Risk Management of Human and Organizational Factors for the Escape and Evacuation of Offshore Installations

BY

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Abstract

Human and organizational factors, from the organizational level to the procedural and technical levels, can impact personnel. The human and organizational factors associated with personnel responses should be identified and managed in the emergency escape plan. This study presents a framework for human and organizational factors risk management in the escape and evacuation of offshore installations. The design and development of the framework are divided into four categories: a) identifying the presence of human and organizational factors in the safety barriers of escape and evacuation systems, b) estimating the probability of how human and organizational factors can affect personnel responses, c) combining the probabilities of personnel failing to respond with the consequential effects to assess risks, and d) applying a safety hierarchy to risk management of human and organizational factors in the escape and evacuation system. The first case study considered in this thesis examines the Macondo blowout, finding that insufficient emergency exercises, poor communication, impairment of personnel's physical abilities due to unsafe conditions, and poor emergency preparedness planning contributed to the ineffectiveness of emergency escape and evacuation. In the second study, a Bayesian analysis is used to connect the human and organizational factors that affect every safety barrier. Using illustrative data, the study identifies the scheduled maintenance of alarm systems as a critical human and organizational factor for notifying personnel of emergencies on offshore installations. In the third study, personnel response to emergency alarms is shown to be affected by cold temperature, strong winds, and darkness during emergency scenarios, thereby impacting risk. The fourth study is used to complete the risk management framework of human and organizational factors. In the fourth study, a safety hierarchy consisting of inherent safety, engineering safety, and procedural safety is used in the risk management framework. Examples of engineering safety presented in the study are the use of lighting and dynamic exit signs in assisting personnel to escape from hazardous areas. In terms of procedural safety, personnel who received frequent practice of escape activities performed better than personnel without such practice. To conclude this study, the framework is identified as a practical tool for minimizing and managing human and organizational factors and risks present in the escape and evacuation of offshore installations.

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Chapter 1

Introduction

1.1 Overview

Offshore installations operating in remote areas or harsh environmental conditions demand a high priority be placed on safety. Escape and evacuation is one of the features of a safety management program for offshore installations. The main purpose of escape and evacuation is to protect personnel from potential severe injuries and loss that can be caused by major internal and external events.

Examples of emergency situations are well blowout, the loss of containment in risers, pipelines, or process facilities, fires and explosions, the collapse of an installation's structure, collisions involving vessels or helicopters, and severe weather conditions (Wallace, 1992). Each emergency scenario may require different types of approaches and strategies regarding escape and evacuation. In such challenging scenarios, escape and evacuation operations depend on appropriate personnel responses and performance.

Not all escape and evacuation practices and preparations can be implemented and operated as accurately as planned in the emergency response plan. Uncontrolled emergency scenarios introduce chains of events that can affect personnel and their performance. The presence of evolving hazards, such as intense heat and black smoke, can also influence a personnel's ability in making decisions and taking action (USCG, 2011). Human and organizational factors may exist unnoticed in the safety barriers of escape and evacuation and emerge as contributing factors, leading to the failure of escape and evacuation operations (i.e. latent and active failures). Safety barriers of escape and evacuation can include basic survival training, emergency drills and exercises, alarm systems, emergency equipment, personal survival equipment, systematic procedures, command and control, and compliance with regulations and safety laws (CAPP, 2010; HSE, 1997; IADC, 2014; OGP, 2010; Maan, 2007).

1.2 Problem Identified

Personnel who have to interact with the presence of hazards and human and organizational factors in emergency scenarios will not always be able to perform escape and evacuation effectively (Paté-Cornell, 1993; Robertson and Wright, 1997; USCG, 2011). Examples of human and organizational factors related to such situations are a lack of knowledge and skills due to inadequate training and emergency drills provided by the operators of offshore installations. A main concern in the escape and evacuation system and its operations are human and organizational factors, which may go unnoticed in barriers involving equipment, regulations and procedures, organizational factors, and training.

1.3 Objective of Study

This research aims to develop a framework for human and organizational risk factors assessment and management for the escape and evacuation system of offshore installations. The framework should be able to improve or manage personnel responses and performances that are affected by human and organizational factors in escape and evacuation.

1.4 Scope of Work

The framework of human and organizational factors risk management is developed according to the following steps:

i) Identifying evolving hazards and human and organizational factors that can lead to unsafe escape and evacuation operations.

ii) Estimating the probability of personnel and organizational factors that can cause unsafe escape and evacuation operations.

iii) Assessing the risks associated with performance in escape and evacuation involving harsh environmental conditions.

iv) Developing risk management strategies to reduce and manage risks associated with performance.

The lists of steps are summarized in Figure 1.1.

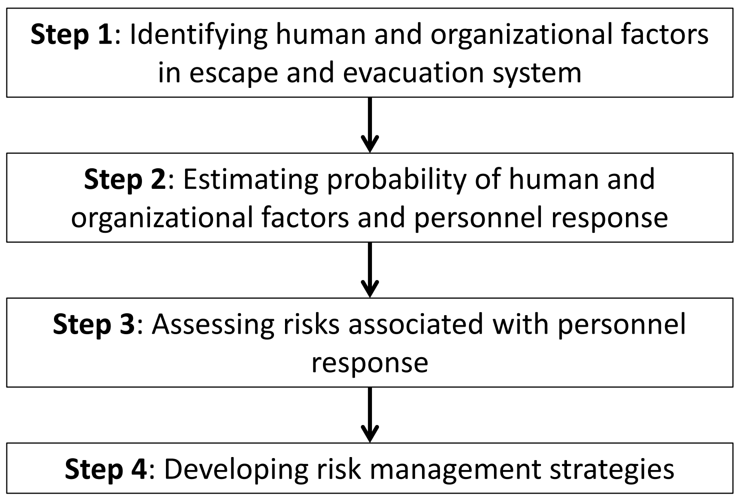

Figure 1.1: Steps for developing a framework of human and organizational factors.

1.5 Organization of Thesis

This thesis is organized as follows:

i) Chapter 2 discusses the novelty and contribution of the research work.

ii) Chapter 3 describes studies related to human and organizational factors and risk assessment.

iii) Chapter 4 explains the development of a framework for human and organizational factors.

iv) Chapter 5 presents a research paper titled ‘Human and Organizational Factors Assessment of the Evacuation Operation of BP Deepwater Horizon Accident’.

v) Chapter 6 presents a research paper titled 'Prioritizing Safety Critical Human and Organizational Factors of EER Systems of Offshore Installations in a Harsh Environment'.

vi) Chapter 7 presents a research paper titled 'Dynamic Risk Assessment of Escape and Evacuation in a Harsh Environment'.

vii) Chapter 8 presents a research paper titled 'The Use of a Virtual Environment in Managing Risks Associated with Human Responses in Emergency Situations on Offshore Installations'.

viii) Chapter 9 concludes the research work and discusses research limitations and future work.

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Chapter 2

Contributions and Novelty

2.1 Contributions

This research is directed to people in the field of engineering, safety, risk analysis, and human factors. The contributions of this research include the introduction and development of:

i) A framework to identify human and organizational risk factors in the escape and evacuation system.

ii) A model to quantify human and organizational factors that contribute to unsafe escape and evacuation operations.

iii) A strategy to minimize risks of human and organizational factors associated with personnel performance.

The contributions are further discussed in Sections 2.1.1 to 2.1.3.

2.1.1 Development of a Framework for Identifying Human and Organizational Factors

A framework is designed to identify and address the presence of human and organizational factors in safety barriers for the escape and evacuation system. The human and organizational factors involved in every safety barrier can lead to the poor performance of personnel in accomplishing escape and evacuation activities. The uniqueness of the framework is explained in Section 2.2.1. The application of the framework is also discussed in the first research paper (Chapter 5) entitled 'Human and Organizational Factors Assessment of the Evacuation Operation of BP Deepwater Horizon Accident'.

2.1.2 Development of a Model for Quantifying Human and Organizational Factors

A model is created to quantify the human and organizational factors that can affect personnel responses and their performance in escape and evacuation activities. The model first estimates the probability of the failure of personnel responses. The probability data of human and organizational factors is obtained from the translation of guidewords as described in Section 2.2.2, which makes the model unique. The model is then extended to assess risks associated with personnel by including the consequential effects of failing to respond safely in the escape and evacuation. A second research paper entitled 'Prioritizing Safety Critical Human and Organizational Factors of EER Systems' in Chapter 6 and a third research paper entitled 'Dynamic Risk Assessment of Escape and Evacuation in a Harsh Environment' in Chapter 7 discuss the application of the model in the escape and evacuation operations.

2.1.3 Development of a Strategy for Minimizing Risks

A strategy is used to reduce or manage risks associated with personnel responses. The strategy is arranged systematically according to the hierarchy, from inherent safety to engineering safety and finally to procedural safety. The strategy used in this research is novel because of the last part of the framework of risk management that includes the presence of human and organizational factors as described in Section 2.2.1. Chapter 7 presents the application of the strategy in the fourth research entitled 'The Use of a Virtual Environment in Managing Risks Associated with Human Responses in Emergency Situations on Offshore Installations'.

2.2 Novelty

2.2.1 The Integration of Human and Organizational Factors in the Framework of Risk Management

This research presents human and organizational factors integrated qualitatively and quantitatively in the framework of risk analysis and risk management of the operation of escape and evacuation on offshore installations. This research emphasizes the presence of human and organizational factors a) in the organizational level, b) during the interaction between personnel and emergency equipment, and c) in the event when personnel are performing the escape and evacuation in poor weather conditions. The integration of human and organizational factors in the framework is shown in Chapters 4 to 8.

2.2.2 The Use of Guidewords in Standard Practices as Probability Data

This research work uses probability data that are translated from guidewords available in offshore oil and gas industry standard practices and guidelines. The use of the guidewords as data may reflect the effectiveness of standard practices and guidelines provided by regulators. This is illustrated in this research study. Further explanation of translating guidewords to probability data is available in Chapters 6 and 7.

Chapter 3

Literature Review

3.1 Overview

This research work studies four areas in the process of developing a framework for human and organizational risk management. The four areas are as follows:

i) human and organizational factors,

ii) the use of Bayesian analysis for the study of human and organizational factors,

iii) risk assessment, and

iv) risk management.

These areas are further reviewed and discussed in Sections 3.2 to 3.5.

3.2 Human and Organizational Factors

Human factors are widely discussed based on the Swiss cheese model introduced by Reason (2000). In defining human factors, HSE (2009) emphasized three aspects: the individual, the job assigned to the individual, and the organization in which the individual is employed. The interaction between the individual, the job, and the organization should be enhanced using a life-cycle. The life-cycle has a link connecting the organization to the job, followed by a second link between the job and the individual, and continued with another link between the individual to the organization. The link between the individual and the organization may illustrate the impact of organizational factors on an individual.

The definition of human factors can broaden to include an organizational factor. The success of an organization depends on individuals' performances without the presence of human factors (AIChE, 2007). The decisions made by organizations can influence the performance of the individuals working for them. The organization's goals can shape or mould the culture and environment in which an individual works.

Based on studies defining human and organizational factors, this research work defines human and organizational factors in the context of the emergency escape described in Chapter 5.

3.3 Bayesian Analysis for Human and Organizational Factors

Human and organizational factors can be studied using a Bayesian analysis. The benefit of Bayesian analysis is the flexibility to integrate human and organizational factors with technical factors, procedures, individuals' abilities, and management systems. The Bayesian analysis introduces a cause-and-effect relationship, which is applicable in investigating human and organizational factors.

Cai et al. (2013) presented a study of human factors during repair actions on offshore environments using Bayesian analysis. The study divides human factors into three categories: individual, organizational, and group factors. From the study, the human factor is identified as a contributing factor and directly proportional to the potential failure of components, which can only be reduced by doing regular maintenance.

Léger et al. (2009) developed a methodology considering technical, human and organizational aspects to anticipate critical situations in high risk industries such as in nuclear power plants and chemical processing plants. The technical, human and organizational aspects are integrated using Bayesian analysis in estimating the failure probability and its outcomes associated with individual actions. The study shows that Bayesian analysis is a practical tool to address the failure of individual actions involving organizational factors and technical systems.

According to the application of Bayesian analysis for human and organizational factors, this research work discusses Bayesian analysis in quantifying human and organizational factors in Chapters 6 and 7.

3.4 Risk Assessment

The risk assessment of human and organizational factors can be described through both qualitative and quantitative analyses. Paté-Cornell and Murphy (1996) introduced the system-action-management (SAM) approach, which has the ability to connect probabilities of system failures to human and management factors. The authors observed the importance of understanding the relationship between human and management factors, which are often overlooked by human factor specialists and engineers. The reason for designing the approach is to improve probabilistic risk analysis (PRA) that primarily deals with technical rather than organizational safety improvements in managing and reducing risks. The SAM approach integrates the PRA of the physical system, decisions and actions that affect the probabilities of basic events, and management factors that influence decisions and actions.

Risk assessment of human and organizational factors can be assessed using a dynamic approach. Dynamic risk assessment should consider time dependencies using prior and posterior probabilities. Instead of depending on periods of time, Cacciabue (2000) presented a dynamic interaction between individual and machine that is able to include human factors into the risk analysis of a complex system. The approach has five basic elements: retrospective-prospective study, task analysis, data and parameters identification, human-machine interaction modelling, and dynamic reliability modelling, for assessing the risk of hazardous material and energy releases due to an accident. The risk assessment considering a dynamic interaction between individual and machine is different from one person to another person, which can result in a variation of levels for risks.

The application of human and organizational factors risk assessment has varied in different industries. Skogdalen and Vinnem (2011) proposed the integration of human and organizational factors into quantitative risk analysis (QRA) that can be differentiated to four levels. The QRA in Level 1 is related to technical analysis without considering human and organizational factors. For the QRAs in Level 2, there is an explanation of human, operational, and organizational factors related to technical analysis and their influence on the system. The QRAs in Level 3 evaluate studies on the human and organizational factors using human error probability (HEP), human reliability assessment (HRA), the human error probability index (HEPI), and techniques for human error rate prediction (THERP). After that, the QRA models are adjusted according to the results from the human and organizational factors studies. Finally, the QRAs in Level 4 present human and organizational factors as important as the technical analysis. From the study, none of the QRAs of offshore installations from five operating companies achieved Level 4. This is one of the reasons the authors stated that the consideration of human and organizational factors in QRA studies is relatively superficial. The paper discusses the challenges of organizational assessment, such as the difficulty to relate all organizational factors with each other and how the organizational assessment depends on observations and interviews, which causes difficulties in detecting deteriorating performance.

The application of risk assessment to human and organizational factors can be observed in a research study on muster activities on offshore platforms (Deacon et al., 2010). The researchers focused on the possible consequences of failing to complete the muster steps in the event of man overboard, gas release, or fire and explosion. Four categories of consequence severity were introduced: a) effect on individual health, b) effect on the ability to complete the muster, c) effect on the severity of the muster initiator and d) effect on other personnel on board. The study emphasizes that reducing the categories with the highest severity may be beneficial, but would not reduce the overall consequence severity. Consequences reduction is a practical approach prior to allocating resources to mitigation barrier improvement in the muster steps.

Human and organizational factors risk assessment was recently applied in a virtual environment. Monferini et al. (2013) presented a compound methodology that is able to integrate virtual reality and human and organizational factors concepts by addressing end-users' practical safety issues such as control room operators' training, proper alarm system design, and team coping with emergencies. The methodology consists of a task modeller, fuzzy probability estimator, and artificial logic Bayesian algorithm. The fuzzy probability estimator is developed to estimate human error probabilities (HEPs). The artificial logic Bayesian algorithm tool discloses all possible sequences of events leading to an accident and thus reflects the level of knowledge about the system under analysis. The study identified nine common performance conditions: adequacy of organization, working conditions, adequacy of man-machine interaction, procedures and plans, number of simultaneous goals, available time, the time of the day, training and experience, and crew collaboration. Risks and performance influenced by human and organizational factors can be understood and assessed in a virtual environment prior to changes in the safety management system.

Risk assessment for human and organizational factors using Bayesian analysis is further discussed in Chapter 7.

3.5 Risk Management

Risk management is defined as a coordinated activity of a system or an organization focusing on risks to an individual and environment (ISO, 2009). The activity begins with identifying hazards, understanding and assessing risks, and making decisions to prevent, control and mitigate risks (Amyotte and McCutcheon, 2006). In oil and gas industry practices, safety measures are recommended to reduce the probability of hazards and minimize the impacts they have on individuals and the environment (Aven and Vinnem, 2007).

Risk management can be used to reduce uncertainty in making decisions. Bjerga and Aven (2015) introduce adaptive risk management in dealing with large uncertainties prior to decision making. In situations when people have two different alternatives, they must consider the consequences and uncertainty before taking appropriate action.

Körte (2003) presents a method known as contingent risk and decision analysis to support decision making in complex situations with limited time. A lack of ability to assess risks and the uncertainty of outcomes are the challenges when making correct decisions. The method has nine steps: identification of hazards, consequences definition, decision alternatives, decision influence model, identification of contingent variables, contingent model definition, contingent risk analysis, definition of decision criteria, and decision familiarization and training. All the nine steps are associated with organizational factors, which can contribute to either success or failure of an individual in making decisions during critical situations.

Based on the definition of risk management and its purpose, the research work introduces procedures to reduce or manage risks associated with performance as discussed in Chapter 8.

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Chapter 4

Development of Framework

4.1 Overview

The framework of human and organizational factors risk management for escape and evacuation is developed according to four categories:

i) Identifying human and organizational factors in the escape and evacuation system

ii) Estimating the probability of failure of personnel responses

iii) Assessing risks of failing to perform during escape and evacuation operations

iv) Minimizing risks associated with human personnel responses in escape and evacuation

All these categories are dependent on each other in terms of the development and extension of the framework. The details of each category are described in Sections 4.2 to 4.5.

4.2 Identifying Human and Organizational Factors

The first step in developing the framework is to identify human and organizational factors and hazards that may exist in the safety barriers of the escape and evacuations system. The main purpose of the first step is to address human and organizational factors in every safety barrier prior to emergency situations leading to escape and evacuation.

Escape and evacuation depend on a type of initiating event, such as hydrocarbon releases, fires and explosions, man overboard, and collisions involving vessels or helicopters. Initiating event is a term for emergency situations and a main point to begin the process of identifying human and organizational factors as illustrated in Figure 4.1. The emergency situation initiates the use of safety barriers in the escape and evacuation system. The limitations of safety barriers, in particular emergency response plans, personal survival equipment, facilities and equipment for emergencies, alarm systems, procedures, chain of command, and communication, is the presence of human and organizational factors.

A layer of protection is used to identify the human and organizational factors in every safety barrier. All safety barriers are categorized as organizational, procedural, technical, or personnel. Human and organizational factors present in every safety barrier may impact personnel responses in escape and evacuation.

The sequence of procedures in the framework is shown in Figure 4.1. The framework and its approach are discussed in Chapter 5 of the first research paper entitled 'Human and Organizational Factors Assessment of the Evacuation Operation of BP Deepwater Horizon Accident'.

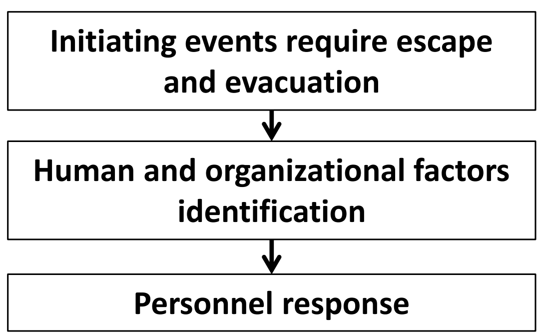

Figure 4.1: The sequence of the procedure to identify human and organizational factors.

4.3 Estimating the Probability of Failure

The second step requires the framework to be extended to describe a model to estimate the probability of personnel responses considering human and organizational factors. The objective of the second step is to determine the failure of personnel performances that have impacts on escape and evacuation operations. Bayesian analysis is used for the calculation of the probability of personnel responses. To obtain the probability, the

Bayesian analysis includes human and organizational factors in every safety barrier provided for escape and evacuation systems. The details of the second part of the framework and its application are discussed in Chapter 6 of the second research paper entitled 'Prioritizing Safety Critical Human and Organizational Factors of EER Systems of Offshore Installations in a Harsh Environment'. Figure 4.2 shows the sequence of procedures to find the probability of human responses considering human and organizational factors.

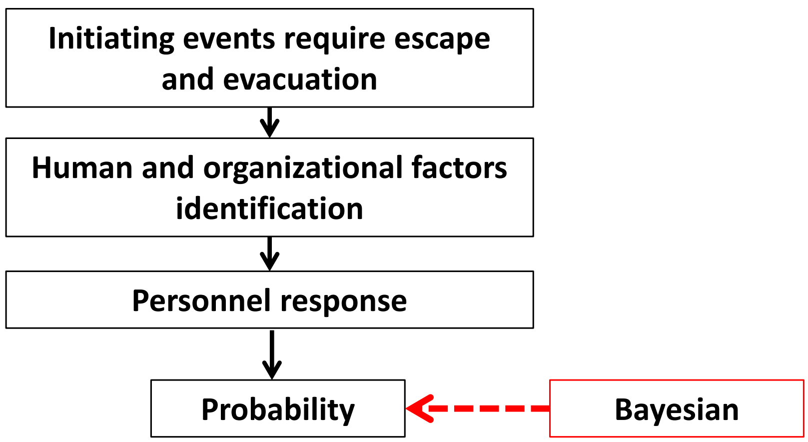

Figure 4.2: The sequence of the procedure to estimate probability of personnel responses.

4.4 Assessing Risks of Failing to Respond

The third step of the framework development involves assessing risks associated with personnel responses. The third step is an extension of the second part of the framework as shown in Figure 4.3. The purpose of the third step is to analyse the probability and the impacts of the failure of performing escape and evacuation activities considering the presence of human and organizational factors. Risks can be measured and assessed by quantifying the probability of the failure and its consequences. The risk assessment is designed to be a dynamic risk assessment that is applicable to changing safety barriers or environmental conditions over time. Dynamic risk assessment means that risks associated with personnel responses can be updated based on new information and the probability of environmental conditions and types of safety barriers at different times. Chapter 7 contains the third research paper entitled 'Dynamic Risk Assessment of Escape and Evacuation in a Harsh Environment' and has more information regarding risk assessment and its use, including harsh environmental conditions in the risk assessment.

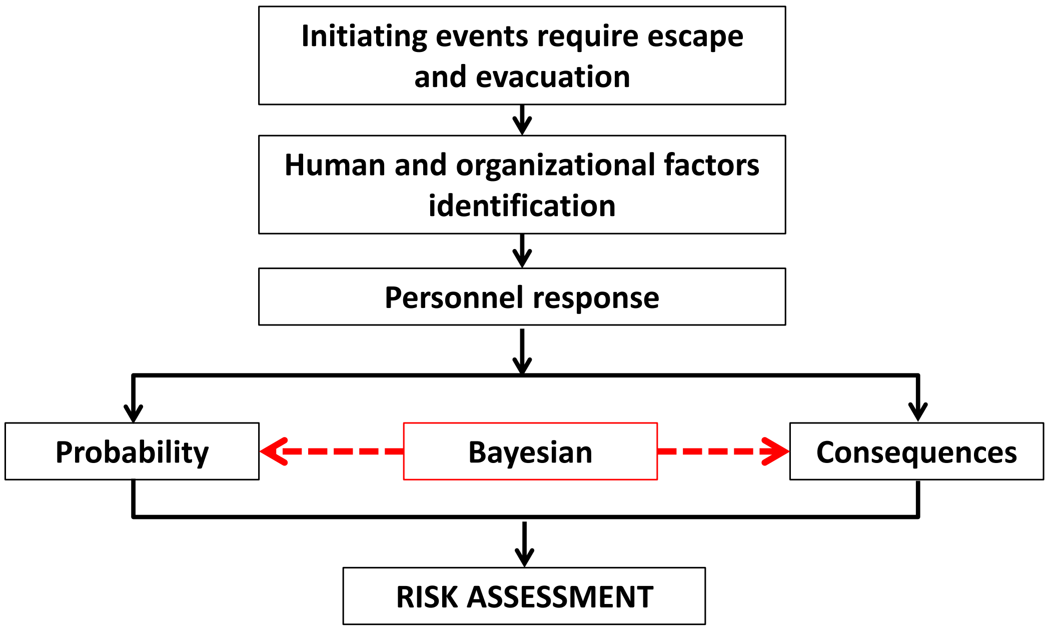

Figure 4.3: The sequence of the procedure for assessing risks associated with personnel responses.

4.5 Minimizing Risks Associated With Personnel Responses

Figure 4.4 presents the fourth step of the framework, which also completes the framework development. The fourth step includes a risk management of personnel responses considering human and organizational factors. After assessing the risks of human responses, risk acceptance is used to determine whether it is acceptable, or not, according to the safety rules or organization. If the risk is low and acceptable to the organization and safety rules, escape and evacuation operations are presumed to be safe for the personnel. In case the risk is unacceptable, the risk must be controlled considering the existing and newly designed safety barriers. The uniqueness of the risk management in this part of the work is the use of a safety hierarchy in designing and implementing safety barriers based on weaknesses in human responses. Chapter 8 has information on the risk management and its application to emergency escape as presented in the fourth research paper entitled 'The Use of a Virtual Environment in Managing Risks Associated with Human Responses in Emergency Situations on Offshore Installations'.

