in accurately predicting HEP. In this step, any m-EPC which is relevant to sub-task selected from the list of 38 possible statement in SOHRA. If there is more than one m-EPC selected for the sub-task, the APOA (assessed proportion of effect) for the m-EPC is required.

Step 5. APOA calculation: The APOA is the judgement of experts as to the impact of the m-EPC through the HEP of the sub-task being assessed (Gibson et al. 2012). Since there is uncertainty in the APOA calculation, this paper brings a methodologic solution by adopting fuzzy sets in consideration of the impacts of uncertainty in the APOA on the calculated HEP. Thus, the fuzzy sets deal with the vagueness of expert judgements and expression in decision-making during the weighting process of m-EPC (Akyuz 2016). In conventional SOHRA, the weighting process of m-EPC is to undertake by adopting AHP method. To deal with aforementioned limitation, this paper extends AHP under a fuzzy environment. Hence, a modification of the strength of the effect of m-EPC is provided through the weighting process. Accordingly, the main step of Buckley's Fuzzy-AHP algorithm is followed (Gumus et al. 2013; Celik, Gumus, and Alegoz 2014).

(i) *Construct pairwise comparison matrix*: In this part, a pairwise comparison matrix is built up. To achieve this purpose, Equations (2) and (3) Is used by nominating linguistic terms

$$\tilde{M} = \begin{pmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ \tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & \tilde{a}_{12} & \cdots & \tilde{a}_{1n} \\ 1/\tilde{a}_{21} & 1 & \cdots & \tilde{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{a}_{n1} & \tilde{a}_{n2} & \cdots & 1 \end{pmatrix} \tag{2}$$

where

$$\tilde{a}_{ij} = \begin{cases} \tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9} & \text{criterion } i \text{ has relative importance to criterion } j \\ 1. & i = j \\ \tilde{1}^{-1}, \ \tilde{3}^{-1}, \ \tilde{5}^{-1}, \ \tilde{7}^{-1}, \ \tilde{9}^{-1} & \text{criterion } i \text{ has less importance to criterion j} \end{cases} \tag{3}$$

(ii) *Check consistency ratio (CR):* In this part, the consistency of comparison matrix is checked whether the judgements inserted in the comparison matrix are reasonable or not. If the CR value is found equal to or less than 0.10, the matrix is considered consistent.

(iii) *Calculate geometric mean*: A geometric mean method is used to calculate the fuzzy geometric mean. In this context, Equation (4) is applied.

$$\tilde{r}_i = (\tilde{a}_{i1} \otimes \tilde{a}_{i2} \otimes \cdots \otimes \tilde{a}_{in})^{1/n} \tag{4}$$

where $\tilde{a}_{in}$is fuzzy comparison value of criterion i to criterion n.

(iv) *Calculate fuzzy weight*: In this part, fuzzy weights of each criteria are determined by using Equation (5) where $\tilde{w}_i = (lw_i, mw_i, uw_i)$ denotes fuzzy weight of i^{th} criteria.

$$\tilde{w}_i = \tilde{r}_i \otimes (\tilde{r}_1 \oplus \tilde{r}_2 \oplus \cdots \oplus \tilde{r}_n)^{-1} \tag{5}$$

(v) *Defuzzification:* In this step, the centre of area is applied by using Equation (6) for defuzzification. Thus, the best non-fuzzy performance (BNP) value (crisp weight) of each criterion is calculated.

$$BNPw'_i = [(uw_i - lw_i) + (mw_i - lw_i)]/3 + lw_i. \tag{6}$$

(vi) *Normalisation:* In the last part, normalisation is performed to the crisp weights by using Equation (7).

$$BNPw_i = \frac{BNPw'_i}{\sum_{i=1}^{n} BNPw'_i}. \tag{7}$$

Step 6. HEP calculation: A simple calculation method, illustrated in Equation (8), is defined to determine the likelihood of human error (Williams 1988). The HEP calculation is performed for each sub-task that is being defined in HTA. In order to determine human reliability performance, the final HEP value is ascertained by applying dependency rule.

Table 1. Notation rules.

