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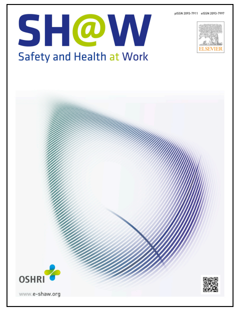

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Human Error Probability Assessment during Maintenance activities of Marine Systems

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Human Error Probability Assessment during Maintenance Activities of Marine Systems

Structural Abstract

Objective: The objective of this study is to develop Human Error Probability model considering various internal and external factors affecting the seafarers' performance.

Background: Maintenance operations on-board ships are highly demanding. Maintenance operations are intensive activities requiring high man-machine interactions in challenging and evolving conditions. The evolving conditions are weather conditions, workplace temperature, ship motion, noise and vibration and workload and stress. For example, extreme weather condition affects the seafarers' performance hence increasing the chances of error and consequently, can cause injuries or fatalities to personnel. An effective human error probability model is required to better manage maintenance on board ships. The developed model would assist in developing and maintaining effective risk management protocols.

Method: The human error probability model is developed using probability theory applied to Bayesian Network. The model is tested using the data received through the developed questionnaire survey of more than two hundreds experienced seafarers with more than five years of experience. The model developed in this study is to find out the reliability of human performance on particular maintenance activities.

Results: The developed methodology is tested on the maintenance of marine engine's cooling water pump for engine department and anchor windlass for deck department. In the considered case studies, human error probabilities are estimated in various scenarios and the results are compared between the scenarios and the different seafarer categories. The results of the case studies for both departments are also compared.

Conclusion: The developed model is effective in assessing human error probabilities. These probabilities would get dynamically updated as and when new information is available on either internal (i.e. training, experience and fatigue) or external factors (i.e. environmental and operational conditions such as weather conditions, workplace temperature, ship motion, noise and vibration and workload and stress) changes.

Keywords: Reliability assessment, Maintenance operation, Marine system, Human factors, Human probability

1. Introduction

International Maritime Organization (IMO) accident investigation reports cite that about a quarter of all maritime accidents are initially due to machinery failure [1]. Therefore, maintenance of the machinery in marine systems is very important. Moreover, maintenance of the machinery also minimises the severity of the failure, prevents unexpected downtime, extends the life of the machinery and helps to decrease the number of accidents. Maintenance of on-board ship machinery is conducted by the seafarers and is expected to contain unintentional errors. According to a previous accident investigation report, around 80% of shipping accidents are due to human error [2]. Examples of previous accidents due to human error during maintenance activities on marine machinery are explained in [3]. Different internal and external factors affect the seafarers' performance and sometimes those factors are responsible for the human error. Internal factors such as lack of training and experience, and high level of fatigue have significant impact on seafarers' performance [4]. These factors have either a positive or negative impact on seafarers' performance. For example, high level of training and experience has a positive impact on seafarer's performance whereas high level of fatigue has a negative influence on seafarers' performance. Details about the lack of seafarers training, experience and high level of fatigue are explained in [3] and [5].

Moreover, external factors affecting the seafarers' performance include marine environmental and operational factors and these also have a significant impact on seafarers' performance. Marine environmental factors such as weather conditions, workplace temperature and operational factors such as ship's motion, workload and stress and noise and vibration have significant influence on seafarers' performance.

According to an investigation by the United Kingdom Protection and Indemnity (UK P&I) Club, accidents related to human error cost the shipping industry around $541 million per year [6]. Furthermore, human error related accidents also result in major injury and loss of life to seafarers. Therefore, to reduce risk of accidents, human error assessment is one of the vital components in probabilistic risk analysis for the shipping industry.

Researchers [3, 7-11] applied human reliability assessment techniques to several engineering applications. [7] applied this concept to investigating human performance in offshore platform musters. [10] investigated this technique in pre- and post-maintenance procedures of offshore oil and gas facilities. Recently, [12] studied the impact of job stress and satisfaction on workforce productivity in an Iranian petrochemical industry. In another effort, [3] estimated the probability of human error during maintenance procedures of marine engines. The previous studies mentioned above proved the importance of estimating human errors in risk assessment of various engineering systems. Furthermore, [13] guidelines proposed adopting the human error probability assessment to enhance the safety of shipping industry.

Some of the most common available human error likelihood techniques are; Technique for Human Error Rate Prediction (THERP) by [14] Success Likelihood Index Method (SLIM) by [15] and Human Error Assessment and Reduction Technique (HEART) [16]. THERP approach does not offer suitable guidance to represent the Error Producing Conditions (EPC) and scenario development [17]. SLIM approach is based on expert judgement and various uncertainties affected the final outcomes [18]. HEART have some doubts over the consistency of the method as dependency and interaction among contributory factors to EPC is not accounted for in this approach [19]. Additionally, most of the above-cited approaches assume unrealistic independence between human factors and associated actions. None of the aforementioned techniques have the capability of updating probability when new information is available. Updating probability is important to instantly reanalyse posterior HEP based on newly available information.

Bayesian Network (BN) is a mathematical graphic based model represented by each variable as a node with the directed links forming arcs between them. BN provides a natural way to handle missing data, allows a combination of data with domain knowledge, and assists in learning about causal relationships among variables. Moreover, BN can provide fast responses to queries [18]. BN has been applied in various industries for assessing the HEP [18, 20-22]. [21] applied BN for predicting HEP in the nuclear power industry. [22] applied BN in predicting the HEP in the aviation industry. [18] applied BN to human reliability assessment during evacuation in offshore emergency conditions.

The main objective of this paper is to develop a human reliability assessment technique for more accurate HEP assessment in the maintenance activities of marine operations using BN. Application of the developed methodology will help the shipping industry to assess the probability of seafarers’ error accurately. Additionally, the developed methodology will assist in improving the safety and reliability of the maintenance activities of marine operations. The methodology developed in this study is based on BN and has the capability of dynamic updating when new information about the state of internal and external factors available.

