THE ROLE OF HUMAN FACTORS IN MARITIME ENVIRONMENTAL RISK ASSESSMENT: A CASE STUDY OF OIL SPILL RESPONSE

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SUMMARY

Human error is one of the significant factors attributed to marine accidents. This paper aims to assess the potential contribution of human errors in improving maritime environmental risk management. Success Likelihood Index Method (SLIM), has been adopted to systematically estimate human error potentials for designated tasks in pollution prevention, along with fuzzy sets to deal with subjectivity in the process of using experts' judgments. An oil spill response operation was investigated due to its considerable risks for the marine environment. Environmental factors, familiarity, and fatigue were observed as having a high impact on human performance. Besides its theoretical insight, the paper provides practical insights into the prevention of marine pollution. This study is presented as a reference providing a contribution to estimating the impact of human errors on maritime accidents. The paper is also intended to contribute to other risky industries where human errors can lead to fatal consequences.

NOMENCLATURE

C/E	Chief Engineer
C/O	Chief Officer
DPA	Designated Person Ashore
HEP	Human Error Probability
HSEQ	Health, Safety, Environment&Quality
HTA	Hierarchical Task Analysis
IMO	International Maritime Organisation
ISM Code	International Safety Management Code
PSF	Performance Shaping Factor
SLI	Success Likelihood Index
SLIM	Success Likelihood Index Method
SOLAS	Safety of Life at Sea
STCW	Standards of Training Certification and Watchkeeping

1. INTRODUCTION

The human factor is a topic of concern in maritime transportation. The IMO pays considerable attention to the human factor in safety engineering. Human error is an element of human factor issues. The consequences of human error can be fatal such as loss of life, environmental pollution or loss of commodity (Gul *et al*., 2017; Akyuz, 2017). Therefore, maritime regulatory bodies have been struggling to understand better the potential of human errors. The human element is addressed by the IMO to highlight the importance of the role of the human in the maritime industry. The IMO has adopted the ISM Code under SOLAS Convention chapter IX as well as the STCW Convention to improve seafarers' qualifications and competence (Chauvin *et al.*, 2013). On the other hand, human errors remain an issue in overall maritime safety. Almost 80 per cent of marine accidents are due to human errors (Wiegmann & Shappell, 2017). Thus, maritime safety researchers have aimed to investigate human-oriented errors for minimizing marine accidents. Much of the human factor research in the maritime domain has focused on collision-related accidents (Yildirim *et al*., 2017; Sotiralis *et al*., 2016; Martins & Maturana, 2010), groundings (Graziano *et al*., 2016; Akyuz, 2015a; Akhtar & Utne, 2014), fire and explosion (Puisa, 2019; Baalisampang *et al*., 2018; Wang *et al*., 2013) and oil spills (Akyuz & Celik, 2018; Goerlandt & Montewka, 2015).

Human reliability has received increasing attention focusing on the contributions of human error within safety-critical systems (Boring *et al*., 2009). Most of the authors conducted research on the calculation of HEPs to highlight the importance of the human factor such as critical shipboard operations in maritime transportation (Islam *et al*., 2018; Akyuz, 2015b; Akyuz & Celik, 2015) offshore platforms and terminals (Deacon *et al*., 2013; DiMattia *et a*l., 2005) and marine accidents (Xi *et al*., 2017; Kim *et al*., 2011). Human error analysis is critical for understanding the role of the human factor in maritime risk management. While there are various risks associated with marine works, evaluation of human error contributions in maritime industries is vital to enhance the safety level. Risk can be stated as the combination of the probability of an occurrence of a hazard and severity of injury (Akyuz & Celik, 2018). The topic is highly cited in maritime transportation literature since the nature of marine works contains a wide range of negative outcomes. Therefore, most researchers have focused on risk management addressing human error (Tseng, 2019; Goerlandt & Montewka, 2015; Montewka *et al*., 2014; Faghih-Roohi *et al*., 2014).

Since the consequences of human error are potentially catastrophic for marine environments, human life and commodities carried by ships, analysis of human error is of paramount concern. This paper attempts to perform research on human error contributions to maritime environmental risk management. To accomplish this, a robust hybrid method is adopted under SLIM and Fuzzy sets. In the paper, while the SLIM is utilized to systematically estimate human errors, fuzzy sets theory is used to handle subjectivity in the process of experts' judgments stage. Hence, a fuzzy SLIM hybrid approach provides the utmost contribution to estimate human errors during maritime environmental risk assessment. Human errors are one of the key attributes of oil spill incidents at sea. This study points out the necessity to predict the circumstances under which human errors increase through an illustrative case of oil spill response in the maritime sector.

