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Quantitative human error assessment during abandon ship procedures in maritime transportation

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ABSTRACT

Human error prediction is always onerous work in the maritime domain since it is very difficult to obtain empirical data. One accepted method, Success Likelihood Index Method (SLIM), is utilized to assess human error as data is very scarce in the marine industry. The SLIM provides a quick tool to predict human error and evaluate human error probability (HEP) that occurs during the completion of a specific task. The weakness of the method is the subjectivity in the process of experts' judgments causing difficulties in ensuring consistency. To remedy this gap, this paper proposes a fuzzy based SLIM technique which provides more accurate estimation during human error quantification. In the proposed approach, while the SLIM is utilized to estimate HEP, the fuzzy sets deal with the vagueness of expert judgments and expression in decision-making during the weighting process of performance shaping factors (PSF). To illustrate the proposed approach, the abandon ship procedure in marine transportation has been selected since the evacuation of the ship is critical to prevent the loss of life in the case of emergency. The outcomes of the paper can be utilized by ship owners, safety managers as well as ship management companies to minimize the likelihood of human error occurring within a specific task and to enhance overall levels of safety on-board a ship in the marine environment.

1. Introduction

In maritime transportation, human error assessment can pose a major challenge since there are numerous hazardous jobs such as cargo loading, cargo unloading, ballasting, de-ballasting, cargo tank washing, gas inerting, gas freeing, ship to ship cargo transferring, etc. performed on-board ship. Statistics show that most marine accidents are due to human error (EMSA, 2015; Akyuz, 2015a; Corovic and Djurovic, 2013). The consequence of human error may pose acute hazards to human life, the ocean environment and property. The human factor is critically important for maritime transportation, however, the quantification of human error is quite difficult due to data scarcity in records (Akyuz and Celik, 2015a). Despite a set of rules and regulations adopted by maritime authorities to reduce marine accidents caused by human errors in recent years, many studies have highlighted that accidents continue to occur (Ugurlu et al., 2015; Chauvin et al., 2013; Gaonkar et al., 2011). Therefore, maritime safety practitioners are seeking alternative solutions to minimize human error and enhance safety in maritime transportation. In this context, this paper suggests an alternative practical approach to quantify human errors. Thus, critical human failure can be assessed from technical and operational aspects.

In cases of maritime disaster such as collision, grounding, flooding or fire on-board ship, the decision to abandon ship can be ordered by the master of the vessel to prevent the loss of life. At this point, crew performance plays a critical role to minimize hazards that may arise due to human errors. In the literature, although numerous research papers have been undertaken, those related to emergency ship procedures have been limited. In their article, Hu et al. (2013) discussed flooding emergencies on-board ships. The authors adopt M-H method to solve problems during flooding emergencies. A similar study was conducted to support emergency planning decisions during ship flooding emergency response (Varela et al., 2014). The paper utilizes the benefits of a simulation which is supported by a Virtual Environment in real-time. There has been a variety of research addressing passenger ship evacuation in an emergency situation since the consequences could be disastrous in the case of a serious accident occurring (Vanem and Skjong, 2006). Therefore, much attention has been given to the enhancement of evacuation techniques on board passenger ships as they are carrying thousands of passengers on-board ship (Lee et al., 2003). For instance, Park et al. (2015) have recently introduced evacuation analysis on passenger ships by using experimental scenarios. In the paper, authors focus on the validation of SIMPEV by using computer simulation. Likewise, another study was performed to simulate and validate a passenger

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ship evacuation case (Wang et al., 2014a). Furthermore, another study with respect to the evacuation of passenger ships was proposed by Vanem and Ellis (2010) in order to provide substantial decision support to the ship's officer in charge of evacuation. The paper presents a cost-effectiveness assessment by using RFID technology. A study, introduced by Jasionowski (2011), was prepared from a different perspective in terms of evacuation of a passenger ship. The study discusses a prototype of an ergonomic decision support function in response to a distressed flooding situation. There are also a couple of novel studies upon evacuation in an emergency situation in different industries such as off-shore platforms, the energy sector, petrochemicals, mining, etc. (Shen et al., 2015; Wang et al., 2014b; Deacon et al., 2013; Cruz and Krausmann, 2009; Dimattia et al., 2005).

Since emergency evacuation is one of the most critical issues in various domains, human error assessment is quite substantial in the event of abandoning ship to enhance safety and prevent the loss of life in the marine environment. The well-known case of the Costa Concordia, in which 32 people lost their lives, is a tragic example that illustrates the importance of the role of human error during an evacuation process. Therefore, the aim of this paper is to introduce a practical hybrid tool for performing quantitative human error assessment in the event of abandoning ship in maritime transportation. The proposed approach can be used to determine HEP by overcoming the vagueness of experts' judgments. Thus, quantification of human error for each step of the abandon ship procedure can be calculated. On the basis of outcomes, human error reduction measures will be recommended to prevent the loss of life and to improve safety levels on-board ships. The proposed approach attempts to combine fuzzy sets into SLIM technique in order to get a comprehensive and rational framework to assess HEP. In this context, the paper is organized as follows; this section gives an introduction and a brief literature review of evacuation. The next section introduces methodologies and defines the proposed approach. Section three illustrates how the proposed approach can be applicable to the abandon ship procedure. Section four includes the conclusion and the contribution of research to maritime transportation.

2. Research methodology

This study presents a hybrid approach by combining fuzzy sets and SLIM technique in order to quantify HEP values systematically in the event of an abandon ship event in maritime transportation. A brief definition of both methodologies are presented in the next section.