Description	Sub-task dependency	Notation for task HEP
Parallel system	High dependency	$HEP_{Task} = Min\{HEP_{Sub-task\ i}\}$
	Low or no dependency	$HEP_{Task} = \prod (HEP_{Sub-task\ i})$
Serial system	High dependency	$HEP_{Task} = Max\{HEP_{Sub-task\ i}\}$
	Low or no dependency	$HEP_{Task} = \sum (HEP_{Sub-task\ i})$

Table 1 provides notations for the dependency between the sub-tasks in line with the PSA (He et al. 2008; Akyuz and Celik 2015a).

$$HEP = GEP \times \left\{ \prod_i [(EPC_i - 1)APOA_{pi} + 1] \right\}. \quad (8)$$

4. Illustrative example: the case of preparing ship for navigation

A comprehensive human reliability assessment through procedures of preparing ship for navigation is conducted in this section to show the applicability of the proposed approach.

4.1. Preparing ship for navigation

There are a large number of significant tasks involved during preparation ship for navigation since it is one of the most fundamental attributes of good seamanship. Preparing ship includes bridge, deck, and engine departments which have to prepare themselves well for safe navigation of ship (ICS 2016). The international maritime organisation adopted standards of training certification and watchkeeping (STCW) and international safety management (ISM) Code to bring provisions with the aim of improving navigation safety with regard to the preparing ship. The Bridge Procedure Guide provides a practical guide by considering the aforementioned convention and code in order to ensure the maintenance of safe navigation at all times (ICS 2016).

The master of the ship is responsible person for preparing the ship by arranging a meeting with the chief officer and the chief engineer to discuss all matters necessary for the ship's departure from the port. There are numerous tasks that are being completed in bridge, engine, and deck prior to navigation, and those are to be taken care of without error. Therefore, human reliability is of paramount importance to ensure safety of the ship and the crew.

4.2. A real-shipboard environment definition and task analysis

To illustrate the proposed approach, a real ship preparing for navigation case was selected since it includes a wide range of complexities and careful consideration required for the safety of the ship and the crew. The bulk carrier ship departed from Ambarli Port, and arrival Port is going to be West Cost of Africa. There were about 16k tons of cement cargo loaded on-board ship. Special permission from the port authorities was obtained to attend on-board ship. The portable camera recorded all events in the course of ship preparation to get marine experts to watch. After completion of cargo operation (about evening time), the ship crew commenced ship preparing for navigation. All crew participated to ship preparing for navigation except duty officer, duty engineer, duty A/B (able seaman), and duty oiler. The master of ship commanded operation. At the time of preparation, the weather was partly cloudy, and sea state was smooth. The crew was exhausted due to the excessive workload, and the shipboard environment conditions were at a satisfactory level. With the assistance of master and camera records, a task analysis was performed. Table 2 shows the HTA for preparing the ship for navigation which consists of three main departments: bridge, deck, and engine.

4.3. Analysis of respondents

A comprehensive survey was exercised with marine experts after recorded events during preparing the ship for navigation. The expert's judgement provides necessary input data to perform HRA since there is a lack of human error data in maritime transportation. However, most quantitative research upon HRA suffers core human error data, and one of the methods is to overcome such difficulties by incorporating expert judgements to

Table 2. HTA for preparing ship for navigation.

	Sub-task	Preparing ship for navigation
Bridge	1.1	Check voyage plan, charts, and necessary publications
	1.2	Ensure that electronic navigational aids (Navtex, GMDSS,AIS) are working
	1.3	Check gyro/magnetic compass and repeaters
	1.4	Set radars, echo sounder and GPS to standby by position
	1.5	Check bridge-engine room engine telegraph, RPM indicator and emg. stops
	1.6	Test steering gear and manual/auto pilot system
	1.7	Make sure that VHF and portable radios are ready to use
	1.8	Check navigation and signal lights
	1.9	Check sounding signal apparatus
	1.10	Complete necessary documentation including pilot card and ISM forms
	1.11	Get confirmation for readiness of main engine
Deck	2.1	Make sure that draft, stability, and hull strength are in good condition
	2.2	Check if all people (stevedore, labours, agent, etc.) are already disembarked
	2.3	Make sure that all hatch covers are closed and secured
	2.4	Prepare pilot ladder and equipment as requested
	2.5	Check cargo and cargo handling equipment securing
	2.6	Stand by bow anchors
	2.7	Ensure that all hull openings are secured and watertight
	2.8	Carry out a stowaway search
Engine	3.1	Make sure that emergency generator ready for autostart
	3.2	Check and test all alarms
	3.3	Set lub oil system and pump (temperature and pressure)
	3.4	Check cooling water system
	3.5	Control main engine temperature
	3.6	Check fuel oil system and boiler
	3.7	Start generators and air compressor
	3.8	Test engine telegraph and communication in conjunction with bridge
	3.9	Check steering gear and gyro
	3.10	Open main air starting valve and blown main engine
	3.11	Close turbocharger drain valves
	3.12	Report to bridge that engine is ready for use
	3.13	Check indicators and alarms regularly

