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Original Article

Human Error Probability Assessment During Maintenance Activities of Marine Systems

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A B S T R A C T

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 seafarers' performance, 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. Thus, the objective of this study is to develop a human error probability model considering various internal and external factors affecting seafarers' performance.

Methods: 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 >200 experienced seafarers with >5 years of experience. The model developed in this study is used 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 changes in either internal (i.e., training, experience, and fatigue) or external (i.e., environmental and operational conditions such as weather conditions, workplace temperature, ship motion, noise and vibration, and workload and stress) factors.

1. Introduction

International Maritime Organization accident investigation reports cite that about a quarter of all maritime accidents are initially due to machinery failure [1]. Therefore, maintenance of machinery in marine systems is very important. Moreover, maintenance of machinery also minimizes the severity of the failure, prevents unexpected downtime, extends the life of machinery, and helps 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 errors [2]. Examples of previous accidents due to human errors during maintenance activities on marine machinery are explained by Islam et al. [3]. Different internal and external factors affect the seafarers' performance and sometimes those factors are responsible for human errors. Internal factors such as lack of training and experience, and a high level of fatigue have significant impact on seafarers' performance [4]. These factors have either a positive or a negative impact on seafarers' performance. For example, high levels of

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training and experience has a positive impact on seafarer's performance, whereas a high level of fatigue has a negative influence on seafarers' performance. Details about the lack of seafarers' training and experience, and a high level of fatigue are explained by Islam et al. [3,5].

Moreover, external factors affecting 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 Club, accidents related to human errors 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], and investigated this technique in pre- and post-maintenance procedures of offshore oil and gas facilities. Recently, Hoboubi et al. [12] studied the impact of job stress and satisfaction on workforce productivity in an Iranian petrochemical industry. In another effort, Islam et al. [3] estimated the probability of human errors during maintenance procedures of marine engines. Previous studies mentioned above proved the importance of estimating human errors in risk assessment of various engineering systems. Furthermore, International Maritime Organization [13] guidelines were proposed adopting the human error probability (HEP) 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 by Swain and Guttmann [14], success likelihood index method by Kirwan [15], and human error assessment and reduction technique [16]. The technique for human error rate prediction approach does not offer suitable guidance to represent the error-producing conditions and scenario development [17]. The success likelihood index method approach is based on expert judgment, and various uncertainties affected the final outcomes [18]. The human error assessment and reduction technique have some doubts over the consistency of the method as dependency and interaction among contributory factors to error-producing conditions 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 reanalyze the 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]. Groth and Mosleh [21] applied BN for predicting the HEP in the nuclear power industry. Mu et al. [22] applied BN for predicting the HEP in the aviation industry. Musharraf et al. [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' errors 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 is available.

BN will also help represent the relationships between human factors and seafarers' actions in a hierarchical structure. In this paper, the second section provides fundamental description of BN, explains the development of methodology, details the development of a BN model, and demonstrates the application of the developed technique to case studies. Results and discussions are presented in the third section. The final section summarizes and concludes the paper.

2. Materials and methods

2.1. Fundamentals of BN

BN is a probabilistic model that represents interaction of variables through 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. A CPT provides a broad description of probabilistic interaction. It also has the ability to model the probabilistic dependency among a discrete node and its parent nodes. Probabilities in a 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, a CPT denotes the prior probability variable [29]. If there are "n" variables $X_1, X_2, \ldots, X_n$, 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 follows:

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

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 a BN model:

- $X_1, X_2, \ldots, X_n$, set of variables (nodes)
- The interaction (edges) among the variables
- $P(X_i|Pa(X_i))$ conditional probability distribution for each variable X_i.

The section "Development of a BN model for the maintenance activities of marine operation" illustrates the BN model for the maintenance activities of marine operations.