2.1. Fuzzy sets

Fuzzy sets are employed if there is vagueness or imprecision in human judgments in the decision making process. Zadeh (1965) first introduced the theory as an extension of the classical notation of sets. Since then, it has been used in a wide range of disciplines to overcome ambiguity in decision-makers ideas. A linguistic value can be represented by the approximate reasoning of fuzzy set numbers (Celik and Gumus, 2015). The linguistic values are utilized to transform decision makers' ideas or assessments into meaningful information. The theory can be applied models where expert/decision-maker knowledge can be stated in natural language such as high, medium or low (Castiglia and Giardina, 2013). At this point, the fuzzy linguistic concept is very practical to help express very complicated or ill-defined circumstances in traditional quantitative definitions (Casamirra et al., 2009).

In fuzzy set theory, a fuzzy subset A in X is characterized by a membership function $\mu_A(x)$, which associates each element x in X with a real number in the interval [0, 1]. The function $\mu_A(x)$ shows the membership of x in the fuzzy set A (Castiglia and Giardina, 2013). The membership function of fuzzy sets can be expressed in different shapes, triangular or trapezoidal being the most frequent ones in the literature. Triangular fuzzy set numbers are expressed as triplets (x_1, x_2, x_3) and the membership function $\mu_A(x)$ is defined as follows.

$$\mu_A(x) = \begin{cases} \dfrac{x - x_1}{x_2 - x_1}, & x_1 \le x \le x_2 \\ \dfrac{x - x_3}{x_2 - x_3}, & x_2 \le x \le x_3 \\ 0, & \text{otherwise} \end{cases} \quad \text{where } x_1 < x_2 < x_3 \tag{1}$$

On the other hand, trapezoidal fuzzy set numbers are expressed as x_1, x_2, x_3, x_4 and the membership function $\mu_A(x)$ is stated as follows.

$$\mu_A(x) = \begin{cases} \dfrac{x - x_1}{x_2 - x_1}, & x_1 \le x \le x_2 \\ 1 & x_2 \le x \le x_3 \\ \dfrac{x - x_4}{x_3 - x_4}, & x_3 \le x \le x_4 \\ 0, & \text{otherwise} \end{cases} \quad \text{where } x_1 < x_2 < x_3 < x_4 \tag{2}$$

2.2. Slim

SLIM (Success Likelihood Index Method), a decision-analytic approach, is one of the practical techniques to estimate human error probability throughout the completion of a specific task (Embrey et al., 1984). It is quite practical in the human error probability prediction process in cases where it is difficult to acquire human error data (Park and Lee, 2008). Although the method heavily relies on experts' judgments, it can be a good alternative to calculate human error data in maritime transportation due to the lack of error data. The PSF, which has considerable influence on human performance, can be quantified in SLIM and converted into the form of a preference index. Thus, a Success Likelihood Index (SLI) is elicited by using experts' judgments. The SLI is calibrated with existing human error data to calculate the HEP value. The main steps of SLIM can be expressed as follows.

- Task analysis and scenario definition
- PSF derivation
- PSF rating
- Weighting of PSF
- Calculating SLI
- Converting SLI into HEP

In order to calculate SLI values, Eq. (3) is used. In the equation, n denotes the number of PSFs, r_i represents the rating scale of PSFs and w_i gives the weight of importance of the PSF.

$$SLI = \sum_{i=1}^{n} r_i w_i, 0 \le SLI \le 1 \tag{3}$$

Accordingly, the SLI value is transformed into the HEP value by using Eq. (4) where a and b are constant (Embrey et al., 1984).

$$Log(HEP) = aSLI + b \tag{4}$$

2.3. Proposed approach: fuzzy SLIM

This section proposes a hybrid approach combining fuzzy sets and SLIM to perform quantitative human error prediction in the event of an abandon ship procedure in maritime transportation. A