In this context, the paper is organized as follows. Section 1 gives the motivation behind the study as well as basic literature reviewing. Section 2 introduces the research methodology including SLIM and fuzzy sets. Section 3 presents a numerical demonstration of the case of an oil spill response. Section 4 concludes the research and proposes future research potential.

2. FUZZY-SLIM APPROACH

This paper conducts a quantitative prediction of human error to understand the role of human factors in marine environmental risk management. To address this concern, the SLIM method is employed under the environment of the fuzzy sets. The next part will briefly introduce methods and defines how they will be integrated.

2.1 FUZZY SETS

Fuzzy sets are broadly used in the literature in cases of vagueness or imprecision in human judgment in the decision-making process. The method is applicable to a wide range of disciplines where ambiguity and vagueness is a concern. Zadeh (1965) presented fuzzy sets theory as an extension of the classical notation of sets. In the theory, the approximate reasoning of fuzzy set numbers can use to define the linguistic values (Celik & Gumus, 2015). To address this concern, the linguistic values are used to convert decision makers' ideas or assessments into meaningful information (Akyuz, 2016). Castigla & Giardina (2013) states fuzzy sets are appropriate models during decision-maker knowledge and can be stated in natural language (i.e., high, medium or low). In this context, it is quite practical to figure out complicated or ill-defined situations in basic quantitative statements (Casamirra *et al*., 2009). In the theory, a fuzzy subset A in X is defined by a membership function $\mu_A(x)$, which incorporate each element x in X with a real number in the interval [0,1]. The function $\mu_A(x)$ illustrates the membership of x in the fuzzy set A (Castigla & Giardina, 2013). In the literature, there are different way of illustrating membership function of fuzzy sets such as triangular or trapezoidal. Triangular fuzzy set numbers are triplets (x_1, x_2, x_3) and the membership function $\mu_A(x)$ is explained as follows (Akyuz, 2016).

$$\mu_A(x) = \begin{cases} \dfrac{x - x_1}{x_2 - x_1}, & x_1 \le x \le x_2 \\ \dfrac{x - x_3}{x_2 - x_3}, & x_2 \le x \le x_3 \\ 0, & otherwise \end{cases}$$

$$where \ x_1 < x_2 < x_3 \tag{1}$$

Likewise, trapezoidal fuzzy set numbers are introduced as x_1, x_2, x_3, x_4 and the membership function $\mu_A(x)$ is depicted as follows (Akyuz, 2016).

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

$$where \ x_1 < x_2 < x_3 < x_4 \tag{2}$$

2.2 SLIM

HEP methods are used in a wide range of industries which pose a high risk due to the nature of the work. One of the most robust empirical HEP methods is SLIM. SLIM systematically estimates the probability of human error. The method was derived for the nuclear energy industry but successfully adapted to other industries such as offshore (DiMattia, 2004; DiMattia *et al*., 2005; Khan *et al*., 2006; Islam & Yu, 2018), and maritime (Xi & Guo, 2011; Islam *et al*., 2016; Akyuz & Celik, 2017; Islam *et al*., 2017), etc. The method was introduced by Embrey *et al*. (1984) to calculate HEP.

Since there is a lack of numerical data in maritime transportation, the method presents a practical solution to estimate human error. Expert judgments are used if data are unavailable (Sandon & Harvey, 2004). However, one of the major gaps with the application of SLIM is to rely on expert judgements (Park & Lee, 2008). To remedy this gap, fuzzy sets theory is adopted to tackle ambiguity and vagueness by a decision-maker.

In the SLIM approach, the effect of some relative factors called performance shaping factors (PSFs) are paramount to assess human errors. PSF s, which are any factors relating to the task, individuals or working environment, influence human performance negatively or positively (Grozdanovic, 2005). The PSF can be practically quantified by SLIM. Hence, a SLI is elicited by using experts' judgments (Akyuz, 2016). The SLI value can be calibrated with human error data to predict the probability value. The basic application steps of the SLIM is defined as follows.