2.2. Methodology

The methodology developed, based on the BN approach, is used in this study to estimate the HEP for the maintenance activities of marine systems. The use of BN will help 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 Fig. 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 categorized in four categories: A, B, C, and D. These seafarer categories depend on the levels 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 "Environmental and operational factor CPT for ED".

In Step 2, it is necessary to select the factors that affect seafarers' error making during on-board maintenance activities. Both internal and external performance-affecting factors are selected in this study, as performance shaping factors (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. Environmental factors are further categorized as weather conditions and workplace temperature, while operational factors are ship motion (roll and pitch), workload and stress, and noise and vibration. These factors are selected according to previous studies [30–33]. It should be noted that seafarers' opinions are also taken into account prior to selecting these factors. Each seafarer has >5 years' experience in the maintenance activities on-board ships. The performance-affecting factors selected 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 the expert's opinion as mentioned above.

The final step (Step 3) is to apply the developed BN model and estimate the HEP. If no new information is 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.

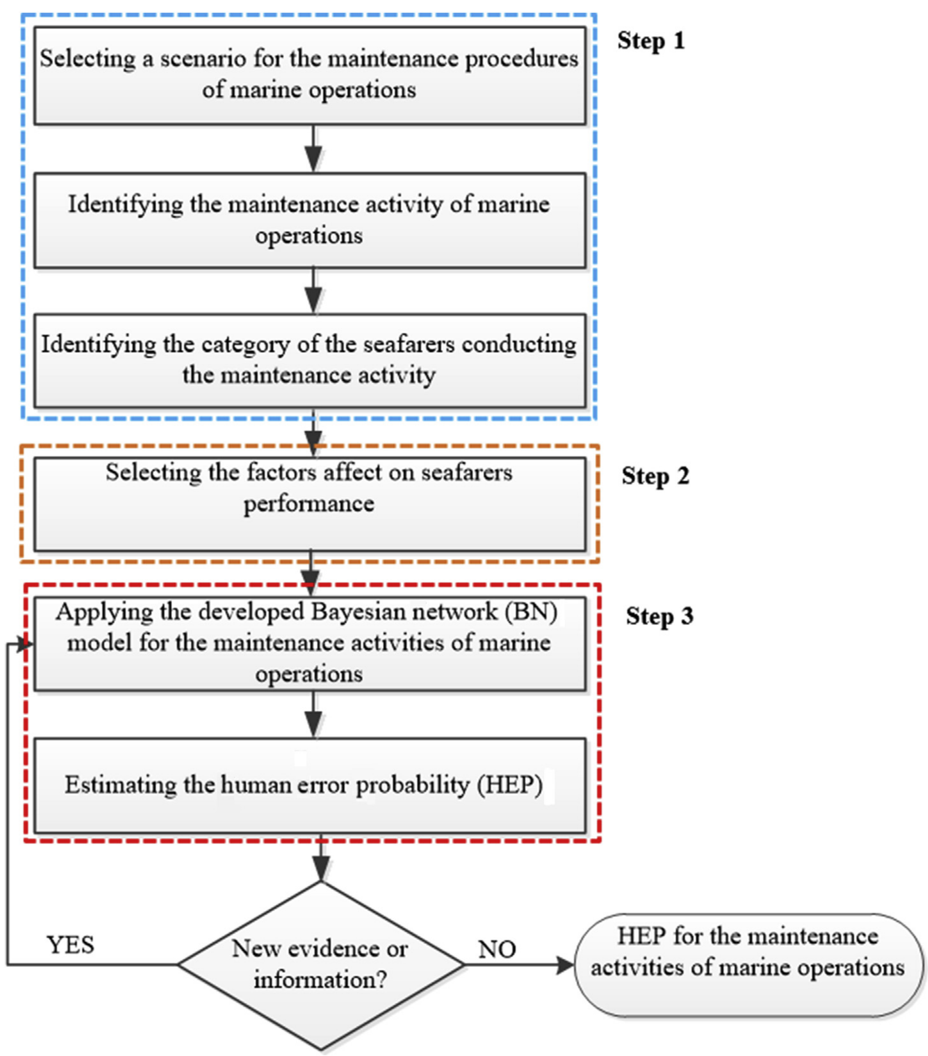

Fig. 1. Methodology developed for estimating the HEP during the maintenance activities of marine operations. HEP, human error probability.