BN will also help represent the relationships between human factors and seafarers' actions in a hierarchical structure. In this paper, Section 2 provides fundamental description of BN; Section 3 explains the development of methodology; Section 4 details development of BN model; and Section 5 demonstrates the application of the developed technique to case studies. Results and discussions are presented in Section 6. Finally, Section 7 summarises and concludes the paper.

2. Fundamentals of BN

BN is a probabilistic model which represents interaction of variables through the direct acyclic graph and Conditional Probability Tables (CPTs) [23]. The networks consist of nodes and edges. Each node represents a probability of distribution either discrete or continuous. The nodes represent a set of random variables and edges joining the nodes represent direct dependencies between the variables. Generally, BN comprises quantitative and qualitative sections. The conditional probabilities associated with the variables are the quantitative section and nodes and edges are the qualitative section of the network. The relationship between the nodes is described using CPTs [24-28]. All the variables of the network are presented in a CPT. The CPT provides a broad description of probabilistic interaction. A CPT also has the ability to model the probabilistic dependency among a discrete node and its parent nodes. The probabilities in the CPT denote the probabilities of each state given the state of the parent variable. Conversely, if a variable in BN does not have parent variables, the CPT denotes the prior probability variable [29]. If there are "n" variables $X_1, X_2, \ldots \ldots, X_n$, in the network and $Pa(X_i)$ represents the set of parents of each X_i, then joint probability distribution for the network is estimated as:

$$P(X_1, X_2, \ldots \ldots, X_n = \prod_{i=1}^{n} P(X_i | PaX_i)) \quad (1)$$

Where, $P(X_i|Pa(X_i))$ is the discrete conditional probability distributions of X_i given its parents. Thus the following information is required to develop BN model.

- $X_1, X_2, \ldots \ldots, X_n$, set of variables (nodes)

- The interaction (edges) among the variables
- $P(X_i|Pa(X_i))$ conditional probability distribution for each variable X_i.

Section 4 illustrates the BN model for the maintenance activities of marine operations.

3. Methodology

The methodology developed, based on the BN approach, is used in this study to estimate HEP for the maintenance activities of marine systems. The use of BN will help to represent a relationship between human factors and actions to estimate the HEP. There are three main steps in the developed methodology to estimate the HEP as illustrated in Figure 1.

Figure 1.

In step 1, scenario selection, identification of the maintenance activity and category of the seafarers for the maintenance procedures of marine operations are required. To select a scenario an impact of marine environmental and operational conditions affecting on-board operations is necessary. Similarly, it is essential to identify the type of maintenance activity requiring to be performed based on the maintenance schedule/ emergency situation. It is then necessary to identify the category of the seafarers conducting the maintenance activity. The seafarers in this study are categorised in four categories; A, B, C and D. These seafarer categories depend on the level of the seafarers' training, experience and fatigue. Dividing the seafarers into different categories based on their rank, experience and duration of the voyage are discussed in detail in section 4.2.1.

In step 2, it is necessary to select the factors that affect the seafarers' error making during on-board maintenance activities. Both, internal and external performance-affecting factors are selected in this study, as PSFs are considered in two different categories [18]. Furthermore, most important performance factors are selected according to the expert's opinion. The internal factors are training, experience and fatigue, while the external factors are environmental and operational conditions. The environmental factors are further categorised as weather conditions, workplace temperature, while operational factors are ship motion (roll and pitch), workload and stress, and noise and vibration. These factors are selected according to the previous studies by [30-33]. It should be noted that seafarers' opinions are also taken into account prior to selecting these factors. Each seafarer has more than five years' experience in the maintenance activities on board ship. The selected performance affecting factors in this study possibly have an influence on each other. However, only the individual effect of the factors on seafarers' performance is considered in this study. The states of each selected external factor are also selected considering expert's opinion as mentioned above.

The final step (step 3) is to apply the developed BN model and estimate the HEP. If there is no new information available regarding seafarers' performance affecting factor, then it will be the HEP for that maintenance activity of marine operations. However, if new information is available, then it is essential to go back to the start of step 3 in order to add the new evidence to update the estimated HEP.

4. Development of a BN model for the maintenance activities of marine operation

As outlined in Section 3, the methodology developed in this study is based on the BN approach. The unique feature of the BN will allow accurate estimation of the HEP. To develop the BN model, firstly all the root causes that are not directly influenced by any other variables are selected. The variables are selected according to the experienced seafarers' opinions. These variables affect the seafarers' performance during the maintenance activities on-board. All the root causes are each then assigned a node, as illustrated in Figure 2. In the second step, all the variables such as external and internal factors directly influenced by the root nodes are also selected according to the experienced seafarers' opinions. This hierarchical process continues until the network is completed. The final network for the maintenance activities in marine operations is illustrated in Figure 2.

Figure 2.

BN model requires prior probability for the parent nodes and CPT for the child nodes. Details about the prior probabilities and CPTs are discussed in the following sections.

4.1 Prior Probabilities

In this study, prior probabilities are considered as a first approximation of the conditions. The prior probabilities are provided by experienced seafarers who have more than 10 years' experience as a marine engineer. The prior probability values range between 0 to 1 ("0" lowest and "1" highest). Prior probabilities for the internal and external factors are illustrated in Table W1 and Table W2 respectively. On-board ship, there are two departments, Engine Department (ED) and Deck Department (DD) who are responsible for maintenance activities. ED seafarers perform the maintenance activities in the engine room and DD seafarers normally perform their maintenance activities on the weather deck. Prior probabilities for all categories of seafarers (A to D) of ED and DD are similar for internal and external factors.

In Table W1, internal factors' prior probability illustrates that whenever the levels of training and experience are high and the level of fatigue is low, the prior probability is low and vice versa. Moreover, in Table W2, external factors' prior probability shows that, in marine environmental and operational conditions, weather, workplace temperature, ship motion (roll and pitch), noise and vibration and workload and stress have a "normal" state rather than a "moderate" one. It is also less likely to have "high/extreme" state.