deliver quantitative results (Yang et al. 2013). Therefore, three well-known shipping companies that have dry bulk cargo ship fleets were visited. The surveys were performed with the marine experts who have been working for long years at sea. The details of marine experts are provided in Table 3. The HTA and camera record were presented to marine experts and asked to evaluate each sub-task being completed in the course of the real ship preparing for navigation. Also, they were asked to assess APOA according to the fuzzy linguistic statements.

4.4. GTT and m-EPC selection

The consensus of marine experts is obtained in course of selection GTT and m-EPC for each sub-task that is being assessed since there are five marine experts participating in the survey. Table 4 shows nominated GTT and m-EPC, respectively.

4.5. APOA calculation

After assigning relevant GTT and m-EPC to each sub-task, the APOA calculation is performed by following Buckley's Fuzzy-AHP algorithm. Thus, the proportion of each m-EPC effects through HEP can be calculated. Five set pairwise comparison matrices (including 26 sub-tasks which have more than one m-EPC) were established in excel forms and sent to the marine experts along with Buckley's triangular fuzzy scale, which is provided in Table 5 (Buckley 1985; Gumus et al. 2013).

Each expert was asked to assess the importance level of each m-EPC as per scale through 26 sub-tasks. In this paper, sub-task 1.5 is described as a sample since there are excessive sub-tasks described in the HTA. The pairwise comparison of sub-task 1.5 with respect to five experts is presented in Table 6.

The linguistic assessment of the five experts is converted to the TFNs. Since there are five experts, the fuzzy arithmetic average operation is performed. Accordingly, Table 7 demonstrates the TFNs of the pairwise comparison for sub-step 1.5.

Then, the consistency of each comparison matrix is calculated. The CR of the sub-step 1.5 is 0.0993. Since the CR value is less than 0.10, the assessment inserted in the comparison matrix is considered as reasonable and consistent (Akyuz 2016). The CR values for all sub-steps are calculated and found consistent. After calculated CR values, the fuzzy geometric means and fuzzy weights of the sub-steps are obtained. Then, defuzzification is applied to compute the priority weights of each sub-steps. In the final step, the normalisation of the defuzzified weights is determined. Table 8 illustrates defuzzified and normalised weights of the sub-step 1.5, respectively. Table 9 shows results of the defuzzified and normalised weights for the entire sub-steps along with the CR values.

Table 3. Details of marine experts.

Marine expert	Position	Title	Educational Level	Years marine experienced
1	Superintendent	Master	MSc.	16
2	DPA	Master	BSc.	12
3	Operation Manger	Master	BSc.	10
4	Technical Manager	Chief Eng.	BSc.	18
5	Superintendent	Master	MSc.	9

Table 4. Selected GTT and m-EPC for each sub-task.

Department	Sub-task	GTT	Nominated m-EPC
Bridge	1.1	E	m-EPC17, m-EPC34
	1.2	E	m-EPC22
	1.3	H	m-EPC2, m-EPC13, m-EPC15
	1.4	G	m-EPC1, m-EPC13, m-EPC14
	1.5	G	m-EPC2, m-EPC15,m-EPC17, m-EPC22
	1.6	E	m-EPC22
	1.7	E	m-EPC3, m-EPC17
	1.8	G	m-EPC23, m-EPC32
	1.9	G	m-EPC2, m-EPC13, m-EPC14
	1.10	D	m-EPC17, m-EPC22
	1.11	H	m-EPC2, m-EPC14, m-EPC17
Deck	2.1	D	m-EPC17, m-EPC26
	2.2	G	m-EPC2, m-EPC17, m-EPC33
	2.3	F	m-EPC13, m-EPC23
	2.4	E	m-EPC27, m-EPC33
	2.5	E	m-EPC22, m-EPC25, m-EPC27
	2.6	G	m-EPC2, m-EPC13, m-EPC26, m-EPC32
	2.7	H	m-EPC2, m-EPC11, m-EPC14, m-EPC23
	2.8	G	m-EPC17, m-EPC25, m-EPC33
Engine	3.1	E	m-EPC17
	3.2	G	m-EPC2, m-EPC13, m-EPC15
	3.3	F	m-EPC24
	3.4	E	m-EPC18, m-EPC22
	3.5	H	m-EPC14, m-EPC23, m-EPC26
	3.6	G	m-EPC15, m-EPC26
	3.7	E	m-EPC34
	3.8	G	m-EPC2, m-EPC10, m-EPC14
	3.9	D	m-EPC22
	3.10	E	m-EPC17, m-EPC24
	3.11	F	m-EPC15, m-EPC25, m-EPC27
	3.12	G	m-EPC10, m-EPC26
	3.13	G	m-EPC14, m-EPC23, m-EPC26, m-EPC32

