HUMAN FACTOR RISK ASSESSMENT OF A MAINTENANCE OPERATION IN OFFSHORE PROCESS SYSTEM

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Human factor risk assessment of a maintenance operation in offshore process System

by

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Dedicated to my

Mother-Zari, Father-Parviz, wife-Zarnaz, Little son- Kasra and Sisters- Gita and Bita

ABSTRACT

It is known that "human error" is the primary cause of the majority of incidents occurring in process activities. Such incidents can lead to unacceptable outcomes. Each year, there are billions of dollars lost and many injuries/deaths occurring as a result of human error which could have been avoided. Human factors play an important role in causation of these human errors leading to losses. Human factor is the information about human characteristics and behavior controlling human performance. Human errors are inevitable due to the noticeable role of human in operation, maintenance, analysis, decision making, and expert judgments, particularly in complex systems. To reduce the human error, the methods of Human Error Probabilities (HEPs) have been identified. Each technique has its own advantages and disadvantages and may need to be tailored for use within a specific scenario. The focus of this research is to develop comprehensive methodologies to estimate the HEPs in pre and post-maintenance procedures of process facilities. It also develops a risk-based methodology to investigate the reliability of human performance in harsh and cold environments. The methods "Success Likelihood Index Method (SLIM) and Human Error Assessment and Reduction Technique (HEART) HEART" have been used for this purpose. Using HEART methodology, the HEP in different scenarios in an offshore platform is estimated. Also, the high-risk activities in pre and post maintenance of process equipment are identified and the HEPs are reduced through a risk-based decision- making methodology.

SLI methodology is used to calculate the HEP of the procedures for removing process components from service and returning the equipment to service as a possible failure scenario. Consequences and the individual risks are assessed for each component, and then the overall

risk is estimated by adding these individual risks. Also, the HEP is assessed by integrating the SLIM with the Technique for Human Error Rate Prediction (THERP) to generate the nominal HEP data when sufficient information is not available.

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Table of Contents

List of Table

List of Figures

List of Symbols, Nomenclature or Abbreviations

Abbreviations

AA: Area Authority

AHP: Analytical Hierarchy Process

ANOVA: Analysis of variance

APJ: Absolute Probability Judgment

APOA: Assess the Proportion of Affect

BT: Bow-Tie

C: Cognitive

CBP: Computer-Based Procedure

CBT: Computer-Based Training

EPC: Error-Producing Condition

ET: Event Trees

FT: Fault Tree

FTA: Fault Tree Analysis

GEP: Generic Error Probability

GFBF: Group Factor Barrier Failure

GT: Generic Task

HEART: Human Error Assessment and Reduction Technique

HEP: Human Error Probability

HFBF: Human Factor Barrier Failure

HRA: Human Reliability Assessment

HSE: Health and Safety Executive

HTA: Hierarchical Task Analysis

HVAC: Heating, Ventilation, and Air Conditioning

I: Instrumentations

IFBF: Individual Factor Barrier Failure

IQR: Interquartile Range

JEHDI: Justification of Human Error Data Information

M: Management

MF: Modifying Factor

OIM: Offshore Installation Manager

OFBF: Organizational Factor Barrier Failure

P: Physical

PC: Paired Comparisons

PHEA: Predictive Human Error Analysis

PIF: Performance Influencing Factor

POS: Probability of Success

PSA: Probabilistic Safety Analysis

PSF: Performance Shaping Factors

PTW: Place Permit to Work

PTWC: Permit to Work Coordinator

QRA: Quantitative Risk Analysis

RFID: Radio Frequency Identification

SA: Situation Awareness

SBM: Single Buoy Moorings

SLIM: Success Likelihood Index Method

SLIM-MAUD: Success Likelihood Index Method – Multi Attribute Utility Decomposition

THERP: Technique for Human Error Rate Prediction

WFS: Workforce Supervisor

Symbols

a : Constant

b : Constant

Pi : Probability

R : Rate

W: Weight

List of Appendices

1 Introduction

1.1 Overview

The human factor plays an important role in the safe operation of process facilities. Hence, information about human capacities and behaviors should be applied systematically to risk analysis and safety assessment. Many models are available to estimate human error probability (HEP). However identifying an appropriate technique for specific operational conditions remains a challenge. Each HEP technique has its own advantages and disadvantages and may need to be tailored for use within a specific scenario.

Human error in offshore facility has been investigated by different researchers in the last decades and as a result, many methods have been developed to calculate the HEPs. Among all the methods, Success Likelihood Index Method (SLIM) and Human Error Assessment and Reduction Technique (HEART) methodologies are the most comprehensive and highly flexible methods in human reliability assessment. These two methods have been considered in this research to calculate the HEPs to measure the risk. Consequently, risk reduction measures were considered to prioritize and minimize the risk. A risk-based approach is applied to offshore process facilities to investigate the role of human error in pre- and post-maintenance procedures. In the context of risk-based maintenance, the main focus has been on the application of risk as a tool to prioritize or optimize the maintenance plan and schedule which consequently helps to reduce the overall risk. This study is aimed at illustrating the role of human error in maintenance, which is likely to make a significant contribution to the overall risk by endangering the safety of the facility.

1.2 The role of Human Error in Risk Analysis

Human error includes people's mental and physical abilities and limitations and the effect they have on a system's performance, equipment and design. Human engineering, or the inclusion of human factors, should be taken into account when thinking about how machines and systems are designed, operated, and maintained. This study will use a system approach as a methodology to the topic. Also, the application of the methodology is illustrated via case studies while directions for future research are discussed.