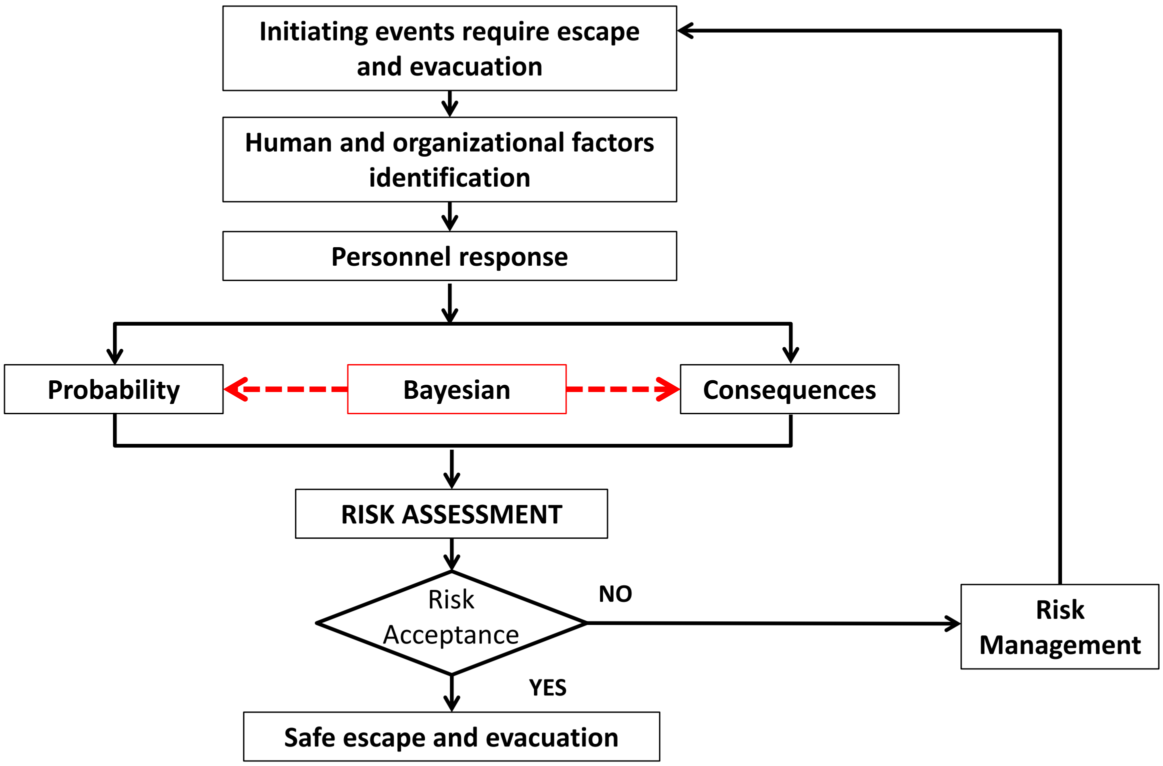

Figure 4.4: The complete sequence of procedures for assessing and managing risks associated with personnel responses.

Chapter 5

Human and Organizational Factors Assessment of the Evacuation Operation of BP Deepwater Horizon Accident

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Preface

This manuscript of research paper has been published in volume 70 of Safety Science. The first author introduced a framework for identifying human and organizational factors in safety barriers. The application of framework is applied to EER operations during the Macondo blowout. This manuscript was supervised and reviewed by Drs. Faisal Khan, Brian Veitch, and Scott MacKinnon.

Abstract

The offshore oil and gas industry is applying more advanced technologies to explore and produce petroleum in challenging environmental regions. To meet the demands of these conditions, operators need to take suitable precautions relating to emergency response and evacuation procedures in terms of technology, management, operations, and personnel competence. The successful evacuation operations are dependent upon a comprehensive preparedness should an incident occur. However, many reports of offshore accidents

reveal that human factors contribute to the failure of evacuation. This paper addresses and discusses the contribution of human factors to the evacuation operations of the BP Deepwater Horizon accident using a proposed tool. A framework of the tool consists of the evacuation protective layers and the evacuation preparedness plan. Human factors are discussed and analysed at different stages; that is, the organization, personnel's competence, the evacuation procedures, and the emergency equipment. As a result, the insufficient emergency drills and exercises, poor communications, impairment of personnel physical ability due to unsafe conditions, and poor emergency preparedness plan were identified as human factors contributing to the unsuccessful evacuation operations of the Macondo well blowout.

5.1 Introduction

Escape, evacuation, and rescue (EER) from offshore installations is a last line of defense in preventing loss of life and serious injury from unsafe and hazardous conditions, such as well blowouts, uncontrolled fire, an impending or actual ship collision, extreme weather, loss of containment of a riser or subsea pipeline, and loss of containment in the process facilities (IADC, 2010; Wallace, 1992). Unsuccessful EER operations can have tragic outcomes with a high number of fatalities, such as the Piper Alpha platform disaster, the Alexander L. Kielland accommodation platform collapse, and the Ocean Ranger tragedy (Cullen, 1990; Skogdalen, Khorsandi & Vinnem, 2012; USCG, 1983).

Human factors play a role in the unsuccessful or unsafe evacuation of offshore structures. Failures such as the late activation of a general alarm, personnel's ability to act being compromised by the hazards, incompetent management of lifeboats and life rafts, lack of command and control, as well as communication problems have been addressed in many evacuation operations of offshore accidents. Many qualitative and quantitative studies on EER in offshore installations have been done by human factors researchers

(Basra & Kirwan, 1998; Gould & Au, 1995; Musharraf et al., 2013; Woodcock & Au, 2013; Yun & Marsden, 2010). Studies involving human errors in EER often result in recommendations such as improving EER training (Deacon, Amyotte, & Khan, 2010; DiMattia, Khan, & Amyotte, 2005; Kennedy, 1993; Skogdalen, Khorsandi, & Vinnem, 2012). However, there is a absence of studies that relate the human factors to individual characteristics, the emergency equipment, the EER procedures, and a system concurrently, which could affect the success or failure of EER operations.

This paper proposes a tool for addressing human factors issues based on the barriers related to the evacuation operations. The main purpose of this tool is to identify and assess the contributions of human factors in evacuation operations that lead to an unsafe evacuation. Evacuation outcomes in the BP Deepwater Horizon accident are studied using this proposed tool. This will provide insight into human responses during emergencies that may help to improve emergency evacuation systems. The discussion emphasizes the contribution of human factors associated with environmental, organizational, and individual characteristics.

5.2 Development of a Tool for Assessing Human Factors in the Evacuation Operations of BP Deepwater Horizon Accident

5.2.1 Defining Evacuation Operations

Evacuation can be defined as a process of leaving an installation and its vicinity, in an emergency, in a systematic manner and without directly entering the sea (Cullen, 1990; HSE, 1997; OGP, 2010). Successful evacuation will result in persons being transferred to a place of safe refuge, meaning a safe onshore location, or a safe offshore location or marine vessel with suitable facilities.

For this study, the evacuation operations sequence follows basic EER stages as provided by OGP (2010). The sequence begins with an initiating event resulting in an evacuation, which is when the offshore installation manager (OIM) assessed the severity of the unsafe conditions and decided to abandon the installation. It follows the sequence of an evacuation alarm, translation through emergency routes to a muster point and then to an egress point. Finally, the sequence considers leaving the installation as a final stage to stop the sequence.

5.2.2 Framework for Assessing Human Factors in the Evacuation Operations

This paper introduces three (3) components as indicated by a gray box in Figure 5.1. Those components are the development of evacuation protective layers, identification of human factors in the evacuation protective layers, and comparison of the evacuation operations with an evacuation preparedness plan. The information obtained in the human factors assessment will be meaningful to enhance evacuation preparedness planning and improve the effectiveness evacuation operations. Each component is further described in Sections 5.2.3, 5.2.4, and 5.2.5.

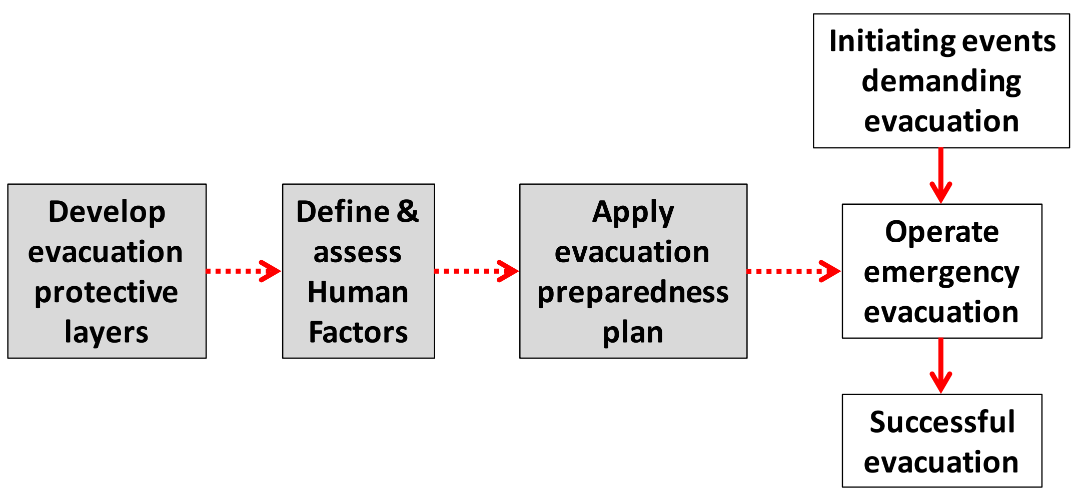

Figure 5.1: A framework for assessing the contributions of human factors.

5.2.3 Development of Evacuation Protective Layers

The evacuation preparedness generally consists of the installation’s organization, personnel, evacuation procedures, and emergency equipment. Figure 5.2 shows the evacuation preparedness as a series of protective layers. Applying the protective layers, or barriers, in the evacuation preparedness could possibly increase the likelihood of successful evacuation operations. The protective layers are dependent on each other to reduce the risks associated with emergency scenarios.

According to industry-based guidelines, operators of an offshore installation play a critical role in the evacuation preparedness (CAPP, 2005; CAPP, 2010; HSE, 1997; IADC, 2010). The installation's organization represents the outermost layer of the evacuation preparedness. At this level, the organization will decide on the quality of evacuation preparedness applied to the installation. The organization's choice of the level of quality for evacuation preparedness can directly affect the risk to offshore personnel. Placing evacuation procedures and emergency equipment before the protective layers of personnel is meant to shield personnel from emerging hazards. Personnel must follow the evacuation procedures while using the emergency equipment to assist them to move towards a designated safe area and subsequently to abandon the installation.

Hypothetically, unorganized and inadequate evacuation preparedness could result in four non-ideal outcomes:

i) *Minor Accident*: An event with faulty emergency equipment that may cause minor or major injuries.

ii) *Accident*: An event with faulty emergency equipment and inadequate evacuation procedures that may cause major injuries and temporary or permanent disability.

iii) *Major Accident*: An event with faulty emergency equipment, inadequate evacuation procedures, and incompetent personnel that may cause one or more injuries, fatalities, and damage to property.

iv) *Catastrophic accident or disaster*: An event with faulty emergency equipment, inadequate evacuation procedures, incompetent personnel, and poor organization that may cause multiple fatalities and extensive damage to property, production, and the environment.

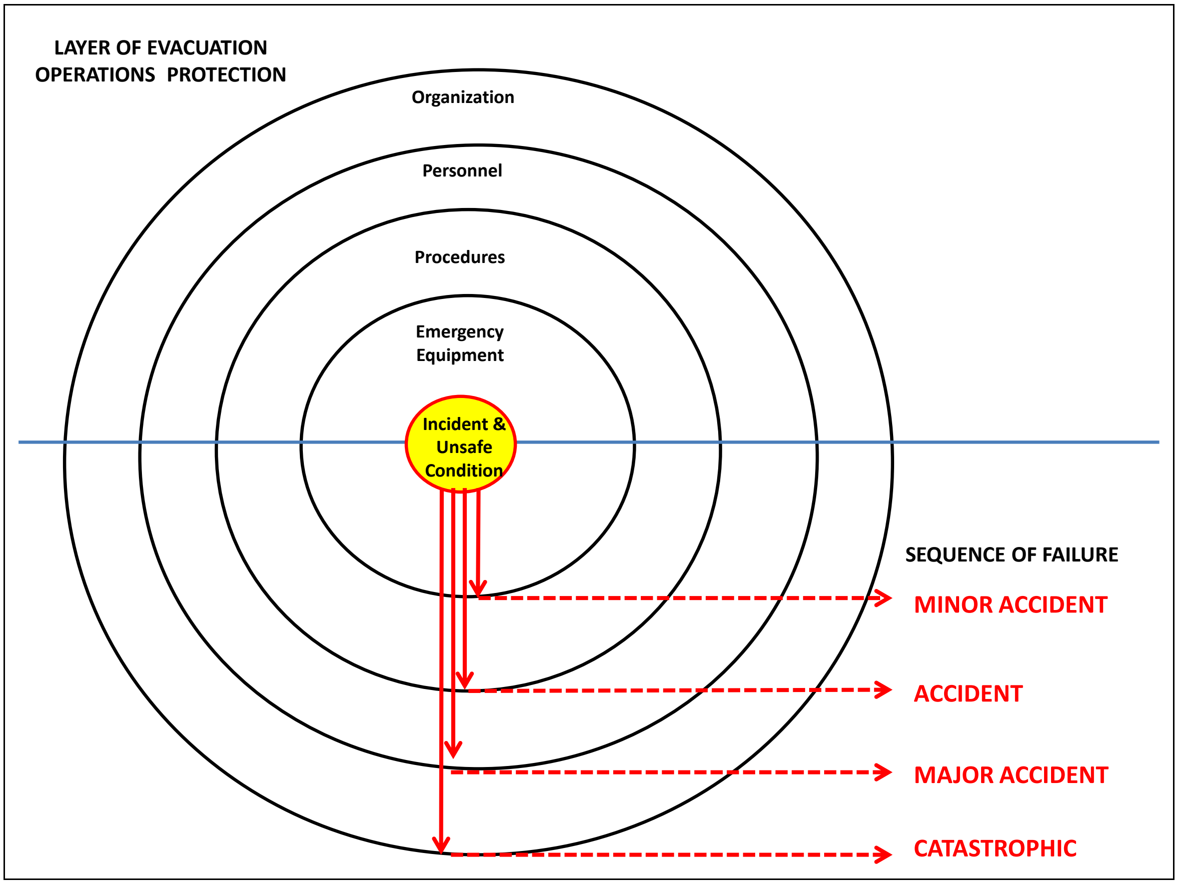

Figure 5.2: Schematic diagram of the evacuation protective layers.

5.2.4 Identification of Human Factors in Evacuation Operations

Human factors in the evacuation preparedness can increase the risk to all personnel and enlarge the margin of unsuccessful or unsafe evacuation operations. Human factors are generally defined as individual, organisational, and environmental elements that influence personnel's behaviours and affect personnel's safety (HSE, 2009).

The barriers related to the mitigation of unsafe conditions or the susceptibility to human factors can be described by Reason's Swiss cheese model. Breaches in these barriers can be due to unsafe acts or undetected defects. The presence of holes in one barrier does not necessarily cause a significant negative outcome. A fatal outcome can happen when holes in many layers momentarily line up to allow a trajectory of incident opportunity to bring hazards directly to unprotected victims (Reason, 2000). Based on Figure 5.3, the catastrophic accident would only happen if the emergency equipment, the evacuation procedures, personnel, and the organization concurrently failed to maintain impenetrable barriers.

Consideration of human factors in the evacuation preparedness of offshore installations is a key to successful responses or performances during the evacuation operations. The organization must first recognize human factors in the organizational structure of evacuation preparedness, which can be safety culture, documentation, an evacuation procedures design, emergency equipment design, emergency drills and exercises, and communications. For example, procedures must be simple and concise so that personnel are easy to understand and remember when in emergencies. The organization must also address human factors and remove latent conditions in the new or existing emergency equipment to reduce the probability of failure. As an example, proper scheduled maintenance, inspection, and testing of emergency equipment can reduce likelihood of technical problems during emergency. The organization must consider personnel's human factors, such as skills, communications, stress, fatigue, the level of knowledge, the mental capabilities, and the physical conditions, in order to prevent personnel from making errors or performing unsafe acts. Conducting emergency drills containing unexpected events and credible evacuation operations can provide the necessary experiences needed to understand the overall risk of the EER process. Table 5.1 lists a few human factors, which are normally investigated in the offshore major accidents, based on the evacuation protective layers.

Human factors can be addressed proactively and reactively. A proactive manner is better than a reactive manner (AIChE, 2007). The reactive manner refers to the organization using investigation reports of offshore installation accidents to identify and assess human factors.

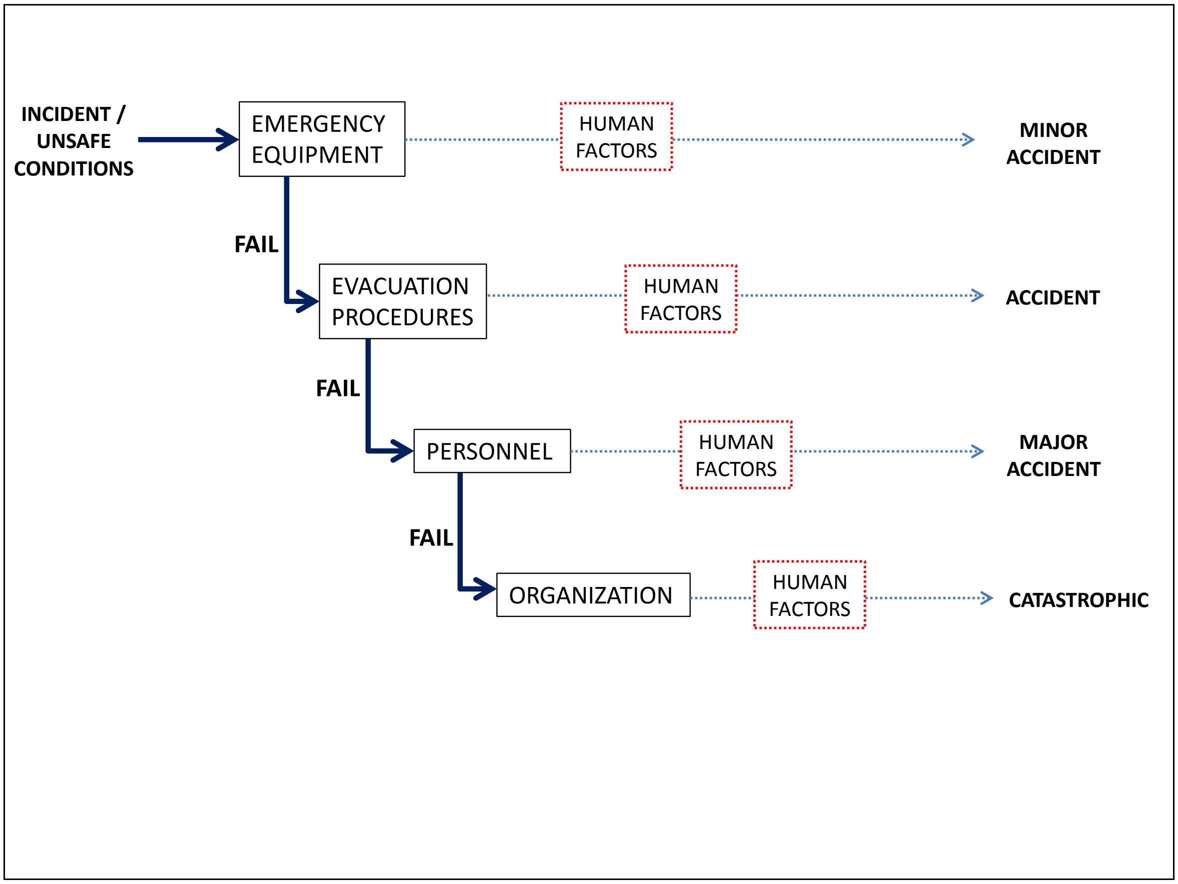

Figure 5.3: An event tree for failures of the protective layers in the evacuation operations.

Table 5.1: Human factors identified in the evacuation operations.

Emergency equipment	Evacuation Procedures	Personnel	Organization
• Inspection • Maintenance • Capacity • Availability	• Command and control • Documentation • Rules and Regulations • Supervision • Training	• Knowledge • Experience • Training • Skills • Physical conditions • Psychology	• Communication • Compliance with offshore regulations • Emergency management plan • Leadership • Procedures system • Roles and responsibilities • Safety culture • Safety management system • Emergency drills and exercises

5.2.5 Comparing Evacuation Operations of BP Deepwater Horizon Accident with Evacuation Preparedness Plan

The basic structure of an evacuation preparedness plan consists of the evacuation protective layers, evacuation sequences, and environmental conditions, as shown in Figure 5.4. The environmental factors, such as darkness, smoke, heat, noise, fog, and coldness, and hazard conditions, such as fires and explosions, must be considered in all the evacuation protective layers and throughout the evacuation sequence.

Figure 5.4 can be used to assess the evacuation operations and to identify a series of human factors contributing to the unsafe evacuation operations. Each stage of evacuation operations must be assessed beginning from the emergency equipment to the evacuation procedures, personnel, and the organization. The assessment must include event types demanding evacuation operations, such as a loss of containment, fires and explosions, severe weather, and hydrogen sulphide (H_2S) releases.

Starting with the initiating incident, the alarm system would be used as a primary source of information regarding an emergency situation. Detectors on the installation, in particular for smoke, gas, and fire, are normally attached to an alarm system to indicate the presence of one or more hazards. When personnel receive notification of an emergency situation, they must immediately move to a designated safe area using an emergency route. In the case that a primary emergency route has been blocked or damaged by explosions, the personnel should know a secondary emergency route to a muster station and lifeboat embarkation point. At the muster station, personnel must register their names as part of a head count system, prior to movement to the lifeboat station. The coxswain must be knowledgeable and well-trained in manoeuvring the lifeboats to the closest possible safe place.

For a better understanding, a case study of evacuation operations on the BP Deepwater Horizon illustrates the method for assessing human factors is discussed in Section 5.3.

SURROUNDED BY ENVIRONMENTAL FACTORS

Incident demanding evacuation → **ALARMS** → **ACCESS** → **MUSTER** → **EGRESS** → **EVACUATE** → **SAFE EVACUATION**

Acknowledging the incident	*Personnel moving from the area of hazardous condition*	*Personnel assembling in a muster station*	*Personnel moving to boarding area*	*Personnel leaving the installation*
ALARMS	**ACCESS**	**MUSTER**	**EGRESS**	**EVACUATE**
Emergency equipment - Smoke/gas/fire detectors - Audible and visible Alarms - General Alarms - Public Announcement	**Emergency equipment** - 2 emergency routes with signage - Adequate lighting/ illuminating routes - Sprinkler	**Emergency equipment** - 2 muster stations with lighting - Heat/fire/blast protection - Personal protective equipment (PPE)	**Emergency equipment** - Egress route - Adequate lighting - Helicopter - Lifeboat	**Emergency equipment** - Lifeboat/ life raft/ helicopter - Adequate lighting
Procedures - Acknowledge the incident - Inform and communicate the situation	**Procedures** - Move to the exit route - Move along the route - Direct to muster station	**Procedures** - Register name - Headcount - Communicate the next action - Wear PPE if required	**Procedures** - Move to lifeboat - Occupy the lifeboat - Prepare to launch	**Procedures** - Launch the lifeboat - Maneuver the lifeboat - Leave the installation
Personnel - Follow instructions and procedures - Safe behaviours - Skills - Physical conditions	**Personnel** - Follow instructions and procedures - Safe behaviours - Skills - Physical conditions	**Personnel** - Follow instructions and procedures - Safe behaviours - Skills - Physical conditions	**Personnel** - Follow instructions and procedures - Safe behaviours - Skills - Physical conditions	**Personnel** - Follow instructions and procedures - Safe behaviours - Skills - Physical conditions
Organization - Inspection and maintenance of emergency equipment. - Communicate the emergency status	**Organization** - Inspection and maintenance of emergency equipment. - Housekeeping to remove obstructions. - Communicate the accessibility and conditions of emergency routes	**Organization** - Inspection and maintenance of emergency equipment. - Person in charge for headcount take the responsibility - Crowd control by the person in charge for headcount	**Organization** - Inspection and maintenance of emergency equipment. - Control the situation - Give command/ instruction to leave - Coxswains take the responsibility	**Organization** - Inspection and maintenance of emergency equipment. - Communicate about lifeboat launching - Coxswains are well-trained to launch and maneuver the lifeboat - Communicate for the rescue process

Figure 5.4: Schematic diagram of evacuation preparedness plan with basic requirements.

5.3 Case Study: The BP Deepwater Horizon Accident

The BP Deepwater Horizon (Macondo well blowout) investigation report presents meaningful input information for assessing pertinent human factors in the evacuation operations considered in this paper's proposed tool. Details of the event are described in Sections 5.3.1, 5.3.2, and 5.3.3.