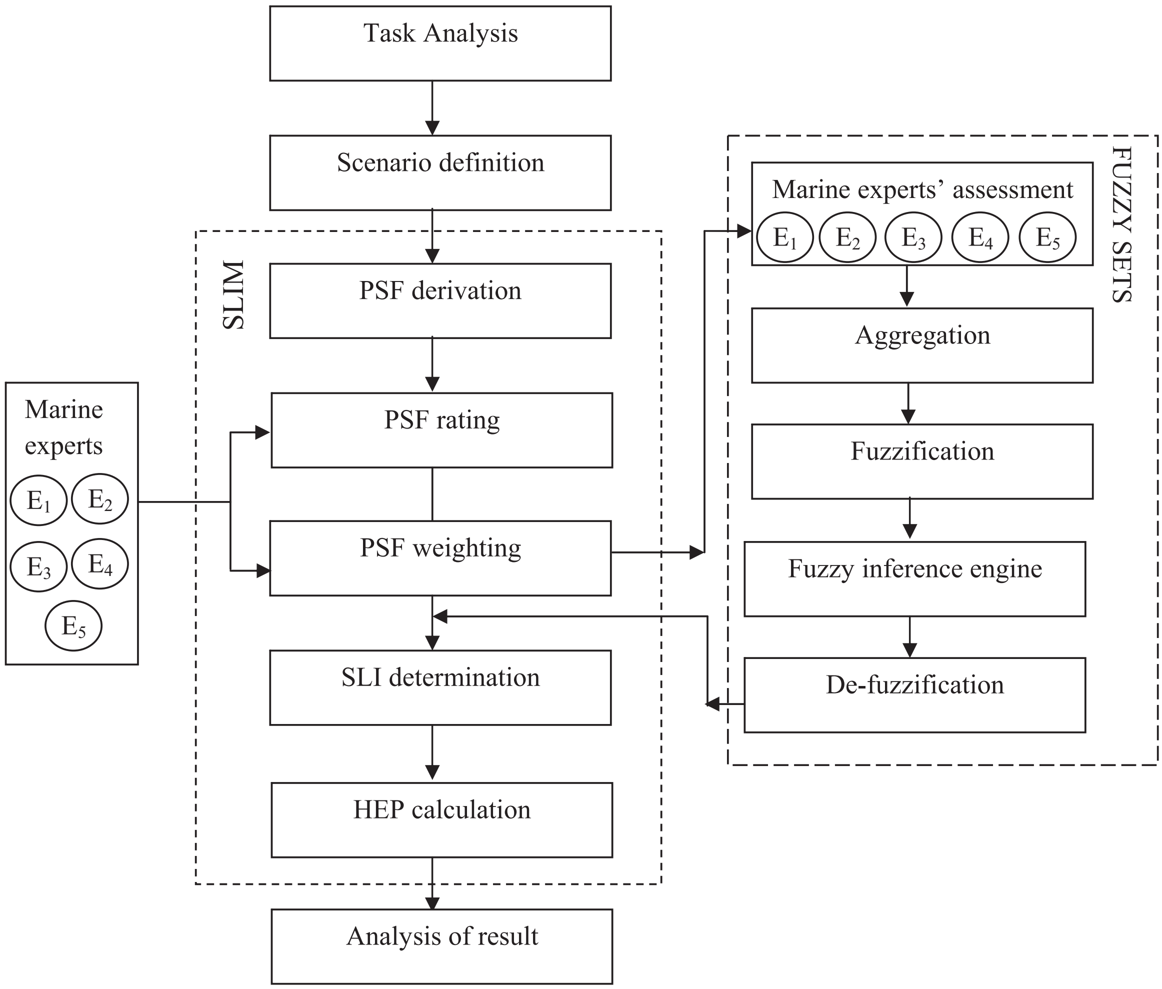

Fig. 1. A flow chart of proposed approach.

flow chart of the proposed approach is illustrated in Fig. 1. The main steps of the proposed approach are expressed as follows.

2.3.1. Step 1- Task analysis

In this section, task analysis is conducted to identify relevant steps in accordance with the scenario. It addresses activities that the ship's crew must complete successfully one by one. The task analysis is conducted in compliance with Hierarchical Task Analysis (HTA) where the main task consists of sub-tasks (Shepherd, 2001).

2.3.2. Step 2- Scenario definition

This section defines a variety of scenarios in the course of the event. This scenario involves numerous conditions such as weather conditions, the working environment, fatigue, workforce morale, stress, noise level, experience, etc.

2.3.3. Step 3- PSF derivation

In this section, the group of experts elicits a set of PSFs that affect human performance in the event of the task. The PSFs can be various factors such as time availability, ergonomics, task complexity, poor working environment, age, etc., that are the most significant factors affecting the tasks.

2.3.4. Step 4- PSF rating

After elicited PSFs, each of them are assigned a value from 1 to 9 in a liner scale by the experts. The most negative score is generally 1 if a PSF has a significant influence upon the task. It means that if lower PSF's performance is required, for example time limitation, the highest score is 1. The experts adjust their assessment on the basis of conditions occurring during the task. The assessments made by experts are independent from the influence of other PSFs.

2.3.5. Step 5- PSF weighting

In this section, the weighting procedure is applied to prioritize PSF in terms of the influence on each task. Thus, the relative importance of each PSF can be determined. In traditional SLIM technique, the PSF weighting is conducted on the basis of experts' direct percentage assessment. To overcome this weaknesses, this paper adopts fuzzy linguistic expression in the representation of percentage assessment. Thus, expert weighting assessment upon PSF can be converted into linguistic values such as very low, medium, or high in the decision-making. The fuzzy linguistic expression in the representation of percentage assessment of PSFs may enhance the accuracy of the outcome. In this context, the relation among the linguistic terms and triangular fuzzy numbers are expressed with respect to the Fig. 2 (Castiglia and Giardina, 2013).

In light of the fuzzy linguistic variables, the following membership functions can be described respectively (Akyuz and Celik, 2015b; Castiglia and Giardina, 2013).

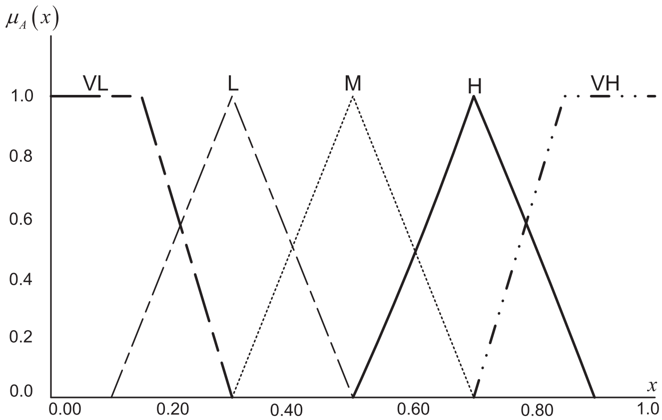

Fig. 2. Fuzzy linguistic variables of PSF assessment.

$$\mu_{VL}(x)=\begin{cases}1.0, & 0.0<x\le 0.15\\ \dfrac{0.3-x}{0.15}, & 0.15<x\le 0.3\\ 0, & otherwise\end{cases} \tag{5}$$

$$\mu_{L}(x)=\begin{cases}\dfrac{x-0.1}{0.2}, & 0.1<x\le 0.3\\ \dfrac{0.5-x}{0.2}, & 0.3<x\le 0.5\\ 0, & otherwise\end{cases} \tag{6}$$

$$\mu_{M}(x)=\begin{cases}\dfrac{x-0.3}{0.2}, & 0.3<x\le 0.5\\ \dfrac{0.7-x}{0.2}, & 0.5<x\le 0.7\\ 0, & otherwise\end{cases} \tag{7}$$

$$\mu_{H}(x)=\begin{cases}\dfrac{x-0.5}{0.2}, & 0.5<x\le 0.7\\ \dfrac{0.9-x}{0.2}, & 0.7<x\le 0.9\\ 0, & otherwise\end{cases} \tag{8}$$

$$\mu_{VH}(x)=\begin{cases}\dfrac{x-0.7}{0.15}, & 0.7<x\le 0.85\\ 1.0, & 0.85<x\le 1\\ 0, & otherwise\end{cases} \tag{9}$$

2.3.6. Step 6- SLI determination

After having calculated PSF rating and weighting values, the SLI is determined by applying Eq. (3). The SLI predicts the probability of situations in which numerous human errors may occur.