4.2 Development of CPT for the BN model

There is a lack of available CPT data for the maintenance activities in marine operations. As a result, it is necessary to develop CPT for BN model. BN model requires CPTs for environmental, operational, internal, external factors and HEP for the maintenance activities of marine operations. CPTs for the environmental and operational factors are developed by conducting a questionnaire survey among experienced seafarers around the world. On the other hand, CPTs for internal, external factors and HEP for the maintenance activities of marine operations are developed based on expert judgment.

As mentioned earlier although ED and DD seafarers perform their tasks separately, some of the environmental and operational factors in ED may affect the seafarers' performance differently than those in DD. Therefore, it is necessary to develop the environmental and operational factors CPT separately for both departments.

There are three steps to develop the CPT for environmental and operational factors as illustrated in Figure 3. In step-1, a questionnaire was developed to determine the impact of the selected child nodes (variables) in order to develop the CPT.

Figure 3.

In step-2, a Survey Monkey link was created to conduct the data collection. The Survey Monkey link was sent to a total of 400 experienced seafarers around the world, 200 in each department (i.e. engine and deck). In step-3, Seafarers' survey data was received from ED and DD and the CPT for both departments was developed.

4.2.1 Environmental and operational factors CPT for ED

A total of 121 responses were received from the engine department (response rate of 60.5%). The received survey data was then categorised according to the seafarers' level of training, experience and fatigue. Prior to categorising the data, it was considered that failure or success of a maintenance activity depends on skill levels. Seafarers of ED hold various ranks on ships. All these ranks require a certain level of training and experience. These ranks for ED are chief engineer, second engineer, third engineer, fourth engineer and cadet engineer from highest to lowest respectively. Category "A" is considered the (highest rank) chief engineer with 10 years or more experience and voyage duration of 1 month. Category "B" is allocated to second engineer with 8 years' experience and voyage duration of 2 months. Category "C" relates to third engineer with 6 years' experience and voyage duration of 3 months. Category "D" is the fourth engineer with 5 years' experience and voyage duration of 4 months. Though the cadet engineer is also part of the ED, he/ she has not been considered in this study as a cadet engineer is always supervised by the upper ranked seafarers.

Among the 121 survey responses, category A, B, C and D level responses are 31, 45, 25 and 20 respectively. The CPTs are developed for all the categories individually. The CPTs for environmental factors are developed by using Equation 3.

$$Dependency = 1 - \frac{V}{5} \quad (3)$$

Where, V is the difference between two factors considered 95% of confidence and 5 is the maximum value from the survey (as the questionnaire was developed using a five likert scale of 1 to 5, where 1 is considered to be not important and 5 extremely important respectively). If the performance affecting factors survey value is more than 1, then the dependency results are considered as a poor condition in CPT. On the other hand, if the two performance affecting factors survey value is 1 and dependency result is 1 then the result 1 is considered as a good condition in CPT. The developed CPT for the environmental and operational factors for the seafarers' categories (A to D) of the ED are presented in Table X3 to Table X10. Table X3 to Table X6 shows the CPT for environmental factors. The environmental factor "poor" is the condition where marine operations should be stopped or recommended to proceed with extreme caution (high-risk condition). Moreover, environmental factor "good" is the condition where marine operations will be continued with acceptable risk, depending upon the type of organization. CPT's for operational factors are presented in Table X7 to Table X10 and operational factors "poor" and "good" mean the same as environmental factors "poor" and "good".

4.2.2 Environmental and operational factors CPT for (DD)

A total of 114 responses were received from the engine department (response rate of 57%). The ranks for DD are captain, chief officer, second officer, third officer and deck cadet. All these ranks require a certain level of training and experience. Categories for the DD seafarers are considered in the same way as the ED seafarers' category. Though deck cadet is also part of the DD it has not been considered in this study. The 114 responses received were categorised as A, B, C and D level and numbered 25, 38, 34 and 17 respectively. The CPTs are developed for all the categories individually. DD environmental factors CPTs for the seafarer categories (A to D) are the same as the ED as mentioned in Table X3 to Table X6. However, CPTs for operational factors are developed similar to ED as mentioned in section 4.2.1 and illustrated in Table Y11 to Table Y14.

4.2.3 CPTs for the internal and external factors, and HEP for the maintenance activities of marine operations

The CPT's for internal factors, external factors and maintenance activities of marine operations are the same for all the seafarers' categories (A to D) and were developed according to the experts opinions. Table Z15 illustrates the CPT for the seafarers' internal factors. The CPT values range from 0 to 1 where "0" is lowest and "1" highest. If either of these two factors (i.e. training and experience level) are high or the fatigue level is low, the probability of internal factor is good and vice versa. However, CPT for seafarers' external factors values are 0 and 1 as illustrated in the Table Z16. When either of the factors (environmental /operational) are considered as poor, the probability of external factor is "poor". On the other hand, when both of the factors (environmental and operational) are good, then the probability of external factor is "good".

The CPT for maintenance activities of marine operations is illustrated in Table Z17. When both factors (internal and external) are bad, then the probability of maintenance activities is "failure". However, when internal factor is bad and external factor is good, then it is uncertain whether the maintenance activity is "failure" or "success". Moreover, when internal factor is good and external factor is bad, then the probability of maintenance activity is "failure" (considering that the external factors influence seafarers' performance more than the internal factors).

The CPTs for internal factors, external factors and HEP estimation of maintenance activities of DD is developed similar to ED and illustrated in Table Z15, Table Z16 and Table Z17 respectively. By computing the developed CPTs, and using prior probability received from the experts, BN model is developed for the maintenance activities of the marine operations.

5. Application of the Methodology: Case Study

The developed methodology is applied in two different case studies. In the first case study, the developed methodology is applied for the maintenance procedures of a marine engine's cooling water pump to estimate the HEP (for ED). Maintenance of the cooling water pump is very important as it helps in cooling the marine engine to reduce the damage to its material. In the second case study, the developed methodology is applied for the maintenance procedures of an anchor windlass to estimate the HEP (for DD). An anchor windlass is a device used for ship anchor handling. To get the desired output from the windlass, maintenance is essential.