Human errors are often the result of improper implementation of strategies and poor management and supervision, with supervisors encouraging workers to find short cuts to increase productivity, often leading to harmful errors. Regardless of whether an individual can provide a rational for committing an error that resulted in unwanted consequences, it should be considered an error; however, the efforts made to stop errors from occurring are often hindered by the lack of a consensus of what actually should be considered a human error.

Incorporating HEPs in the development of operational procedures can significantly improve the overall reliability of the system. There have been efforts to assess HEPs using the aforementioned methods as part of risk analysis.

Different approaches are used in risk analysis such as Quantitative Risk Analysis (QRA) and Probabilistic Safety Analysis (PSA) to identify major hazards and risks of potential accident scenarios. These approaches are being applied to improve the level of safety in aerospace, nuclear, and chemical process facilities. The result of risk analysis is normally considered by decision-makers and safety experts to improve the performance of safety measures in a facility for the risk being within an acceptable range. Risk analysis techniques have been integrated into design, inspection, and maintenance scheduling of process systems, resulting in risk-based design of safety measures, risk-based design of process systems and risk-based inspection and maintenance.

The estimation of risk resulting from human error in a specific scenario is considered. Several techniques are available for accident scenario modeling such as Fault Tree (FT), Event Tree (ET), and Bow-Tie (BT). ET has widely been used to explore the probability of consequences resulted from an initiating event. Considering the initiating event, the occurrence probability of each consequence is calculated based on the occurrence/nonoccurrence of a set of events or success/failure of components.

The methodology developed in this research can be applied to maintenance procedures of any equipment or process facility onshore and offshore. This would help to better understand the role of HEP in risk analysis and consequently to increase the overall reliability and safety of the process system.

1.3 Human Error Probability Assessment Techniques

The study of human factors is an important area of safety and risk engineering and it includes the systematic application of information about human characteristics and behavior to improve the performance of human-machine systems (McSweeney et al., 2008). HEP has predominantly been a focus of the nuclear power industry through the development of expert judgment techniques such as SLIM and the Technique for Human Error Rate Prediction (THERP) (Swain et al., 1983).

The goals of HEP estimationare (Skelton, 1997):

- Preventing of death or injury of the workers
- Preventing of death or injury to the general public
- Avoiding damage to a plant
- Stopping any harmful effects on the environment

- Preventing damage to third parties

Therefore, incorporating HEP and related human operations and procedures in the facilities should improve reliability of the overall systems (Swain et al., 1983).

Several studies (Apostolakis et al., 1988; Kirwan and James, 1989; Zamanali et al., 1998) have compared different methods (e.g. SLIM, HEART and THERP) for finding HEP. These studies report both the advantages and disadvantages of these techniques with respect to HEP under various scenarios (Stanton et al., 2002; Salmon et al., 2003; Park et al., 2008). Thus, a thorough review of each technique is required.

Analytic Hierarchy Process (AHP) (Saaty, 1980) can be used for comparing among the alternative HEP methods using multiple-criteria. The AHP has three important components (Alidi, 1996):

- Structuring the problem into a hierarchy which includes a goal and subordinate features (decomposition)
- Pair-wise comparison among elements in each level (evaluation)
- Propagation of level specific, local priorities to global priorities (synthesis)

In these components, subordinates level of hierarchy may consist of objectives, scenarios, events, actions, outcomes and alternatives. Pair-wise comparisons are done for various components in each level considering the elements in the higher level. Comparing these components may be done as preference, importance and likelihood.

There are different techniques available to estimate HEP, not all of which are usable for different scenarios. Therefore, one needs to be familiar with the advantages and disadvantages of each technique based on previous investigations to select the suitable methodology for the specific case. SLIM is one of the most flexible techniques, based on presumably independent Performance Shaping Factors (PSFs). However, it is difficult to ensure whether these PSFs are independent. HEART is a quick and simple technique to use with little investigator training, although the reliability of the method is yet not proven. Moreover, the lack of existing validation studies and its high dependency on expert opinions are some of the HEART's limitations. THEARP was claimed as one of the most precise techniques to determine HEP, but it is not useful in error reduction and is highly dependent on the assessors. Therefore, choosing the specific level by the assessors may lead to different results. Absolute Probability Judgment (APJ) is another technique to obtain HEP for specific applications. The expert discussion used in this technique helps to quantify and qualify the HEPs. APJ is to some extent prone to certain biases as well as personality/group problems and conflicts. Paired Comparisons (PC) is another technique that can reveal the relative importance of different human errors and quickly estimate the HEPs. However, this method is not suitable for complex predictions of human error. The homogeneity of the events is an assumption in this technique that could be subject to error. Finally, in Predictive Human Error Analysis (PHEA) technique, error reduction strategies are offered as part of the analysis, in addition to error prediction. However, this technique does not model cognitive components of error mechanism. As evident from above discussion, each technique has its own advantages and disadvantages and may need to be tailored for use within a specific scenario.

1.4 Motivation

The study of human factors is an important area in risk analysis of process systems. It includes the systematic application of information about human characteristics and behavior to improve the performance of human-machine systems and to increase the safety of the process. Over the last few years, a number of major accidents occurred in different industries as a result of human errors in operation, analysis, and decision-making..

Therefore, studies have been devoted to analyze the factors contributing to human errors in specific scenarios in order to reduce the human error. Researchers and industry have been attempting to decrease human error by changing equipment or process, changing procedure or changing management system. However, most of these attempts have neither studied the human factors in a systematic manner nor recognized the role of human error in risk analysis and decision-making.

The present research is aimed at developing an engineering framework to identify human error in the risk analysis of process facilities, and to reduce its contribution to the risk through improved risk-based decision-making.