5.3.1 The BP Deepwater Horizon Evacuation Operations

A few studies have been conducted to focus on the evacuation operations of BP Deepwater Horizon. Skogdalen, Khorsandi & Vinnem (2012) discussed human performance and Rathnayaka, Khan & Amyotte (2013) studied the event failures involving human actions in the BP Deepwater Horizon evacuation operations. Both studies have no discussion on the contribution of human factors to the unsafe evacuation operations.

This paper presents and discusses the evacuation operations starting from the activation of evacuation alarm to personnel leaving the installation.

5.3.2 Major Incident Demanding Evacuation Operations

Deepwater Horizon was a mobile offshore drilling unit (MODU) owned by Transocean. On April 20, 2010, Haliburton and BP operators conducted two types of pressure test to determine the installation's ability to drill to a depth of 9,000 ft (DHSG, 2011; USCG, 2011). At the time, the OIM and senior leaders were not present on the drill floor to supervise these tests. After the drilling crew finished the tests, they observed abnormal pressures on the drill pipe. Within a minute, hydrocarbons suddenly flowed out of the riser. As the flammable gas dispersed and found an ignition source, probably some electrical equipment, an initial explosion and subsequent fire occurred on the drill floor. Unfortunately, personnel were not prepared for the well blowout and possible consequences. Two indications of well blowout are discussed in Table 5.2.

Table 5.2: BP Deepwater Horizon major incident demanded the evacuation operations.

Descriptions of events	Identification of Human Factors Based On Protective Layers				Human Factors concerned
	1. Equipment	2. Procedures	3. Personnel	4. Organization	
Emergency Procedures for Uncontrolled Escape of Hydrocarbons	Insufficient training for personnel handling the equipment in case of a blowout and its consequences	Insufficient training for personnel exercising the procedures in a case of a blowout and its consequences	Lack of training and experience in credible evacuation operations	Poor organization of emergency drill and exercises	Insufficient emergency drill and exercises
Prior to the Macondo disaster, there were two blowout incidents: - Crew delayed in responding to indications that hydrocarbons were flowing into the well (no ignition happened).	No communication for preparing equipment in case of a blowout and its consequences	No instruction for applying procedures involving a blowout and its consequences	No communication regarding indications of a blowout	No effective communication of similar incidents	Poor communication
- Operators delayed in responding to an unanticipated, hazardous influx of hydrocarbons into the wellbore (no ignition happened).	No preparation prior to a blowout and its consequences	No written procedures or safe limits of a well blowout	Unfamiliar with indications of a well blowout	No documentation of emergency preparedness	Poor organization of emergency preparedness

5.3.3 Sounding of Alarms

The MODU had gas detectors and ventilation systems in extremely hazardous areas which contain highly concentrated hydrocarbons. However, the BP Deepwater Horizon accident investigators found the gas detectors were set to an ‘inhibited’ mode which means the released gas could be reported to the control panel but no alarm would sound (USCG, 2011). Table 5.3 presents the description of alarms and the human factors involved in the alarm system.

Table 5.3: The event of alarm sounded for evacuation operations.

Descriptions of events	Identification of Human Factors Based On Protective Layers				Human Factors concerned
	1. Equipment	2. Procedures	3. Personnel	4. Organization	
Alarms were sounded after the explosion.	Late alarm activation	Delayed emergency notification	Heard the alarm after the explosion	Delayed emergency notification	Delayed communication for emergency situation
Multiple alarms activated without acknowledging situation.	Multiple alarms activated	Ineffective notification of emergency situation	Personnel did not receive information regarding emergency situation	Ineffective communication of emergency situation	Ineffective communication due to multiple alarms
General Alarm (GA) activated manually after the explosion.	Late communication on emergency situation	Delayed communication	Heard the alarm after the explosion	Delayed communication	Delayed communication
No Public Announcement (PA) regarding decision to muster prior to explosion.	PA used after explosion	Incorrect action	Received late information to muster	Person in-charge did not follow the emergency procedures	Mistake

5.3.4 Moving Through Emergency Routes

After the explosion, fires, and loss of electrical power, one of the crew ordered a muster to the designated emergency station. Later, another announcement required personnel to report to secondary muster stations. Details of personnel moving through emergency routes are described in Table 5.4.

Table 5.4: The event of personnel moved along the emergency routes.

Descriptions of events	Identification of Human Factors Based On Protective Layers				Human Factors concerned
	1. Equipment	2. Procedures	3. Personnel	4. Organization	
Some workers did not see or hear any alarms after the explosion.	Late activation alarms not heard	Delayed emergency procedures	Physical ability impaired by explosion effects	Explosion noise over the late alarm sound	Explosion effects caused physical limitations
Chaos in the area due to darkness.	Lighting failure	Personnel performed evacuation in darkness	Darkness caused stress	No person in-charge to control the situation	Darkness affects personnel's action and decision
The workers re-route to the secondary muster station due to impaired route and flames.	Inaccessible route	Personnel removed debris before can move	Personnel decided to re-route and acted promptly	Second emergency route was provided	Decision to re-route
The automatic sprinklers were discharging thus causing a slowdown in travel time.	Sprinklers activated	Sprinkler slowed travel time	Personnel attention distracted by sprinkles	Not anticipate the route affected by activated sprinkler	Sprinkler distracted personnel and slowed travel time
Many of the survivors had difficulty finding their way out of the areas due to darkness.	Lighting failure	Darkness affected personnel	Darkness caused poor visibility	Not anticipate the route affected by darkness	Darkness caused physical limitations
The deck was slippery because of the drilling mud and other fluids.	Slippery route	Personnel traveled in unsafe condition	Personnel had to pay attention while moving	Not anticipate the route affected by unsafe conditions	Unsafe condition required attention
The lighting for the escape routes was provided by the transitional power system. The normal power system failed and was not restored.	Explosion effects caused lighting failure	No emergency procedures assessment for power failure	Darkness caused poor visibility	Not anticipate the failure of power system	Darkness caused physical limitation

5.3.5 Assembling at the Secondary Muster Station

The explosions, and the fire that followed, produced intense heat and overpressure. The MODU did not have barriers to provide effective blast protection for personnel. Consequently, the muster of personnel at the secondary muster station was chaotic. Table 5.5 lists the events of personnel muster at the designated station and the human factors identified during muster.

Table 5.5: The event of personnel assembled at the designated muster station.

Descriptions of events	Identification of Human Factors Based On Protective Layers				Human Factors concerned
	1. Equipment	2. Procedures	3. Personnel	4. Organization	
The crew failed to register their name at the stations.	Personnel were at secondary muster station	No name registration	Personnel violated emergency procedures	Poor command and control	Inadequate supervision
No accurate headcount.	Personnel were at secondary muster station	No headcount	Stress	Poor command and control	Inadequate supervision
The efforts to headcount failed because the workers jumped off the lifeboat.	Personnel were at secondary muster station	Personnel violated emergency procedure	Poor judgement and perception reasoning	Inadequate supervision	Inadequate supervision
Intense heat from the fire thus the crew concerned they would not survive.	Inadequate heat protection	Poor emergency procedures design	Intense heat caused poor perception reasoning	Poor organizing emergency preparedness plan	Poor organizing emergency preparedness
The assistant driller attempted to take a headcount. Headcount failed due to confusion.	Personnel were at secondary muster station	Headcount was irrelevant in the state of confusion	Quantitative judgement became difficult	Inadequate leadership	Inadequate leadership
The master was not helping to minimize the chaos and confusion surrounding the muster and evacuation.	Personnel were at secondary muster station	No communication of emergency situation	Stress could cause personnel had poor perception reasoning	No communication	Poor communication
The first complete muster of evacuated crew was only completed after more than an hour later in Damon Bankston.	Different place for muster and headcount	Violation in rules	Personnel violated one of rules	Inadequate supervision	Inadequate supervision

5.3.6 Moving to the Point of Embarkation

The route to the lifeboat embarkation point did not have adequate lighting to facilitate personnel entering the lifeboats as the accident happened at night. Descriptions of personnel moving to the lifeboat embarkation point are presented in Table 5.6.

Table 5.6: The event of personnel moved to the lifeboat embarkation point.

Descriptions of events	**Identification of Human Factors Based On Protective Layers**				**Human Factors concerned**
	1. Equipment	**2. Procedures**	**3. Personnel**	**4. Organization**	
Some personnel made wrong time estimation and thus simply jumped to the water.	Personnel did not board the lifeboat	Insufficient emergency drill and exercises in estimating time	Inexperienced personnel had a poor perception reasoning	Poor organizing emergency drill and exercises	Insufficient emergency drill and exercises
Personnel had poor visibility due to inadequate lighting at the stations.	Inadequate lighting for the station	Poor emergency procedures design	Inadequate lighting caused poor visibility	Lack of emergency equipment inspection	Lack of inspection
Personnel felt the intense heat from a drill floor or a moon pool fire.	Inadequate heat protection equipment	Poor emergency procedures design	Heat affected physical	Lack of emergency equipment inspection	Lack of inspection
The boundaries established at the bow life raft embarkation station were inadequate to shield evacuating personnel from exposure to radiant heat.	Inadequate heat protection equipment	Poor emergency procedures design	Heat affected physical	Lack of emergency equipment inspection	Lack of inspection

5.3.7 Leaving the Installation

Prior to the lifeboats launching, personnel had to deal with environment factors, such as the lifeboats being covered with drilling mud as a result of the well blowout, insufficient lighting at the evacuation station, and the flames and heat. Launching and handling the lifeboats and life raft in these environment factors were difficult for the coxswain and personnel. Further description of the evacuation and the human factors are explained in Table 5.7.

Table 5.7: The event of personnel evacuated the installation.

Descriptions of events	Identification of Human Factors Based On Protective Layers				Human Factors concerned
	1. Equipment	2. Procedures	3. Personnel	4. Organization	
11 survivors were unable to evacuate BP DH in their predetermined lifeboats.	Capacity of one lifeboat was 73-occupants	Early launching lifeboat	Personnel did not alert people left behind	Inadequate leadership	Inadequate leadership
Personnel had to wedge themselves into the cramped lifeboat because some of the injured were lying down.	Capacity of lifeboat reduced	Poor of emergency procedures design involving injured personnel	Stress due to cramped lifeboat	Poor organization of emergency preparedness plan	Poor organization of emergency preparedness plan
The coxswain waited to receive the master's order.	Personnel boarded the lifeboat	No communication of launching order	No communication between the coxswain and the master	Poor organizing communication	Poor communication
Transocean operation manager instructed the coxswain to launch in the absence of the master.	Lifeboat was ready to be launched	Launching order from other than master	Inappropriate decision-making	A split chain of command	Bypass chain of command
Transocean manager climbed on top of the lifeboat to activate the windshield wiper and clean the lifeboat's windshield of drilling mud.	Lifeboat was affected	Emergency procedures design did not consider the consequences of blowout	Situation awareness	Responsibilities	Situation awareness of unsafe conditions
Inadequate lighting over the water into which the lifeboats were to be launched.	Inadequate lighting	Lifeboat was launched in darkness	Poor visibility	Failure to provide adequate lighting	Poor visibility due to inadequate lightning
Some personnel chose the life raft instead of Lifeboats 3 and 4 due to unsure safe transit to the aft deck.	No communication on status of transit	No communication established to report the status of emergency equipment	No communication received to make the decision	Poor reporting structure	Poor communication
Personnel's efforts to quickly launch the life raft with a line still attached to the MODU.	Life raft was not ready to be launched	No training of personnel using life raft and following emergency procedures	Incompetent and inexperienced	Poor emergency preparedness plan in using life raft	Poor emergency preparedness plan
Life raft occupants were tossed about and one personnel fell out of the life raft upon its impact with the water.	Poor life raft safety design	No training of personnel using life raft	Incompetent and inexperienced	Poor emergency preparedness plan in using life raft	Poor emergency preparedness plan
Personnel used life raft were subjected to extreme environmental conditions, that is, entry of smoke, radiant heat, and inadequate lighting.	Poor life raft safety design	No training of personnel using life raft	Unsafe conditions affected physical	Lack of life raft inspection	Lack of inspection

The Central Control Room (CCR) was aware that crew members were jumping overboard but they focused on evacuation issues	No equipment for Man Over Board (MOB)	Violation of emergency procedures	Difficulty to handle two situations at the same time	No man overboard training provided to personnel	Poor emergency preparedness plan
Lifeboat 2 did not perform as a rescue boat due to the availability of offshore supply vessel, that is, Damon Bankston.	Availability of external boat	Violation of emergency procedures	The coxswain did not perform the assigned roles and responsibilities	Inadequate leadership	Inadequate leadership
The master, the senior dynamic positioning operator (SDPO), the Chief Electronics Technician, and the motorman jumped directly into the water because the fixed metal ladders damaged	Inadequate emergency equipment backup	Emergency procedures design did not include back-up equipment	Aware of damaged ladders	Poor emergency preparedness plan to include back-up equipment	Poor emergency preparedness plan
Damaged 15 to 20 feet of the ladders were not repaired.	Inadequate emergency equipment backup	Emergency procedures design did not include and inspect back-up equipment	Insufficient knowledge on importance of back-up equipment	Poor emergency preparedness plan to include and inspect back-up equipment	Poor emergency preparedness plan

5.4 The Contribution of Human factors to the BP Deepwater Horizon Evacuation Operations

Using the method for addressing human factors, the evacuation operations in the BP Deepwater Horizon were influenced by human and organizational factors, such as lack of emergency evacuation exercises for personnel, poor communications, inadequate leadership, lack of emergency equipment inspection prior to the well blowout, and poorly organized emergency preparedness plan and structure. Unsafe environmental conditions, such as darkness, intense heat, and a series of fires, were identified as factors leading to the catastrophic accident. Although the incident was considered to be a catastrophic accident, there were no deaths reported due to the unsuccessful evacuation operations (USCG, 2011).

5.4.1 Lack of Emergency Drills and Exercises

BP management categorized a well blowout under the Emergency Procedures for Uncontrolled Escape of Hydrocarbons operations (USCG, 2011). Although BP management identified the possibility of hydrocarbons release, the management failed to provide the comprehensive evacuation preparedness and training to all personnel working on the installation. Personnel were not equipped with good knowledge and experience of possible emergency situations and evacuation operations. Lack of emergency training exercises were identified as a critical factor exemplified by responses such as personnel jumping into the water. Mistakes and violations of some important steps in the evacuation operations happened because personnel failed to gain adequate knowledge and experience from the emergency training exercises.

5.4.2 Poor Communication

BP management failed to establish effective communications in the evacuation preparedness plan. The catastrophic accident may have been avoided if BP management and Deepwater

Horizon communicated and documented the indicators of a well blowout prior to the catastrophic accident.

The severity of the situation on board the mobile offshore drilling unit (MODU) was not communicated to all personnel in a timely manner. The situation showed that communication, in particular the general alarm, was not sounded promptly by the person in charge. According to emergency response standard operating procedures, an authorized person must activate the general alarm manually after two gas detectors were triggered (USCG, 2011). There was no effective application of the emergency communication medium for notifying the personnel of the emergency situation.

There was no clear communication regarding the command and control between the OIM, master, coxswains, and personnel. Failure to communicate the commands contributed to the uncontrolled event escalation, especially in handling and managing the anxiety of personnel.

5.4.3 Physical Limitations Due To Distractions

In the BP Deepwater Horizon accident, multiple noisy alarms were found to be distractions to personnel assessing the emergency situation. The explosion and fire elements, such as noise, heat, and flying debris, and activated sprinkler were also distractions that slowed personnel while moving through the emergency routes. Those distractions affected individual information processing and prevented individuals from performing the evacuation safely. As there was no backup power after the explosion, personnel had to perform the evacuation operations in darkness. Therefore, personnel's ability to perform was affected by the darkness. Personnel were also highly stressed because they were unfamiliar with the evacuation operations and the consequences of a well blowout.

5.4.4 Poor Emergency Preparedness Plan

Prior to the BP Deepwater Horizon accident, BP management was irresponsible in establishing an effective emergency preparedness plan to face credible emergencies. BP management failed to systematically inspect and test of emergency equipment. The heat protection was not reliable in reducing the consequences of fires and explosions. Reliability of the emergency lighting using the power system decreased as the power system was damaged by the explosion. The impairment of the lifeboats and the life rafts due to hazardous conditions and injured personnel were not anticipated. BP management were not being responsible in maintaining and repairing the damaged emergency ladders. If the organization had repaired the ladders, four people would not have had to jump directly into the water.

Poor organization of evacuation preparedness resulted in inadequate leadership defining command, control, and responsibilities. The lines of authority and shift of responsibilities in the event of an emergency was unclear to some of personnel (Skogdalen, Khorsandi & Vinnem, 2012). As a result, the personnel in-charge neglected assigned roles and responsibilities. Key personnel such as the OIM and master were not available in the control room to supervise personnel prior to the well blowout.

5.5 Recommendation to Reduce Human Factors in the BP Evacuation Preparedness Plan

Taking emergency drills and exercises as a main factor to successful evacuation operations, the organization, personnel, emergency procedures design, and equipment must control and minimize human and organizational factors at the same time. The organization should have a strong safety culture to encourage participation from all level to involve in the credible emergency drills and exercises using an evacuation simulation. A positive participation could identify weakness in roles and responsibilities, communication, and command and control. The organization must motivate personnel to discuss safety-related concerns of the emergency drills and exercises to increase personnel's skills in the emergency. Besides, the organization must supply personnel with necessary knowledge to evacuate quickly and effectively and increase personnel's competency to use the emergency equipment effectively, such the lifeboats and life raft. In return, personnel must make every effort to acquire the necessary skills and knowledge for offshore survival. Furthermore, personnel should demonstrate their competence in the use of both emergency equipment and techniques. The organization and personnel must regularly check the emergency equipment and procedures associated with their capacities, arrangement, and performance standards during the emergency drills and exercises. Moreover, a stress management is crucial to personnel and the organization to avoid panic, unsafe behaviours, and wasting time when dealing with the emergencies.

5.6 Conclusions

This paper discusses a tool for addressing and assessing the human factors in the evacuation operations of BP Deepwater Horizon accident and the emergency preparedness plan. The human factors are defined according to the evacuation protective layers, that is, organization, personnel, evacuation procedures, and emergency equipment. Using the BP Deepwater Horizon evacuation operations as a case study, the assessment has revealed several human factors in the evacuation operations, such as poor communications, insufficient emergency drills and exercises, the unsafe conditions affected physical capability, and inadequate emergency preparedness.

Findings from this paper are focused on the contribution of human factors as a qualitative technique only. A quantitative data analysis of the human factors can be generated as a reference and lesson learned to other offshore installations. For future work, the human factors associated with risks will be assessed using the Bayesian approach to estimate probability of the evacuation operation's success, and to enhance the application of the proposed methodology to offshore installations.

5.7 Acknowledgements

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Chapter 6

Prioritizing Safety Critical Human and Organizational Factors of EER Systems of Offshore Installations in a Harsh Environment

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Preface

This manuscript has been submitted to and accepted in Safety Science journal. The first author developed a methodology to calculate the probability of success of personnel responses in EER activities. Drs. Faisal Khan, Brian Veitch, and Scott MacKinnon reviewed the work and provided a constructive suggestion to make this manuscript suitable for publication.

Abstract

This paper introduces a methodology for identifying critical human and organizational factors in the escape, evacuation and rescue (EER) systems of offshore installations in a harsh environment. To elucidate the complex dependence of human and organizational factors on risky incidents, this methodology uses a Bayesian network (BN) and a sensitivity analysis to assess the criticality of these factors. As a case study, the methodology is applied to the activation of an emergency alarm and considers the consequences introduced because of a harsh environment. The results of the case study show that the probability of success for personnel to become aware of an emergency alarm is most likely affected by noise due to strong wind. Using the proposed methodology, the probability calculations include the human and organizational factors that stem from the organizational level and extend to the evacuation procedures, emergency equipment, and personnel to provide a more practical result than the probabilities estimated by expert judgements.

Keywords: Bayesian network; EER systems; Harsh environment; Human and organizational factors; Sensitivity analysis

6.1 Introduction

Human and organizational factors can be defined as environmental, individual, organizational, cultural, and equipment, affecting human physical perception, behaviour and performance. Both human and organizational factors are primarily concerned with optimizing human performance in all tasks with the aim of achieving a safe operation (CCPS, 2007; UK Energy Institute, 2011). Human and organizational factors in the escape, evacuation and rescue (EER) system of offshore installations operating in a harsh environment must be well understood to avoid harm to personnel and damage to structure. Examples of human and organizational failures as described in the Piper Alpha platform disaster are inadequate training, lack of communication between personnel and management, and insufficient procedures and arrangement for safe EER operations (Mearns et al., 2001).

An initiating event, such as a well blowout, loss of containment, fire and explosion, and collision, require personnel to leave their work area, move to a safe place, and abandon the installation (OGP, 2010). Previous studies investigated and discussed qualitative methods for identifying hazards in the EER operation (Kennedy, 1993; Gould and Au, 1995; Boyle and Smith, 2000; Woodcock and Au, 2013). Fire and toxic or flammable gas releases are better known as chemical hazards (AIChE, 1999; Asseal and Kakosimos, 2010). Heat radiation from a fire or explosion and subsequent structural damage of emergency equipment are other potential hazards (USCG, 2011). Congestion in escape routes, unavailable alternative escape routes, inaudible alarms, and environmental conditions such as darkness, fog, cold temperature, and storms, jeopardise the safety outcomes of EER operations (Timco and Dickins, 2005; Matskevitch, 2007).

Performing EER activities in the presence of harsh environmental conditions is challenging to personnel and management on offshore installations (Bercha et al., 2004). There is a need to study human and organizational factors in EER systems associated with harsh environmental conditions and hazards to improve safety of personnel. This paper presents a methodology for prioritizing human and organizational factors and discusses the relationships of harsh environmental conditions to these factors in the EER system. The methodology is a probabilistic analysis of EER systems considering human and organizational factors for offshore installations in a harsh environment. The safety of the EER system is assessed in terms of a) the probability of human responses influenced by human and organizational factors and environment conditions, and b) the contributions of critical human and organizational factors to safe operations. To reflect the complex dependence of the human and organizational factors and harsh environmental conditions on the risks, the methodology uses a Bayesian network (BN) and a sensitivity analysis.

6.2 Development of a Methodology for Prioritizing Human and Organizational Factors

Figure 6.1 shows the methodology for identifying and assessing critical human and organizational factors in the EER system of offshore installations.

6.2.1 Identify Input and Output Parameters

EER systems consist of safety planning and management, evacuation procedures, emergency equipment, and human actions (HSE, 1997; HSE, 2002; CAPP, 2010). From the EER system, two types of parameters, input and output, can be assigned to begin the study. Input parameters are safety planning and management, evacuation procedures, emergency equipment, and personnel physical abilities. Harsh environments and weather conditions, such as cold temperature, poor visibility, sea ice and wind, can also be added as input parameters. An output parameter is a human response that depends on input parameters. The output parameter can also be called a basic event.

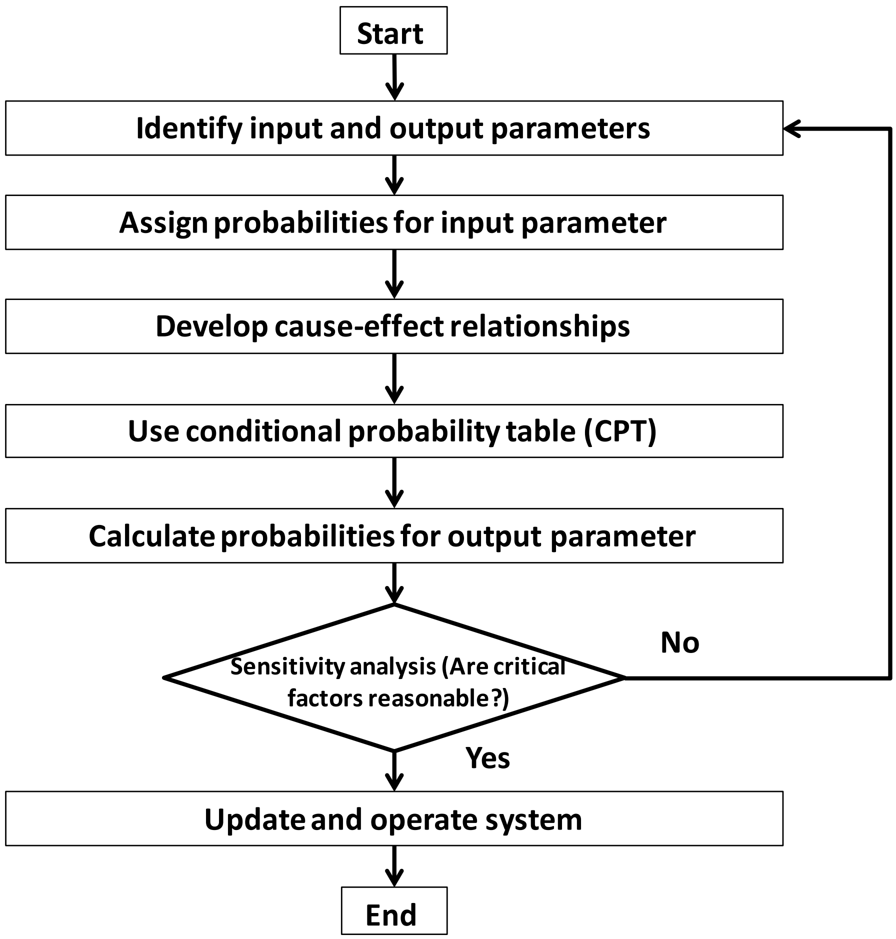


Figure 6.1: Procedures for analyzing critical human and organizational factors in the EER system.