5.1 Case Study 1 (Engine Department)

There are three steps in the developed methodology to estimate the HEPs for the maintenance procedures of a marine engine cooling water pump. The first step is the scenario selection, identification of the maintenance activity and categorisations. In this case study, two scenarios are selected according to the marine environmental and operational conditions.

In the first scenario, a ship is at berth and seafarers (categories A/ B/ C/ D) are conducting the maintenance of a marine engine cooling water pump. The seafarers are performing the maintenance activity in normal weather conditions, normal workplace temperature in the engine room, low level of ship motion, mid-range of workload and stress level and low level of noise and vibration.

In the second scenario, the same seafarers (categories A/ B/ C/ D) are conducting a similar maintenance activity. However, considering the existing conditions, new information is available that while weather condition, level of ship motion, level of workload and stress are the same, the workplace temperature changes from normal to extreme, and noise and vibration level increases from low to high. In the second step, the factor affecting the seafarer's performance is selected according to the specified scenario. Finally, the BN model developed for the maintenance activities of marine operations is applied in order to estimate the HEP for the maintenance procedures of a marine engine cooling water pump. However, for the second scenario, the seafarers' performance affecting factors are updated according to the new available information and the BN model is applied to estimate the new HEP.

Figure 4.

Similarly, considering all the other categories (A/ B/ C/ D) of scenario 2, HEP results are obtained and presented in section 6.

5.2 Case Study 2 (Deck Department)

The developed methodology is also applied to estimate the HEPs for the maintenance procedures of an anchor windlass. In this case study, two different scenarios are selected according to the marine environmental and operational conditions.

In the first scenario, a ship is at berth and seafarers (category A/ B/ C/ D) are conducting the maintenance of an anchor windlass. The seafarers are performing the maintenance activity in normal weather conditions, normal workplace temperature on the weather deck, low level of ship motion, workload and stress level is mid-range and low level of noise and vibration are experienced.

In the second scenario, the same group of seafarers (categories A/ B/ C/ D) are conducting a similar maintenance activity. However, considering the existing conditions, new information is available that while weather condition, level of ship motion, level of workload and stress are the same, the workplace temperature changes from normal to extreme, and noise and vibration level increases from low to high. In the second step, the factors affecting the seafarer's performance are selected according to the scenario. Finally, the developed BN model for the maintenance activities of marine operations are applied in order to estimate the HEP for the maintenance procedures of an anchor windlass. However, for the second scenario, the seafarers' performance affecting factors are updated in the BN model according to the new available information to estimate HEP. Seafarers DD case studies of scenario 1 and 2 are also obtained in the similar way as ED, and HEP results are presented in Section 6.

6. Results and discussions

The application of the developed methodology to the case studies is summarised in Figure 5 and Figure 6. In Figure 5 and Figure 6, "X" axis illustrates the categories of the seafarers and "Y" axis shows the HEPs. The HEPs for all four categories (A to D) of the seafarers in ED and DD are estimated. Scenarios 1 and 2 of the ED illustrate the HEPs for the maintenance activity of a marine engine cooling water pump and are presented in Figure 5. Similarly, scenarios 1 and 2 of the DD demonstrate the HEPs for maintenance activity of the anchor windlass and results are presented in Figure 6.

Figure 5.

Figure 6.

The case study results show that HEPs related to the seafarers from A to D category increased respectively for both ED and DD. The reason is that the level of seafarers training and experience decreased and fatigue level increased from category A to D respectively. Moreover in scenario 1, HEPs for the seafarers' categories A to D in both departments (ED and DD) depict a similar trend. This means that level of training, experience and fatigue affects seafarers' performance. This is common in both departments. The environmental and operational conditions do not affect seafarers' performance in the considered scenario (scenario 1) because the levels of these conditions are considered to be normal, mid-range and low.

In scenario 2, HEPs are increased for both department's maintenance activities due to changing the workplace temperature from normal to extreme and levels of noise and vibration from low to high. It is proved that as soon as the workplace temperature changes from normal to extreme and levels of noise and vibration from low to high, the HEPs also started to increase. Interestingly, in scenario 2, seafarers' categories A and B HEP are same in both ED and DD. This confirms that extreme workplace temperature and high levels of noise and vibration affect the seafarers in both departments similarly. However, categories C and D HEPs increased in both departments. It clearly shows that the chances of error increase with an increase in the level of fatigue and a decrease in the level of training and experience. Moreover, the HEPs for seafarers' categories C and D in ED and DD have a significant difference and are higher in ED than DD. This means that the extreme workplace temperature and high levels of noise and vibration affect the seafarers' performance more in ED than the seafarers in DD.

The HEPs are found to be high in scenario 2 for the seafarers' categories A to D in both the departments as mentioned above. Extreme workplace temperature decreases the seafarers' ability to concentrate on the maintenance activities and lowers the performance, thus HEPs increase. Moreover, extreme workplace temperature influences seafarers' body temperature causing it to rise, which could lead to health issues and therefore likelihood of errors increases [33]. Furthermore, extreme workplace temperature leads to loss of seafarers' body fluid which in turn decreases the performance and increases the HEP [19]. In the same way, high levels of noise and vibration degrade seafarers' stamina and alertness, which in turn affects their performance, thus increasing HEPs. Moreover, persistent exposure to high levels of noise and vibration causes fatigue and confusion. This significantly affects seafarers' maintenance activities on board ship and increases HEPs. Furthermore, high level of noise and vibration impact on the quality of seafarers' perception, memory and reasoning thus increasing HEPs [34].

There are some differences in the results between the seafarers' categories, as all seafarers' categories are not affected by the same level of extreme workplace temperature and high levels of noise and vibration. Thus, the HEPs for the seafarers' category with comparatively low training and experience and high fatigue level are higher (i.e. categories C and D) than categories A and B. Due to the high level of experience, A and B category seafarers' are not affected similarly to those in categories C and D. Further discussion on the effect of experience on human performance is provided by [34].