1.5 Organization of the thesis

This thesis is written in manuscript format (paper based) and is organized as follows:

Chapter 2 discusses the novelties and contributions this thesis has made in safety and risk assessment and of human performance in different environments. It comprises innovative applications of HEP methods in QRA, a new methodology to assess the HEPs in maintenance procedures, and estimate the HEP in harsh and cold environments

Chapter 3 presents the literature review. The literature review reports on human error identification methods, risk analysis, and the role of human error in different process operations.

Chapter 4 is devoted to HEP evaluation methodologies. This chapter provides evaluation of some of the most suitable techniques for HEPs and compares these techniques based on their applicability and limitations in process systems. This content of this chapter was presented at the *National Conference on Safety Engineering & HSE Management at Sharif University of Technology in March 2010* (*http://www.cpsl.ir/index_e.aspx*).

Chapter 5 proposes a new methodology to assess the HEPs in maintenance procedures. This research provides an analysis of human factors in pre- and post- maintenance of pumps by using the HEART methodology. This chapter is published by *Process Safety and Environmental Protection (http://dx.doi.org/10.1016/j.psep.2012.11.003).*

In Chapter 6, the SLIM is integrated with the THERP to generate the nominal HEP data when it is unavailable. Also, Radio Frequency Identification (RFID) tools have been utilized to re-quantify the HEPs. This chapter is submitted to *Reliability Engineering and Safety System.*

Chapter 7 discusses the differences between the HEPs and related risk in normal and cold conditions, by using HEART methodology. This methodology is applied to the post-maintenance tasks of a pump in offshore oil and gas facility. This chapter is accepted for publication in the *Journal of Human Factors.*

Chapter 8 presents another systematic application of human characteristics and behavior to increase the safety of a process system. The HEP is calculated for each activity using the SLIM. This chapter is submitted to the Journal of *Reliability Engineering and Safety System.*

Chapter 9 presents the summery of the thesis and the main conclusions drawn through this work. Recommendations for future work are presented towards the end of the chapter.

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2 Novelty and contribution

2.1 Overview

The novelties and contributions of this work are classified into three categories:

- Application of human error probabilities methods to quantitative risk analysis.
- A new methodology to assess the HEPs in maintenance procedures.
- A new methodology to estimate the HEP in harsh and cold environments.

In this chapter, these novelties are briefly explained while the details are presented in the relevant chapters.

2.2 Application of HEP methods in QRA

A risk-based methodology is developed to assess the human factor risk in offshore pre- and post- maintenance procedure. The HEPs are estimated by applying the SLIM process. After obtaining the HEPs based on a specific scenario, the final value of the risk is calculated by integrating the HEPs and consequence analysis outcomes. If the risk exceeds predefined acceptable criteria, it will be reduced through either implementation of additional safety barriers or improving the performance of existing safety measures. HEP reduction can also be accomplished through re-designing the activities. This contribution is drawn from Chapters 8.

2.3 A new methodology to assess the HEPs in maintenance procedures

A risk-based methodology is developed to assess the risks of human errors in maintenance activities. The HEPs are estimated by applying the HEART process. After obtaining the HEPs based on a described work activity or scenario, the final value of the risk is calculated by integrating both the HEPs and the consequence analysis results. Whenever the calculated risk exceeds acceptable criteria that are based on specified guidelines, then a risk management approach is employed to minimize the risk. This contribution is discussed in Chapter 5.

2.4 A new methodology to estimate the HEP in harsh and cold environments

To demonstrate the variation in HEPs, a new methodology is developed applicable in harsh and cold environments. This methodology is build upon revisions of the HEART methodology to accentuate the human activities in harsh and cold environments. It is applied to post-maintenance procedures of a condensate pump in offshore oil and gas facility. The scenarios were selected based on maintenance reports of an offshore platform. Then, the most frequently occurring scenario in the facility was selected to implement the methodology.

3 Literature review

3.1 Human Error

Human error is considered a part of everyday functioning and it is expected that people will make errors; they are some of the most undesirable aspects of daily life. Human error takes the shape of human behavior that can be considered undesirable, unacceptable and shows a lack of attentiveness. Although many errors are often detected and corrected before causing harm, and are often a way of predicting future problems, human errors are the cause of 50 to 90% of all accidents, the result of which can have long term consequences. However, human errors can be better dealt with and tolerated in terms of the design and manufacturing of mass-produced products through attempts to produce systems and processes that are complex, industrial and professional in nature.

Human failure and human fault all refer to different concepts; however it is necessary to differentiate them to minimize their harm. "Human fault" on the other hand, indicates a sense of blame, with errors being caused due to negligent or intentional behavior that is often punishable. To a further extent "human failure" indicates a massive error that has far reaching consequences that are often moral in nature and is often entirely inexcusable. An understanding of raw data, relevant data, and productive data and what differentiates them is important to understanding these concepts. In a recent study done on the problems, defects and process errors seen in a chemical plant, five main sources were found as the cause of these problems with the failure to follow standard procedures and stay within proper operational discipline being the main cause of human errors.

This, together with the second most common source of errors, that is the inability to follow proper operational practices, such as regular and necessary inspections, repairs, and modifications of equipment, accounted for 63% of the problems seen. These human errors can often be avoided by addressing system design defects and make sure workers have the proper knowledge and training methods. The effect of human factors on system design and the debate on whether to view from an operation perspective will be the focus of the proposed research. The role of managers and engineers and how they assess human factor issues is also highly important, as changes cannot be made if these key players fail to acknowledge human factors issues when dealing with problems related to cost and delays in a project's progress.