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

As outlined in the preceding section, the methodology developed in this study is based on the BN approach. The unique feature of the BN will allow an accurate estimation of the HEP. To develop the BN model, first 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. Each of the root causes is then assigned a node, as illustrated in Fig. 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 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 Fig. 2.

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

2.3.1. 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 >10 years' experience as a marine engineer. The prior probability values range between 0 and 1 ("0" indicating lowest and "1" highest values). Prior probabilities for the internal and external factors are illustrated in Tables 1 and 2, respectively. On-board ships, there are two departments, engine department (ED) and deck department (DD), which 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–D) of the ED and DD are similar for internal and external factors.

Table 1
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 2
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 0.92	Medium 0.06	High 0.02	Operational
Noise and vibration	0.97	—	0.03	
Workload and stress	Midrange 0.91	Underload 0.06	Overload 0.03	

In Table 1, 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 2, 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 a "high/extreme" state.

2.3.2. Development of CPT for 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 a CPT for a BN model. A BN model requires CPTs for environmental,

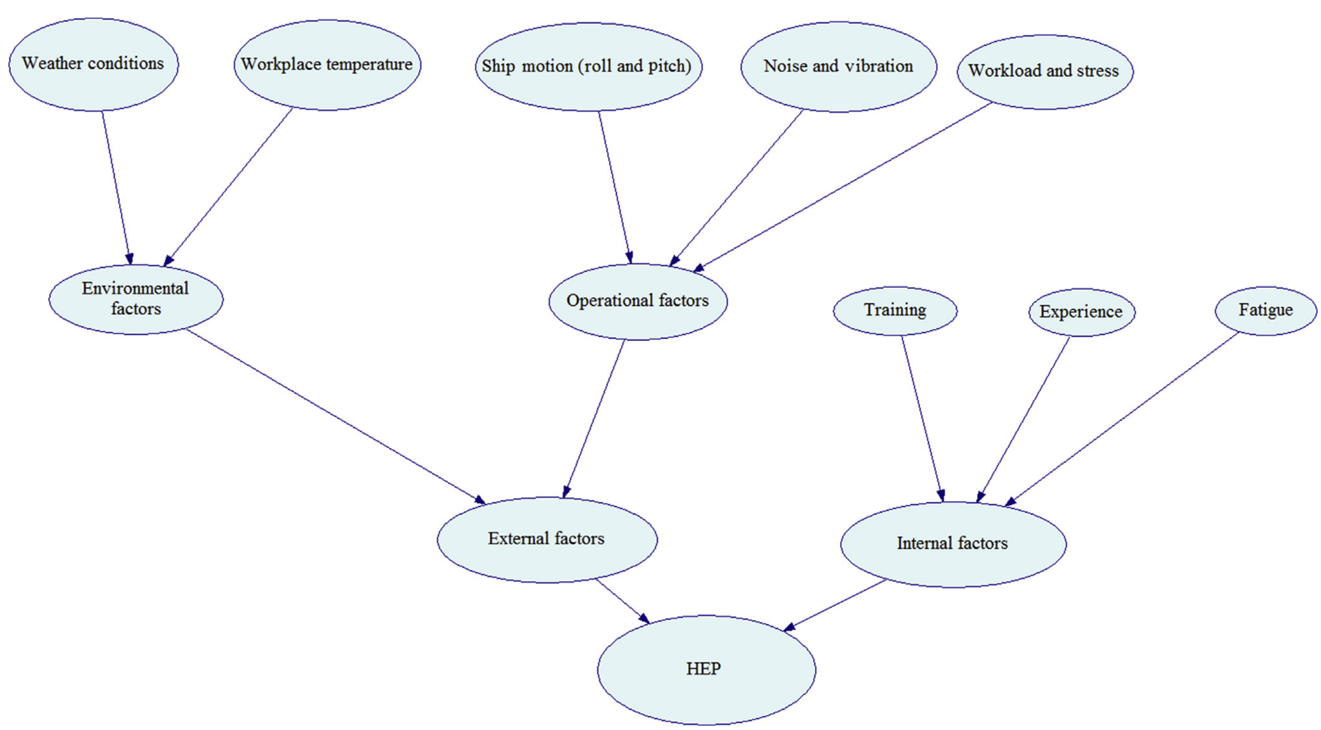

Fig. 2. BN model for the maintenance activities of marine operations. BN, Bayesian network; HEP, human error probability.

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operational, internal, and 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 contrary, CPTs for internal and 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 the ED may affect the seafarers' performance differently from those in the DD. Therefore, it is necessary to develop the environmental and operational factor CPT separately for both departments.

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