4.6. HEP calculation

The likelihood of human error for each sub-task during preparing ship for navigation is calculated in accordance with Equation (9). In this context, Table 10 demonstrates the calculated HEP values for each sub-task.

4.7. Comparison with fuzzy-SLIM approach

This section performs a comparison of the result with another robust methodology to validate the outcomes of the research. In this context, a SLIM is selected since it has capable

Table 5. Triangular fuzzy scale and linguistic terms.

Linguistic variables	Triangular fuzzy number	Reciprocal fuzzy number
Equally important (EI)	(1, 1, 1)	(1, 1, 1)
Intermediate value (IV)	(1, 2, 3)	(1/3, 1/2, 1)
Moderately more important (MMI)	(2, 3, 4)	(1/4, 1/3, 1/2)
Intermediate value (IV)	(3, 4, 5)	(1/5, 1/4, 1/3)
Strongly more important (SMI)	(4, 5, 6)	(1/6, 1/5, 1/4)
Intermediate value (IV)	(5, 6, 7)	(1/7, 1/6, 1/5)
Very strong more important (VSMI)	(6, 7, 8)	(1/8, 1/7, 1/6)
Intermediate value (IV)	(7, 8, 9)	(1/9, 1/8, 1/7)
Extremely more important (EMI)	(9, 9, 9)	(1/9, 1/9, 1/9)

Table 6. The pairwise comparison matrix for sub-task 1.5.

	m-EPC2	m-EPC15	m-EPC17	m-EPC22
m-EPC2	(EI, EI, EI, EI, EI)	(1/MMI, 1/EMI, 1/MMI, 1/MMI)	(1/IV, 1/IV, 1/MMI, 1/IV, 1/MMI)	(IV, MMI, EI, IV, EI)
m-EPC15	(MMI, IV, MMI, MMI, MMI)	(EI, EI, EI, EI, EI)	(IV, IV, MMI, IV, EI)	(SMI, IV, IV, IV, MMI)
m-EPC17	(IV, IV, MMI, IV, MMI)	(1/IV, 1/IV, 1/MMI, 1/IV, EI)	(EI, EI, EI, EI, EI)	(MMI, MMI, MMI, MMI, MMI)
m-EPC22	(1/IV, 1/MMI, EI, 1/IV, EI)	(1/EMI, 1/EMI, 1/EMI, 1/EMI, 1/MMI)	(1/MMI, 1/MMI, 1/MMI, 1/MMI)	(EI, EI, EI, EI, EI)

Table 7. The TFNs of the pairwise comparison for sub-task 1.5.

	m-EPC2	m-EPC15	m-EPC17	m-EPC22
m-EPC2	(1, 1, 1)	(0.24, 0.317, 0.467)	(0.3, 0.433, 0.8)	(1.2, 1.8, 2.4)
m-EPC15	(2.2, 3.2, 4.2)	(1, 1, 1)	(1.2, 2, 2.8)	(3, 4, 5)
m-EPC17	(1.4, 2.4, 3.4)	(0.45, 0.567, 0.9)	(1, 1, 1)	(2, 3, 4)
m-EPC22	(0.583, 0.667, 0.9)	(0.203, 0.257, 0.35)	(0.25, 0.333, 0.5)	(1, 1, 1)

Table 8. The weights of the sub-task 1.5.