This importance placed on human error is understandable, considering that it is such a major cause of accidents and potential negative consequences in areas such as nuclear power and other complex technological sectors. To deal with this problem, the probability of human error needs to be strictly monitored for its potential effect on system failure, and the means to effectively manage and reduce failure (error) rates while people learn from their mistakes is necessary. With the implementation of these strategies it is necessary to include the available data on modern technological systems and their relationships with human errors in order to determine their probability. New approaches need to be suggested based on error state exclusion and systematic learning to find out how to properly manage the incidence of human error as well as safety indicators.

The kinds of responses to and treatments of human error differ depending on the undesirable consequences, which occur as a result. Norman (1981) and Reason (1990) an "error" occurs in situations where an act is committed both intentionally and unintentionally, however, the error itself and the original intention of the act are often viewed separately. Actions, which have not succeeded as planned, are often attributed to errors as a result of unintentional actions, whereas actions that were carried out as planned or intended yet didn't achieve their results are seen as being erroneous in their original actions.

Regardless of the intention, the occurrence of undesired outcomes is clearly the common factor here; however, unwanted outcomes do not necessarily indicate negative results, as the results of human errors sometimes occurs or can only be seen at a later time. Undesired outcomes may also refer to outcomes which did not have a negative effect, but still had the potential to. The treatment of errors should depend more on a recognition that an error actually occurred rather than the outcome of what actually has occurred as a result of an action.

The intentional violation of a procedure does not fall under the definition of a human error; however, when potentially dangerous outcomes occur as a result, these types of actions are considered human errors. The exploratory attitude, part of a formal training program with results in unintentional actions, should not be considered as falling under the definition of human error. The need to encourage adaptation and creatively developing skills to improve on mistakes and promote learning is what should be stressed in the context of human errors.

Hollnagel (1993), for example, shows one such divergent opinion, using the term "erroneous actions", which he indicates is "an action which fails to produce the expected result and which therefore leads to an unwanted consequence".

According to Dekker (2005) the view of errors as "ex post facto constructs rather than as objective, observed facts". In other words the predisposition for the bias including the people, who have been participated, investigated and had imposed their knowledge and future expectations. The observers do not bring us near to understand the experience in the real situation for which there is no error-"the error only exists by virtue of the observer and his or her position on the outside of the stream of experience."

Dekker (2005) views the perspective of what is an error as influenced by personal knowledge and experience, with these personal ideals determining errors as "ex post facto constructs rather than as objective, observed facts."

Sanders and McCormick (1993), view human errors as inappropriate decisions that have a negative effect on system safety effectiveness and performance. Sanders and McCormick also argue that providing a classification system can help to organize human error data and provide insight into how errors can be prevented. Lawton and Parker (1998) provide one such system, placing human errors into two categories, "non-intentional errors" which are often related to human cognitive errors and the inability of humans to function perfectly in terms of both information processing and short-term memory and "violations" which are intentional deviations from proper safety procedures, which are the result of both psychological and social factors. The occurrence of violations, according to Atkinson (1998), are at least partially caused by tendency of people to put in as little effort as possible as well as an indifferent workplace. Several studies have determined that such errors are a major cause of accidents in construction (Suraji et al., 2001) and manufacturing (DuPont Safety Resources, 2000; Lawton and Parker, 1998; Rasmussen et al., 1994; Sanders and McCormick, 1993). The actual participation of human error as a causal factor is more difficult to determine, however, as it ranges from percent (Suraji et al., 2001) to 96 percent (DuPont Safety Resources, 2000) the wide range possibly being determined by finding the root cause of such accidents. Determining these root causes is difficult, however, as it depends greatly on the opinion and discretion of the analyst. Such investigations to determine the cause of these events are often interrupted or stopped when an explanation or cure is found or if there is simply a lack of information (Rasmussen et al., 1994).

It is very unlikely, however, that human errors will ever be eliminated entirely, however, as people demonstrate continuously adaptive behaviors in dynamic work systems and the regular enforcement of rules designed to limit human errors are often limited due to financial and time restrictions (Rasmussen 1997). As a result, workers may be encouraged to simply work in a manner in which they barely avoid causing accidents and often are forced to work in risky conditions (Rasmussen, 1997). To control this problem, Rasmussen et al. (1994) suggest that clear and determined boundaries should be set in an attempt to minimize human errors when designing work systems, and should be set in an environment which they are respected and error-tolerant (Rasmussen et al., 1994).

3.2 Risk assessment

Many techniques and methodologies have been proposed since the 70's for risk assessment (Khan & Abbasi, 1998). Quantitative and qualitative risk assessments are two types of the risk evaluation system (Ferdous, 2007). Qualitative risk assessment is mostly used to identify the hazards associated with a process and it is usually used as a preparation step for consequence analysis (Hauptmanns, 1988; Lees, 1996). Quantitative risk assessment analyses system risk in terms of numerical evaluation of consequence and occurrence probability of an unwanted event.

Risk analysis approaches such as QRA and PSA have widely been applied to identify major hazards and risks of accident scenarios and also to improve the level of safety in aerospace, nuclear, and chemical process facilities. The result of risk analysis is normally considered by decision-makers to decide the plans of reasonable levels of risk or by safety experts to improve the performance of safety measures in a facility to reduce the risk to an acceptable range.

Further, in the recent decade, risk assessment techniques have been integrated into design, inspection, and maintenance scheduling of process systems, resulting in risk-based design of safety measures (Piccinini and Demichela, 2008; Khakzad et al., 2011), risk-based design of process systems (Demichela and Piccinini, 2004; Khakzad et al., 2013) and risk-based inspection and maintenance (Apeland and Aven, 2000; Khan and Haddara, 2003; Khan et al, 2004; Khan and Haddara, 2004). In the context of risk-based maintenance, the main focus has been on the application of risk as a tool to prioritize or optimize the maintenance plans and schedules which consequently helps to reduce the overall risk.