In Step 2, a Survey Monkey link was created to conduct 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 were received from the ED and DD, and CPTs for both departments were developed.

2.3.2.1. Environmental and operational factor CPT for ED. A total of 121 responses were received from the ED (a response rate of 60.5%). The received survey data were then categorized according to the seafarers' levels of training, experience, and fatigue. Prior to categorizing the data, it was considered that the failure or success of a maintenance activity depends on skill levels. Seafarers of the ED hold various ranks on ships. All these ranks require a certain level of training and experience. These ranks for the ED, from the highest to the lowest, are chief engineer, second engineer, third engineer, fourth engineer, and cadet engineer. Category "A" is considered the highest rank—chief engineer with experience of 10 years or more 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 related to fourth engineer with 5 years' experience and voyage duration of 4 months.

Table 3
CPT for environmental factors (category A of engine department)

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

CPT, conditional probability table.

Although a 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. CPTs are developed for all the categories individually. CPTs for environmental factors are developed using Eq. (2).

$$Dependency = 1 - \frac{V}{5} \quad (2)$$

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-point Likert scale, where 1 is considered to be not important and 5 extremely important). If the survey value of performance-affecting factors is >1, then the dependency results are considered as a poor condition in a CPT. By contrast, if the survey value of two performance-affecting factors is 1 and dependency result is 1, then the result 1 is considered as a good condition in a CPT. CPTs developed for the environmental and operational factors for seafarer categories (A–D) of the ED are presented in Tables 3–10. Tables 3–6 show the CPTs 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. CPTs for operational factors are presented in Tables 7–10, and operational factors "poor" and "good" mean the same as environmental factors "poor" and "good".