6.2.2 Assign Probabilities for Input Parameter

Data on the failure probability for evacuation operations have been reported in the literature (DiMattia et al., 2005; Khan et al., 2006; Deacon et al., 2010; Deacon et al., 2013; Musharraf et al., 2013). Oil and gas regulatory and industry guidelines on emergency response and evacuation operations, specifically the prevention of fire and explosion, and emergency response (PFEER) (HSE, 1997) and EER (CAPP, 2010), medical assessment (CAPP, 2013a), and standard practice for training (CAPP, 2013b), can be useful references for estimating probabilities involving human and organizational factors for offshore installations in a harsh environment. Provisions in the guidelines can be considered as factors affecting human responses, as well as the performance of EER systems. The guidelines incorporate useful guidewords that can be translated to numerical values for provisions applied to input parameters using a scale of probability (Norrington et al., 2008). For the purpose of illustrating the methodology presented in this paper, we have posited probabilities corresponding to the guidewords in the PFEER and CAPP guidelines, as shown in Table 6.1.

Table 6.1: Numerical conversion of guidewords.

Guideword	Probability
Shall	0.80 to 1.00
Should	0.65 to 0.79
Can or May	0.50 to 0.64

6.2.3 Develop Cause-Effect Relationships

A Bayesian network (BN) can provide an assessment of uncertainties in the context of the assumed relationships of human and organizational factors (Ren et al., 2008; Trucco et al., 2008; Wang et al., 2011a; Wang et al., 2011b). The relationship can be based on three types of structural properties of the BN, which are serial, common cause, and common effect connections (Celeux et al., 2006; Langseth and Portinale, 2007; Fenton and Neil, 2013). The development of the relationship is known as a directed acyclic graph (DAG), which also refers to a qualitative element. For this study, the relationship may consist of safety planning and management, emergency equipment, evacuation procedures, and human responses. Figures 6.2 and 6.3 show examples of common cause and effect relationships used for analysing evacuation operations considering human and organizational factors, and harsh environmental conditions.

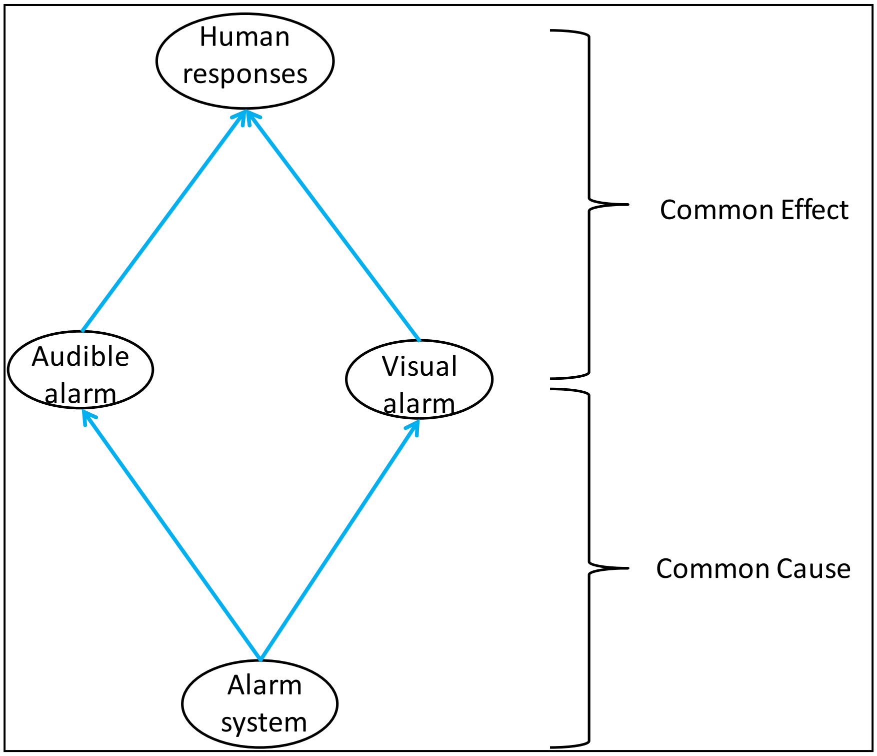


Figure 6.2: Common cause and effect relationships.

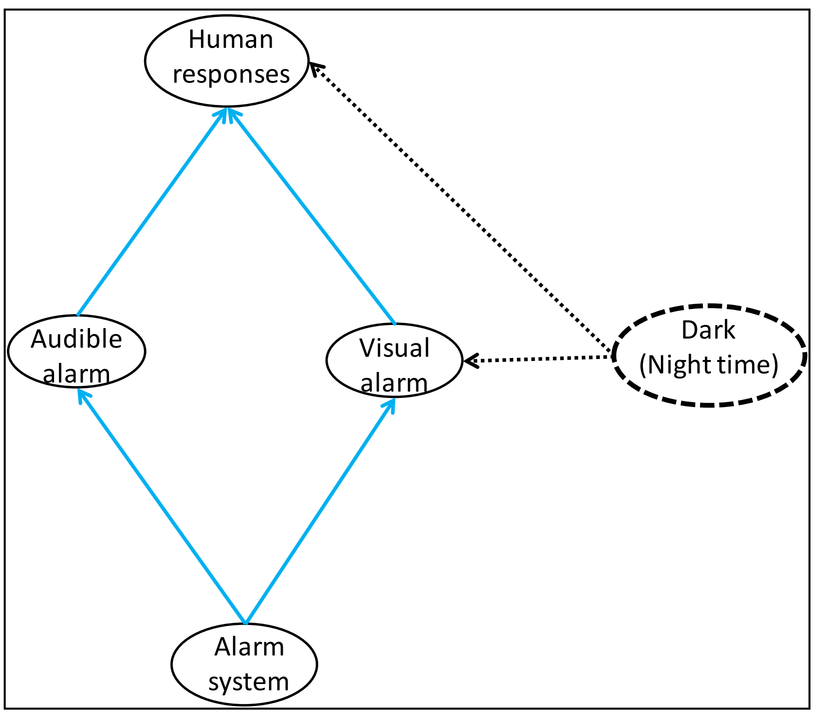


Figure 6.3: The presence of environmental conditions in the cause and effect relationships.

6.2.4 Provide Conditional Probability Table

The output parameter depends on its relationships to input parameters and their probabilities. Both the probability and cause-effect relationship can be placed in a conditional probability table (CPT). The CPT can show the interaction between input and output parameters in terms of a quantitative measure. In this paper, each parameter is discrete and has binary states, such as 'yes' or 'no' and 'good' or 'poor'. Table 6.2 lists an example of a CPT for an alarm system and an audible alarm used in EER operations (Chen, 2011). When the alarm system is available and reliable, the audible alarm may either work properly or ineffectively. The audible alarm can be activated manually by personnel. The availability of the alarm system refers to data obtained from probability of failure on demand (PFD).

Table 6.2: A conditional probability table of the reliability of the audible alarm.

Alarm system	Availability 0.99	Unavailability 0.01
Reliability of audible alarm:		
Good	0.99	0.50
Poor	0.01	0.50

The CPT involving the alarm system can be extended with the inclusion of environment conditions and human response. Table 6.3 shows an example of a CPT for personnel to be aware of an alarm. The CPT consists of an alarm system, a visual alarm, darkness, and human response (Chen, 2011; Yun and Marsden, 2010). These parameters in the CPT show an interaction based on noisy-OR gates. In a Bayesian network, the noisy-OR gate can describe the interaction between causes and their common effects (Oniśko et al, 2001). This is illustrated by parameters in Table 6.3. As the alarm system is available, the visual alarm can be visible in darkness. Human response, such as *personnel aware of or detect alarm*, may depend on effectiveness of the visual alarm in darkness.

Table 6.3: A conditional probability table of human response (aware of alarm).

Alarm system	Availability 0.99				Unavailability 0.01			
Visual alarm	Good 0.99		Poor 0.01		Good 0.50		Poor 0.50	
Darkness	Yes 0.81	No 0.19	Yes 0.81	No 0.19	Yes 0.81	No 0.19	Yes 0.81	No 0.19
Aware:								
Yes	0.90	0.50	0.50	0.50	0.50	0.50	0.50	0.50
No	0.10	0.50	0.50	0.50	0.50	0.50	0.50	0.50

6.2.5 Calculate Probabilities of Output Parameter

The calculation for the output parameter depends on the number of input parameters. As in Table 6.3, for a case with 3 factors and 2 levels each, there are 8 combinations with a binary state outcome, which requires 16 calculations. More specifically, for a state 'Yes' of *personnel aware of the emergency alarm*, it must involve eight (8) calculations of Bayesian. The same applies for a state of, 'No', *personnel not aware of the emergency alarm*.

The calculation begins with marginalizing the output parameter. This is followed by calculation using Bayes' theorem, with new evidence included in the calculation. An example of calculation for a visual alarm that has only one input parameter is shown below. The new evidence may refer to monitoring the state of 'Good' visual alarm with regard to 'Available' alarm system.

Step 1: To marginalize probability

P(Visual=Good) = P(Visual=Good | Alarm system=Available) P(Alarm system=Available) + P(Visual=Good | Alarm system=Unavailable)P(Alarm system=Unavailable)
= 0.9803

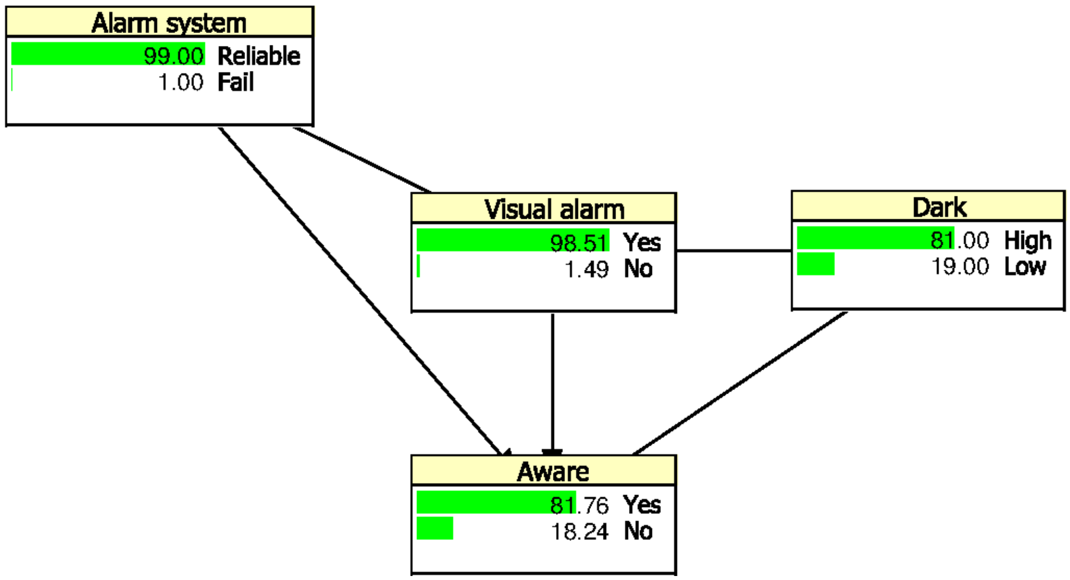
P(Visual=Poor) = P(Visual=Poor | Alarm system=Available) P(Alarm system=Available) + P(Visual=Poor| Alarm system=Unavailable) P(Alarm system=Unavailable)
= 0.0179

Step 2: To add new evidence

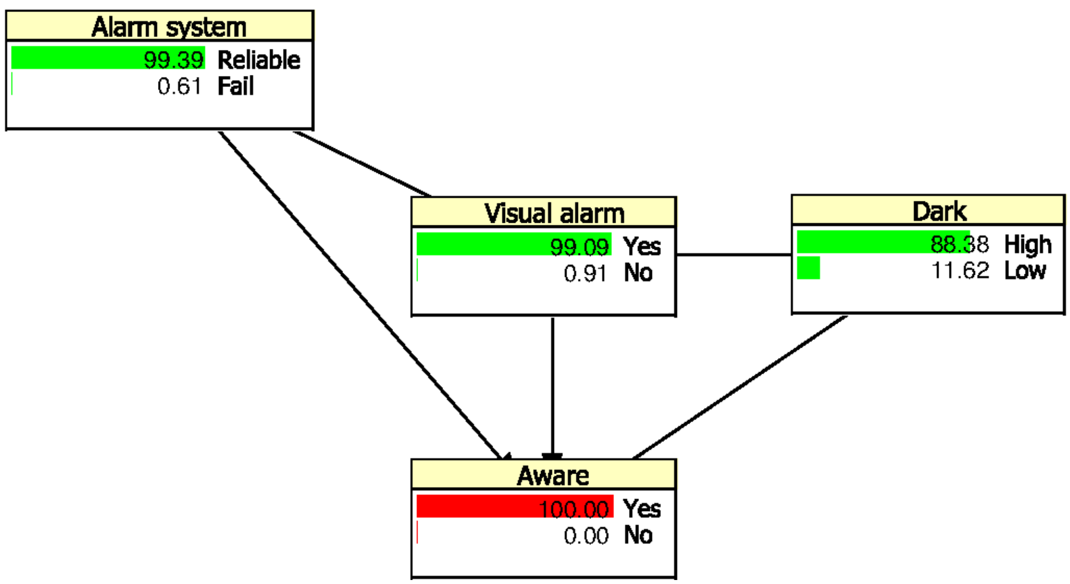
$$P(Alarm = Available\ |Visual = Good) = \frac{P(Visual=Good\ |\ Alarm=Available)\ P(Alarm=Available)}{P(Visual=Good)}$$

$$= 0.9997$$

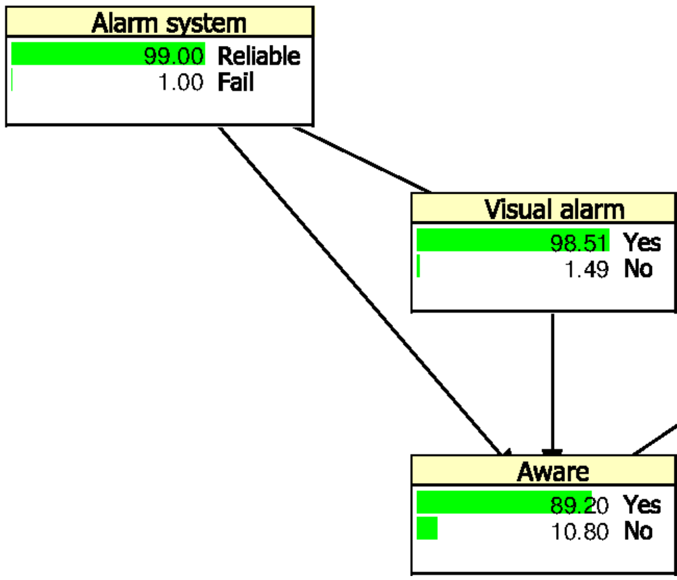
The calculations applied here to a small number of input parameters can also be applied to large numbers of input parameters. A complex network consisting of many input parameters requires many more calculations, which is not feasible to be done manually (Weber et al., 2012). The calculation for a complex network can be done using Hugin, a model-based decision support software (Hugin Expert, 2014). Calculation in the Hugin software generates all probabilities in the form of percentages. The probability value can be obtained by dividing the percentages by 100 percent. Figure 6.4(a) shows an example of marginalizing BN calculation of the probability of personnel becoming aware of the emergency alarm. Figures 6.4(a) and (b) have new evidence and use a backward analysis with the application of Bayes' theorem in the Hugin software. The bars of 'aware' and 'dark' are the observations to be studied or investigated. The Hugin software will set each observation in turn to have a probability value of 1.00. The observation is considered as a piece of knowledge or new evidence to update the belief of reasoning associated with large and complex systems.


Alarm system
99.00 Reliable
1.00 Fail
Visual alarm
98.51 Yes
1.49 No
Dark
81.00 High
19.00 Low
Aware
81.76 Yes
18.24 No

(a)


Alarm system
99.39 Reliable
0.61 Fail
Visual alarm
99.09 Yes
0.91 No
Dark
88.38 High
11.62 Low
Aware
100.00 Yes
0.00 No

(b)



(c)

Figure 6.4: An example of updating probability for (a) a complex BN (b) with an assumed output parameter, and (c) with an assumed input parameter.

6.2.6 Verify the Human and Organizational Factors Using a Sensitivity Analysis

To verify the qualitative element and cause-effect relationships, a sensitivity analysis is a practical approach used in the methodology. Sensitivity analysis can identify potential flaws and prioritize input parameters in order to reduce the uncertainties in the most sensitive probabilities and assumptions. In the methodology, a sensitivity analysis can consist of a) measuring the level of uncertainty related to input parameters, b) determining the level of uncertainty that can affect the output parameter, c) determining the possible stability of the results that depend on the input parameter, and d) estimating confidence limits of the results. A tornado chart is a useful way to present the critical input parameters that can also affect the output parameter. By recognizing the critical factors within the EER system, measures can be taken to improve the probabilities of safe human responses and evacuation operations.

6.3 Case Study

To study critical factors for safe evacuation operations on offshore installations in harsh environments, the paper discusses the results obtained in the proposed methodology. The case study illustrates the methodology as applied to human responses in an emergency scenario, such as *personnel aware of the emergency alarm*.

6.3.1 Parameters and Probabilities

Input parameters include safety planning and management, evacuation procedures, emergency equipment and personnel physical abilities. Details of input parameters are shown in Table 6.4. The output parameter reflects *personnel awareness of the emergency alarm* activated due to an emergency situation.

For most input parameters in Table 6.4, the probability is based on guidewords because the parameter cannot be measured directly. These guidewords can be translated into probability values based on numerical conversion as in Table 6.1. An alternative is to rely upon expert judgement. The probabilities of good alarm systems, including detectors and alarms, are equal to 0.99 each, information which is available in the literature (Chen, 2011). The probabilities of environmental conditions are estimated based on a research study for a potential Arctic development (Yun and Marsden, 2010). Table 6.5 shows the probability of a harsh environment in January in the northern hemisphere.

Table 6.4: Input parameters for personnel to become aware of emergency alarm.

Parameter	Provisions	Guideword	References
Safety planning and management	Alarm system	Shall be effective	PFEER (Regulation 11)
Evacuation procedures	Operational readiness	Shall be effective	PFEER (Regulation 11)
	Scheduled inspection	Shall ensure	CAPP (EER; 6.7)
		Should ensure	PFEER (Regulation 8 and 11)
	Scheduled maintenance	Shall ensure	CAPP (EER; 6.7)
		Should ensure	PFEER (Regulation 8 and 11)
Emergency equipment	Fire and gas detectors	Shall provide	PFEER (Regulation 10)
	Audible alarm	Shall provide	PFEER (Regulation 10 and 11)
		Shall ensure	CAPP (EER; 6.1.1)
	Visual alarm	Shall provide	PFEER (Regulation 10 and 11)
		Shall ensure	CAPP (EER; 6.1.1)
Individual	Hearing	Required	Offshore medical check up
	Vision	Required	Offshore medical check up
	Stress or psychological demands	Potential extended	CAPP (Medical; 2.3.3 and 2.4)
Human response	Detect alarm	Shall ensure	CAPP (EER; 6)
		Shall give	PFEER (Regulation 11)

Table 6.5: The probability of harsh environment in January (Yun and Marsden, 2010).

Harsh environmental conditions	Probability
Low temperature (<-40^{o}F)	0.13
High wind (>35 knots)	0.02
Dark (17 – 22 hours)	0.81

6.3.2 Common Cause-Effect Relationships

Figure 6.5 shows the relationship that includes all input parameters beginning from alarm systems to evacuation procedures, equipment, physical conditions and human response. A long night period, strong wind and cold temperature as in Table 6.5 are attached to the node ‘Detect alarm’. If there is a high level of noise from the wind and surrounding facilities, the sound of an audible alarm may not be noticeable and distinguishable. Noise from the wind may also affect personnel in detecting the sound of the activated emergency alarm. A visual alarm is also activated at the same time. The visual alarm can be the main source of notification to personnel in conditions when audible alarms are more difficult to detect.

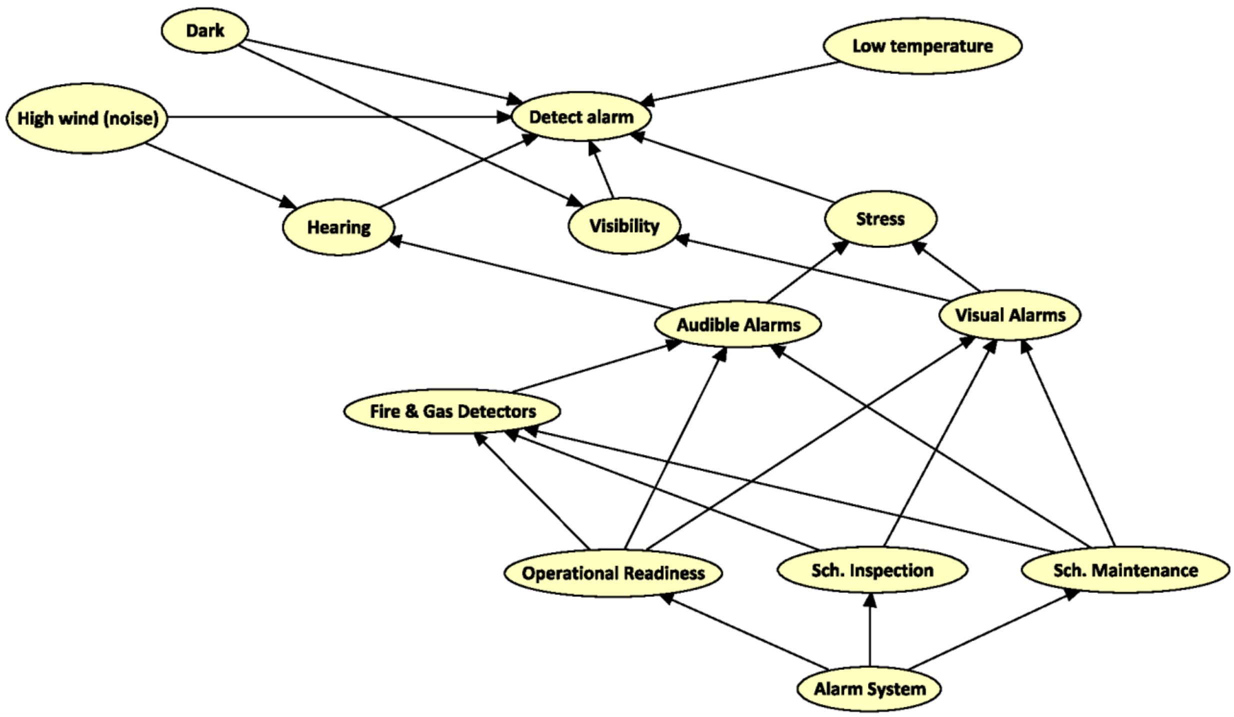
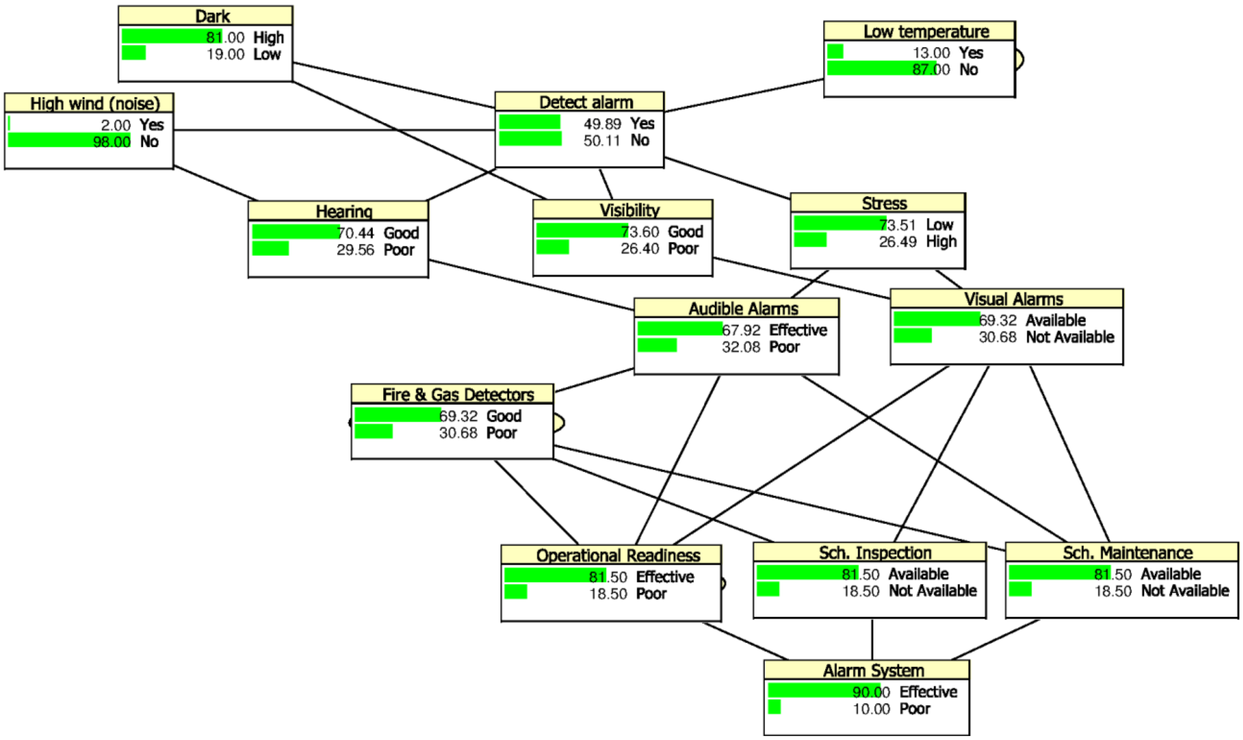


Figure 6.5: The relationship of input and output parameters in the Bayesian network representing Arctic January conditions.