	Fuzzy geometric means	Fuzzy weights	Defuzzified weights	Normalised weights
m-EPC2	(0.542, 0.705, 0.973)	(0.087, 0.145, 0.263)	0.17	0.151
m-EPC15	(1.678, 2.249, 2.769)	(0.269, 0.462, 0.75)	0.49	0.451
m-EPC17	(1.059, 1.421, 1.87)	(0.17, 0.292, 0.506)	0.32	0.295
m-EPC22	(0.415, 0.489, 0.63)	(0.066, 0.1, 0.171)	0.11	0.103

of quantifying the probability of human error in practically. The SLIM provides a practical result in the quantification process of human error. The comparison is exercised with SLIM under fuzzy environment since fuzzy sets cope with the vagueness of experts' judgement and expression in decision-making in prioritisation process of PSFs. The SLIM (Embrey et al. 1984) is the first-generation HRA technique developed to quantify and predict the HEPs by focusing on factors called PSFs that have a considerable effect on human performance (Grozdanovic 2005; Liu et al. 2021). The technique relies on the expert judgements in the data derivation process due to the lack of numerical data (Erdem and Akyuz 2021). As the core point of the SLIM, domain experts select a set of task-related PSFs, rank them on a linear scale in order of importance, and weigh their perceived importance on a given task, respectively. In conjunction with the quantification of PSFs, the obtained success-likelihood index (SLI) for each determined task is calibrated to predict the occurrence of HEP. In the basic SLIM approach, the decision-making process is rather subjective since the values to be nominated to PSFs may vary from one expert to the other. At this point, the weakness of the experts' judgements is minimised, and the accuracy of outcomes is increased by incorporating fuzzy logic. The main steps of the hybrid method that systematically quantify the HEP values are divided into the following steps: (i.) PSF derivation, (ii.) PSF rating, (iii.) PSF weighting, (iv.) SLI determination, (v.) HEP calculation. The following equations are used (Erdem, Akyuz, and Arslan 2021)

$$SLI = \sum_{i=1}^{n} r_i w_i, \quad 0 \leq SLI \leq 1 . \tag{9}$$

Table 9. Defuzzified and normalised weights of m-EPCs.

Sub-task	m-EPC	Defuzzified weight	Normalised weight	CR
1.1	m-EPC17	0.810	0.791	
	m-EPC34	0.210	0.209	
1.2	EPC22	1.000	1.000	
1.3	m-EPC2	0.688	0.657	0.098
	m-EPC13	0.110	0.106	
	m-EPC15	0.248	0.237	
1.4	m-EPC1	0.665	0.636	0.097
	m-EPC13	0.102	0.098	
	m-EPC14	0.279	0.267	
1.5	m-EPC2	0.165	0.151	0.099
	m-EPC15	0.493	0.451	
	m-EPC17	0.322	0.295	
	m-EPC22	0.112	0.103	
1.6	m-EPC22	1.000	1.000	
1.7	m-EPC3	0.332	0.321	
	m-EPC17	0.701	0.679	
1.8	m-EPC23	0.772	0.744	
	m-EPC32	0.266	0.256	
1.9	m-EPC2	0.123	0.117	0.097
	m-EPC13	0.667	0.631	
	m-EPC14	0.266	0.252	
1.10	m-EPC17	0.264	0.246	0.089
	m-EPC22	0.736	0.754	
1.11	m-EPC2	0.692	0.659	0.098
	m-EPC14	0.115	0.109	
	m-EPC17	0.243	0.232	
2.1	m-EPC17	0.341	0.312	0.087
	m-EPC26	0.659	0.688	
2.2	m-EPC2	0.111	0.107	0.094
	m-EPC17	0.533	0.515	
	m-EPC33	0.391	0.378	
2.3	m-EPC13	0.332	0.321	
	m-EPC23	0.702	0.679	
2.4	m-EPC27	0.687	0.659	
	m-EPC33	0.355	0.341	
2.5	m-EPC22	0.255	0.244	0.086
	m-EPC25	0.108	0.103	
	m-EPC27	0.683	0.653	
2.6	m-EPC2	0.353	0.335	0.097
	m-EPC13	0.491	0.465	
	m-EPC26	0.124	0.118	
	m-EPC32	0.086	0.082	
2.7	m-EPC2	0.575	0.540	0.089
	m-EPC11	0.074	0.070	
	m-EPC14	0.151	0.142	
	m-EPC23	0.265	0.249	
2.8	m-EPC17	0.277	0.263	0.094
	m-EPC25	0.106	0.101	
	m-EPC33	0.669	0.636	
3.1	m-EPC17	1.000	1.000	
3.2	m-EPC2	0.295	0.279	0.088
	m-EPC13	0.097	0.092	
	m-EPC15	0.664	0.629	
3.3	m-EPC24	1.000	1.000	
3.4	m-EPC18	0.575	0.543	
	m-EPC22	0.483	0.457	
3.5	m-EPC14	0.650	0.627	0.081
	m-EPC23	0.182	0.175	
	m-EPC26	0.205	0.198	
3.6	m-EPC15	0.678	0.639	
	m-EPC26	0.383	0.361	

(*Continued*)

Table 9. Continued.