Moreover, the HEPs for categories C and D in ED and DD have a significance difference. HEPs for categories C and D in ED are higher than in DD. This confirms that the extreme workplace temperature and high levels of noise and vibration affects the seafarers' performance more in ED than those in DD. This is because in ED, maintenance activities are performed in the engine room which is generally located below the waterline of the ship. Moreover, engine room machinery radiates extreme heat and the engine room does not have much air circulation and is an enclosed space. Seafarers thus feel uncomfortable and HEPs are going to increase. Furthermore, due to the enclosed space in the engine room, noise is reflected and becomes increased in intensity which in turn affects seafarers' performance more and increases the HEP [35]. On the other hand, the maintenance activities on the DD are generally performed on the weather deck. Thus even in extreme temperature, natural air circulation is available which affects the seafarers' performance less than ED and decreases the HEPs. Additionally, on the weather deck, noise does not increase in intensity as it is not an enclosed space, thus, DD seafarers' are less affected by the noise compared to those in ED and HEPs are going to decrease.

One of the main advantages of the developed methodology in this study, is that once new evidence is available the likelihood of failure or success of any maintenance activity can be revised as discussed in section 3. Therefore, the HEPs and the probability of failures can be updated considering the existing operational and environmental conditions. Conventional human reliability assessment techniques do not have this advantage. Therefore, the developed methodology is capable of estimating the HEP more precisely.

7. Conclusions

The negative influence of internal and external factors affect seafarers' performance and play an important role in making errors during maintenance activities on-board. To estimate the HEP accurately, it is necessary to consider interdependency between the performance-affecting factors and seafarers' actions. The developed methodology in this study is capable of representing complex dependencies among the performance affecting factors and seafarers' actions to include uncertainty in modelling. Moreover, the developed methodology is better illustrated as conditional dependencies by means of direct causal arcs among dependent variables. The CPTs for environmental and operational factors are used in the developed methodology by conducting a questionnaire survey among experienced seafarers' to estimate the HEP more accurately. The developed methodology is effective for both the HEP estimation and updating in the light of new information. Therefore, the developed methodology is a superior technique to traditional HEP assessment techniques. The developed methodology is applied to estimate HEP in various real life scenarios as demonstrated in the case studies. The case study results show that category "A" chief engineer/captain (highest rank) with 10 years or more experience and duration of the voyage of 1 month has the lowest HEP and category "D" fourth engineer/third officer with 5 years' experience and duration of the voyage for 4 months has the highest. The HEPs fluctuate with the changes in internal or external factors. According to the HEP result, captain/ or chief engineer can select the particular category of seafarer who is most reliable to perform the maintenance activities in a particular scenario in order to reduce the HEP. Moreover, the estimated HEPs for the maintenance activities of marine operations will help in taking remedial actions to reduce HEPs and shipping accidents.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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Appendix W. Prior probabilities for the maintenance activities of marine operations

Prior probabilities for the maintenance activities of marine operations see Tables W1 and W2.

Appendix X. CPT for the environmental and operational factors of ED

For the environmental and operational factors CPT of ED see Tables X3 to X10.

Appendix Y. Operational factors CPT for DD

For the operational factors CPT of DD see Tables Y11 to Y14.

Appendix Z. CPT for internal, external factor and HEP for the maintenance activities

For the internal, external factors and HEP for the maintenance activities CPT see the Tables Z1 to Z3.

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Tables

Table W1. Prior probability for internal factors

Category	Training		Experience		Fatigue	
	Low	High	Low	High	Low	High
A	0.01	0.99	0.01	0.99	0.99	0.01
B	0.02	0.98	0.02	0.98	0.98	0.02
C	0.03	0.97	0.03	0.97	0.97	0.03
D	0.04	0.96	0.04	0.96	0.96	0.04

Table W2. Prior probability for external factors

Parent node	States			External factors
	Normal	Moderate	Extreme	
Weather conditions	0.90	0.07	0.03	Environmental
Workplace temperature	0.95	-	0.05	
Ship Motion (roll and pitch)	Low	Medium	High	Operational
	0.92	0.06	0.02	
Noise and vibration	0.97	-	0.03	
Workload and stress	Mid-range	Underload	Overload	
	0.91	0.06	0.03	

Table X3. CPT for environmental factors (category-A)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table X4. CPT for environmental factors (category-B)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table X5. CPT for environmental factors (category-C)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	0.80	0.60	1.00
Environmental factor (good)	1.00	0.20	0.20	0.20	0.40	0.00

Table X6. CPT for environmental factors (category-D)

Weather conditions	Normal		Moderate		Extreme	
Workplace temperature	Normal	Extreme	Normal	Extreme	Normal	Extreme
Environmental factor (poor)	0.00	0.80	0.80	1.00	0.80	1.00
Environmental factor (good)	1.00	0.20	0.20	0.00	0.20	0.00

Table X7. CPT for operational factors (category-A)

Ship Motion (Roll and Pitch)	Low						Medium						High					
Workload and Stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and Vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.40	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00

Table X8. CPT for operational factors (category-B)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.80	0.80	0.60	1.00	0.60	1.00	0.80	0.80	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.4	0.20	0.20	0.40	0.00	0.40	0.00	0.20	0.20	0.40	0.00	0.40	0.00	0.40	0.00

Table X9. CPT for operational factors (category-C)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	1.00	0.00	1.00	1.00	1.00	0.00	0.80	0.00	0.80	0.80	1.00	0.80	1.00	0.80	1.00	1.00	1.00
Operational factor (good)	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.20	1.00	0.20	0.20	0.00	0.20	0.00	0.20	0.00	0.00	0.00

Table X10. CPT for operational factors (category-D)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	1.00	0.00	1.00	1.00	1.00	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Operational factor (good)	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table Y11. CPT for operational factors (category-A)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.60	0.60	0.80	0.60	0.80	0.40	0.80	0.60	1.00	0.40	0.80	0.40	0.80	0.40	0.80
Operational factor (good)	1.00	0.40	1.00	0.40	0.40	0.20	0.40	0.20	0.60	0.20	0.40	0.00	0.60	0.20	0.60	0.20	0.60	0.20