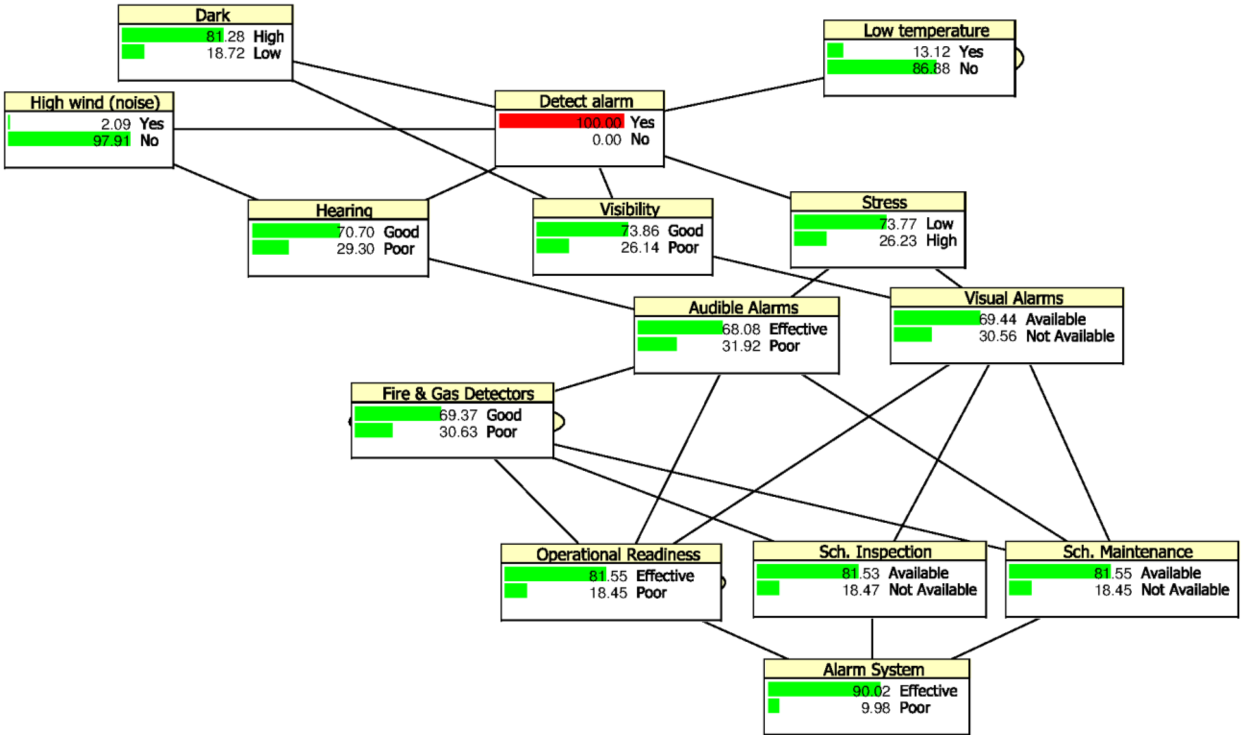
6.3.3 Updating Probability

Bayesian networks in Figures 6.6(a) and (b) are the same network as in Figure 6.5, with the addition of the probability values. Figure 6.6(a) presents the Bayesian network of detecting an emergency alarm with the probability values. All input parameters in Table 6.4 are assumed to have a *prior* probability of 0.85 or 0.90, which are in the range assigned in Table 6.1. This is further assumed to represent a good EER system. Given the effects of wind, cold temperature, and the darkness of night, the probability value for personnel to be aware of the alarm (*Detect alarm*) is 0.50. The main reason for the low probability value is the dependency of input parameters on each other, which results in a low joint probability value.

Figure 6.6(b) shows the Bayesian network of *Detect alarm* that has been set as a new evidence for the backward analysis. Table 6.6 summarizes the updated probability values in Figures 6.6(a) and (b). Appendix 6-A contains diagrams and information of the BN when new evidence of environmental conditions is 100 percent 'True' and added in the Bayesian analysis.



(a)



(b)

Figure 6.6: Bayesian network with (a) probability values in Arctic January conditions and (b) 'Detect alarm' is set as a new evidence.

Table 6.6: Summary of updating probability values for personnel to become aware of the emergency alarm.

Environment conditions (100% True)	Organization	Procedures			Equipment			Individual			Response
	Alarm system	Scheduled maintenance	Scheduled inspection	Operational readiness	Visual alarm	Audible alarm	Detectors	Hearing	Visibility	Stress	Detect Alarm
Low temperature	0.90	0.82	0.82	0.82	0.69	0.68	0.69	0.70	0.74	0.74	0.50
Darkness	0.90	0.82	0.82	0.82	0.69	0.68	0.69	0.70	0.74	0.74	0.50
Strong wind	0.90	0.82	0.82	0.82	0.69	0.68	0.69	0.74	0.74	0.74	0.52

6.3.4 Sensitivity Analysis and Confidence Limit

A tornado chart can provide information on the degree of uncertainty of an output parameter. The largest bar in the tornado chart represents an input parameter that contributes the most to the output parameter.

Figure 6.7 demonstrates the results of a sensitivity analysis. From the result, we can see that alarm awareness is most sensitive to ‘High wind’, followed by ‘Darkness’ and ‘Low temperature’. Referring again to Table 6.5 and Figure 6.6(b), the probabilities of wind and cold temperature are low. The probabilities and results from the sensitivity analysis can confirm that severe effects of wind, darkness, and low temperature reduce chances of personnel being aware of the emergency alarm.

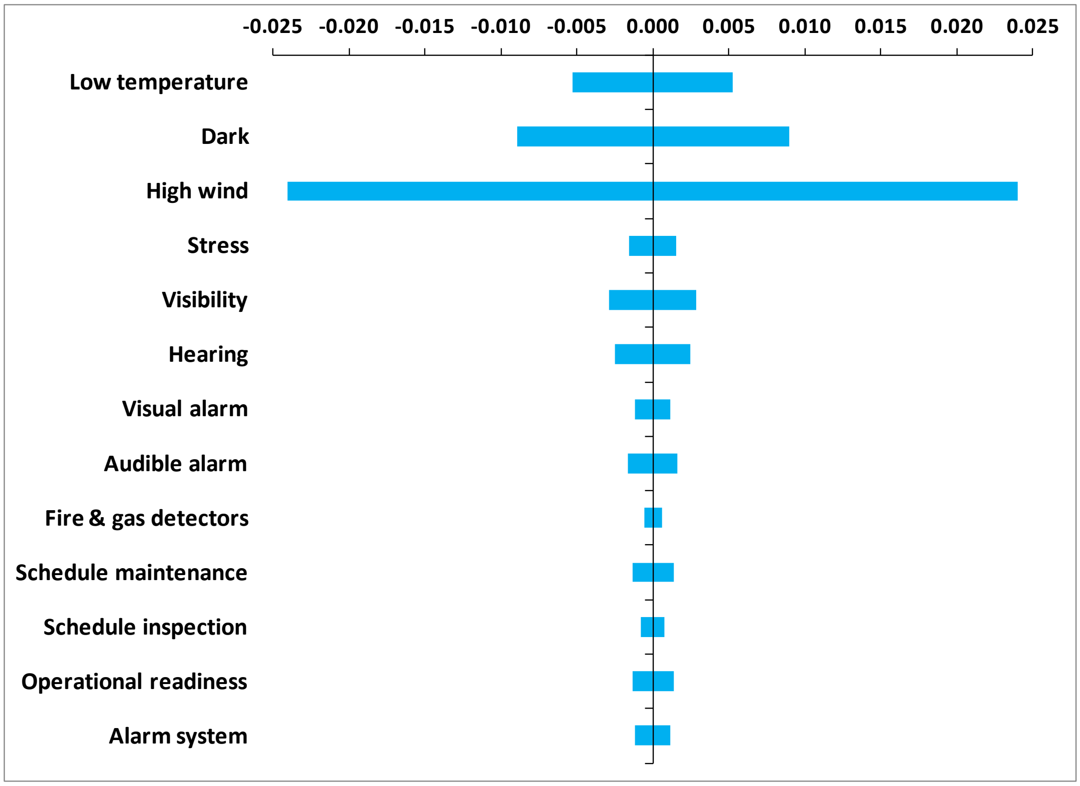


Figure 6.7: Result of a sensitivity analysis for personnel being aware of alarm.

To estimate uncertainty of an output parameter, a confidence limit is developed (see Figure 6.8). The estimation is based on the value of the confidence interval, such as 90, 95, or 99 percents. In this paper, we consider a confidence limit of 95 percent. The input parameters of environment conditions have the highest probability value compared to others. A numerical value at the confidence interval will give upper and lower limits of input parameters as listed in Table 6.7. The upper and lower limits of input parameters in Table 6.7 are basically the same information from Figure 6.8. Based on the analysis, at a 95 percent confidence interval, low temperature, darkness, and high wind have more influence than other parameters.

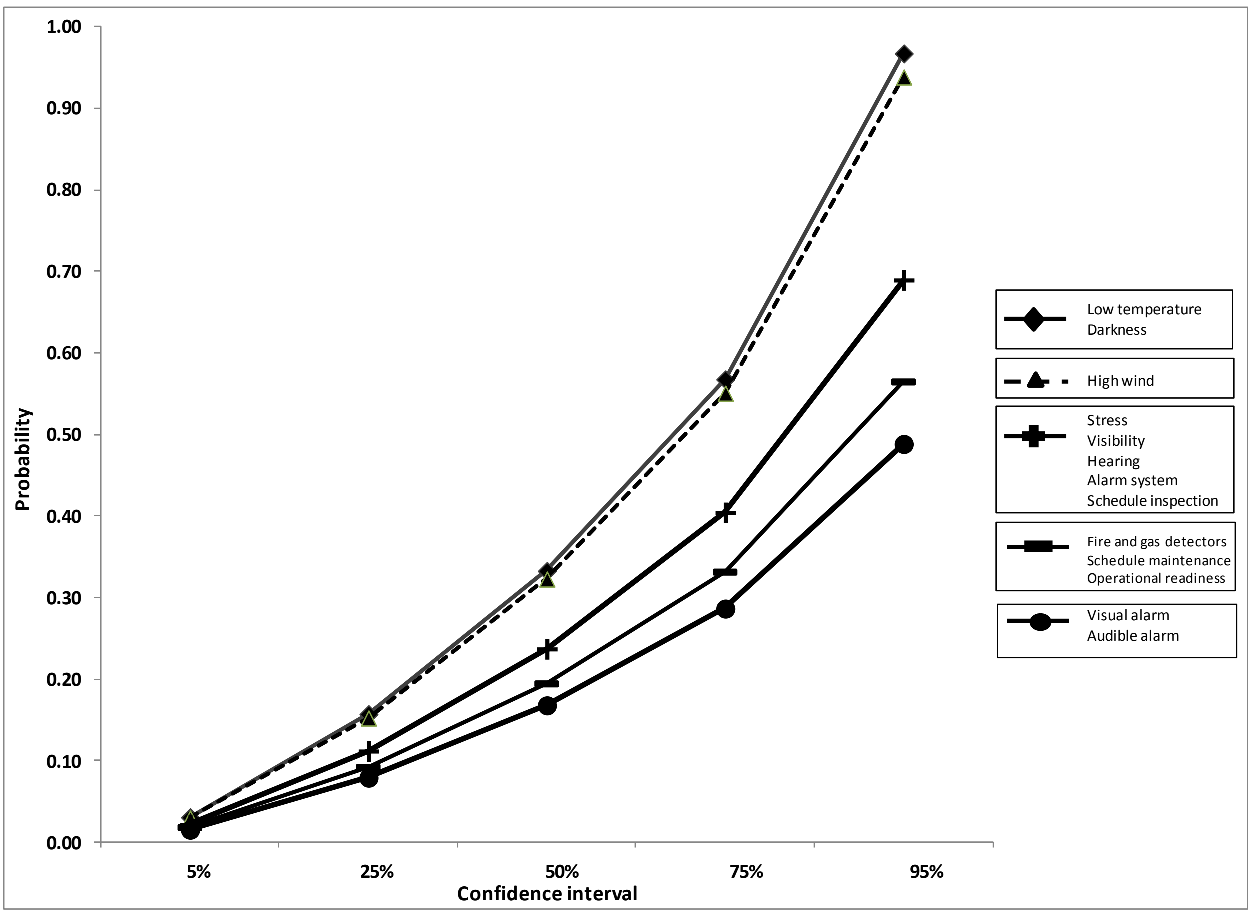


Figure 6.8: Confidence limits for ‘Detect alarm’.

Table 6.7: Upper and lower limits of input parameters.

Detecting alarm	Upper limit	Lower limit
Low temperature	0.967	0.031
Dark	0.960	0.031
High wind	0.939	0.030
Stress	0.690	0.022
Visibility	0.690	0.022
Hearing	0.690	0.022
Visual alarm	0.489	0.016
Audible alarm	0.489	0.016
Fire & gas detectors	0.564	0.018
Schedule maintenance	0.564	0.018
Schedule inspection	0.691	0.022
Operational readiness	0.564	0.018
Alarm system	0.690	0.022

6.4 Discussion

6.4.1 Comparison between the Proposed Methodology and Other Models

The probabilities calculated using the interaction of the human and organizational factors in the organization, evacuation procedures, emergency equipment, and personnel levels (see Table 6.8) are relatively higher than the probabilities estimated by DiMattia et al. (2005) and Musharraf et al. (2013). Previous studies using Bayesian network (BN) and the Success Likelihood Index Methodology (SLIM) to calculate human error probabilities (HEP) did not consider interaction between human response and environment conditions and possible effects on probability of success or failure.

The BN often generates an appropriate likelihood function using expert judgements in the estimation process (Siu and Kelly, 1998). There are several drawbacks to using expert judgements related to subjective data, such as a spread or divergence of expert opinions, the dependencies between the opinions of different experts, the reproducibility of the results of risk studies, and the need to calibrate expert probability assessments (Cooke, 1991). The failure probabilities based on guidewords used in this paper are different from the probabilities calculated using judgements from experts as a source of data. For example, DiMattia et al. (2005) and Musharraf et al. (2013) considered experts' opinions as data in calculating probability values of human reliability.

Data related to human and organizational factors are scarce, which prompts the use of expert opinions. The proposed methodology can minimize dependency on experts to give precise probability numbers for interaction between nodes in calculating the probabilities for human responses. For new or existing offshore installations, the interaction nodes between input parameters and harsh environment conditions may give information to experts and operators in evaluating performance of EER operations. Introducing the interaction and quantifying guidewords to find the probability value of human responses in emergency conditions can provide a better definition of effective and safe EER systems to offshore operators. The interaction consisting of human responses and the guidewords translated to numerical values can also be a source of information in complying with regulations related to EER systems.

Table 6.8: Comparison of probabilities between the current study and previous studies.

Human response	**Studies to find a failure probability value**		
	This paper use BN	**Musharraf et al. (2013) use BN for HEP**	**DiMattia et al. (2005) use SLIM for HEP**
Detect alarm	0.501	0.414	0.396

6.4.2 Effects of Critical Human and Organizational Factors

Based on the methodology applied in determining personnel awareness of an emergency alarm, the trajectory of critical human and organizational factors starts within the organization level, passes through the evacuation procedures, emergency equipment, and personnel levels, and eventually shapes the human responses (Reason, 1990). Organization resources and constraints can shape an individual's ability and behaviours. Failure of human responses is a product of poor EER systems involving the organizational, operational, cognitive and physical conditions.

For instance, there are three types of faults involving alarm systems (Kennedy, 1993; Gould and Au, 1995). The sensitivity analysis identifies the scheduled maintenance as a critical factor. Faults in the alarm system can be minimized through periodic examination, testing, and remedial actions. The organizational failure to emphasize the implementation of scheduled inspection and maintenance (i.e. leading indicators) can result in a deterioration of reliability and consequently, failure of the system's function to alert personnel in a timely manner. In brief, the alarm system, scheduled maintenance, and emergency notification are strongly dependent on each other.

Human and organizational factors associated with faults and harsh environmental conditions are some of the main problems in EER operations. The operators of offshore installations can identify potential accidents in EER operations when they understand and acknowledge critical human and organizational factors. The Bayesian network approach that considers parameters in the organization, equipment and evacuation procedures can provide a better understanding of effects of environment conditions to human responses while performing EER activities on offshore installations.

6.5 Conclusions

This paper introduces a methodology to identify critical human and organizational factors in the evacuation operations and EER system of offshore installations in a harsh environment. Critical human and organizational factors in the evacuation operation affect performance of the organization, evacuation procedures, emergency equipment, and personnel. A Bayesian network and sensitivity analysis are two techniques applied for prioritizing human and organizational factors and the associated risks. Based on the results, the human and organizational failures can be identified starting from the organization and management level and moving to the activities of EER that involve equipment and procedures. Personnel are vulnerable to the hazards while performing the EER operations. The offshore installation's organization must acknowledge the critical human and organizational factors prior to an EER improvement program. The results of sensitivity analyses are a reasonable basis for use in the evacuation improvement program to produce better safety performance during emergency scenarios and EER operations.

Both input and output parameters in estimating the probability value of human responses may not truly reflect implementation of regulations on offshore installations. To make the results of BN more credible using the described methodology, it is recommended to use data from an experiment study on human responses in emergency situations. The experimental study using a virtual environment can provide a credible data for analysing human responses in emergency conditions with the presence of harsh environmental conditions. Results based on experimental data using the approach in this paper will be more appealing and convincing to researchers and offshore operators to gain information on safety in EER systems.

6.6 Acknowledgements

The authors would like to thank the Atlantic Innovation Fund (AIF) and Natural Science and Engineering Research Council of Canada (NSERC CREATE) for the financial support necessary for this research study. The authors would also like to extend thanks to the reviewers who gave comments on the paper.

Appendix 6-A

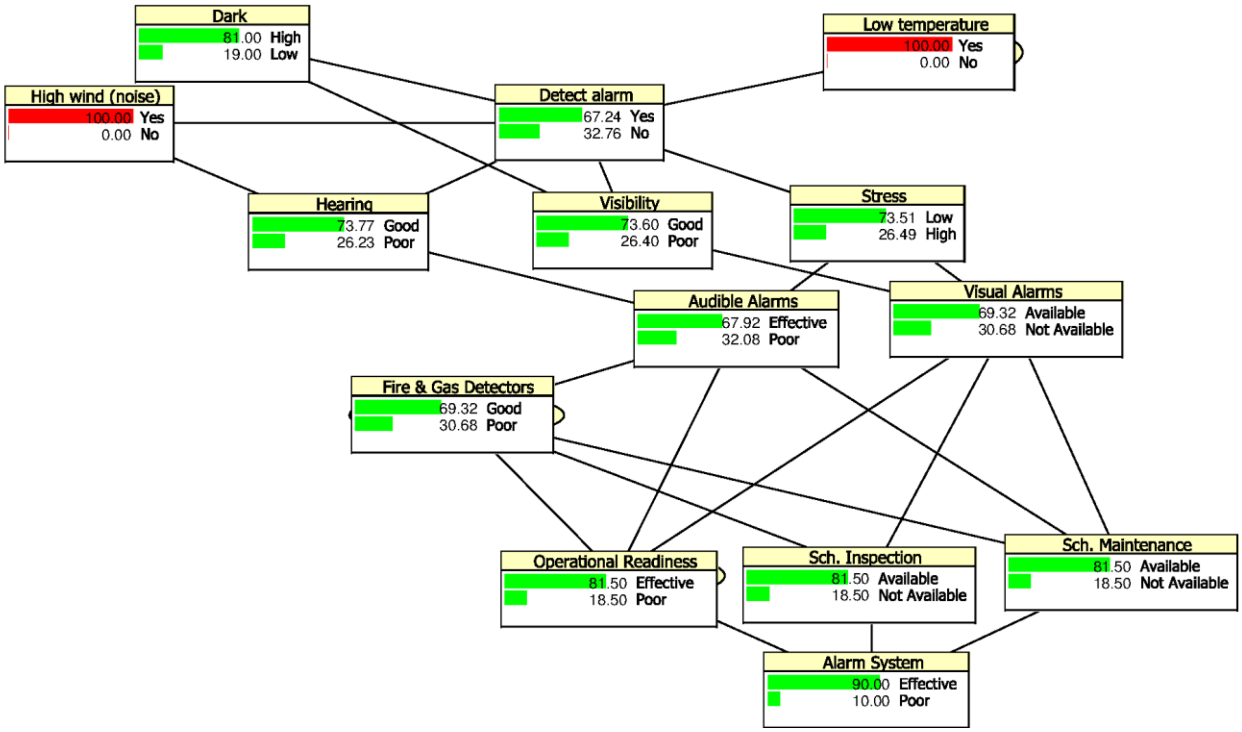


Figure 6.A1: Bayesian network for ‘High wind’ and ‘Low temperature’ have a likelihood of 1.00.

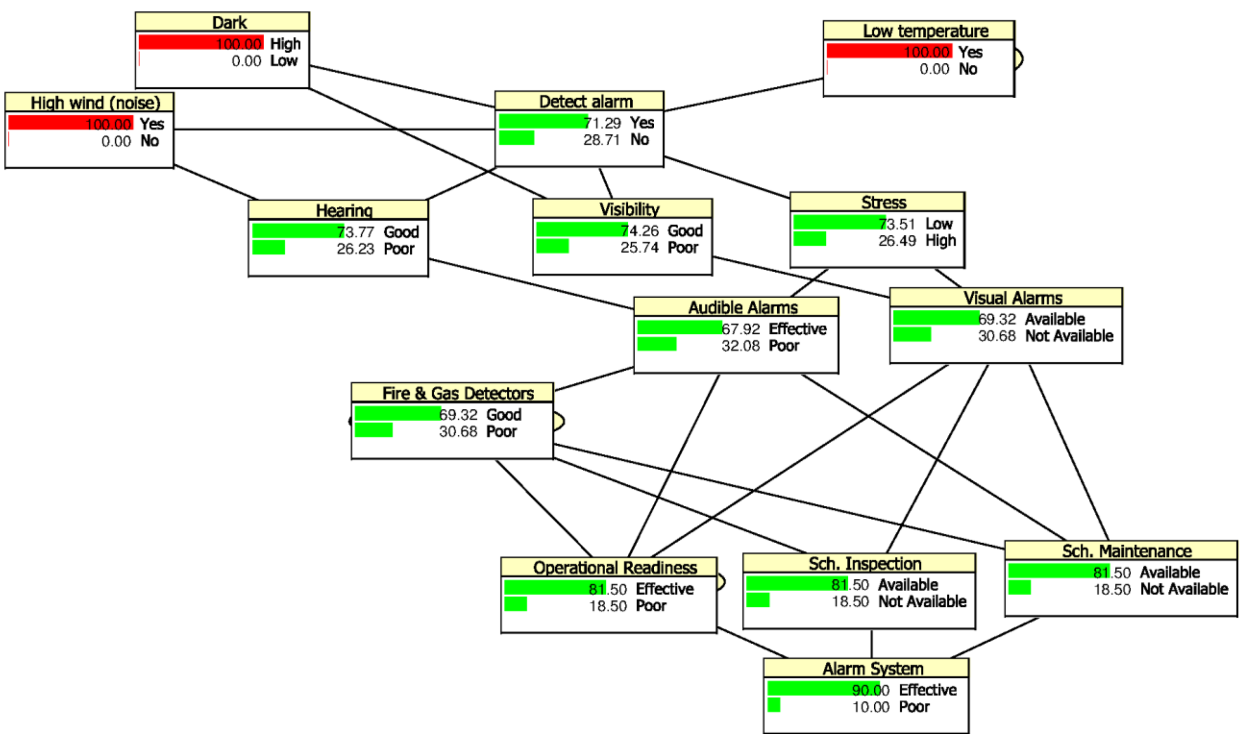


Figure 6.A2: Bayesian network for ‘High wind’, ‘Dark’ and ‘Low temperature’ have a likelihood of 1.00.

Table 6.A1: The conditional probability table of *personnel detecting alarm* when the hearing condition is good.