2.3.7. Step 7- HEP calculation

In this section, the calculated SLI values can be transformed into HEP values using Eq. (2). In order to define constant *a* and *b* values in the equation, the SLI values are calibrated. To calibrate the SLI, the HEP values of at least two tasks have been already acquired.

3. Application

The proposed approach is demonstrated with abandon ship procedures in maritime transportation, as this task can pose serious potential hazards for a ship's crew. The SLIM is one of the best empirical techniques to quantify human error since there is a lack of human error data in the maritime industry. Likewise, fuzzy sets are the best practice to tackle the ambiguity and vagueness in the human error detection problem. Utilizing the fuzzy sets and the SLIM constitutes a unique contribution by predicting the possibility of human error accurately for critical shipboard procedures.

3.1. Abandon ship procedure on cargo ships

Abandoning ship is one of the most crucial and serious decisions that is made by the master of the ship. The decision is usually very difficult since the crew might encounter very dangerous situations. The master of the ship is the person responsible for giving an abandon ship order in case of emergency (such as collision, fire, explosion, sinkage, grounding or flooding of the vessel). There are three different types of crafts on-board a ship that can be used during an abandon ship event; lifeboats (open top, enclosed or free fall), life rafts and rescue boats. The lifeboat (free-fall type) is the fastest and safest mode during an abandon ship process since life raft and rescue boat evacuations take a more time when compared to lifeboats. Abandoning ship is especially critical for crude oil tanker ships due to the hazardous cargo carried on-board ship. Crude oil tankers are special types of vessels built to transport crude oil from oil rigs to refineries. They have separate cargo tanks, cargo lines and cargo pumps, as well as cargo valves. Due to the fact that crude oil cargo can pose considerable harm to human life, the marine environment and the ship itself in the cases of cargo spillage, leakage or explosion, emergency abandon ship procedures play a key role in successful evacuations.

3.2. Problem statement

The abandon ship drill is one of the most significant practical trainings on-board ships. Abandon ship procedures are generally found to be major weaknesses of the crew and may result in tragedy. In view of recent ship disasters, abandon ship procedures are investigated and analyzed by maritime authorities. According to the SOLAS (Safety of Life at Sea) convention, an abandon ship drill shall be conducted at least once a month. Crew on-board the ship shall participate in each abandon ship drill since the aim of the drill is to ensure loss prevention during an evacuation in an emergency situation. At this point, the crew's performance and ability to complete a quick and efficient evacuation on-board the ship is very critical. The expectation from the crew is to conduct an abandon ship procedure without any operational failure. Therefore, it is necessary to determine the probability of human error for each task during abandon ship procedures on-board a ship since the consequences could cause potential harm to human life and the marine environment.

3.3. Analysis of respondents

Due to the lack of human error data in marine transportation, the experts' judgments are used to assess human error during an abandon ship procedure. The experts' judgments provide necessary input in the presence of various options in decision-making. In order to perform an effective and accurate PSF rating and weighting, three different shipping companies with crude carrier ship fleets were contacted. The cargo carrying capacity of the fleets vary from 50k DWT (deadweight tons) to 185k DWT. A comprehensive survey was carried out with the executive managers, including superintendents and DPAs (Designated Person Ashore). The marine experts have wide experience and knowledge since they have worked for long years at sea as Masters and Chief

Table 1
Marine experts' profile details.

Marine Expert No	Company	Position	Educational level	Years marine experienced	Age
1	Company A	Superintendent	Graduate	24	49
2	Company A	Senior DPA	Undergraduate	19	44
3	Company B	Superintendent	Gradate	12	39
4	Company B	Senior DPA	Undergraduate	14	41
5	Company C	Junior DPA	Graduate	8	36

Table 2
HTA of abandon ship procedure in crude oil tanker.

Abandon ship procedures
1. Prepare to abandon ship
1.1 Raise the alarm
1.2 Call the Master of ship
1.3 Make announcement for abandon ship
1.4 Send distress messages (Mayday)
1.5 Report the situation
2. Gather at muster station
2.1 Make sure that all crew gathered at muster station
2.2 Check that all crew are suitable donned lifejackets
2.3 Brief all crew for abandon ship procudures
2.4 Confirm crew fully understand procedures
2.5 Instruct crew to embark the lifeboat
3. Launch the lifeboat
3.1 Make sure that all crew, except those who have duties for launching, embark the lifeboat
3.2 Set the engine control for restart
3.3 Check the launching area is clear of any obstructions and water depth is enough
3.4 Check engine running satisfactorily
3.5 Close the drain plug
3.6 Disconnect battery charger
3.7 Make sure that all crew embark to designated seats and fastened the seat belts
3.8 Close and secure hatches and door
3.9 Switch on electrical system into battery power
3.10 Release the lifeboat by operating hydraulic releasing
4. Further actions
4.1 Start engine
4.2 Open the ventilations
4.3 Clear from the vessel
4.4 Operate radio distress signal

Officers. The experts' profiles are demonstrated in Table 1. In the survey, HTA of abandon ship procedures was presented to the marine experts and they were requested to assess the rating of PSFs for each of the sub-tasks. Also, they were asked to weight the PSFs with respect to fuzzy linguistic statements.