Table Y12. CPT for operational factors (category-B)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	0.80	0.60	1.00	0.60	1.00	0.80	0.80	0.60	1.00	0.60	1.00	0.60	1.00	0.60	1.00
Operational factor (good)	1.00	0.40	1.00	0.20	0.40	0.00	0.40	0.00	0.20	0.20	0.40	0.00	0.40	0.00	0.40	0.00	0.40	0.00

Table Y13. CPT for operational factors (category-C)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.60	0.00	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00
Operational factor (good)	1.00	0.40	1.00	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00

Table Y14. CPT for operational factors (category-D)

Ship Motion (roll and pitch)	Low						Medium						High					
Workload and stress	Mid-range		Underload		Overload		Mid-range		Underload		Overload		Mid-range		Underload		Overload	
Noise and vibration	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Operational factor (poor)	0.00	0.80	0.00	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00	0.80	1.00
Operational factor (good)	1.00	0.20	1.00	0.00	0.00	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00	0.20	0.00

Table Z15. CPT for seafarers' internal factors

Training	Low				High			
Experience	Low		High		Low		High	
Fatigue	Low	High	Low	High	Low	High	Low	High
Seafarers' internal factors (poor)	1.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00
Seafarers' internal factors (good)	0.00	0.00	1.00	0.00	1.00	0.00	1.00	1.00

Table Z16. CPT for seafarers' external factors

Environmental factors	Bad		Good	
Operational factors	Bad	Good	Bad	Good
Seafarers' external factors (poor)	1.00	0.00	0.00	0.00
Seafarers' external factors (good)	0.00	1.00	1.00	1.00

Figures

Captions

Figure 1. Developed methodology for estimating the HEP during the maintenance activities of marine operations

Figure 2. BN model for the maintenance activities of marine operations

Figure 3. Development of a CPT for the environmental and operational factors

Figure 4. Developed BN to estimate the HEP for the maintenance of marine engine cooling water pump (scenario 2, category-A)

Figure 5. HEP estimation of the case studies for ED

Figure 6. HEP estimation of the case studies for DD

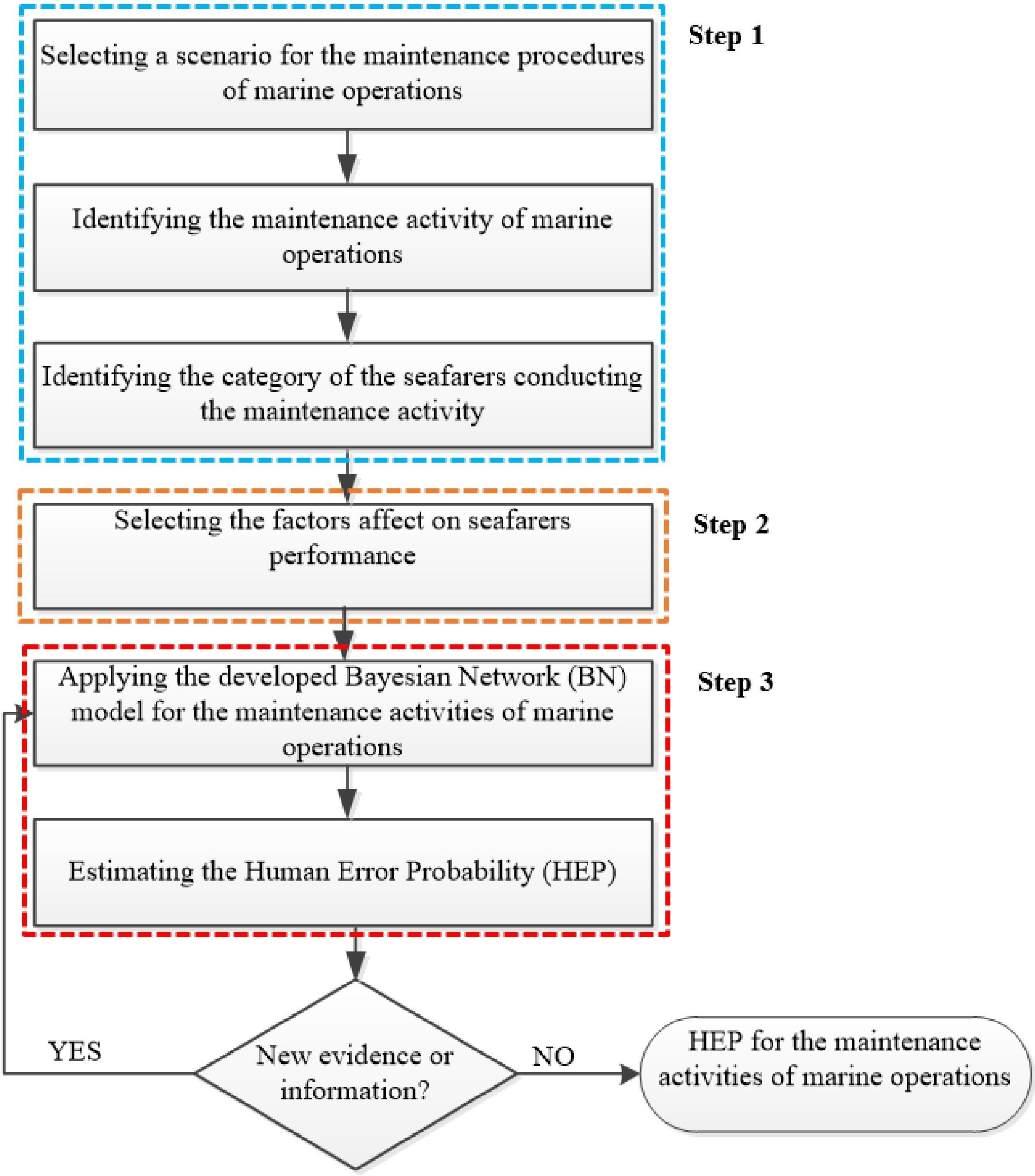

Selecting a scenario for the maintenance procedures of marine operations
Identifying the maintenance activity of marine operations
Identifying the category of the seafarers conducting the maintenance activity
Step 1
Selecting the factors affect on seafarers performance
Step 2
Applying the developed Bayesian Network (BN) model for the maintenance activities of marine operations
Estimating the Human Error Probability (HEP)
Step 3
New evidence or information?
YES
NO
HEP for the maintenance activities of marine operations

Figure 1.