- Task analyzing and scenario definition
- PSF elicitation and rating
- PSF weighting
- SLI calculation
- Converting SLI into HEP value

2.3 A HYBRID METHODOLOGY: SLIM UNDER FUZZY SETS ENVIRONMENT

A hybrid method, SLIM under fuzzy sets environment, is discussed in this section to systematically quantify the human error in maritime risk management. The basic steps of the methodology are as follows.

Step 1- Task analysis and scenario definition: In the first step of the methodology, extended task analysis and scenario definition is performed to define the main steps. The task analysis should involve relevant activities that the crew on-board ship must complete. Accordingly, a HTA is carried out to perform a detailed analysis of sub-tasks and main tasks of the work (Shepherd, 2001). The scenario definition is performed right after task analysis. It should include numerous scenarios such as the experience of the crew, working environment, fatigue, workforce morale, weather conditions, stress, noise level, etc.

Step 2- PSF elicitation and rating: In the second step, PSFs are elicited from experts. The PSFs can include different conditions that affect task performance such as ergonomics, safety culture, task complexity, teamwork, time availability, age, etc. The PSF rating is performed by the experts after the elicitation process. Each PSF is ranked from 1 to 9 on a linear scale in order of importance on the related task. In case the PSF has a considerable influence on the task, 1 is assigned as the highest value. In other words, 9 is the appropriate value to be assigned if that PSF has the lowest importance on the task.

Step 3- PSF weighting: In this step, experts judge the contribution of each PSF to cause human error. Accordingly, a relative weight is assigned for each one (Embrey *et al.*,1984). In the basic SLIM, the expert nominates assess portion of the PSF effect. This assumption is subjective. Therefore, the inconsistency arises during the weighting process. To tackle the aforementioned limitation, the SLIM is modified by fuzzy sets. Thus, linguistic assessment of experts through PSF are converted crisp values to increase the accuracy of the outcome. In this context, the relation among the linguistic terms and triangular fuzzy numbers can be stated according to the Figure 1 (Castiglia & Giardina, 2013).

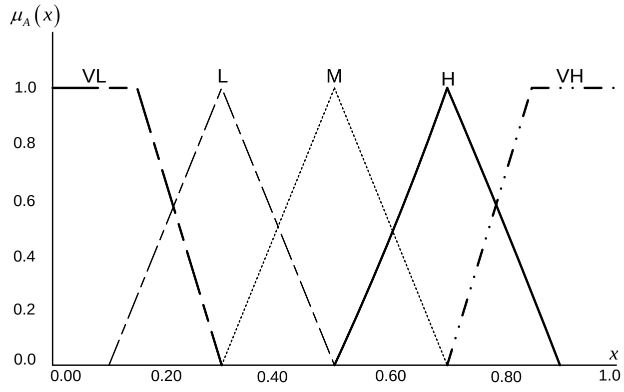

Figure 1. Linguistic terms and triangular fuzzy numbers

The following membership functions are depicted in compliance with fuzzy linguistic variables (Castiglia and Giardina, 2013).

$$\mu_{VL}(x) = \begin{cases} 1.0, & 0.0 < x \leq 0.15 \\ \dfrac{0.3 - x}{0.15}, & 0.15 < x \leq 0.3 \\ 0, & otherwise \end{cases} \tag{3}$$

$$\mu_{L}(x) = \begin{cases} \dfrac{x - 0.1}{0.2}, & 0.1 < x \leq 0.3 \\ \dfrac{0.5 - x}{0.2}, & 0.3 < x \leq 0.5 \\ 0, & otherwise \end{cases} \tag{4}$$

$$\mu_{M}(x) = \begin{cases} \dfrac{x - 0.3}{0.2}, & 0.3 < x \leq 0.5 \\ \dfrac{0.7 - x}{0.2}, & 0.5 < x \leq 0.7 \\ 0, & otherwise \end{cases} \tag{5}$$

$$\mu_{H}(x) = \begin{cases} \dfrac{x - 0.5}{0.2}, & 0.5 < x \leq 0.7 \\ \dfrac{0.9 - x}{0.2}, & 0.7 < x \leq 0.9 \\ 0, & otherwise \end{cases} \tag{6}$$

$$\mu_{VH}(x) = \begin{cases} \dfrac{x - 0.7}{0.15}, & 0.7 < x \leq 0.85 \\ 1.0, & 0.85 < x \leq 1 \\ 0, & otherwise \end{cases} \tag{7}$$