Hearing	Good																															
	0.70																															
High wind (noise)	Yes																No															
	0.02																0.98															
Dark	High								Low								High								Low							
	0.81								0.19								0.81								0.19							
Visibility	Good				Poor				Good				Poor				Good				Poor				Good				Poor			
	0.74				0.26				0.74				0.26				0.74				0.26				0.74				0.26			
Low temperature	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
	0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87	
Stress	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26
Detect Alarm																																
Yes	0.99	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
No	0.01	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

Table 6.A2: The conditional probability table of *personnel detecting alarm* when the hearing condition is poor.

Hearing	Poor																															
	0.30																															
High wind (noise)	Yes																No															
	0.02																0.98															
Dark	High								Low								High								Low							
	0.81								0.19								0.81								0.19							
Visibility	Good				Poor				Good				Poor				Good				Poor				Good				Poor			
	0.74				0.26				0.74				0.26				0.74				0.26				0.74				0.26			
Low temperature	Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No		Yes		No	
	0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87		0.13		0.87	
Stress	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26	0.74	0.26
Detect Alarm																																
Yes	0.99	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
No	0.01	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50

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Chapter 7

Dynamic Risk Assessment of Escape and Evacuation in a Harsh Environment

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Preface

This manuscript is prepared and submitted to Risk Analysis. The first author developed a methodology for a dynamic risk assessment. The methodology is applied to escape and evacuation operations of offshore installations in harsh environmental conditions. Drs. Faisal Khan, Brian Veitch, and Scott MacKinnon have reviewed the methodology and this manuscript prior to submission.

Abstract

Execution of escape, evacuation and rescue (EER) on offshore installations in harsh environmental conditions poses potential risks. A risk assessment must be prepared to improve safety of personnel performing EER activities. This paper presents a methodology for assessing risks in EER conducted in such challenging conditions. The methodology considers an event tree analysis, a Bayesian network, and a risk assessment to integrate both qualitative and quantitative elements. A risk assessment of personnel responding to the emergency alarm is studied using the proposed methodology and considering the probability of coldness, strong wind, and darkness. The possible consequences of personnel not responding to the alarm during a hydrocarbon release include severe burns and death. To reduce uncertainty of the results, a sensitivity analysis is performed to verify the input parameters and safety barriers, such as human responses and emergency equipment. Application of the risk assessment considering dynamic environment conditions in the study of alarm recognition illustrates the importance of defining and setting the risk acceptance criteria to be used for safe EER on offshore installations.

Keywords: *EER, event tree, Bayesian analysis, dynamic risk assessment, harsh environment*.

7.1 Introduction

For offshore installations operated in harsh environments, the operator must address remoteness and the physical environment in escape, evacuation and rescue (EER) systems. Performing EER in the presence of severe weather, cold temperature, poor visibility, sea ice and ice bergs can reduce personnel's chances of survival (Timco and Dickins, 2005; Palmer and Croasdale, 2013). During emergencies, personnel depend on the reliability of equipment and safety barriers to protect them from undesirable outcomes.

Safety planning and management, emergency equipment, and evacuation procedures are safety barriers required for emergency preparedness and EER systems of offshore installations (HSE, 1997; CAPP, 2010). By adhering to standard regulations, both emergency equipment and safety barriers are expected to work effectively during emergency situations. Personnel can familiarize themselves with evacuation procedures and emergency equipment in the basic survival offshore training. Other than scheduled inspection and maintenance, the equipment and safety barriers should be tested through a series of emergency drills on offshore installations considering hazards that may be present during an emergency.

As part of the regulatory approval process, the operator of offshore installations must prepare a risk assessment that includes EER systems (OGP, 2010a). The main focus of risk assessment is risk of fatality during EER (Vinnem, 1998). Estimating risks to personnel, in particular life-threatening and major injuries, can prompt the operator to prepare procedures that improve the chances of success in EER operations.

This paper presents a methodology for assessing risks during EER on offshore installations in harsh environmental conditions. The risk assessment is dynamic in the sense that it accounts for changes in safety barriers and environment conditions over time. The methodology is illustrated using a case study. The case study uses probability data based on assumptions and expert judgement, because data for EER systems considering emergency equipment, evacuation procedures, human and organizational factors, and harsh environmental conditions are scarce, or unavailable.

7.2 Concept of Risk Assessment for EER in Harsh Environment

Three parameters in this risk assessment are environment conditions, human responses, and equipment as safety barriers, which relate to EER systems shown in Figure 7.1. Emergency equipment is activated depending on emergency scenarios and environment conditions. During emergency scenarios, the environment conditions may affect the effectiveness of emergency equipment, as well as the performance of personnel to complete the EER tasks. A risk assessment becomes dynamic with the integration of new information or observations of environment conditions, equipment, and human responses that change over time.

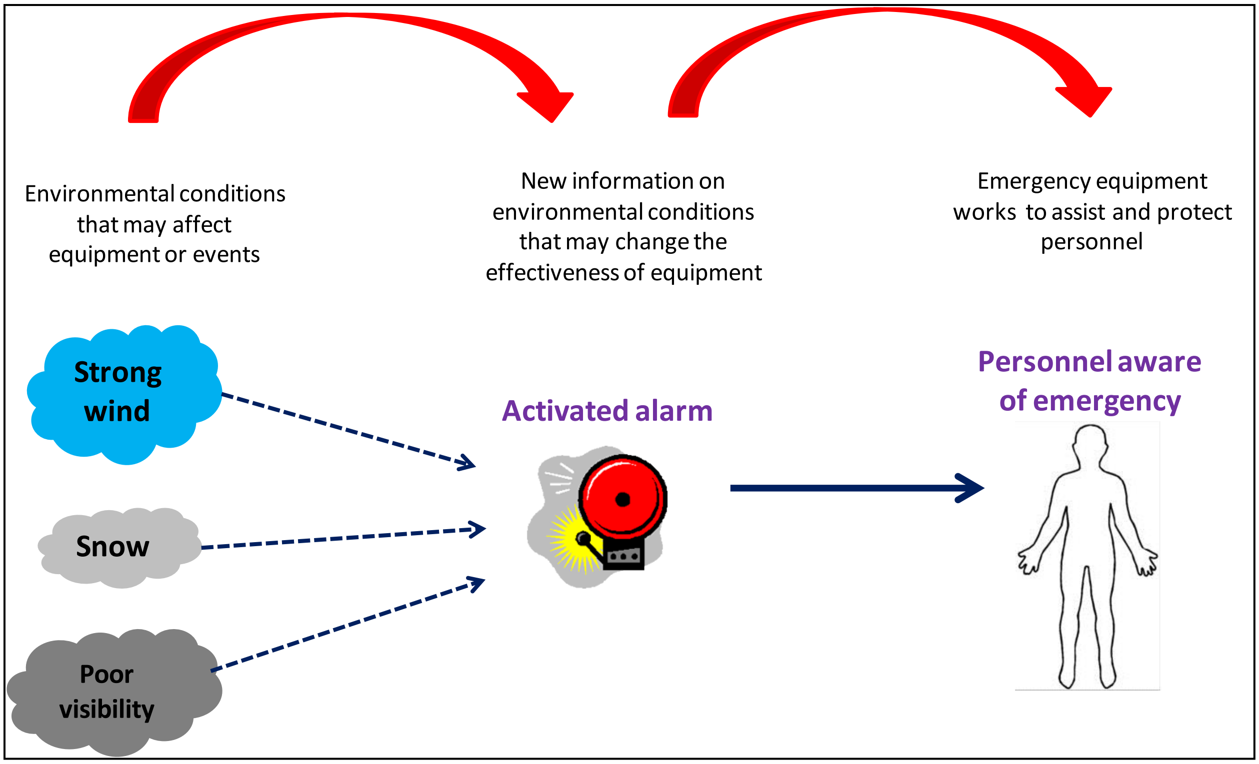

Figure 7.1: The effect of harsh environmental conditions on equipment and an individual.

7.3 Methodology

Figure 7.2 presents a methodology for developing a risk assessment of EER systems.

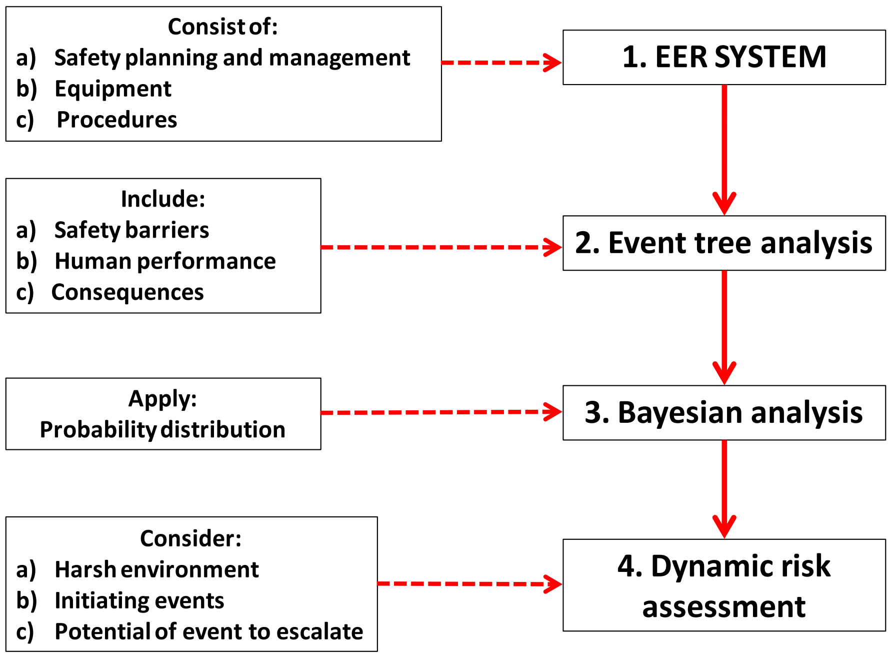

Figure 7.2: A methodology for developing a risk assessment of EER systems.

7.3.1 Event Tree Analysis

An event tree analysis is used to show the sequences of events involving emergency equipment, evacuation procedures, and human performance for every step. The event tree consists of probability of occurrence for outcomes of safety barriers performance in the emergency (Landucci et al., 2015). During emergency scenarios, the reliabilities of safety barriers can be degraded by environmental conditions and the presence of poor human performance and organizational factors (Paté-Cornell and Murphy, 1996). To integrate the sequence of events with harsh environment, human, and organizational factors, information in the event tree can be converted into a Bayesian network.

7.3.2 Bayesian Analysis

There are many studies that convert an event tree analysis to Bayesian analysis (Meel and Seider, 2006; Kalantarnia et al., 2009; Kalantarnia et al., 2010). The process of conversion should include developing a Bayesian network prior to Bayesian analysis. The Bayesian network is employed to study dependency or relationships among emergency equipment, evacuation procedures, and human performance based on a conditional probability table (CPT) (Eleye-Datubo et al., 2006; Matellini et al., 2013). Human and organizational factors, and the effect of environmental conditions can be included in the Bayesian network. Hugin software is used here as a tool for developing the Bayesian network (Hugin Expert, 2014).

7.3.3 Dynamic Risk Assessment with Environmental Conditions

To perform a dynamic risk assessment, the task can be divided into two parts: a) calculating and updating probabilities of occurrence for all safety barriers and environment conditions, and b) analysing effects and consequences of failure to complete EER to personnel. The emergency equipment, evacuation procedures, human actions, and environment conditions can have two outcomes during an emergency scenario (Guanquan and Jinhui, 2012): fail or succeed. The number of failures or successes is assumed to be a discrete variable to give a probability of occurrence. The probability distribution for a discrete variable is called a discrete probability distribution. Binomial distribution is one example of a discrete probability distribution used in the paper.

The Bayesian network can be extended to include harm to personnel and damage to emergency equipment. In terms of harm, the consequences can include both personnel's injury and fatality (Vinnem, 2007). Types of injuries can be first, second, and third degree burns (Assael and Kakosimos, 2010).

Section 7.4 presents a case study using this proposed methodology.

7.4 Case Study

An initiating event that initiates the evacuation process of personnel can be a release of hydrocarbon fluid and gas that could potentially result in fires and explosions (DNV, 2015). The proposed methodology is used here in the early stage of EER, which includes the activation of emergency alarm (OGP, 2010b). The case study focuses on personnel in a working area when the emergency alarm is triggered.

7.4.1 Prior Probability

The case study begins with collecting probability data, from available sources for emergency equipment, human actions, and harsh environmental conditions, as described in Sections 7.4.2 to 7.4.5. A *prior* probability is required in analyses involving an event tree, a Bayesian network, and a risk assessment.

7.4.2 Emergency Equipment

According to oil and gas regulatory and industry guidelines on emergency preparedness and EER, alarm systems consist of detectors and both audible and visual alarms (HSE, 1997; CAPP, 2010; CAPP, 2013). Information on the reliability of detectors and alarms is available in literature reviews (Chen, 2011). The reliability of detectors and alarms can be used as a *prior* probability as shown in Table 7.1.

Table 7.1: A prior probabilities of alarm systems.

Step	Equipment	A *prior* probability
Alarm	Gas and fire detectors	0.99
	Audible alarm	0.99
	Visual alarm	0.99

7.4.3 Human Actions

Failure probability of human performance during evacuation operations on offshore installations can be found in the literature (DiMattia et al., 2005; Khan et al., 2006; Deacon et al., 2010; Deacon et al., 2013; Musharraf et al., 2013). Previous research on estimating probabilities of human performance did not include environment conditions, which can influence the results. Based on the limitation in the previous studies, it is appropriate to consider the highest probability of success of human actions, information which is available in the literature review (Musharraf et al., 2013). Table 7.2 summarizes the list of probabilities used in this paper.

Table 7.2: A prior probabilities of human actions.

Step	Action	A *prior* probability
Alarm recognition	Aware (hear and see the alarm)	0.92
	Respond to alarm	0.83

7.4.4 Environment Conditions

The probability of environmental conditions is estimated based on a research study by Yun and Marsden- (2010). Table 7.3 shows the probability of a harsh environment in January and February.

Table 7.3: The probability of harsh environment in January.

Harsh environmental conditions	Probability	
	January	February
Low temperature (< -40^{o}F)	0.13	0.20
High wind (> 35 knots)	0.02	0.02
Dark (17 – 22 hours)	0.81	0.60

7.4.5 Injury and Death

The probability of injury and death are calculated considering the distance of flame surface to human exposure is 30 m and personnel wear winter clothes that give a large coverage of skin area (Assael and Kakosimos, 2010). Table 7.4 shows the probability of first and second degree burns and fatality.

Table 7.4: Probability of injury and death in fires.

Injury and death	Probability
First degree burn	0.14
Second degree burn	0.10
Death	0.06

7.4.6 Event Tree

As the primary physical barriers, gas, heat, and fire detectors can detect the hazards of hydrocarbon releases during the emergency scenario. Audible and visual alarms are the second safety barriers, with the purpose to notify personnel of the presence of hazards on the offshore installation. Upon hearing or seeing the alarm, personnel have to secure the work area, stop hot work, and move to muster stations. Figure 7.3 shows the sequence of alarm activation in a case of hydrocarbon releases on offshore installations.

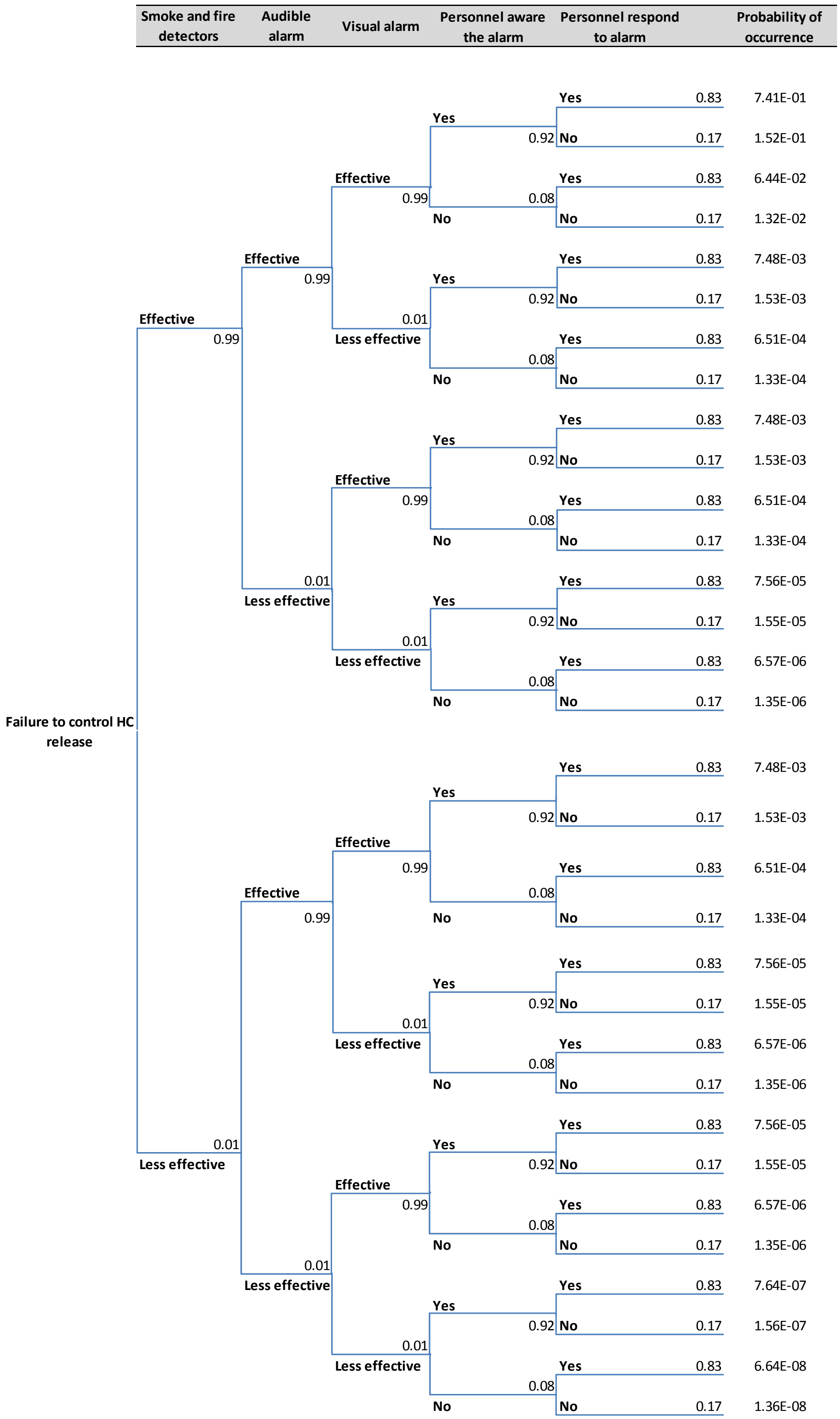

Figure 7.3: The event tree of alarm activation.

7.4.7 Bayesian Network

Figure 7.4 illustrates the Bayesian network for personnel responding to the activated emergency alarm. The detector is assigned as a parent node to both audible and visual alarms. Nodes of coldness, darkness, and high winds are connected to equipment (alarm) and human actions (aware and respond), where applicable. The node of respond is a child node and is the outcome of the relationships between equipment and environment conditions.

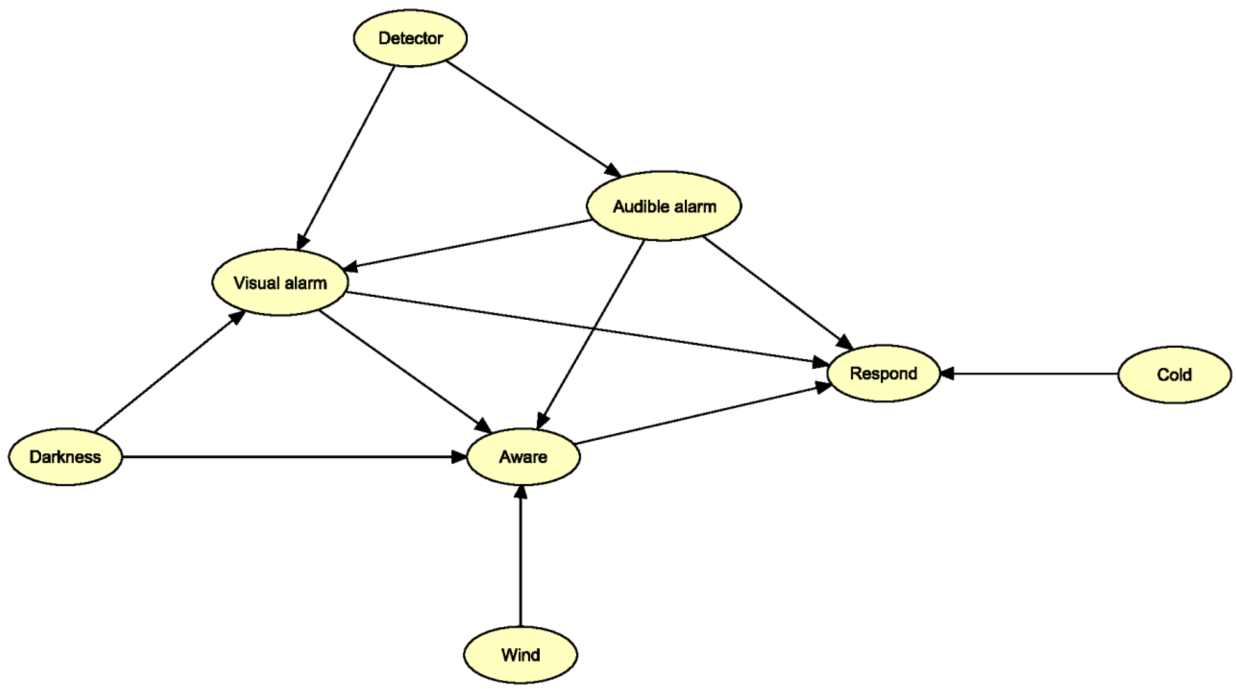

Figure 7.4: A Bayesian network for personnel responding to the emergency alarm.

7.4.8 Risk Assessment

In this model, the initiating event is a release of hydrocarbon on an offshore installation. The worst scenario would be combustion of the flammable substances followed by a series of fires. It is appropriate to note that intensity and heat radiation, as a result from the combustion, is beyond the scope of this paper. The respond node is connected to a consequence node so that the probability of injury and death is identified. Figure 7.5 illustrates the risk assessment with consequences using Bayesian network. In the diagram, 1 means ‘yes’ or ‘true’ and 0 represents ‘no’ or ‘false’. In the consequence node, 0 and 1 refer to first and second degree burns, respectively. The possibility of fatality is represented by an indicator number 2 in the node.

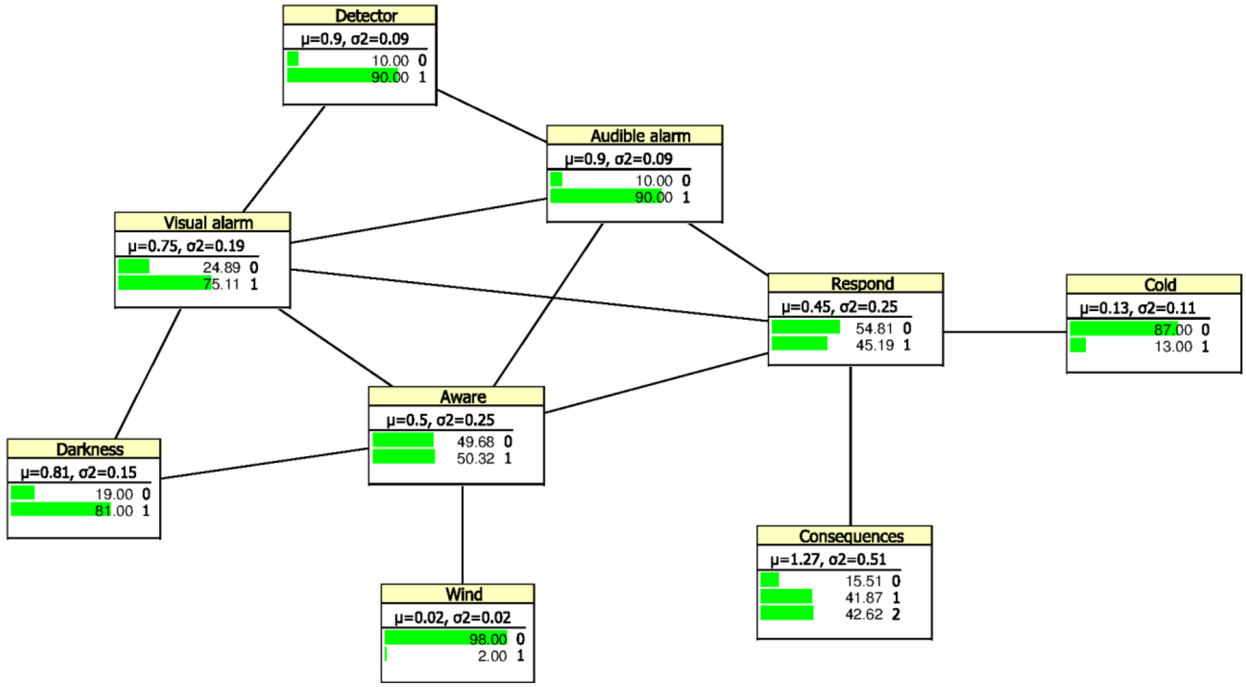

Figure 7.5: A Bayesian network for responding to alarm with probabilities in January.