3.3 Human Error in different process operation

Estimation of the HEP has been done in the emergency situation in order to assess the contribution of the operator error to major accident likelihood. To perform the requested action correctly by an operator in an emergency situation, the human performance is dependent of the available time. In different scenarios the amount of time required for an operator to act appropriately without loss of containment were estimated over a period of time. (Claudio Nespoli and Sabatino Ditali, 2010).

Taking care to limit probable mistakes in different functions and ensuring reasonable performance of various parts of systems in compliance with determined goals are some of the specific goals of human-machine systems. More complex systems need more resources for their maintenance and keeping their specified functions. Since maintenance of systems with a suitable standard and in accordance with specified goals requires resources, therefore any reduction of costs through relevant considerations is vital.

Therefore those who are involved in maintenance & repair of systems should have some special qualities like judgment and analysis of their work under these special conditions. Good knowledge about their professional requires and specifications are a natural condition for their confident functioning in the concerned system.

For anyone, in any circumstances it is possible to make different mistakes. Most accidents are related to human mistakes, the weak design of a system or machine failure. A system that makes the operator apply their maximum physical and mental capacities may put him at risk of further mistakes.

A common proverb about the repair and maintenance of systems says "If it isn't broken, don't fix it". But fortunately today this idea is rejected. There is another proverb about repair instructions that says as "A stitch in time saves nine". That means an on-time repair may prevent a further repairs. Therefore we have four following sections in repairs & maintenance affairs (Dhillon, 2002):

1- Preventive Maintenance
2- Predictive Maintenance
3- Corrective Maintenance
4- Over Haul

Preventive maintenance means regular visits of components including different systems and machinery to assess the oil, voice, temperature, vibration and other factors (depending upon the type of unit) and repairing difficulties before any damages and disorders in utilization functions. As a result it is very important and useful to have regular sheet and daily time tables based upon relevant experiences of repair specialists, specifically the instructions of manufacturers, and inserting the daily checking bill in it. It is more effective to have repair files for all machines and systems, and registration of the relevant technical specifications, and partial repairing works in fault finding process.

Predictive maintenance means displaying & registering systems for controlling problematic factors such as vibration, temperature, pressure and other physical /chemical quantities required for estimation of machinery and systems. It is also known as monitoring. It is necessary to be ensured about the correct efficiency of measuring systems and their periodic regulation and calibration.

Corrective maintenance means any recognition of different factors which may cause further problems along with removing them by corrective methods. Modification & Improvement functions are also in parallel with corrective maintenance. Therefore it is more effective to bear a powerful Technical / Engineering unit for this purpose.

Fundamental or Programmed repairs involve dismantling all parts of constructions for further inspection; evaluation and troubleshooting were hidden from the view of the operator and from further repairs. Also overhaul may include any replacement of expired parts and a general cleaning of a system within specified periods.

Dhillon (2006) review literatures to understand the importance of human error in maintenance, the occurrence of maintenance errors results for many reasons, such as poor design factors including issues involving equipment, maintenance, and work layout, and difficulties faced by workers, such as improper work tools, fatigue on overstressed workers and environmental factors, such as humidity, lighting, temperature, etc. Lastly, improper training, the use of outdated maintenance manuals and a lack of proper experience contribute to high numbers of maintenance errors. Improving the work environment and practices by taking these factors into account, such as providing more experience, ensuring emotional stability and hiring workers who have a greater aptitude for their environment reported less fatigue and more satisfaction, improving team work and boosting morale.

As mentioned above, human errors can impact safety and performance in various ways. One prominent example is how the number of breakdowns due to poor repairs can potentially increase the risks associated with equipment failure and a rise in personal accidents. The Human factor in reliability group has recognized how human factors' interaction with maintenance operations can potentially lead to safety hazards. This group, however, provides limited guidance for managers and engineers to attempt to address these various safety issues. This group has attempted to determine the roles that safety and reliability play in regards to maintenance errors by studying their own organization by applying methods aimed at reducing these types of errors in their own workplace through practical means. In an attempt to reduce human errors in maintenance operations, managers and other group members created a guide which identifies 18 factors which need to be addressed and means of identifying and dealing with these problem areas, which has recently been published by the Health and Safety Executive (HSE) and can potentially be of great value to the Aviation Industry.

Although human errors in maintenance have not received much academic attention, it has recently been found that most human errors occur in the maintenance phase and maintenance workers clearly have an important role in keeping equipment workable and reliable. One such study focuses on various literatures that has been published on the topic and can be potentially beneficial for the maintenance engineering field. A survey conducted by Pekkarinen et al. (1993) studied the amount of risk facing maintenance workers during a period when a chemical plant was shut down to help improve maintenance policies. Nelson (1996) argued that accident occurrence due to maintenance activities as well as over speed protection equipment should be a cause for concern in this industry. Balkey (1996), however, asserted that risk based inspection procedures and human error procedures in fossil fuel plants must be taken into account when conducting inspection procedures. Further data is contributed by Eves' (1985) report on accidents which occurred in the chemical manufacturing industry during times of maintenance.