Step 4- SLI calculation: After determined PSF rating and weighting values, the SLI is calculated according to equation (8). The SLI estimates the probability of situations where various human errors may occur. Within equation (8), n states the number of PSFs, r_i gives the rating scale of PSFs and w_i defines the PSF weighting.

$$SLI = \sum_{i=1}^{n} r_i w_i \,, \quad 0 \leq SLI \leq 1 \qquad (8)$$

Step 5- Converting SLI into HEP: The aim of the final step is to convert SLI value to HEP. In this context, equation (9) is used. In the equation, a and b values are constant. (Embrey *et al*., 1984).

$$Log\,(HEP) = aSLI + b \qquad (9)$$

3. ASSESSMENT OF HUMAN ERROR CONTRIBUTION: THE CASE OF OIL SPILL RESPONSE

In this paper, human error contribution is evaluated quantitatively in the situation of the oil spill. The human factors contributions are identified and their risk levels are determined.

3.1 OIL SPILL RESPONSE AT SEA

Marine environment protection is one of the core concerns for the industry. Ships are well-known as pollution sources of the seas. Oil spills, caused by ships, can contribute to huge environmental damages along with profound impacts on marine ecosystems and human health. There have been catastrophic oil spill accidents such as Exon Valdez (Arata *et al*., 2000; Peterson *et al*., 2003), Amoco Cadiz (Atlas *et al*., 1981; Dauvin, 2000), Prestige (Laffon *et al*., 2006; Loureiro *et al.*, 2009), Torrey Canyon (Smith, 1968; Southward & Southward, 1978; Wells, 2017), etc. recorded in the past. It is critical that prevention barriers are put in place in order to eliminate or minimize the risk of oil spill events occurring. According to the muster list, most of the crew must participate in oil spill response. The expectation from the ship crew is to complete each task during the oil spill response without any error.

3.2 EXPERT DEFINITION

One of the significant challenges in maritime transportation is to gather data. Due to commercial issues, most shipping companies are not willing to distribute related data. Using expert judgement is a solution to tackle this aforementioned limitation.

This paper uses marine experts' judgements to assess human error contributions to oil spill responses. Five marine experts from three different ship management companies volunteered to participate in this study. The details of marine experts are shown in Table 1. A comprehensive survey was carried out with these experts who are working for the Health, Safety, Environment and Quality department. In the survey, oil spill response procedures were presented to the marine experts. The marine experts assessed PSFs rating and weightings in accordance with fuzzy linguistic statements.

Table 1. Description of Expert Competencies

Marine Expert No	Company	Position	Marine experienced (year)	Age
1	A	Master	10	35
2	A	DPA	8	37
3	B	HSEQ Manager	13	43
4	C	HSEQ Manager	18	47
5	C	DPA	6	39

3.3 TASK ANALYSING

Table 2 shows tasks to be completed for the procedure of oil spill response. The procedure has been collected from participating in shipping companies. Task analysis for the oil spill response in an emergency is demonstrated in Table 2. The procedure is comprised of sixteen tasks based on the priority of actions.

Table 2. Oil spill response procedures

Task no	Action to be performed	Priority of action	Responsible person
1	Sound emergency alarm	Immediate	Any person discovering
2	Cease all cargo / bunkering operation	Initial	Officer on duty
3	Close manifold valves	Initial	Officer on duty
4	Turn off the ventilation system in the accommodation	Initial	Engineer in charge
5	Turn off the ventilation system in the engine room	Initial	Engineer in charge
6	Stop or reduce the flow of oil	Initial	Officer on duty
7	Commence clean-up procedures using absorbent and solvent	Initial	C/O
8	Comply with reporting procedures	Initial	Master
9	Assess fire risk from the release of flammable substance	Secondary	C/O
10	Reduce oil level in the relevant tank by	Secondary	C/O and C/E

	dropping oil into an empty tank		
11	Reduce the oil level in suspected tanks	Secondary	C/O and C/E
12	Drain oils in the affected line into the empty or slack tanks	Secondary	C/O and C/E
13	Prepare pumps for the transfer of oil into the other tanks	Secondary	C/E
14	Pump water into the leaking tank to prevent further oil loss	Further	C/O
15	Arrange a diver for investigation if oil leakage is under the waterline	Further	Master
16	Calculate stress and stability of ship if necessary	Further	Master and C/O

3.4 SCENARIO DEFINITION

An actual case study addressing an oil spill response drill on the main deck is considered in this analysis. The oil spill drill was carried out during daylight when the container ship was at anchor. Ship crew, except the duty officer and the duty engineer (who were in bridge and engine watch), participated in the oil spill drill that was conducted at the bunkering station. At the time of the oil spill drill, the shipboard conditions were at a satisfactory level. The crew participating in the drill were well-rested. The weather was partly cloudy and the sea was moderate. A portable camera was used to record and monitor the oil spill drill events and was later presented to the marine experts for further assessment.