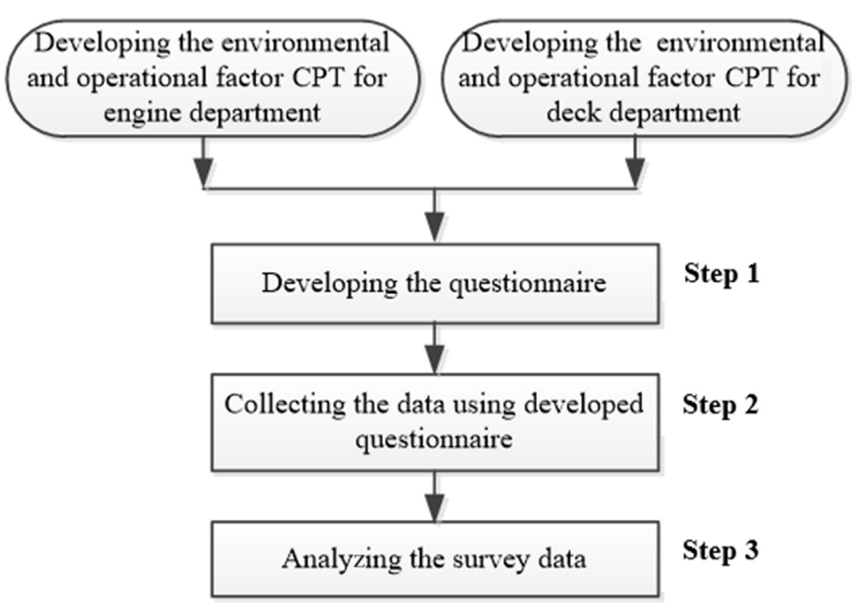

Fig. 3. Development of a CPT for environmental and operational factors. CPT, conditional probability table.

Table 4
CPT for environmental factors (category B of engine department)

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

CPT, conditional probability table.

Table 5
CPT for environmental factors (category C of engine department)

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

CPT, conditional probability table.

Table 6
CPT for environmental factors (category D of engine department)

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

CPT, conditional probability table.

2.3.2.2. Environmental and operational factor CPT for DD. A total of 114 responses were received from the ED (response rate of 57%). The ranks for the 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 seafarer categories. Although a deck cadet is also part of the DD, this category has not been considered in this study. The 114 responses received were categorized as A, B, C, and D levels, with the numbers of responses being 25, 38, 34, and 17, respectively. CPTs are developed for all the categories individually. DD environmental factor CPTs for the seafarer categories (A–D) are the same as those for the ED, as mentioned in Tables 3–6. However, CPTs for operational factors are developed similar to those of the ED, as mentioned in the preceding section and illustrated in Tables 11–14.

2.3.2.3. CPTs for internal and external factors, and HEP for maintenance activities of marine operations. CPTs for internal factors, external factors, and maintenance activities of marine operations are the same for all the seafarer categories (A–D) and were developed according to expert opinions. Table 15 illustrates the CPT for the seafarers' internal factors. 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 levels) is high or the fatigue level is low, the probability of internal factor is good and vice versa. However, the values of the CPT for seafarers' external factors are 0 and 1, as illustrated in Table 16. When either of the factors (environmental/operational) is considered poor, the probability of external factor is "poor". On the contrary, when both 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 17. When both factors (internal and external) are bad, then the probability of maintenance activities is a "failure". However, when the internal factor is bad and external factor is good, then it is uncertain whether the maintenance activity is a "failure" or "success". Moreover, when the internal factor is good and external factor is bad, then the probability of maintenance activity is a "failure" (considering that the external factors influence seafarers' performance more than the internal factors).

CPTs for internal and external factors, and HEP estimation of maintenance activities of the DD are developed similar to those of the ED and illustrated in Tables 15, 16, and 17, respectively. By computing the developed CPTs and using prior probability received from the experts, a BN model is developed for the maintenance activities of the marine operations.

2.4. 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 the ED). Maintenance

Table 7
CPT for operational factors (category A of engine department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 8
CPT for operational factors (category B of engine department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

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Table 9
CPT for operational factors (category C of engine department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 10
CPT for operational factors (category D of engine department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 11
CPT for operational factors (category A of deck department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 12
CPT for operational factors (category B of deck department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 13
CPT for operational factors (category C of deck department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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

CPT, conditional probability table.

Table 14
CPT for operational factors (category D of deck department)

Ship motion (roll and pitch)	Low						Medium						High					
Workload and stress	Midrange		Underload		Overload		Midrange		Underload		Overload		Midrange		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 15
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

CPT, conditional probability table.

Table 16
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

CPT, conditional probability table.

Table 17
CPT for HEP of the maintenance activities of marine operations

Seafarers internal factors	Bad		Good	
Seafarers external factors	Bad	Good	Bad	Good
Maintenance activities of marine operations (failure)	1.00	0.50	1.00	0.00
Maintenance activities of marine operations (success)	0.00	0.50	0.00	1.00

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 the DD). An anchor windlass is a device used for ship anchor handling. To get the desired output from the windlass, maintenance is essential.