3.4. Task analysis and scenario definition

A hierarchical task analysis for the procedure of abandoning ship with a free-fall lifeboat is demonstrated in Table 2. The procedure comprises of four main tasks which are i) Prepare to abandon ship, ii) Gather at muster station, iii) Launch the lifeboat and iv) Further actions, respectively. The total number of sub-tasks is twenty four.

A variety of scenarios are defined for the abandon ship procedures once the task analysis is completed. In order to achieve these purposes, a real shipboard abandon drill was selected. Special permission was obtained to come aboard and monitor the drill. The abandon ship drill was carried out at noon time as the crude oil tanker was at anchored in the Ahirkapi anchorage area. All crew, except the duty officer and the duty engineer (who kept watch on the bridge and in the engine room), participated in the abandon ship drill which was carried out on the lifeboat deck. A free fall lifeboat was launched. At the time of the drill, the shipboard environment conditions were at a satisfactory level. The crew were rested enough since the vessel had been at anchorage for more than 2 days. The noise level and mental workload were acceptable. The weather was cloudy and the sea was moderate. All events from the beginning to the end were recorded by portable camera to present to the marine experts for evaluation.

3.5. Deriving and rating PSF

In order to enhance the consistency of application, this paper adopts eight PSFs. Six of them have been successfully elicited by twenty-four member ERT (Elicitation Review Team) whose primary job functions were: engineering (fourteen), operations (six), health and safety (three), and administration (one) (DiMattia et al., 2005). The elicitation process was performed for off-shore platform musters. The rest of the PSFs (communication and safety culture) were added to enhance the quality of research since communication skills are of utmost importance in maritime transportation as the crew are most likely to be multicultural. Likewise, safety culture is considered an important performance driver. With this in mind, eight PSFs were presented to marine experts for review and comment. At the end of the discussion, the aforementioned PSFs were approved by the marine experts. Table 3 shows the nominated PSFs (DiMattia et al., 2005).

In light of the nominated PSFs, the marine experts were asked to evaluate the rating in terms of the level of compliance for each PSF for each sub-task. Table 4 gives PSF ratings based on the marine experts' assessments. Since there were five marine experts to evaluate each task, the mathematical means were obtained.

Table 3
Nominated PSFs.

No	PSF	Definition
1	Stress	Have negative effect upon human performance and referred to level of undesirable conditions and circumstances.
2	Complexity	Imply how difficult action/task is to carry out in the given context.
3	Training	Organized activity or action either performed at shore and on-board ship aiming to improve performance.
4	Experience	Imply that familiarity and knowledge of task over the years.
5	Time availability	Amount of time that the crew must complete task on an abnormal event.
6	Environmental factors	Factors affect the crew performance such as weather, condition of lifeboat, condition of muster station, etc.
7	Communication	Act of transferring information/order from one place to another during performed task.
8	Safety culture	Reflect perception, attitudes or beliefs that ship crew share in relation to maritime safety.

Table 4
PSF ratings based on the marine experts' assessment.

Task	Sub-task	PSFs							
		Stress	Complexity	Training	Experience	Time availability	Environmental factors	Communication	Safety culture
1.									
	1.1	4	7	4	6	2	3	4	5
	1.2	3	7	6	6	3	2	6	3
	1.3	3	5	4	5	4	4	4	4
	1.4	2	2	4	3	2	4	3	6
	1.5	3	4	4	2	1	5	3	4
2.									
	2.1	4	6	4	5	3	2	5	6
	2.2	5	6	3	4	3	3	7	5
	2.3	4	6	4	5	4	4	5	4
	2.4	5	3	4	3	6	5	4	6
	2.5	5	3	2	5	6	2	6	4
3.									
	3.1	6	5	4	5	4	3	5	4
	3.2	4	3	3	2	4	4	6	5
	3.3	5	6	4	3	4	3	5	3
	3.4	4	5	5	3	6	5	4	4
	3.5	4	5	3	3	2	4	6	5
	3.6	4	4	3	4	5	5	6	3
	3.7	3	7	4	6	4	3	3	5
	3.8	4	5	6	6	2	4	5	4
	3.9	4	3	3	4	5	5	5	6
	3.10	3	4	3	4	5	3	7	6
4.									
	4.1	4	4	2	5	5	5	6	4
	4.2	5	7	6	3	6	2	5	3
	4.3	3	8	7	5	4	2	4	5
	4.4	3	3	3	3	5	5	5	4

Table 5
Fuzzy linguistic statement of marine experts.

PSF	Marine experts				
	Exp.1	Exp.2	Exp.3	Exp.4	Exp.5
Stress	M	M	L	L	H
Complexity	L	M	VL	L	VL
Training	M	VH	L	M	L
Experience	VH	M	H	M	L
Time availability	M	L	H	L	M
Environmental factors	H	VH	M	M	H
Communication	M	H	H	M	H
Safety culture	L	VL	M	H	L

Table 6
Weight of marine experts and their relative importance.

	we_1	we_2	we_3	we_4	we_5	RI_1	RI_2	RI_3	RI_4	RI_5
Stress	0.30	0.25	0.20	0.15	0.10	1	0.7	0.3	0.3	0.3
Complexity	0.17	0.18	0.35	0.20	0.10	0.3	0.5	1	1	1
Training	0.16	0.25	0.31	0.13	0.15	0.3	1	0.6	0.6	0.6
Experience	0.23	0.32	0.25	0.10	0.10	0.5	0.7	1	1	1
Time shortage	0.12	0.23	0.25	0.15	0.25	0.2	1	0.4	0.4	0.4
Environmental factors	0.11	0.16	0.23	0.25	0.25	0.2	1	0.6	0.6	0.6
Communication	0.12	0.33	0.15	0.15	0.25	0.2	1	0.4	0.4	0.4
Safety culture	0.11	0.29	0.13	0.25	0.22	0.2	0.7	0.6	0.6	0.6