7.5 Results

7.5.1 Probabilities and Consequences

Tables 7.5 and 7.6 illustrate the result of dynamic risk assessment considering the effect of harsh environments upon safety barriers and a personnel’s response. Based on the results, it shows that coldness, darkness and strong winds can affect the effectiveness of safety barriers and a personnel’s response. There are high possibilities that personnel may experience first or second degree burns if they do not respond after hearing or seeing the activated emergency alarm.

Table 7.5: Possible effects of environment conditions to personnel recognizing alarm in January.

Environment conditions	Probability of safety barriers			Probability of human actions		Probability of injury or death		
	Detector	Audible alarm	Visual alarm	Aware	Respond	First degree burn	Second degree burn	Death
Cold	0.90	0.90	0.75	0.50	0.13	0.30	0.48	0.22
Darkness	0.90	0.90	0.81	0.51	0.45	0.43	0.42	0.16
Wind	0.90	0.90	0.75	0.66	0.45	0.43	0.42	0.16

Table 7.6: Possible effects of environment conditions to personnel recognizing alarm in February.

Environment conditions	Probability of safety barriers			Probability of human actions		Probability of injury or death		
	Detector	Audible alarm	Visual alarm	Aware	Respond	First degree burn	Second degree burn	Death
Cold	0.90	0.90	0.56	0.50	0.20	0.33	0.46	0.20
Darkness	0.90	0.90	0.56	0.37	0.44	0.42	0.42	0.16
Wind	0.90	0.90	0.60	0.50	0.44	0.42	0.42	0.16

7.5.2 Sensitivity Analysis

Sensitivity analysis is conducted to verify nodes in the Bayesian network. The result of sensitivity analysis is shown in a tornado chart that provides information on the degree of uncertainty of safety barriers. The largest bar in the tornado chart represents a parent or intermediate node that contributes the most to the child node. In Figure 7.6, coldness and response are identified as the most influential nodes to the consequence node. The same result is observed for the sensitivity analysis of alarm recognition in February as presented in Figure 7.7.

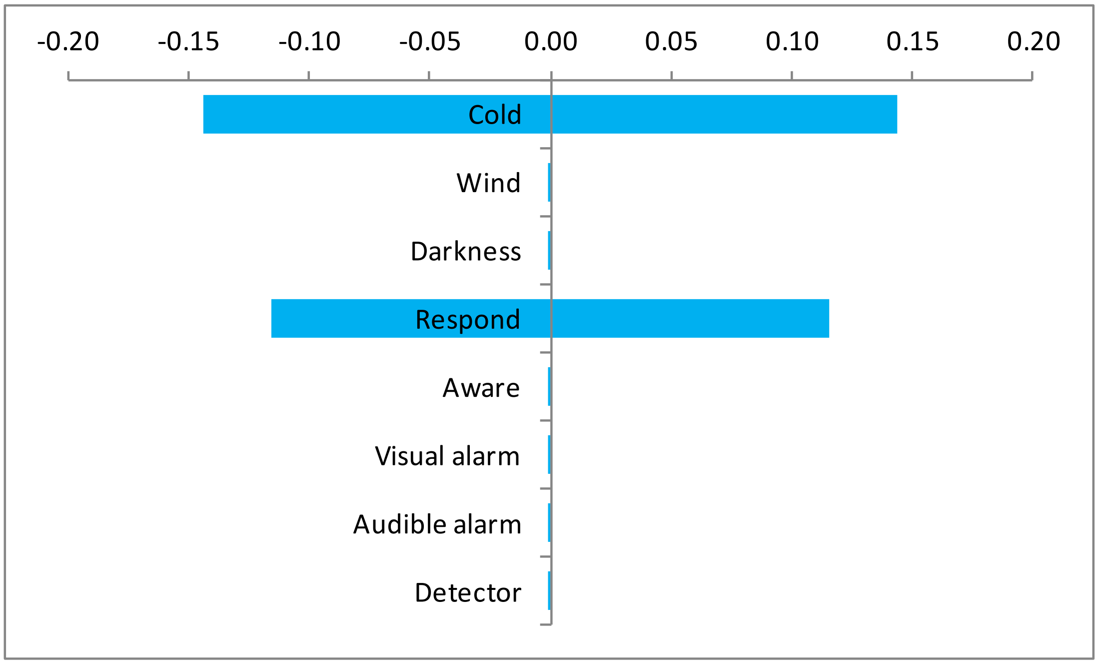

Figure 7.6: Sensitivity analysis for personnel recognizing alarm in January.

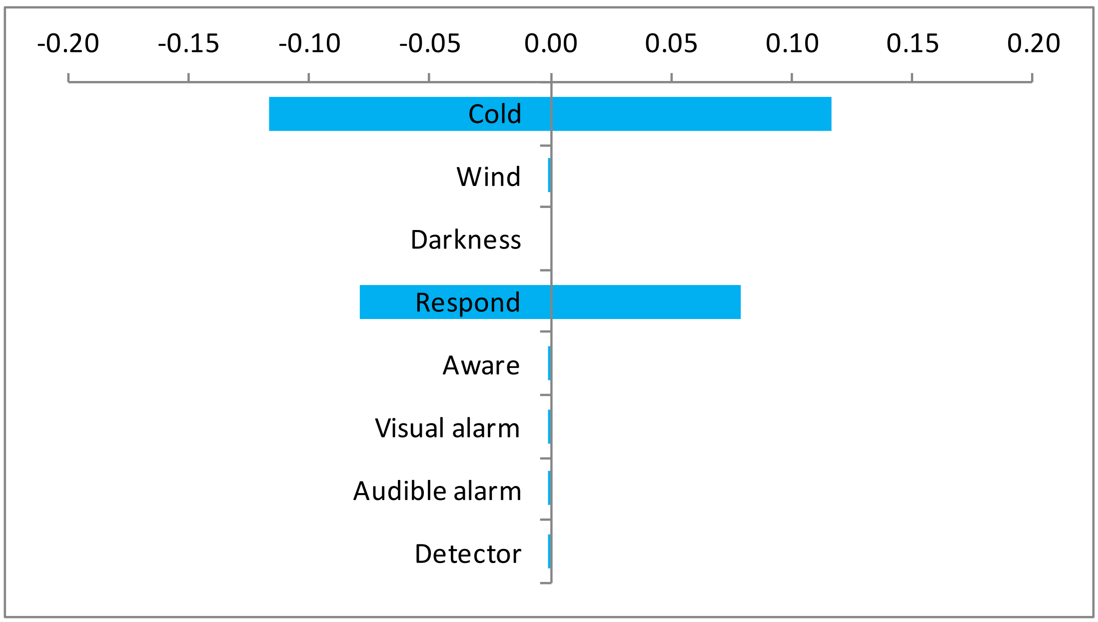

Figure 7.7: Sensitivity analysis for personnel recognizing alarm in February.

7.6 Discussions

Dynamic risk assessment of EER systems that considers harsh environmental conditions can be a basis for decision making regarding safety on offshore installations. The purposes of applying dynamic risk assessment in the EER system are to identify potential accidents while performing EER, update the probability of occurrence of accidents using new data or observations, and provide safety measures based on the potential accidents and consequences.

7.6.1 Identifying Potential Accidents

The risk assessment can address the potential of accidents and their expected consequences. By referring to the probability, the operator of an offshore installation- can identify the most risky activity or sequence of events in EER during poor environment conditions. Information in the dynamic risk assessment can provide a better understanding of effects of environment conditions on safety barriers and human responses while performing EER activities on offshore installations.

7.6.2 Updating Probability

New observations or evidence related to the probability of safety barriers or environment conditions are important in a dynamic risk assessment. Observations can include a) new data associated with safety barriers or environment conditions and b) new cause and effect relationships in a Bayesian network. The new observations update information on the likelihood of accidents and their outcomes.

7.6.3 Providing Safety Measures

Based on the Bayesian network and the probability of occurrence, the operators can identify weaknesses in the sequence of events associated with human responses and safety barriers.

Information in the dynamic risk assessment of EER systems can be a basis for making decisions to provide more training and to improve effectiveness of safety barriers

7.7 Conclusions

The objective of this paper is to present a methodology of risk assessment for EER on offshore installations in harsh environmental conditions. The proposed methodology is applied to a sequence of events involving personnel responding to emergency alarms on an offshore installation. Cold temperature, strong winds, and darkness can affect the effectiveness of equipment and human responses during these emergency situations. The results of a sensitivity analysis show that coldness and human response are contributing factors to personnel responding to the emergency alarm.

In this paper, the study does not specify types of fires and explosions, such as pool fire or jet fire. The types of fires can affect personnel's interaction with the hazard and subsequent escape times. The reaction time of personnel moving to muster station is also associated with a specific layout of offshore installations. The risk assessment of EER at an accommodation area will not have same results as on a drill floor or other areas.

For future work, it is appropriate to focus on reducing risks associated with EER systems by doing a risk management exercise after the risk assessment of personnel performing EER in a harsh environment.

7.8 Acknowledgements

The authors would like to thank the Atlantic Innovation Fund (AIF) and Natural Science and Engineering Research Council of Canada (NSERC CREATE) for the financial support necessary for this research study.

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Chapter 8

The Use of a Virtual Environment in Managing Risks Associated With Human Responses in Emergency Situations on Offshore Installations

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Preface

This manuscript is prepared and submitted to the ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part B: Mechanical Engineering. The first author introduced a risk management using a safety hierarchy for escape and evacuation operations. This manuscript consists of a brief explanation of the framework and integration with the risk management study. Data used in this manuscript is obtained from the experimental study done by the second author. The risk management study and this manuscript have been reviewed by Drs. Faisal Khan and Brian Veitch to ensure this manuscript is suitable for publication.

Abstract

This paper presents the use of a virtual environment in investigating the management of risks associated with human responses in emergency situations on offshore installations. The interaction of personnel using the safety measures in emergency situations can be affected by hazards, environment conditions, and factors such as malfunctioning equipment and inadequate emergency drills. Such situations have the potential to prevent personnel from arriving at a safe area, increase the level of risks, and consequently, cause injuries or fatalities to personnel. A safety hierarchy for risk management introduces inherent, engineering, and procedural safety measures for emergency situations on offshore installations. Experimental data collected from studies of human responses in a virtual environment are used to assess performances and risks in emergency situations. A virtual environment is a practical means to investigate risk management alternatives by validating the effectiveness of safety measures, providing support for improvement, and finally, proposing new design of safety measures.

Keywords: *Emergency situation, human responses, offshore installation, risk management, safety hierarchy*

8.1 Introduction

The organization or operator of offshore installations should prioritize the emergency response plan and safety barriers for the escape operation in emergency situations. Safety barriers for the escape can include an alarm system, primary and alternative escape routes, muster stations, and personal protective equipment. The organization must ensure that personnel practice emergency drills and exercises to familiarize themselves with the equipment and procedures, and identify limitations, potential hazards and risks in performing escape from hazardous areas. The challenges and risks of performing escape depend on an individual's skills and experience, teamwork, procedures, roles and responsibilities, communication, as well as the emergency response plan, environment conditions, and reliability of emergency equipment. All of these factors influence the effectiveness of safety barriers, the success of escape operations, and the safety of individuals should an emergency scenario occur.

The presence of hazards in the escape operation cannot totally be eliminated. Emergency scenarios in the presence of hazards can worsen when personnel fail to interact with emergency equipment and follow procedures consistently. The effects of fires and explosions and poor environmental conditions can cause failures of both personnel responses and the escape.

There are many studies that have introduced or proposed effective tools and techniques as safety measures in emergency situations on offshore installation. DiMattia et al. (2005) and Deacon et al. (2010) proposed prevention and mitigation barriers in risk management focusing on personnel performing escape, evacuation and rescue (EER) activities. Andersen and Mostue (2012) presented integrated operations (IO) on risk management approaches using real-time data, collaborative techniques, and multiple expertise in making better decisions and implementations for the Norwegian oil and gas industry. Colombo and Golzio (2016) introduced a simulation-based approach to train teams, including operators and managers, in making decisions and increasing their competencies as a team in critical situations.

Poor performance or lack of response in emergency situations can result in injuries and fatalities to personnel. There is a need to reduce and manage risks associated with personnel performance in emergency situations on offshore installations. This paper presents the use of virtual environments in managing risks of personnel responses in emergency situations. This paper uses experimental data of human responses obtained from studies using virtual environments.

Section 2 describes the risk management framework. Section 3 explains the risk calculation and its formula. Sections 4 and 5 present two virtual environment experimental studies and data analyses. Section 6 concludes the objective of this paper.

8.2 Developing a Framework of Risk Management for Escape in Emergency Situations

A framework is designed to illustrate the development of risk in emergency situations, its effect on personnel responses, and the procedures for managing risks. Further illustration is shown in Sections 8.2.1 and 8.2.2.

8.2.1 A Framework of Risk Management

Figure 8.1 shows a framework of risk assessment and management for personnel responses in emergency situations. The framework consists of seven elements:

i) emergency situations that require personnel to escape from hazardous areas,

ii) hazards and factors that can affect personnel responses,

iii) probabilities of success and failure of personnel responses,

iv) consequences of failures to respond effectively,

v) risk assessment by integrating probability and consequences,

vi) level of risk accepted by organizations and operators of offshore installations, and

vii) risk management.

This paper focuses on the risk management element. The other elements are presented and discussed in other previous papers (Norazahar et al., 2014; Norazahar et al., 2016a; Norazahar et al., 2016b).

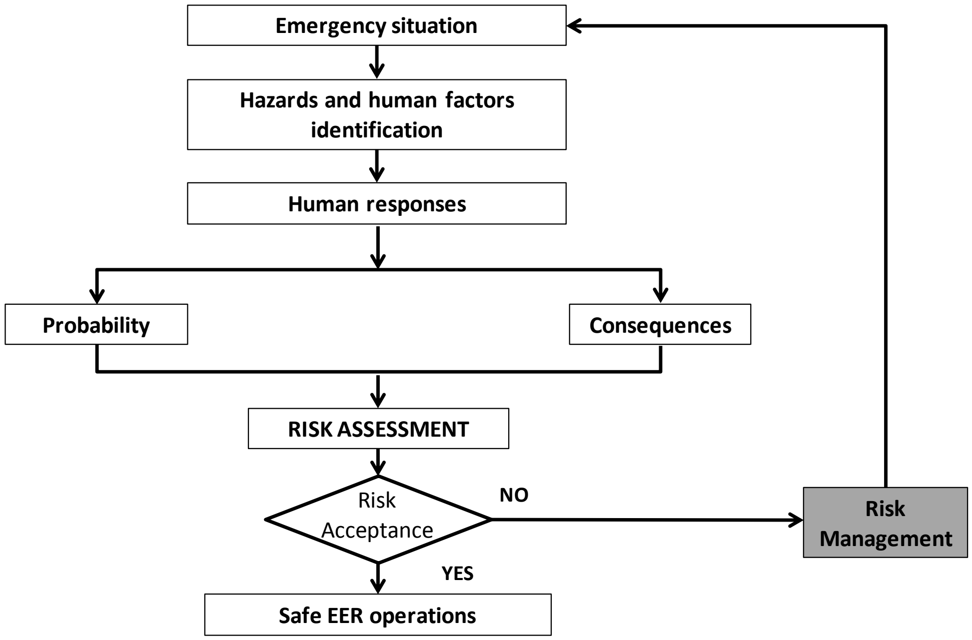

Figure 8.1: The framework of risk management for emergency situations.

8.2.2 Safety Hierarchy

Figure 8.2 illustrates a safety hierarchy that can be implemented through risk management of emergency situations. The safety hierarchy has three safety steps: a) inherent safety, b) engineering safety, and c) procedural safety. The inherent safety measures can include: a) elimination and minimization of hazards, b) substitution of existing equipment, and c) simplification of procedures. Engineering safety requires adding safety equipment to facilities provided for emergency situations. Safety equipment can be either active or passive barriers, and its purpose is to provide reliable safeguards or equipment for reducing risks associated with personnel responses. Modification or changes to equipment must be followed by updating rules and procedures to allow personnel to have a better understanding of hazards, equipment, procedures, human factors and environmental conditions involved in emergency situations.

As case studies in this paper, examples of active safety measures are normal lighting and exit signage. An example of a procedural safety barrier is frequent exposure via drills to enhance individuals' competence. Normal lighting and individuals' competence are explained in Section 8.4.1.2. Details of exit signage as active barriers are described in Section 8.4.2.2.

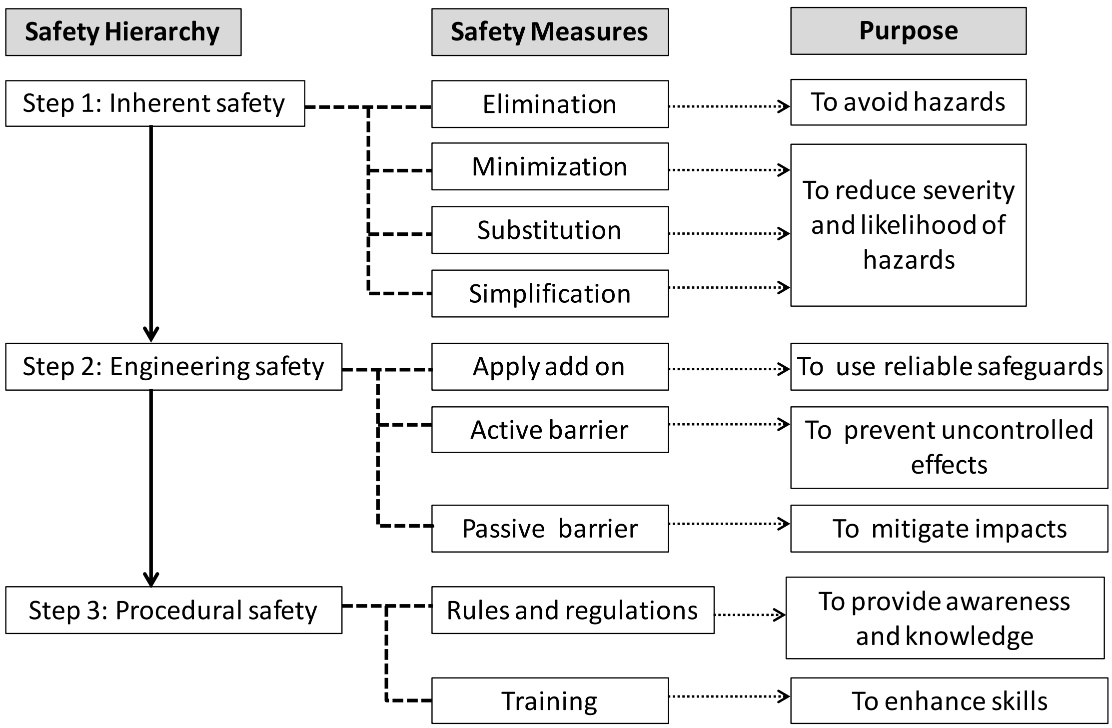

Figure 8.2: Safety hierarchy for managing risks in emergency situations.

8.3 Calculation of Risks

Risk can be defined as a measurement of human responses (or hazards associated with human responses) in terms of the probabilities and consequences. Probability with regard to a specific action is an expression of likelihood and can be quantified to give a discrete value (Kumamoto and Henley, 1996). The consequences of failure are based on subjective evaluation and expressed as injury, fatality, and damage to an offshore structure and the environment. In this paper, risk is assessed with regard to the probability of human responses only. In case studies used here, we treat consequences of failure as neutral (i.e. risk is proportional to probability only).

The probability of human responses is calculated by considering the performance score in the emergency scenarios from two experimental studies, as further explained in Section 8.4. The performance score is analysed to determine the mean and standard deviation (Duarte et al., 2014; Smith, 2015a). Information on mean and standard deviation is used to calculate a probability of failure based on a normal distribution. The probability of failure can be a value on a scale between 0 and 1. This paper assumes a normal distribution to simplify the calculations.

The next step is to estimate the risks associated with the human responses by comparing the probability of failure between the baseline and emergency situation equipped with safety barriers. The calculation of the change in risk is formulated as shown in Equation 8.1.

$$\triangle Risk = High\ probability - Low\ probability \qquad \text{…Equation 8.1}$$

8.4 Case studies: Experimental Scenarios Using Virtual Environment

Data from two published experimental studies of different virtual environments have been selected to provide data for this risk management study. The first experimental study, entitled 'The effect of virtual environment training on participant competence and learning in offshore emergency egress scenarios', is the source of data on human responses in an emergency scenario on an offshore installation (Smith, 2015a). The second experimental study, entitled 'Behavioural compliance for dynamic versus static signs in an immersive virtual environment', is the source of data on behavioural compliance with signage (Duarte et al., 2014).

Both experimental studies were conducted using virtual environments (VE) with the purpose to observe human responses and behaviours during emergency conditions (Duarte et al., 2014; Smith, 2015a; Musharraf et al., 2016). Simulating emergency conditions in the VE can provide a safe medium for participants to acquire artificial experience, which is otherwise impractical and risky to obtain in a real situation. Details of emergency scenarios in the VE are explained in Sections 8.4.1 and 8.4.2.

8.4.1 Offshore Emergency Egress Scenario on an Offshore Installation

Emergency scenarios on an offshore installation were designed and simulated using the All-hands Virtual Emergency Response Trainer (AVERT) software (Smith et al., 2015b; Musharraf et al., 2016). The layout in AVERT includes accommodations, a muster station located on the main deck (3 decks below the accommodations), and a lifeboat station, also located on the main decks. Three routes were provided as egress routes: a) the primary route characterized as an interior route with inside stairwells, and b) secondary and tertiary routes characterized as exterior routes with outside stairwells.

The simulation scenarios begin with the activation of an emergency alarm (General Platform Alarm) that requires personnel onboard to move to a muster station using designated escape routes. In the case of an escalating event, an evacuation alarm (Prepare to Abandon Platform Alarm) is triggered to notify personnel to muster at the designated lifeboat station. Hazards such as blackouts, fire, and smoke were designed in AVERT to create credible emergency scenarios. The emergency scenario with the presence of hazards requires participants to find a safe route to a muster or lifeboat station by avoiding the hazard that blocks escape routes.

8.4.1.1 Participants of study

Thirty-six volunteers participated in the study. Participants were divided into two groups based on video game experience. The groups differed based on the amount of practice the participants in each group received. The 17 participants in Group 1 had repeated training. The 19 participants in Group 2 had a single exposure to training (Smith, 2015a; Smith et al., 2015b). The 17 participants in Group 1 reviewed training tutorials and repeated practice scenarios in preparation for the test scenarios. The 19 participants in Group 2 received the initial tutorial emergency training and no practice scenarios. Both groups completed the same four (4) testing scenarios of emergency response in AVERT.

8.4.1.2 AVERT emergency response test scenarios

Table 8.1 lists four (4) emergency scenarios in AVERT selected for this paper. From these different scenarios, two types of human responses can be analysed for the study of risk management: a) wayfinding in a normal lighting condition and in blackout conditions and b) competency of participants.

Table 8.1: Description of emergency scenarios designed in the AVERT (Smith, 2015a).

Scenario label	Scenario description
TA1	The participants are required to respond to a general platform alarm (GPA) and find a way from their accommodation to their primary muster station.
TA3	The participants are required to respond to a prepare to abandon platform alarm (PAPA) and find a way from their accommodation to their lifeboat station in a blackout scenario due to equipment failure.
TH1	The participants are required to respond to a GPA because there is fire in the galley. The emergency scenario escalates and causes a PAPA activation. In response to the GPA, participants must go to a primary muster station from their accommodation. When the alarm changes to PAPA, the participants change their route and head to a lifeboat station. Both the primary route and muster station have been blocked by the effects of fires.
TH2	The participants are required to respond to a GPA because there is fire on the helideck. The emergency scenario escalates due to explosion and smoke and thus, it causes a PAPA activation. The task is that the participants must go to a primary muster station from their accommodation and change the route heading to a lifeboat station. The secondary route has been blocked by the effects of fires and explosions.

i) Wayfinding in normal lighting condition and blackout scenario

Wayfinding reflects the participants' spatial knowledge of the platform, specifically their understanding of the layout and egress routes. The wayfinding is assessed by considering a) the route selection (primary, secondary, and tertiary routes), b) the arrival at the correct muster or lifeboat station, and c) incorrect deviations along the route. The participants' performance is compared to responses during two different emergency scenarios, which are a) in a normal lighting condition (TA1) and b) a blackout scenario (TA3).

ii) Competency of participants

In this paper, competence is defined as demonstration of knowledge related to alarms recognition, routes and mapping, and hazards avoidance, which participants gained in the training tutorials. The participants were evaluated based on their performance in recognizing types of alarm, re-routing and taking safe routes, avoiding hazards on route, and arriving at the correct muster or lifeboat station. Competency of participants was assessed in two emergency scenarios with escalating events that required them to re-route due to a) primary route and muster station were blocked by fire and smoke (TH1) and b) secondary route was blocked by fires, explosions, and smoke (TH2).

Criteria used in assessing wayfinding and competency of participants are summarized in Table 8.2.

Table 8.2: Criteria in assessing responses of participants during emergency scenarios.

Criteria	**Types of scenarios**	
	Wayfinding in different conditions	**Competency**
Scenarios	- TA1 and TA3	- TH1 and TH2
Criteria for calculating risks	- Take primary, secondary, or tertiary route, - No change of route from one to another route, and - Arrive at the correct location.	- Take primary, secondary, or tertiary route, - Re-route when the route has been blocked or affected by the effects of fires and explosions, - Avoid hazards, and - Arrive at the correct location.