2.4.1. Case study 1 (ED)

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 involves scenario selection, identification of the maintenance activity, and categorization. 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, and at 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 and levels of ship motion, workload, and stress are the same, the workplace temperature changes from normal to extreme, and noise and vibration levels increase from low to high. In the second step, the factor affecting seafarers' 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, seafarers' performance-affecting factors are updated according to the new available information and the BN model is applied to estimate the new HEP (Fig. 4).

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

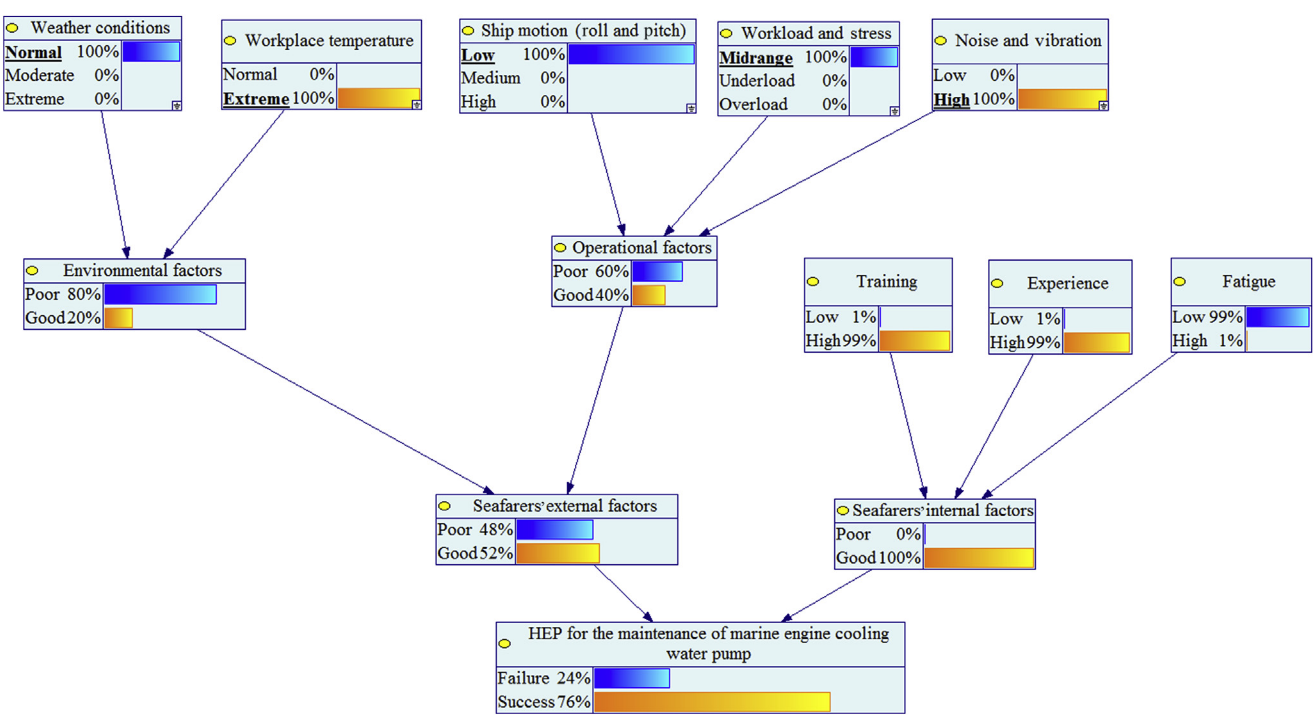


Fig. 4. Development of a BN to estimate the HEP for the maintenance of marine engine cooling water pump (Scenario 2, category A). BN, Bayesian network; HEP, human error probability.

2.4.2. Case study 2 (DD)

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 and at normal workplace temperature on the weather deck, low level of ship motion, midrange workload and stress level, and low level of noise and vibration.