3.6. Weighing PSF

After determining PSF rates, the weighing process is conducted on the basis of a fuzzy linguistic scale. The marine experts assess the importance of the PSF according to the fuzzy linguistic statement which is provided in Table 5. Since the importance of each marine expert's opinion about an attribute might not be equal, the assessments are influenced by the degree of importance of each expert. This is called a non-homogeneous (heterogeneous) group of experts' (Ölçer et al., 2006). A robot tool aggregating multiple expert opinions was presented based on the assigned degree of importance of each expert in the aggregation stage (Ölçer and Odabaşi, 2005). Thus, more accurate and reliable decision-making in the PSF weighting process is obtained. In this context, the method introduced in Ölçer and Odabaşi (2005) is used to adjust the impact level of the expert's judgments in the aggregation stage of the methodology which consists of following basic steps: i) Calculating degree of agreement (S) of the opinions between each pair of experts, ii) Establishing agreement matrix, iii) Determining average degree of agreement (AA) of experts, iv) Calculating the relative degree of agreement (RA), v) Calculating the consensus degree coefficiency, vi) Aggregation result of the fuzzy options (Ölçer and Odabaşi, 2005). The relative importance (*RI*) and weight of experts (*we*) were assigned in accordance with importance observed through the survey with the managers of the companies. Then, *RI* and *we*, provided in Table 6, were determined.

Thereafter, the degree of agreement (S), which is illustrated in Table 7, of the opinions between each pair of marine experts were calculated. The average degree of agreement (AA) and relative degree of agreement (RA) were calculated and the same are

Table 7
Degree of agreement (S).

	S_{12}	S_{13}	S_{14}	S_{15}	S_{23}	S_{24}	S_{25}	S_{34}	S_{35}	S_{45}
Stress	1.00	0.80	0.80	0.80	0.80	0.80	0.80	1.00	0.60	0.60
Complexity	0.80	0.85	1.00	0.80	0.65	0.80	1.00	0.85	0.65	0.80
Training	0.85	0.80	1.00	0.60	0.65	0.85	0.45	0.80	0.80	0.60
Experience	0.65	0.85	0.65	0.45	0.80	1.00	0.80	0.80	0.60	0.80
Time shortage	0.80	0.65	0.65	0.80	0.85	0.85	1.00	1.00	0.85	0.85
Environmental factors	0.85	0.80	0.80	1.00	0.65	0.65	0.85	1.00	0.80	0.80
Communication	0.80	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80
Safety culture	1.00	0.80	0.60	1.00	0.80	0.60	1.00	0.80	0.80	0.60

Table 8
Average degree of agreement (AA) and relative degree of agreement (RA).

	AA (Exp_1)	AA (Exp_2)	AA (Exp_3)	AA (Exp_4)	AA (Exp_5)	RA(Exp_1)	RA(Exp_2)	RA(Exp_3)	RA(Exp_4)	RA(Exp_5)
Stress	0.850	0.850	0.800	0.800	0.700	0.213	0.213	0.200	0.200	0.175
Complexity	0.863	0.813	0.750	0.863	0.813	0.210	0.198	0.183	0.210	0.198
Training	0.813	0.700	0.763	0.813	0.613	0.220	0.189	0.206	0.220	0.166
Experience	0.650	0.813	0.763	0.813	0.663	0.176	0.220	0.206	0.220	0.179
Time shortage	0.725	0.875	0.838	0.838	0.875	0.175	0.211	0.202	0.202	0.211
Environmental factors	0.863	0.750	0.813	0.813	0.863	0.210	0.183	0.198	0.198	0.210
Communication	0.850	0.900	0.900	0.850	0.900	0.193	0.205	0.205	0.193	0.205
Safety culture	0.850	0.850	0.800	0.650	0.850	0.213	0.213	0.200	0.163	0.213

provided in Table 8.

The process of the aggregation stage, $\beta\,(0 \le \beta \le 1)$ which shows the importance of *we* over *RA*, gives the manager's (moderator) dominance over the problem. In this application, β is assumed to be 0.4 (Ölçer and Odabaşi, 2005).

3.7. Determining SLI and calculating HEP

The SLI values of each sub-task were calculated in accordance with Eq. (3) after determining PSF weights. The HEP values for each task were calculated with respect to the Eq. (4) where *a* and *b* are constant and calculated from the SLIs having the lowest and highest values. Whilst human error data is very scarce in marine industry, it is very hard to determine *a* and *b* in the equation. Indeed, base HEP values are unknown. To overcome this limitation, it is reasonable in HRA probabilistic safety analysis to assume that the maximum human failure probability is 1.0 and the minimum is 0.0001 (He et al., 2008; Akyuz, 2015b). Accordingly, Table 9 shows the SLI and HEP values for each sub-task during an abandon ship procedure.

Table 9
SLI and HEP values for each sub-task during abandon ship procedure.

