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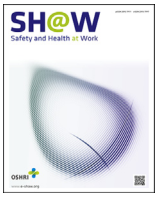

Original Article

Human Error Probability Assessment During Maintenance Activities of Marine Systems

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ABSTRACT

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,...,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,...,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

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