In the second scenario, the same group of seafarers (categories A/B/C/D) is conducting a similar maintenance activity. However, considering the existing conditions, new information is available that while weather condition and levels of ship motion, workload, and stress are the same, workplace temperature changes from normal to extreme, and noise and vibration levels increase from low to high. In the second step, the factors affecting seafarers' performance are selected according to the 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 an anchor windlass. However, for the second scenario, seafarers' performance-affecting factors are updated in the BN model according to the new available information to estimate the HEP. Seafarer case studies of Scenarios 1 and 2 of the DD are also obtained in a similar way to those of the ED, and HEP results are presented in the next section.

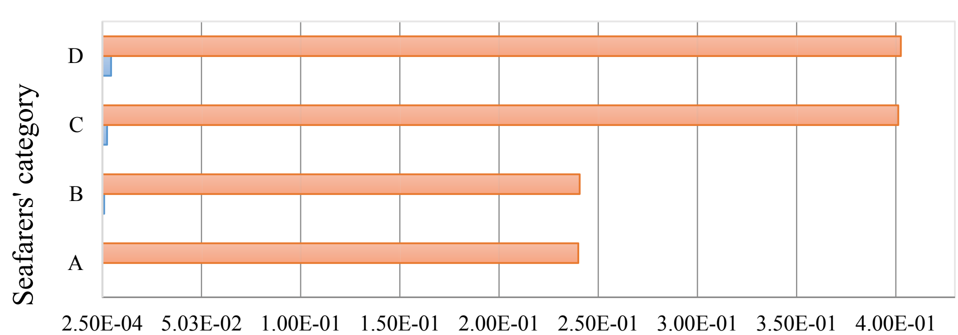
3. Results and discussion

Application of the developed methodology to the case studies is summarized in Figs. 5 and 6. In Figs. 5 and 6, the "X" axis illustrates the categories of the seafarers and "Y" axis shows the HEPs. The HEPs for all four categories (A–D) of the seafarers in the 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 Fig. 5. Similarly, Scenarios 1 and 2 of the DD demonstrate the HEPs for the maintenance activity of the anchor windlass, and the results are presented in Fig. 6.

The case study results show that HEPs related to the seafarers increased from A to D category for both ED and DD. The reason is that the level of training and experience of seafarers decreased and fatigue level increased from category A to category D. Moreover, in Scenario 1, HEPs for the seafarer categories A–D in both departments (ED and DD) depict a similar trend. This means that the levels of training, experience, and fatigue affect seafarers' performance. This is common in both departments. 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, midrange, and low.

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

The HEPs are found to be high in Scenario 2 for the seafarer categories A–D in both the departments, as mentioned above. Extreme workplace temperature decreases seafarers' ability to concentrate on the maintenance activities and lowers their performance; thus, the HEPs increase. Moreover, extreme workplace temperature influences seafarers' body temperature causing it to rise, which could lead to health issues and therefore the likelihood of errors increases [33]. Furthermore, extreme workplace temperature leads to loss of body fluid of seafarers, 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 the HEPs. Moreover, persistent exposure to high levels of noise and vibration causes fatigue and confusion. This significantly affects



	A	B	C	D
Scenario 2	2.40E-01	2.41E-01	4.02E-01	4.03E-01
Scenario 1	2.98E-04	1.18E-03	2.65E-03	4.67E-03

Human error probability (HEP)

Fig. 5. HEP estimation of the case studies for ED. ED, engine department; HEP, human error probability.