Task	Sub-task	SLI	HEP
1.			
Prepare to abandon ship	1.1 Raise the alarm	22.75	0.00004
	1.2 Call the Master of ship	23.27	0.00002
	1.3 Make announcement for abandon ship	20.87	0.00037
	1.4 Send distress messages (Mayday)	15.94	0.10667
	1.5 Report the situation	16.21	0.07840
2.			
Gather at muster station	2.1 Make sure that all crew gathered at muster station	22.13	0.00009
	2.2 Check that all crew are suitable donned lifejackets	22.33	0.00007
	2.3 Brief all crew for abandon ship procudures	22.72	0.00004
	2.4 Confirm crew fully understand procedures	21.53	0.00017
	2.5 Instruct crew to embark the lifeboat	20.05	0.00095
3.			
Launch the lifeboat	3.1 Make sure that all crew, except those who have duties for launching, embark the lifeboat	22.48	0.00006
	3.2 Set the engine control for restart	18.40	0.00634
	3.3 Check the launching area is clear of any obstructions and water depth is enough	20.48	0.00057
	3.4 Check engine running satisfactorily	22.02	0.00010
	3.5 Close the drain plug	19.76	0.00132
	3.6 Disconnect battery charger	20.80	0.00040
	3.7 Make sure that all crew embark to designated seats and fastened the seat belts	22.67	0.00005
	3.8 Close and secure hatches and door	23.03	0.00003
	3.9 Switch on electrical system into battery power	21.18	0.00026
	3.10 Release the lifeboat by operating hydraulic releasing	21.22	0.00024
4.			
Further actions	4.1 Start engine	21.55	0.00017
	4.2 Open the ventilations	22.91	0.00004
	4.3 Clear from the vessel	24.41	0.00001
	4.4 Operate radio distress signal	18.68	0.00456

3.8. Sensitivity analysis

In order to see the β effect on the HEP values, sensitivity analysis is performed. The β values are taken among the 0.0 and 1.0 (Ölçer and Odabaşi, 2005). If a homogenous group of experts is considered, then β is 0. Whilst the importance of each marine expert's opinion against an attribute is not considered equal, the effect of β values should be calculated. Table 10 shows the HEP values with respect to each of the β values. The findings show that this application is not sensitive for the β coefficient. Despite the growth of β values in Fig. 3, the ranking of the HEP values remain unchanged. This shows that the aggregation stage in the course of the PSF weighting process is reasonable and consistent.

At this point, it should be noted that there could be other circumstances indicating importance of β effect on HEP values.

3.9. Findings and discussion

In light of the HEP calculations for each task of an abandon ship procedure, the findings show that high human error risks during abandon ship procedures appear in the preparation phase where two sub-tasks have the highest HEP values. In particular, sub-task 1.4 (Send distress messages - Mayday) and sub-task 1.5 (report the situation) are the main contributory factors that may cause error since they have the highest HEP values among all of the sub-tasks. The officers may panic when faced with a hazard in a particular abandon ship event. The situation may cause high stress which could lead to ambiguity, involve conflict or loss of performance expectations. Hence, they may skip or forget to report the situation since their behavior is un-coordinated. On the other hand, sending a distress message is a relatively simple task for the officer on watch. However, it may be ignored because not enough practical training was provided either on-board the ship or on shore. Furthermore, there is also high risk that exists in the lifeboat launching process. Specifically, sub-steps 3.2 (set the engine control for restart) and 3.5 (close the drain plug) have relatively high HEP values among the relevant tasks. The duty officer (chief officer) is the responsible person to set the free-fall type lifeboat engine control for restart and he may sometimes forget or skip the process since the engine allows the user to start the engine after launching. An able seaman (A/B) is the responsible crew member to close the drain plug during lifeboat launching. He may also forget to close the plug if inadequate inspection is carried out by the duty officer. In the event of an emergency, an increase stress and fuss level of person is certainly possible. Therefore, the crew may face difficulties with concentration and cause an impedence

Table 10
HEP values with respect to β values.

Sub-task	β										
	0.0	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.9**	**1.0**
1.1	0.00007	0.00006	0.00005	0.00005	0.00004	0.00004	0.00003	0.00003	0.00003	0.00002	0.00002
1.2	0.00004	0.00004	0.00003	0.00003	0.00002	0.00002	0.00002	0.00002	0.00001	0.00001	0.00001
1.3	0.00060	0.00053	0.00047	0.00042	0.00037	0.00032	0.00029	0.00025	0.00022	0.00020	0.00018
1.4	0.16560	0.14836	0.13291	0.11907	0.10667	0.09556	0.08561	0.07670	0.06871	0.06155	0.05514
1.5	0.12859	0.11363	0.10041	0.08872	0.07840	0.06928	0.06122	0.05410	0.04780	0.04224	0.03733
2.1	0.00016	0.00013	0.00012	0.00010	0.00009	0.00007	0.00006	0.00006	0.00005	0.00004	0.00004
2.2	0.00014	0.00012	0.00010	0.00008	0.00007	0.00006	0.00005	0.00004	0.00003	0.00003	0.00002
2.3	0.00008	0.00007	0.00006	0.00005	0.00004	0.00004	0.00003	0.00003	0.00002	0.00002	0.00002
2.4	0.00033	0.00028	0.00024	0.00020	0.00017	0.00015	0.00012	0.00010	0.00009	0.00008	0.00006
2.5	0.00166	0.00145	0.00126	0.00109	0.00095	0.00082	0.00072	0.00062	0.00054	0.00047	0.00041
3.1	0.00011	0.00009	0.00008	0.00007	0.00006	0.00005	0.00004	0.00004	0.00003	0.00003	0.00002
3.2	0.01222	0.01037	0.00880	0.00747	0.00634	0.00538	0.00456	0.00387	0.00329	0.00279	0.00237
3.3	0.00108	0.00092	0.00079	0.00067	0.00057	0.00049	0.00042	0.00036	0.00030	0.00026	0.00022
3.4	0.00018	0.00016	0.00013	0.00011	0.00010	0.00008	0.00007	0.00006	0.00005	0.00004	0.00004
3.5	0.00252	0.00215	0.00183	0.00156	0.00132	0.00113	0.00096	0.00082	0.00070	0.00059	0.00050
3.6	0.00072	0.00062	0.00054	0.00046	0.00040	0.00034	0.00029	0.00025	0.00022	0.00019	0.00016
3.7	0.00007	0.00007	0.00006	0.00005	0.00005	0.00004	0.00004	0.00003	0.00003	0.00003	0.00002
3.8	0.00005	0.00005	0.00004	0.00004	0.00003	0.00003	0.00002	0.00002	0.00002	0.00002	0.00001
3.9	0.00047	0.00041	0.00035	0.00030	0.00026	0.00022	0.00019	0.00016	0.00014	0.00012	0.00010
3.10	0.00047	0.00040	0.00034	0.00029	0.00024	0.00021	0.00018	0.00015	0.00013	0.00011	0.00009
4.1	0.00030	0.00026	0.00022	0.00019	0.00017	0.00014	0.00013	0.00011	0.00009	0.00008	0.00007
4.2	0.00007	0.00006	0.00005	0.00004	0.00004	0.00003	0.00002	0.00002	0.00002	0.00001	0.00001
4.3	0.00001	0.00001	0.00001	0.00001	0.00001	0.00001	0.00000	0.00000	0.00000	0.00000	0.00000
4.4	0.00795	0.00692	0.00602	0.00524	0.00456	0.00397	0.00345	0.00301	0.00262	0.00228	0.00198