Sub-task	m-EPC	Defuzzified weight	Normalised weight	CR
3.7	m-EPC34	1.000	1.000	
3.8	m-EPC2	0.153	0.147	0.098
	m-EPC10	0.477	0.460	
	m-EPC14	0.408	0.393	
3.9	m-EPC22	1.000	1.000	
3.10	m-EPC17	0.678	0.639	
	m-EPC24	0.383	0.361	
3.11	m-EPC15	0.171	0.166	0.084
	m-EPC25	0.430	0.417	
	m-EPC27	0.430	0.417	
3.12	m-EPC10	0.678	0.639	
	m-EPC26	0.383	0.361	
3.13	m-EPC14	0.271	0.253	0.095
	m-EPC23	0575	0.537	
	m-EPC26	0.104	0.097	
	m-EPC32	0.121	0.113	

Table 10. HEP values.

Sub-task	HEP	Sub-task	HEP
1.1	6.48E-02	2.6	2.93E-02
1.2	3.28E-02	2.7	9.66E-04
1.3	1.33E-03	2.8	4.01E-03
1.4	2.41E-02	3.1	5.58E-02
1.5	9.80E-03	3.2	2.55E-02
1.6	3.28E-02	3.3	2.55E-02
1.7	7.72E-02	3.4	3.51E-03
1.8	5.67E-02	3.5	2.42E-04
1.9	2.04E-02	3.6	4.94E-03
1.10	1.92E-01	3.7	5.26E-05
1.11	4.40E-04	3.8	2.12E-02
2.1	3.60E-01	3.9	1.48E-01
2.2	8.03E-03	3.10	4.55E-02
2.3	5.91E-02	3.11	1.96E-02
2.4	2.59E-01	3.12	5.39E-03
2.5	7.54E-02	3.13	8.21E-03

Within equation (X), n expresses the number of PSFs, r_i represents the rating scale of PSFs, and w_i represents the weight of the PSFs' relative importance.

$$Log\ (HEP) = aSLI + b. \tag{10}$$

In the equation, a and b are the constant values (Embrey et al. 1984).

In the view of the fuzzy-SLIM approach, the dataset was obtained from five marine experts who participated to survey. The consensus of marine experts judgements was gathered during calculation process. Accordingly, Table 11 illustrates the results of HEP calculations of sub-tasks of preparing the ship for navigation, respectively.

Based on the obtained results, the graphical representation of comparative HEP values of the two fuzzy-based methods for the preparing the ship for navigation is depicted in Figure 2.

In view of the extended HEP assessments, the findings of research are considered consistent and in the range of expectation.

Table 11. Calculated HEP values under fuzzy-SLIM approach.

Sub-task	HEP	Sub-task	HEP
1.1	6.70E-02	2.6	2.44E-02
1.2	8.94E-02	2.7	8.16E-03
1.3	2.19E-03	2.8	3.10E-02
1.4	9.42E-02	3.1	5.49E-02
1.5	7.97E-03	3.2	2.43E-02
1.6	3.36E-02	3.3	7.30E-02
1.7	1.58E-02	3.4	1.01E-03
1.8	4.47E-02	3.5	2.36E-04
1.9	1.87E-02	3.6	1.20E-02
1.10	1.85E-01	3.7	1.31E-04
1.11	7.78E-05	3.8	2.34E-02
2.1	3.22E-01	3.9	1.78E-01
2.2	5.92E-03	3.10	4.27E-02
2.3	4,81E-02	3.11	7.85E-02
2.4	2.07E-01	3.12	5.08E-03
2.5	6.39E-02	3.13	7.71E-03