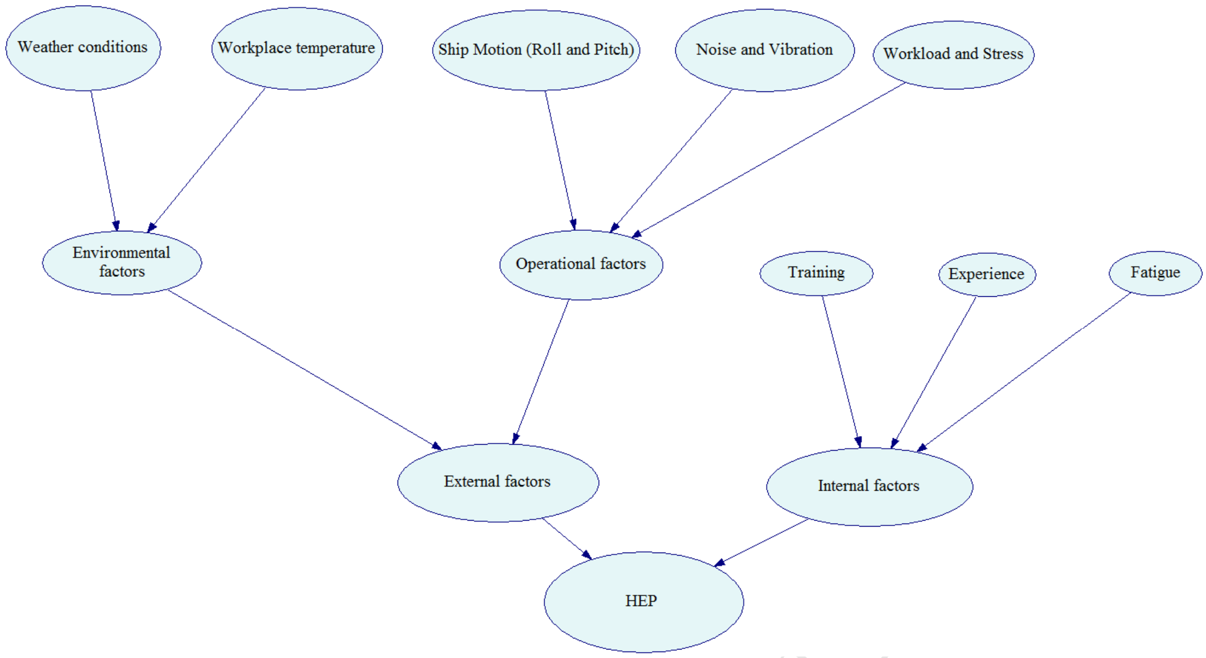


Figure 2.

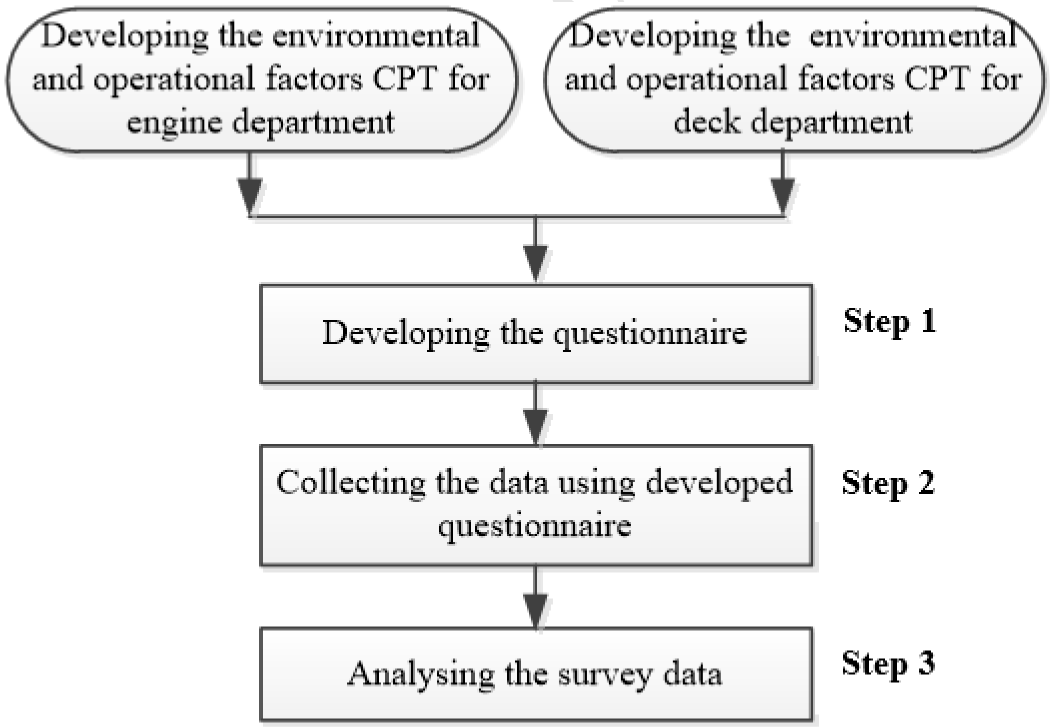


Figure 3.