8.4.2 Behavioural Compliance for Dynamic versus Static Signs in a Building Evacuation

Researchers (Duarte et al., 2014) used an immersive virtual environment known as ErgoVR to investigate dynamic versus static signs on human behaviour during emergency evacuation. ErgoVR simulated a building consisting of four (4) rooms: meeting room, laboratory, cafeteria, and warehouse. The walls of the rooms and hallway have safety signs and exit signs. The experiment required participants to go to every room and look for instructions for the given tasks in the scenario. When the participants entered a warehouse an animation of an explosion followed by a fire suddenly occurred. The fire alarm was triggered due to the explosion and fire in the VE. All corridors except the exit route were affected by the hazard and blocked by flames and smoke. The emergency scenario required participants to follow the exit signs in order to safely evacuate the building.

8.4.2.1 Participants of study

A total of 90 participants consisting of university students were involved in the experimental study. Thirty (30) participants were assigned to each of the following groups according to the different types of exit signs: a) with a minimal design, b) in a static, and c) in a dynamic configuration.

8.4.2.2 Types of exit signage

Available egress routes were marked by exit signs consisting of an arrow and a running figure in a doorway. The experiment varied the number of exit signs available and the type of exit signs (static and dynamic signs). Three different types of exit signs are described in Table 8.3.

Table 8.3: Description of exit signs used in the virtual environment (Duarte et al., 2014).

Type of signage	Description
Minimal exit signs	The scenario of evacuation with minimal design of exit signs is assigned as a baseline with a purpose to assess the impact of exit signs on behavioural compliance.
Static exit signs	The exit route in the VE is equipped with color printed exit signs.
Dynamic exit signs	The exit signs in the VE are designed to have five (5) flashing lights in an orange color and an alarm 'beep' sound activated or de-activated by sensors.

The objective of the study was to investigate human behaviour in complying with exit signs. The participants were expected to move toward the exit door following the exit signs in order to evacuate the building safely. They were given scores for the performance of safe evacuation (Duarte et al., 2014).

8.5 Data Analysis to Determine Risks Associated With Human Responses

Sections 8.5.1, 8.5.2, and 8.5.3 present the results of data analysis for the following factors: wayfinding in normal lighting conditions compared to blackout scenario, competency of participants in emergency offshore evacuation, and behavioural compliance with exit signs, respectively.

8.5.1 Impact of Lighting Condition and Blackout Scenario on Wayfinding

Some participants (Smith, 2015a) used the primary and secondary routes from the accommodations to arrive at the muster station in the testing scenario with a normal lighting condition (TA1). In a blackout scenario (TA3), the participants are required to find a lifeboat station from their accommodation using available routes. The experimental data of TA3 shows that participants used all routes available, which are primary, secondary, and tertiary routes.

The change in risk represents the difference between the probabilities of failure for the blackout and normal lighting scenarios (denoted as $\Delta \text{Risk}_{\text{Blackout}}$). As indicated in Figure 8.3, the value of the change in risk is 0.46. The risk of error in wayfinding is high due to the difference between the use of the primary route in normal lighting conditions and the use of primary, secondary, and tertiary routes in the blackout scenario.

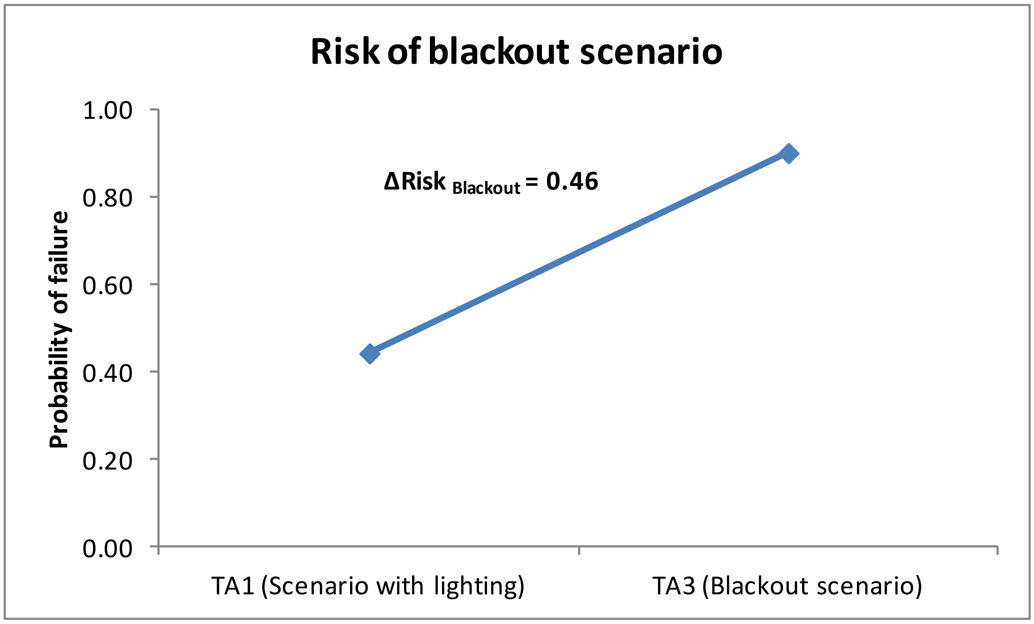

Figure 8.3: Risks of wayfinding in blackout scenario.

8.5.2 Competence

Scenario TA1 can be used as a baseline for assessing the performance of participants in emergency situations. The probability of failure in TA1 is 0.44. The majority of participants in TA1 successfully performed the scenario by selecting and taking a primary egress route from their accommodation to a muster station.

8.5.2.1 Emergency scenario requiring hazards avoidance and re-routing (TH1)

In test scenario TH1 there was a fire and smoke blocking the muster station and primary egress route. Participants were required to re-route from the primary egress route to a secondary route due to the hazard blocking the end of the primary route and muster station. The requirement of participants to re-route was communicated using an evacuation alarm change and a public address (PA) announcement. The performance of participants in Groups 1 and 2 is described below.

i) Performance of participants in Group 1

Based on experimental data, the probability of failure with regard to performance of participants in Group 1 in TH1 is 0.96. There were only four (4) participants who successfully re-routed from the primary to the secondary egress route after hearing the evacuation alarm (PAPA). Three (3) participants only changed their route from the primary to the secondary egress route after encountering the hazards.

The difference in probabilities between TA1 and TH1 is denoted as $\Delta Risk_{Group1}$ with a value of 0.52. The change in risk is shown in Figure 8.4. The experimental data from TA1 and TH1 show that participants preferred to use the primary route as their main means to the muster and lifeboat stations.

ii) Performance of participants in Group 2

The probability of failure of participants in Group 2 in TH1 is 0.94. Of all the participants in Group 2 (n=19), seven (7) participants managed to re-route to the secondary egress route after hearing the evacuation alarm (PAPA) and arrive at the lifeboat station safely.

The comparison of the probabilities of failure between TH1 and TA1 yields in a $\Delta Risk_{Group2}$ of 0.40, as shown in Figure 8.4. The contributing factor to the risk is likely due to a small number of participants who did not change the route from the primary to the secondary egress route even after they heard the evacuation alarm (PAPA) and failed to arrive at the lifeboat station.

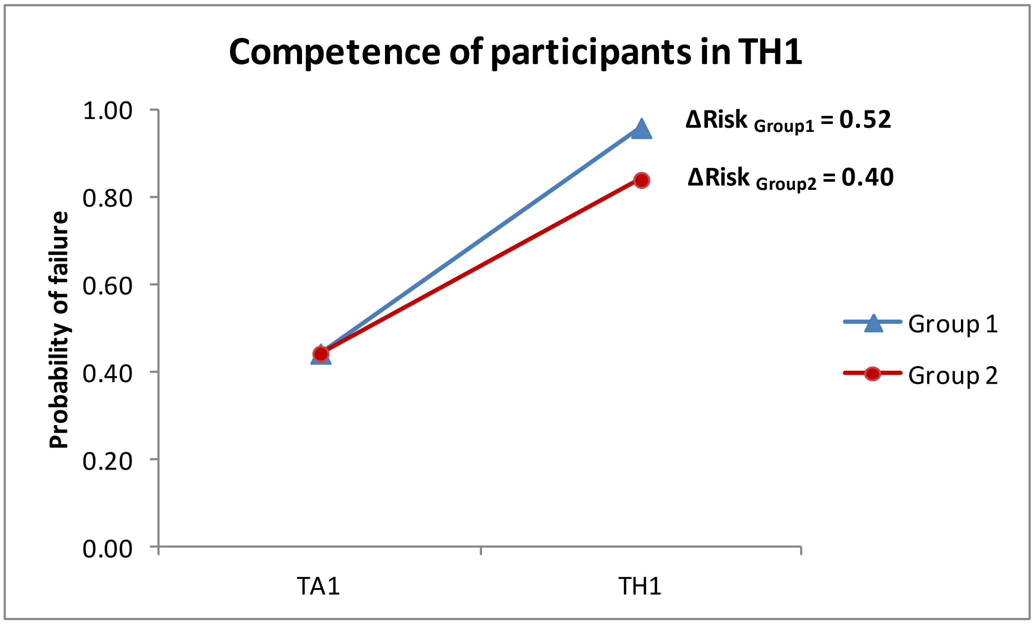

Figure 8.4: Competence and risks in TH1.

8.5.2.2 Emergency scenario requiring hazards avoidance and re-routing (TH2)

The emergency situation in test scenario TH2 involves a fire on a helideck. Fire and smoke blocked the entrance of the secondary and tertiary egress routes. Participants were required to move from their accommodation to the primary muster station and re-route to the lifeboat station due to the escalating event. The requirement of participants to re-route is communicated using an evacuation alarm (PAPA) change and a public address (PA) announcement. The performance of participants in Groups 1 and 2 is described below.

i) Performance of participants in Group 1

The probability of failure of participants in Group 1 in test scenario TH2 is 0.64. There were 12 participants who successfully used the primary route after taking into consideration the evacuation alarm (PAPA) and PA announcement explaining the unsafe condition of a secondary egress route (outside stairwell). Comparing the data of TA1 (as a baseline) to assess performance in TH2, it is found that $\Delta \text{Risk}_{\text{Group1}}$ is 0.20 as presented in Figure 8.5. The contributing factor to the risk value is due to four (4) participants who failed to re-route after hearing the PAPA alarm or after encountering the hazards. There was also one participant who became lost and therefore failed to reach at the lifeboat station.

ii) Performance of participants in Group 2

The probability of failure performance in Group 2 in TH2 is 0.81. Only nine (9) participants managed to successfully re-route and use the primary egress route leading to the lifeboat station. The difference in performance of participants between TA1 and TH2 is denoted as $\Delta \text{Risk}_{\text{Group2}}$ as shown in Figure 8.5. From the data, it is observed that some participants used the secondary egress route as a way to the lifeboat station no matter what the circumstances. These participants did not re-route even after they heard the PAPA alarm and did not re-route after they encountered the hazard.

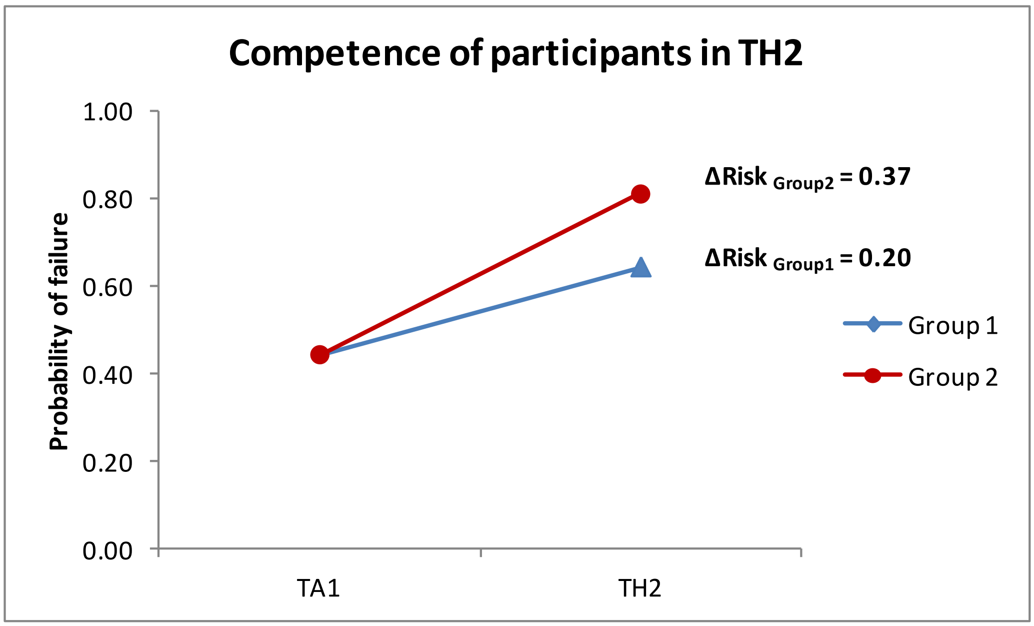

Figure 8.5: Competence and risks in TH2.

8.5.3 Behavioural Compliance with Exit Signs

8.5.3.1 Minimal signs as a baseline

Exit signs with a minimal design were used as a baseline in this case study. Experimental data collected from behavioural compliance of participants with minimal design of exit signs can be compared to behavioral compliance with static and dynamic exit signs. The probability of failure to follow minimal design of exit signs is 0.99. The high probability indicates the participants were not influenced by the minimal exit signs on the egress route.

8.5.3.2 Static exit signs and dynamic exit signs

In Figure 8.6, $\Delta \text{Risk}_{\text{Static}}$ represents the difference in probability between minimal exit signs and static exit signs. It has a value of 0.19. This change in risk shows that the influence of static exit signs is better than a group of participants using minimal exit signs during emergency (Duarte et al., 2014).

In the experimental study, the probability of failure of participants to take egress routes following the direction shown by a dynamic exit signs is 0.71. Using the minimal design of exit signs as a baseline (with the probability of 0.99), the comparison of participants' behavioural compliance with dynamic exit signs is denoted as $\Delta \text{Risk}_{\text{Dynamic}}$. As shown in Figure 8.6, $\Delta \text{Risk}_{\text{Dynamic}}$ has a value of 0.28. The dynamic exit signs had more impact on participants' decision to take egress routes during emergency than the static exit signs.

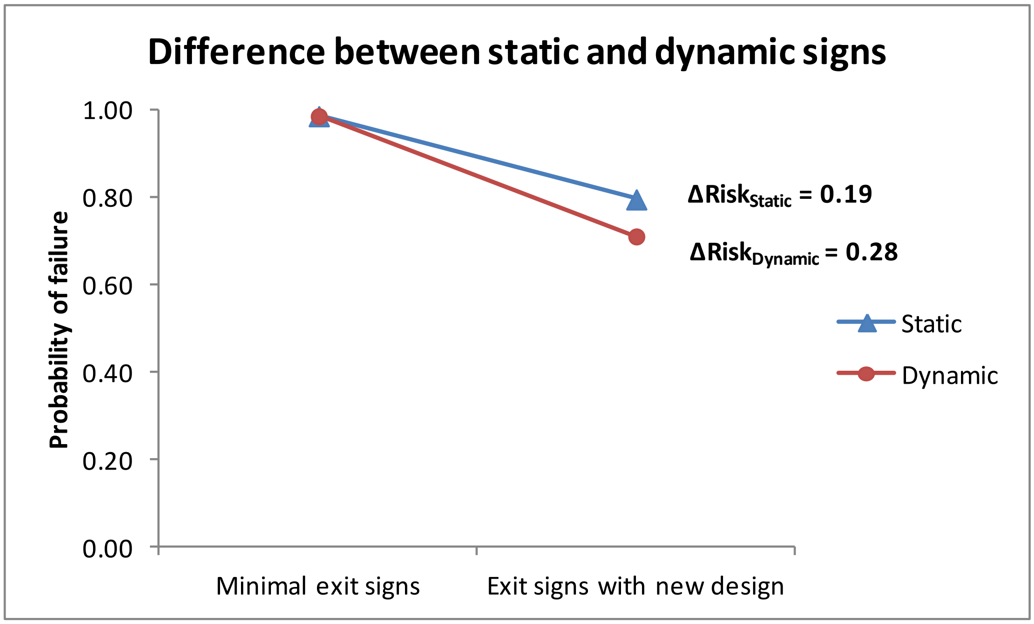

Figure 8.6: Risks of not complying exit signs.

8.6 Discussion

Findings of the use of a virtual environment for assessing risk management options in emergency scenarios are discussed in Sections 8.6.1, 8.6.2, and 8.6.3.

8.6.1 Validating Safety Measures

A virtual environment is a practical tool for an individual to demonstrate their learning, understanding, and skills of escape. There are two types of safety measures validated in both experimental studies presented in this paper: a) engineering safety, which includes lighting and exit signs, and b) procedural safety, which includes competence in emergency scenarios. Participants in both the experimental studies were practiced using the safety measures, which are similar to the safety measures provided on offshore installations. Credible emergency scenarios with the presence of hazards in a virtual environment can allow an individual to interact and familiarize him/herself with the safety measures.

8.6.2 Providing Evidence to Improve Safety Measures

Data of performance in emergency scenarios using virtual environments could provide support and evidence to improve engineering and procedural safety measures. Risks associated with performance in emergency scenarios using virtual environments can demonstrate the need for improvement of the existing safety measures. The improvements can be proposed using a safety hierarchy with the objective to reduce risks associated with performance.

8.6.3 Designing and Implementing New Safety Measures

The use of virtual environments in a risk management study is a starting point for decision making on the design and implementation of new or existing structures or safety measures. A virtual environment can be used to experiment and implement new safety measures for emergency situations. The decision to implement in real life can be based on the performance of individuals interacting with the safety measures in a virtual environment.

8.7 Conclusions

Virtual environment can be used to assess human responses and the risks associated with human responses during emergency situations. The experimental data of human behaviour during emergency scenarios in virtual environments show that participants' performance is dependent on the types of equipment implemented in the environment and the egress route choices that have been trained. Risks are analysed to illustrate the differences between participants' performance with and without the presence of safety measures. Safety measures are identified and discussed according to a safety hierarchy that consists of engineering safety and procedural safety. Participants' performance and their interaction with safety measures can lead to design improvements for emergency equipment. The new design of safety measures should be tested in a virtual environment prior to implementation in real life to avoid making poor decisions in safety management.

This paper presents the risks and the associated safety measures based on data collected in virtual emergency scenarios from two published studies (Duarte et al., 2014; Smith, 2015). The data analysis does not consider the long-term effects of the VE on participants' performance. The calculation of probability based on a normal distribution is not verified scientifically.

For future work, verification such as confidence interval should be included in the risk management study to make the calculation of probability and risk more credible. Data analysis should also consider consequences of failure in performing escape. The risk can be minimized or managed considering both probability and consequences aspects.

8.8 Acknowledgement

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Chapter 9

Conclusions

This research has achieved the objective of the study, which is to develop a framework of human and organizational factors risk assessment and management for the operation of escape and evacuation on offshore installations. The significance of the framework includes the ability to a) identify the presence of human and organizational factors that can affect personnel responses, b) estimate the probability of success of personnel responses considering human and organizational factors and environmental conditions, and c) manage risks associated with personnel responses considering engineering and procedural safety in the operation of escape and evacuation. The conclusion for each part of the framework is described in Sections 9.1 until 9.4.

9.1 A Framework for Identifying Human and Organizational Factors Is Developed Based On Layers of Protection

The framework for identifying human and organizational factors is developed considering layers of protection. Human and organizational factors are defined according to layers of protection that consist of organization, evacuation procedures, emergency equipment, and personnel capabilities. Human and organizational factors are identified when a layer of protection fails to stop or prevent hazards from evolving. The framework of human and organizational factors identification has been applied to assess the escape and evacuation operations of the BP Deepwater Horizon. Human and organizational factors, in particular poor communications, insufficient emergency drills and exercises, unsafe conditions that affect physical capabilities, and inadequate emergency preparedness all affect personnel's ability to perform escape and evacuation activities and increase risks to personnel.

9.2 The Probability of Success of Personnel Responses Is Calculated Using Bayesian Analysis

Bayesian analysis is used to show the relationships between human and organizational factors and equipment and procedures at every level of the protective layers of an escape and evacuation system. From these relationships, the probability of success of personnel responses is calculated considering the human and organizational factors and harsh environmental conditions. Bayesian analysis integrated with sensitivity analysis has identified critical human and organizational factors in the escape and evacuation operations of offshore installations in a harsh environment. Based on the results of sensitivity analysis, the alarm system must be well maintained and assessed for operational readiness to ensure the audible alarm is working effectively in the event of emergency. Personnel must be alert to both audible and visual alarms, particularly in the presence of high wind, darkness, and low temperature, should an emergency occur. Both Bayesian and sensitivity analyses illustrate the importance of the offshore installation's organization acknowledging critical human and organizational factors prior to an escape and evacuation improvement program.

9.3 Risks Associated With Personnel Responses Are Assessed Considering Changes to Barriers and Environment Conditions over Time

The sequence of events involving personnel responses, the use of emergency equipment, and evacuation procedures is translated to cause-effect relationships using Bayesian analysis. The approach is designed to be a dynamic risk assessment that includes safety barriers of the escape and evacuation system and harsh environmental conditions changing over time. The results of using the approach show that cold temperature, strong winds, and darkness can affect the effectiveness of equipment and personnel awareness of alarms during emergency situations.

9.4 Risk Management and Safety Hierarchy Is Validated Using Data from the Experimental Study of Human Responses in Emergency Scenario

The risks associated with personnel responses in emergency situations are analysed with and without the presence of safety barriers. There are two safety barriers applicable to the emergency escape and evacuation, which are engineering safety and procedural safety. Human responses in the presence of engineering safety and procedural safety are observed and assessed in emergency escape and evacuation using a virtual environment. The risk management study using the safety hierarchy shows that the design of emergency equipment and the structure of the surroundings must consider human responses in emergency situations. The design and implementation of safety measures should consider the capacity of humans to react and make decisions during emergencies.

9.5 Research Limitations

There are limitations in this research that may restrict the application of the framework. The limitations are discussed as follows:

9.5.1 Uncertainty in Translating Guidewords in Oil and Gas Industry Standard Practice and Guidelines to Quantitative Probabilities Data

The case studies in Chapters 6 and 7 used as probability data, numbers translated (subjectively) from guidewords. The translation is uncertain, and may give overestimated or underestimated probability values. The presence of uncertainty in the calculation can influence the probability value of personnel responses.

9.5.2 The Scarcity of Human Responses Data during Escape and Evacuation with Hazards and Harsh Environmental Conditions

Data on human responses performing escape and evacuation is difficult to obtain. The application of the framework requires data on human responses while performing escape and evacuation activities considering harsh environmental conditions. The case study in Chapter 7 uses two different types of probability data: a) human responses performing escape and evacuation and b) harsh environmental conditions. The probability data in two different conditions may give inaccurate results.

9.5.3 The Focus of Research Work Is on Emergency Escape Part Only

The case studies presented in the research papers consider failures of personnel to detect an alarm in emergency situations. The framework has not been tested and applied to overall escape, evacuation and rescue (EER) operations. There are no results or discussion on evacuation and rescue operations.

9.6 Future Work

There are recommendations for improving the study. The recommendations are as follows:

9.6.1 Use Experimental Data to Find Probabilities of Human Responses

To obtain credible probability data on human responses, it would be helpful to conduct an experimental study of personnel performing escape and evacuation activities using a virtual environment. The experimental data can reduce the uncertainty related to the probability of failures and effectiveness of escape and evacuation operations. The experimental study should consider the presence of hazards and harsh environmental conditions during emergency response situations. The data from the experimental study will be meaningful to offshore oil and gas industry operations in harsh environmental conditions.

9.6.2 Validate the Framework in an Experimental or a Case Study

The framework of risk assessment and management for human and organizational factors and its application should be validated in an experimental study or case studies of offshore accidents. Validation is important to assessing the practicality of the framework and its application to the offshore oil and gas industry. The framework applied in the experimental or case study can provide evidence of the effectiveness of the framework in assessing and managing risks.

9.6.3 Include Risk Communication in the Framework

The framework of risk management of human and organizational factors for the escape and evacuation system should have a risk communication aspect to explain risk perception to designers, researchers, operators, and people working onboard. Personnel and operators of offshore installations may have a different understanding of the risks associated with escape and evacuation. Risk communication is one approach to ensure that the designers, operators, personnel, and researchers have the same perception of the risks associated with human responses in escape and evacuation activities.

9.6.4 Examine the impact of unsuccessful escape and evacuation operations

The study of personnel failure in the operation of escape and evacuation should be examined in terms of economic valuation to personnel and the organization. The consequences of failures in the escape and evacuation operations can be divided into two categories. The first category of consequences is associated with personnel and includes minor or major injuries, temporary or permanent disability caused by injuries, and fatality during the escape and evacuation operations. The valuation of injuries and disability of personnel should be done by the organization. The responsibility of the organization toward the personnel's health and medical insurance and treatment can fall into the second category of the consequences of the failures of escape and evacuation operations.