to the crew in easily completing a task. Sub-task 4.4 (operate radio distress signal) has also high HEP value. The responsible officer (chief officer or second officer) transmits a radio distress message after seeing the lifeboat clear from the vessel. High stress, inadequate training and inadequate practice can be attributed as major causes for human error.

In the view of the findings, it can be noted that HEP values throughout the abandon ship procedure are broadly accepted as level and crew performance almost completely follows anticipated procedures whilst a few unexpected deviations are still possible. Therefore, human error reduction measures can be recommended for the sub-tasks which have the highest HEP values.

3.10. HEP reduction measure proposal

HEP reduction measures provide technical and operational remedies to minimize human error risk during an abandon ship procedure. Table 11 shows the HEP reduction measures proposal which was created by the consensus of the marine experts.

4. Conclusion

Human error is one of the main contributing factors in most accidents in maritime transportation. The consequences of human error can pose potential harm to human life and the marine and ocean environment. Despite human error assessment being a critical issue for maritime safety practitioners, the quantification process is quite difficult due to limited human error data. Most quantification processes are based on available data from experimental research, simulator studies, or certain derived data. In this context, the aim of this paper is to propose a hybrid tool conducting a quantitative human error assessment in maritime transportation. The proposed approach can provide users a simple way to determine HEP. To achieve this purpose, fuzzy sets are integrated with the SLIM approach. As the fuzzy sets deal with the vagueness of experts' judgments during the PSF weighting in representation of percentage assessment, the SLIM calculates HEP values. Thus, a hybrid approach may enhance the accuracy and consistency of the outcomes. One of the most cited topics in maritime transportation was selected to demonstrate the

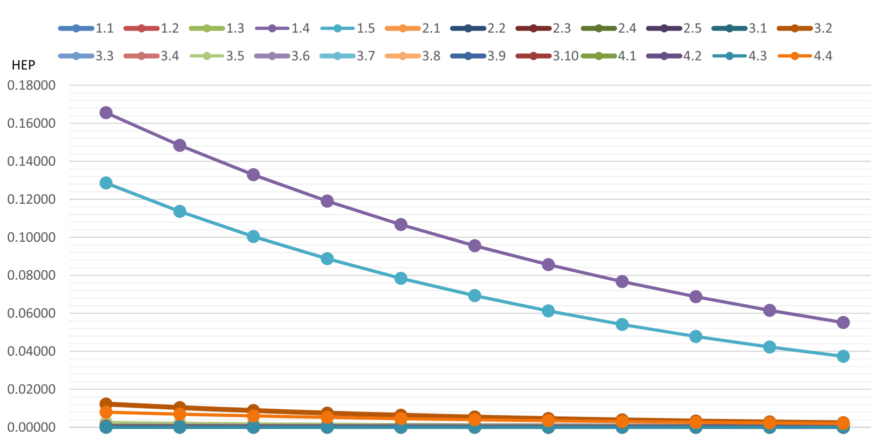

Fig. 3. HEP values with respect to the each β values.

Table 11
HEP reduction measure proposal.

Sub-task	HEP	Reduction measure
1.4	0.10667	Apply theoretical and practical training for sending distress message to speed up process Prepare distress message template and keep it in the system to avoid loss of time Increase interim audit and check if any distress message practice to be held during drills
1.5	0.07840	Provide a checklist to guide the Master/officer how to report situation during in an emergency Prepare distress reporting template in order to save the time Provide practical instruction concerning how to report situation in an emergency
3.2	0.00634	Provide theoretical and practical training for control panel Post illustrated instruction to be followed during setting engine
4.4	0.00456	Provide a training course with respect to stress management before embarking ship. Ensure theoretical and practical trainings to be given for officers about transmitting radio distress message before embarking ship In muster list, post experienced officer to particular task
3.5	0.00132	Provide check list to remind the responsible crew for closing drain plug Instruct officer to re-check condition whether drain plug is closed properly Apply a reminder stencil in vicinity reminding to close plug

proposed approach: an abandon ship procedure aboard a cargo ship.

The HEP value for each sub-task was calculated and the necessary HEP mitigation measures were recommended for the highest HEP values. Thus, the crew safety performance could be improved during abandon ship procedures as the crew's response in an emergency is always a serious concern in maritime transportation.

The proposed approach not only provides a theoretical contribution to maritime literature but also practical contributions to the industry including ship management companies, P&I Clubs, as well as safety managers to prevent the loss of life at sea and to protect the marine environment in terms of assessing and reducing human error probability. While the proposed approach prompts a practical approach, it can be applied to various industries, such as off-shore, aviation, railway, as well as petrochemical, where human error can have fatal consequences. Further study may deal with re-building the PSF rating scale. Instead of rating PSFs from 1 to 9 on a liner scale, they could be transformed into fuzzy linguistic expressions since the concept of the linguistic variable is very useful in conventional quantitative expressions.

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