Raman et al. (1991) contributed guidelines to apply Hazop techniques in the application of maintenance procedures conducted on offshore oil and gas platforms, while Underwood (1991)examine the effect of safety systems in the chemical industry through inspecting various case studies on the topic. Further research has been done by Dhillon and Yang (1995) who developed a new stochastic model to analyze the rates in human error and failed system repairs and how they affected reliability and availability of the machines. After examining the ratio estimation of HEP, Park and Jung (1996) suggested that, through linear transformation, and simple techniques of converting ratios, they can determine objective HEP. Further studies were done by Anderson et al. (1998) on reduced manning and how it affects the types of human errors experienced in systems operations and maintenance. Finally, Mcroy (1998) concluded that collecting samples of the different types of errors and interactions one experiences can be helpful in preventing such errors.

Jacob et al. (1997), in their analysis, found that critical human errors were a common cause for failure as a result of repairs done on two unit standby systems. Similarly, Sur and Sarkar (1996) found that redundant systems regularly caused human errors and logic failure makes a probabilistic model. Four such probabilistic models were developed by Dhillon and Rayapati (1988b) who used supplementary variables method to develop system availability expressions represented by the human errors found in two unit parallel and standby redundant systems. These two researchers also studied standby redundant systems and human error using three stochastic models.

Further studies have been conducted on the topic of systems failures and human errors by Sridharan and Mohanavadivu (1997), who studied three Markov models of two non-identical unit parallel systems, Narmada and Jacob (1996) who used a stochastic model representing a three unit system and Dhillon (1989) who analyzed repairable and non-repairable redundant systems and human errors, establishing a reliability analysis. A basic, but useful, study was done by Reason (1990) who gave an overview of basic error mechanisms and what types of errors occur. In an attempt to deal with the problem of human error, Su et al. (2000) suggested using a knowledge-based system to analyze cognitive types and enhance fault recovery ability using a practical framework, while Gupta et al. (1991) examined overloading effects and critical human error during repair waiting times in a multi-component parallel system.

Chung (1987) examined human error and common-cause failures using a repairable parallel system with standby units. The existence of human error in the form of fault injection was studied by Carr and Christer (2003) who used data on these phenomena to extend the mathematics model of delay-time of inspection maintenance during the inspection process. Ramalhoto (1999) outlined critical safety measures after studying maintenance personnel, while Vaurio (1995), in an attempt to address human errors and common cause failures, supplied a procedure that could be used in various situations to ensure proper maintenance and safety tests for certain systems as well as reviewed some earlier models which attempted to address HEPs in a separate article. Human analysis and repair times in a system were researched by Dhillon and Yang (1993), while Sanders and McCormick (1993) outlined the types of human factors which can contribute to errors in maintenance in direct or indirect ways. Bradley presented a methodology which can be useful in helping determine the causes of human, design and maintenance errors. Miller and Swain (1986) examined the effects of human errors on system performance, equipment or task characteristics and work potential, and how they can be changed to reduce these errors. In an earlier study, Dhillon (1986) outlined the various aspects present with regards to human factors and maintenance, such as reliability and error, revisiting the topic in a 2002 book. Gramopadhye and Drury (2000) gave their theories behind the increases in maintenance and inspection errors, while Dodson and Nolan (1999) examined the human factors behind field tests, production and man-machine function allocation.

3.4 Human error quantification methods

The study of human factors is an important area of process engineering and it includes the systematic application of information about human characteristics and behavior to improve the performance of human-machine systems (McSweeney et al., 2008). HEP has predominantly been a focus of the nuclear power industry through the development of expert judgment techniques such as SLIM and the THERP (Swain et al., 1983).

The goal of HEP is (Skelton, 1997):

- Preventing of death or injury of the workers
- Preventing of death or injury to the general public
- Avoiding damage to a plant
- Stopping any harmful effects on the environment
- Preventing damage to third parties

Therefore, incorporating HEP and related human operations and procedures in the facilities should improve reliability of the overall systems (Swain et al., 1983).

Several studies (Apostolakis et al., 1988; Kirwan and James, 1989; Zamanali et al., 1998; Spurgin and Lydell, 2002) have compared different methods (e.g. SLIM, HEART and THERP) for finding HEP. These studies report both the advantages and disadvantages of these techniques with respect to HEP under various scenarios (Stanton et al., 2002; Salmon et al., 2003; Park et al., 2008). Thus, a thorough review of each technique is required.

There is no single metric or approach to compare for comparing between the alternative HEP methods. The AHP (Saaty, 1980) can help with multiple-criteria decisions. The AHP has three important components (Alidi, 1996):

- Structuring the problem into a hierarchy which includes a goal and subordinate features (decomposition)
- Pair-wise comparison among elements in each level (evaluation)
- Propagation of level specific, local priorities to global priorities (synthesis)

In these components, subordinates level of hierarchy may consist of objectives, scenarios, events, actions, outcomes and alternatives. Pair-wise comparisons are done for various components in each level considering the elements in the higher level. Comparing these components may be done as preference, importance and likelihood.

There has been some degree of research applied to the quantification of HEPs, however only a few of these techniques have been used in practical risk assessments (Embrey et al., 1984).