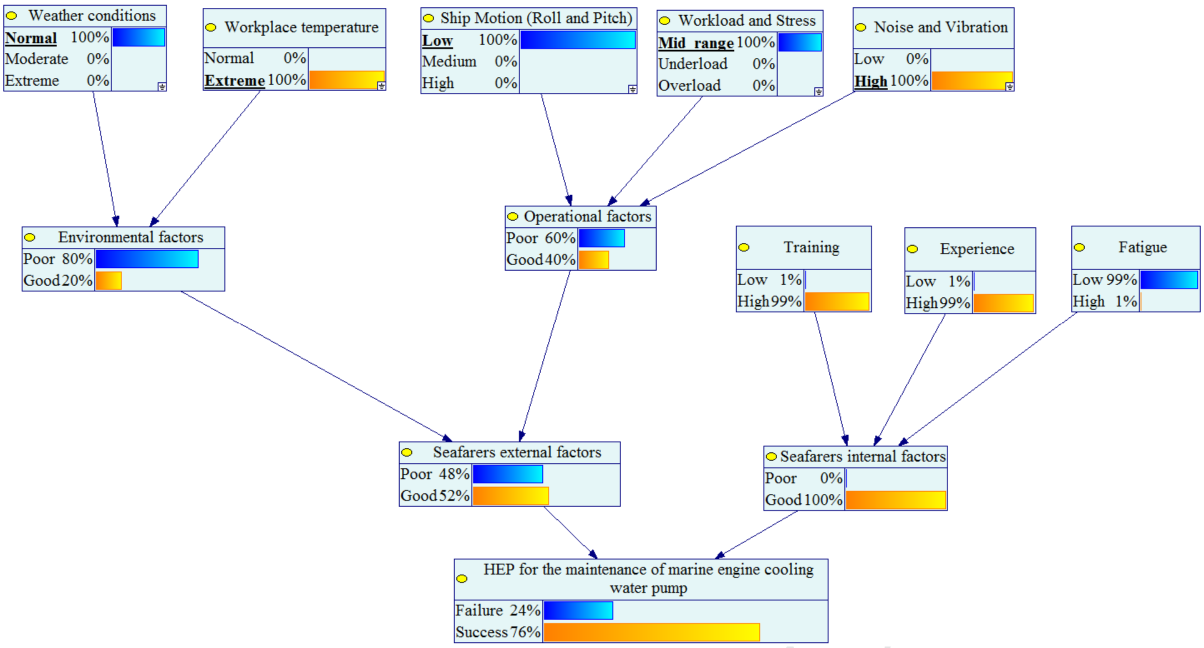


Figure 4.

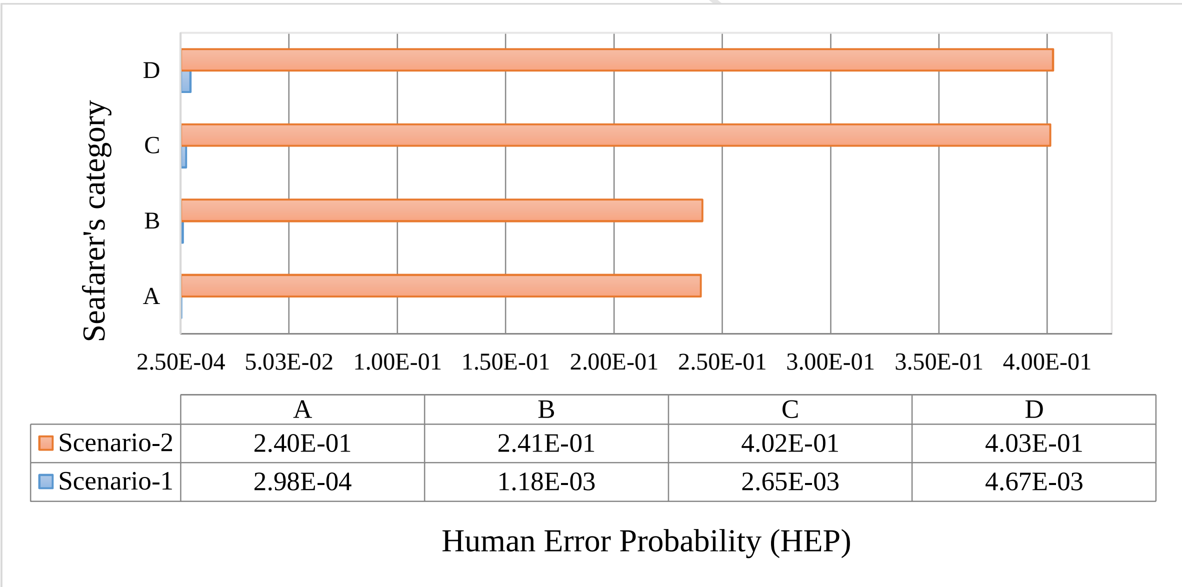
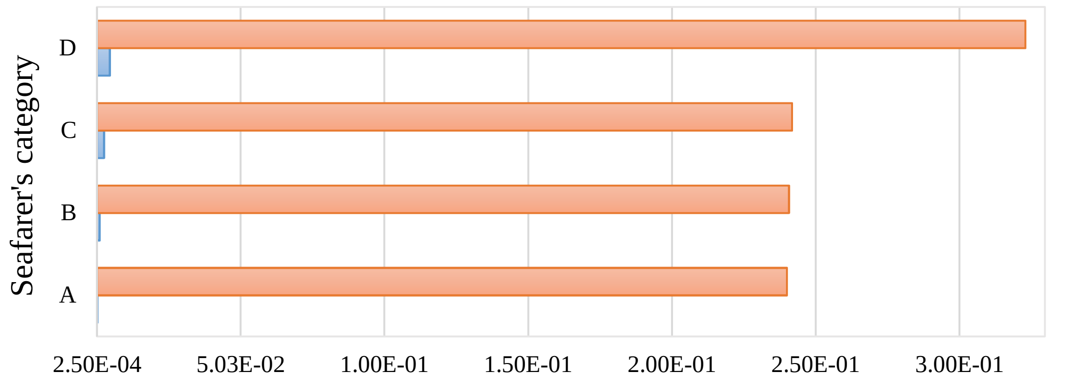


Figure 5.



	A	B	C	D
Scenario-2	2.40E-01	2.41E-01	2.42E-01	3.23E-01
Scenario-1	2.98E-04	1.18E-03	2.65E-03	4.67E-03

Human Error Probability (HEP)

Figure 6.