3.5 DERIVING AND RATING OF PSFs

Derivation of the PSFs was performed by the marine experts. Six PSFs were identified through the consensus of the marine experts. In light of the derived PSFs, the marine experts were asked to evaluate rating in terms of the level of compliance to each PSF for each task.

Table 3 shows the derived PSFs and their ratings based on the marine experts' assessments. Since there were five marine experts participated in to survey, the arithmetic means of them are presented.

Table 3. Derived PSFs and their ratings (Score of 1 to 9)

Task	PSF rating					
	Experience level	**Stress**	**Fatigue**	**Familiarity**	**Limited time**	**Environmental Factors**
1	8	7	8	6	4	4
2	6	6	4	7	6	5
3	6	5	5	6	5	6
4	4	6	5	4	5	4
5	4	6	5	4	4	5
6	5	5	6	5	4	5
7	6	5	4	6	5	8
8	5	6	3	5	4	5
9	3	5	5	3	4	6
10	4	5	6	4	5	6
11	5	6	4	5	4	6
12	5	4	5	5	5	6
13	6	5	5	7	5	7
14	3	5	5	4	4	5
15	3	6	5	4	5	5
16	6	6	5	7	4	7

3.6 PSF WEIGHTING

After deriving and rating of PSFs, the weighting process is conducted on the basis of a fuzzy linguistic scale. The experts evaluate the priority of PSF according to the fuzzy linguistic statement. Table 4 shows the fuzzy linguistic assessment of marine experts and the weight of PSFs.

Table 4. Fuzzy linguistic statement of marine experts

PSF	**Expert 1**	**Expert 2**	**Expert 3**	**Expert 4**	**Expert 5**	**Crisp Values**	**Normalised Values**
Experience level	M	M	L	L	H	0.46	0.16
Stress	L	M	VL	L	M	0.28	0.10
Fatigue	H	VH	M	H	L	0.49	0.17

Familiarity	VH	M	H	M	VL	0.57	0.20
Limited time	M	H	VH	VH	H	0.46	0.16
Environmental factors	H	VH	M	M	H	0.65	0.22

The weight of each PSF to cause the human error was judged for oil spill response procedures. Environmental factors (0.22), familiarity (0.20) and fatigue (0.17) were assigned as the most contributory factors that affect human performance, respectively.

3.7 DETERMINING SLI AND CALCULATING HEP

Equation (8) is applied to determine SLI values for each task. In order to calculate the HEP value, equation (9) is applied. In the equation, *a* and *b* are the constant and derived from the lowest and highest SLIs values (Embrey *et al*., 1984).

Table 5 gives SLI and HEP values accordingly.

Table 5. SLI and HEP values

Task	**SLI**	**HEP**
1	5.99	0.00011
2	5.64	0.00054
3	4.79	0.02668
4	4.52	0.09166
5	4.58	0.06786
6	5.01	0.00954
7	5.86	0.00019
8	4.60	0.06270
9	4.36	0.19285
10	5.04	0.00840
11	4.99	0.01032
12	5.13	0.00557
13	6.00	0.00010
14	4.33	0.21888
15	4.58	0.06786
16	6.20	0.00004

3.8 FINDINGS AND DISCUSSION

Considering each task of the oil spill response process, Task 14 (Pump water into the leaking tank to prevent further oil loss), Task 9 (Assess fire risk from the release of flammable substance) and Task 4 (Turn off the ventilation system in the accommodation) were found to be the most contributory tasks to increase HEP, respectively. Task 14 and Task 9 are under the responsibility of the Chief Officer. He is directly or jointly responsible for 7 of the 16 actions to be taken. This situation may cause high stress and loss of performance. Indeed, stress, experience level, limited time and fatigue were evaluated as dominant performance shaping factors by the marine experts for related tasks. Also, the findings clearly indicated that as the priority of action declines, the occurrence of human error probability increases.