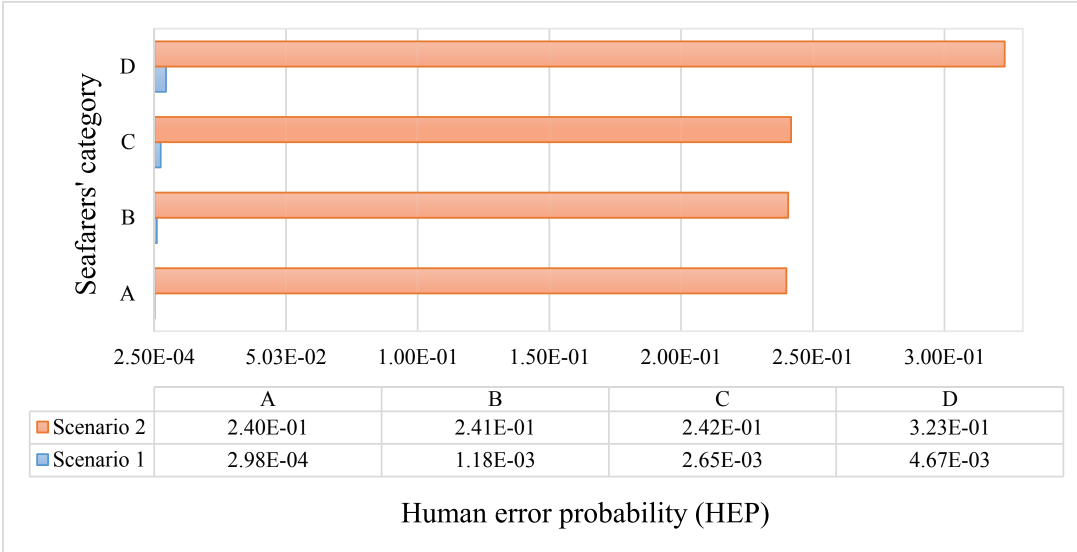


Fig. 6. HEP estimation of the case studies for DD. DD, deck department; HEP, human error probability.

seafarers' maintenance activities on-board ships and increases the HEPs. Furthermore, high levels of noise and vibration impact the quality of seafarers' perception, memory, and reasoning, thus increasing the HEPs [34].

There are some differences in the results between the seafarer categories, as all seafarer categories are not affected by the same level of extreme workplace temperature and high levels of noise and vibration. Thus, the HEPs for the seafarer category with comparatively low training and experience and a high fatigue level (i.e., categories C and D) are higher than those in categories A and B. Owing 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 Irgens-Hansen et al. [34].

Moreover, the HEPs for categories C and D in the ED and DD have a significance difference. HEPs for categories C and D in the ED are higher than those in the DD. This confirms that the extreme workplace temperature and high levels of noise and vibration affect seafarers' performance more in the ED than in the DD. This is because, in the 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 the HEPs 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]. By contrast, maintenance activities in the DD are generally performed on the weather deck. Thus, even at an extreme temperature, natural air circulation is available, which affects seafarers' performance less than that in the 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 noise compared with those in the ED and HEPs decrease.

One of the main advantages of the methodology developed 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 Methodology section. 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.

4. Summary

The negative influence of internal and external factors affects seafarers' performance and plays an important role in making errors during maintenance activities on-board. To estimate the HEP accurately, it is necessary to consider interdependency between performance-affecting factors and seafarers' actions. The methodology developed in this study is capable of representing complex dependencies among the performance-affecting factors and seafarers' actions to include uncertainty in modeling. Moreover, the developed methodology is better illustrated as conditional dependencies by means of direct causal arcs among dependent variables. 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 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 the 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 of experience and duration of voyage of 1 month has the lowest HEP, and category "D" fourth engineer/third officer with 5 years' experience and duration of voyage of 4 months has the highest HEP. HEPs fluctuate with changes in internal or external factors. According to the HEP result, the captain or chief engineer can select the particular category of seafarers who are most reliable to perform the maintenance activities in a particular scenario in order to reduce the HEP. Moreover, the HEPs estimated for the maintenance activities of marine operations will help in taking remedial actions to reduce the HEPs and shipping accidents.

Conflicts of interest

All contributing authors declare no conflicts of interest.

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