3.5 Advanced approaches of human error analysis

The advances in science and technology, made the man-machine system to become more and more reliable and therefore the operation error of human being becomes more and more severe. The human reliability analysis (HRA) has become an essential content of probability safety analysis in the man-machine system. In order to estimate the HEP, various models were introduced including the key performance shaping factor, error correction capability factor, the human operation action error model and operation mission reliability model. These models studied the characteristics of the operator behavior responsible for error, such as human perception ability, judgment, decision-making, and the operation action ability. Human reliability analysis was done using the ET analysis method. Considering the dynamic characteristics of human error, time sequence and the ability of error correction, there are some limitations in human reliability analysis. To overcome this limitation, the dynamic Bayesian networks theory was carried out which is the qualitative analysis and quantitative analysis of human operation action reliability in the complex man-machine system. The method of transform human error ET into dynamic Bayesian network was provided by Luyun Chen et al. (2012). There are three categories of human factor barrier failure (HFBF), which includes individual factor barrier failure (IFBF), organizational factor barrier failure (OFBF) and group factor barrier failure (GFBF). Pseudo-FT is used to illustrate the human factors. It is an incorporation of the intermediate options into FT in order to eliminate the binary restriction. The dynamic Bayesian networks were applied in quantitative risk assessment of human factors on offshore platforms. A method was defined to translate the pseudo-FT into Bayesian networks. This methodology confirmed that within the first two weeks, the human error barrier failure increases and if the repair is considered, it reaches a stable level, whereas it increases continuously when the repair action is not considered (Baoping Cai et al., 2013).

Human error has been identified as an important factor for many offshore and onshore accidents occurrence. Literature review revealed that there is very little data available in human error, which could be secondary to lapses in historical database registry methodology. HRA has been used to estimate the probability that an operator will perform a task in a reasonable time without degrading the system. The Research proposed in Brazil a methodology that HRA should be able to be performed even with shortage of related human error statistical data. PSFs were also evaluated in order to estimate their influence level onto the operator's actions. Both HEP estimation and PSF evaluation were done based on expert judgment using interviews and questionnaires. Group evaluation values obtained by using Fuzzy Logic and Fuzzy Set theory. HEP results were in good agreement with literature published data corroborating the proposed methodology as a good alternative to be used on HRA (C.S. do Nascimento and R.N. de Mesquita, 2012).

Traditional HEP studies were based on fuzzy number concepts, so it was useful only when the lack of data exists. It could not be applied to situations where experts have adequate information. A novel HEP assessment is also proposed by using data combination, defuzzification and transformation processes. In this methodology a test case consisting of three different scenarios were used. In these scenarios, the fuzzy data are close to each other. The outcomes are compared with the results achieved from the traditional fuzzy HEP studies using the same test case. This methodology is capable of providing reasonable results in both situations when the lack of data exists and also when the required data is available (Shuen-Tai Ung, Wei-Min, 2011).The case study was done on the accident at the Chernobyl nuclear power plant which showed that fuzzy reliability analysis gives information from more points of view than probabilistic analysis (Takehisa Onisawa and Yasushi Nishiwaki, 1988).

The conventional fault tree analysis (FTA) is used for estimation of exact probabilities of occurrence of system failure, which found to be very difficult when fault events are imprecise such as human error. A fuzzy FTA model employing fuzzy sets and possibility theory is proposed to tackle this problem (Nang-Fei Pan Nat et al, 2007).

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4 Comparative Evaluation of Human Error Probability Assessment Techniques†

Preface

A version of this manuscript has been presented in the *National Conference on Safety Engineering & HSE Management at Sharif University of Technology in March 2010.* Noroozi was the main lead on the work. The co-authors, Drs. Khan and MacKinnon supervised the work and helped to develop the methodology. The co-author Dr. Abbassi helped gathering the different methodologies. Noroozi assessed HEP techniques while Drs. Khan and MacKinnon reviewed the manuscript and provided the necessary suggestions.

Abstract

Many models are available to estimate HEP. However identifying an appropriate technique for the specific operational conditions remains a challenge. Each technique has its own advantages and disadvantages and may need to be tailored for use within a specific scenario. This research provides evaluation some of the most suitable techniques for HEPs and evaluates these techniques based on their applicability and limitations in process systems. The AHP is used to do a comparative analysis. Based on AHP, the SLIM was selected to obtain HEPs for an emergency building evacuation scenario.

Keywords: Human error, HEP, AHP, SLIM

†Noroozi et al. presented in *National Conference on Safety Engineering & HSE Management at Sharif University of Technology in March 2010*

4.1 Introduction

The study of human factors is an important area of process engineering and it includes the systematic application of information about human characteristics and behavior to improve the performance of human-machine systems (McSweeney et al., 2008). HEP has predominantly been a focus of the nuclear power industry through the development of expert judgment techniques such as SLIM and the THERP (Swain et al., 1983).

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Several studies (Apostolakis et al., 1988; Kirwan and James, 1989; Zamanali et al., 1998; Spurgin and Lydell, 2002) have compared different methods (e.g. SLIM, HEART and THERP) for finding HEP. These studies report both the advantages and disadvantages of these techniques with respect to HEP under various scenarios (Stanton et al., 2002; Salmon et al., 2003; Park et al., 2008). Thus, a thorough review of each technique is required.

There is no single metric or approach to compare for comparing between the alternative HEP methods. The AHP (Saaty, 1980) can help with multiple-criteria decisions. The AHP has three important components (Alidi, 1996):

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In these components, subordinates level of hierarchy may consist of objectives, scenarios, events, actions, outcomes and alternatives. Pair-wise comparisons are done for various components in each level considering the elements in the higher level. Comparing these components may be done as preference, importance and likelihood.

In this research, six different well-known and most usable methods for HEP are evaluated and advantages and limitations of different techniques are presented. Subsequently, AHP is used to compare different techniques, and to choose an appropriate technique for the specific evacuation scenario.

4.2 Human Error Prediction methods

There has been some degree of research applied to the quantification of HEPs, however only a few of these techniques have been used in practical risk assessments (Embrey et al., 1984). Here, some of these techniques will be discussed.