Task 5 (Turn off the ventilation system in the engine room) and Task 15 (Arrange a diver for investigation if oil leakage is under the waterline) have relatively high human error probability values among the other tasks. Task 4 and Task 5 are similar actions to be taken and have initial priority during the oil spill. The duty engineer in charge of bunkering should immediately carry out both tasks. However, the task might be ignored due to lack of experience and insufficient practical training on-board ship. Familiarity and experience level were evaluated to be influential factors by the marine experts for related tasks, already. The Master is responsible for Task 15 and he/she may skip the action due to commercial and financial concern or priority level of the task.

On the other hand, Task 1 (Sound emergency alarm) is found to have the lowest human error occurrence among the other tasks. Sounding the alarm is the crucial action that should be immediately taken and is under the responsibility of any crew on board. In spite of its importance, it is not a complex task. Therefore, it is obviously seen that especially limited time and environmental factors have a remarkable influence on the task. Experience level, stress and fatigue are not evaluated as determinant factors influencing human performances on this task.

In light of the findings, a significant proportion of human errors are occurred especially related to the priority of actions. Further actions might be ignored due to increasing stress and panic. Additionally, stress (0,10), experience level (0,16) and limited time (0,16) are determined as critical and core PSFs that force the crew to make more errors during the oil spill response process. To address all this concern, human error reduction measures should be recommended for the tasks having the highest HEP values and necessary precautions should be taken to minimize human-related risks. For instance, training the experienced officer/crew to assist the responsible person (chief officer for this case) in specific actions when required may provide more awareness and motivation.

Additionally, written instructions and continuous video training may be beneficial for reducing stress and panic.

3.9 CONTROL ACTIONS

The HEP reduction measures provide recommendations to mitigate the potential for human error during critical ship operations. The main aim of the reduction measures is to promote and enhance safety in bunkering operations through the recognition and quantification of human error probabilities.

HEP reduction measures proposal that is created by the consensus of marine experts for the tasks having the highest HEP values are given below in Table 6.

Table 6. HEP reduction measure proposal

Sub-task	**HEP**	**Reduction measure**
4	0.09166	Review the drill period and increase the frequency if necessary Maintain positive pressure inside the accommodation and close air conditioning intakes before bunkering operation. Provide detailed instruction to be followed during oil spill response Collaborate with engine room not to skip any step
9	0,19285	Provide video training for all aspect of fire risk to control the process Identify the level of fire risk according to environmental factors (wind, sea state..etc) and specific properties of the substance Inform the crew about the release of flammable substance before bunkering operation Be aware of ignition sources and keep under observation Determine the initial effects of the fire
14	0,21888	Provide detailed instruction for pump and ballast system in case of emergency Prepare a checklist to remind the further actions to be taken during oil spill response Train the experienced officer to assist the responsible person (C/O) when required Determine the oil leakage location properly Be aware of leaking flow and ship stability during oil spill response

4. CONCLUSIONS

Human related errors have led to devastating consequences for sensitive marine environments. Therefore, assessment of human error contribution in critical shipboard operations becomes necessary. In this context, the paper proposes a hybrid quantitative approach for a better evaluation of the human errors in designated tasks during an oil spill response.

In view of the extended calculations, the results obtained are considered satisfactory and in the range of expectation. The SLIM technique extended with fuzzy logic can effectively be applied for determining the vulnerabilities in the operational process.

The paper provides proactive solutions to reduce risks and enhance safety on board ships. Accordingly, risk reduction measures are recommended to critical tasks (Task 4, Task 9 and Task 14) where the HEP values increased considerably. As far as performance shaping factors are concerned, environmental factors, familiarity and fatigue appear to be the major PSFs that heavily affect human performance during an oil spill response. Accordingly, the influence between PSFs and HEPs should not be ignored in maritime operations.

Increasing awareness and a better understanding of factors underlying human errors (HEs) will guide managers and seafarers on improvement to safety at the organizational level. In this context, vulnerabilities and critical conditions relating to shipboard operations should be emphasized in the safety meetings with simultaneous involvement of crew, safety inspectors and DPA.

The proposed approach will provide both theoretical and practical contributions to literature and the maritime industry in terms of generating remedial actions to reduce HEPs and the occurrence of accidents. The paper is also expected to contribute to other high-risk industries where human error can lead to fatal consequences.

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