4.8. Findings and discussion

In light of the five experts' assistance, the notations defined in Table 1 are used to calculate the total HEP of the whole sub-tasks. Thus, the human reliability of the entire process can be predicted. As the preparing ship for navigation process constitutes three main and 32 sub-tasks in HTA, the total HEP is initially calculated through main steps as the common practice of the reliability estimation. Within this context, the main task 1 (bridge) consists of 11 sequential sub-tasks. As these 11 steps are of high dependency and only failure of all sub-tasks would fail the step, the total HEP of main task 1 is assigned 4.00E-04. Likewise, the total HEP is found 1.00E-03 since the eight sub-tasks in main task 2 (deck) are of high dependency and parallel. The main task 3, on the other hand, will fail if any of the thirteen sub-tasks is failed (serial—high dependency). Therefore, the total HEP for main task 3 is found 1.48E-01. As three main tasks (bridge-deck-engine) are of the low dependency and serial, any one of them is failed, then the entire process will fail. Therefore, the total HEP is the sum of probabilities of three main tasks, which is 1.49E-01.

In the view of extensive human reliability analysis, the crew performance throughout preparing the ship for navigation is found unsatisfactory. According to the contextual control model and probability interval (Hollnagel 1998), the choice of the action is essentially random. Although the crew performance follows a plan, there would be some possible deviations due to observation and execution errors. In light of the findings, it is noted that although tasks during ship preparation for navigation are aimed at increasing safety at sea, the occurrence of crew errors in bridge, deck, and engine is likely to increase the potential risk. The human reliability decreases drastically during some of sub-tasks where HEP values increase. Particularly, sub-task 2.1 (checking draft, stability and hull strength) is one of the main contributing factors to human error. This error is mainly due to not enough attention to detail by the responsible officer, insufficient inspection by shore-based management and not to following process by senior officers. In order to deal with the aforementioned errors, draft and stability calculations along with the strength of hull are regularly monitored by the responsible officer. A regular inspection must be carried out by senior officers. The shore-based management (superintendent or DPA) must check draft and stability records during internal audits.

The sub-task 2.4 (preparing pilot ladder and related equipment) is another critical sub-task where the HEP increases sharply. According to the SOLAS (Safety of Life At Sea), the equipment and arrangements of the pilot ladder efficiently fulfil their purpose of enabling pilots to embark and disembark safely. The reason for the high HEP is mainly caused by poor working environment and physical disability of the crew. To mitigate the human error, the working environment, in particular on-deck where pilot ladder and equipment are placed, must keep clean and tidy as per ISM Code checklists. The responsible crew who rigged the pilot ladder should be rest enough according to the STCW watchkeeping requirement.

The sub-task 1.10 (preparing pilot card and ISM forms) also has a high HEP value due to insufficient inspection performed by senior officers and lack of exercise. To remedy this gap, a clearly illustrated guide can be prepared for officers showing how to complete pilot card and relevant ISM forms. In addition, the frequency of interim audits can be increased. Situation awareness about pilot card and ISM forms should be enhanced by applying practical training before embarking ship. The sub-task 3.9 (checking steering gear and gyro at emergency steering gear room) is another critical task where HEP value comparatively increases. Insufficient training and drill are the main contributor to human error. In order to minimise human error and enhance safety, participation of all engine crew to training and drill should be provided concerning the steering gear and gyro.

5. Conclusion

Preparing cargo the ship for navigation is a considerably important aspect of a safe voyage. There are numerous complicated tasks involved in bridge, deck, and engine departments, and those must be completed prior to commencement of the voyage. The performance of ship crew plays a critical role. At this point, the human reliability assessment is required to assess likelihood of human error occurring throughout the completion of a specific task during ship preparing for navigation. This paper aims at performing a comprehensive human reliability analysing through procedures of preparing ship for navigation. A marine-specific HRA method under a fuzzy logic environment is adopted to monitor the performance of ship crew in terms of their reliability and enhance safety control levels in the operational aspect. To verify the research findings, the fuzzy-SOHRA is compared with fuzzy-SLIM. After performing a detailed analysing, the findings show that the crew reliability performance during the preparing ship for navigation is not satisfactory. There are some possible deviations due to observation and execution errors. In the view of findings, some remedial measures are recommended for tasks with higher HEP in order to reduce the probability of human error.

Since the paper presents a practical approach to monitor the performance of the ship's crew from the point of reliability assessment, the practical contributions of the study are highly welcomed by shore-based safety professionals, ship managers, and masters. Furthermore, the proposed approach is applicable for all marine-based operations and processes as it could provide a flexible tool to systematically monitor the crew's reliability. In a future perspective, the research can be extended through interval type-2 fuzzy logic to increase the ability of handle inexact information and provide better performance result.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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