4.3 Success Likelihood Index Methodology (SLIM)

SLIM was basically designed for HRA, considered as an expert judgment method in probabilistic reliability analysis (Svenson, 1989). SLIM is a method for quantifying the preference in a set of options. Applicability of SLIM in assessing human reliability derives from the consideration that human performance is affected by different factors and additive effects influencing these factors (i.e. PSF) to assess a human response (Kent et al., 1995).

SLIM is a simple and flexible method based on an expert judgment approach. The basic principle of this method is that the likelihood of a particle error occurring in a specific situation is associated with the combined effect of a relatively small set of PSFs (Raafat et al., 1987).

This method has been considered in different forms such as SLIM-MAUD method (Kirwan, 1994). It is a computerized form of SLIM used for determining HEP. Park et al. (2008) combined the SLIM with AHP (AHP-SLIM) and applied it to an assessment of driver error. The results shows that integrating SLIM with AHP is feasible and this method overcome the problems of the potential inconsistency of multiple expert judgments or the problem with the systematic consideration of PSFs. The SLIM procedure is demonstrated in Figure 4.1.

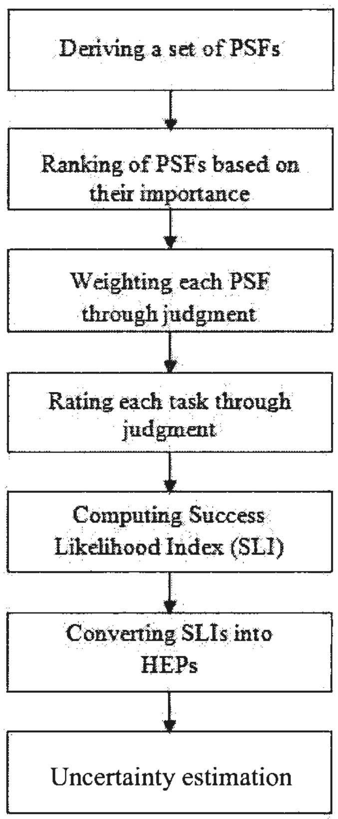

Figure 4.1 The SLIM procedure to obtain HEP (Vestrucci, 1988)

4.4 Human Error Assessment and Reduction Technique (HEART)

HEART is a technique for comparing HEP and its approach is based on the degree of error recovery. Its fundamental basis is that in reliability and risk equations, one is interested only in those ergonomics factors which have a large effect on performance. Therefore, whilst there are many studied available ergonomics factors, and consequent guidelines, which are supported by ergonomics themselves, many of these factors in reality have a negligible effect on the operator's performance. Thus, the factors which have a significant effect are considered in HEART (Kirwan, 1994).

This method is easy to understand, fast and reliable. However, its approach is quite subjective and heavily reliant on the experience of the analyst (Casamirra et al., 2009). This technique, while commonly implemented in industry, can also be applied in the analyses of air traffic management safety cases (Kirwan et al., 2007). The HEART procedure can be seen in Figure 4.2.

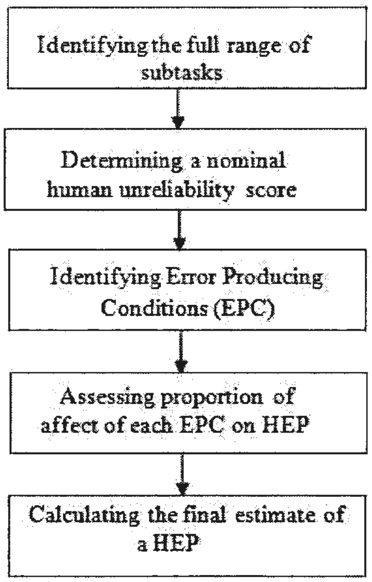

Figure 4.2 The HEART procedure to obtain HEP (Kirwan, 1996)

4.5 Technique for Human Error Rate Prediction (THERP)

THERP is the most common used method in probabilistic safety assessments (Jae et al, 1995). This methodology includes task analyses and erroridentification and representation, as well as HEPs quantification. Probably, because of its relatively large human error database, and its resemblance with engineering approaches, it is used extensively in industrial applications in comparison to other techniques (Kirwan, 1994). THERP uses performance-shaping factors to make judgments about specific situations. In some cases, however, it may be difficult to accommodate all of the factors that are considered significant. While THERP has the advantage of simplicity, it does not account for a dependency of human performance reliability with respect to time. This method includes a set of tables for evaluating HEPs that provides the basic HEP and the range of effect factors related to the activities (Xiaoming et al., 2005). The procedure of THERP methodology is demonstrated in Figure 4.3.

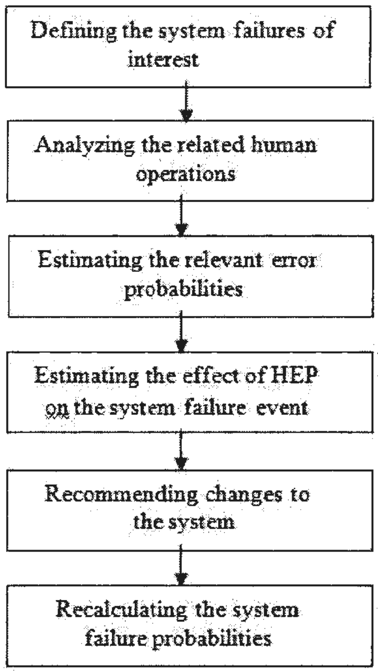

Figure 4.3 The THERP procedure to obtain HEP (Swain et al., 1983)

4.6 Absolute Probability Judgment (APJ)

APJ is a method that employs experts for the direct generation of HEPs. This method differs from most models as it employs large groups of assessors. The assessors should be experts and have background knowledge of probability calculation (Kirwan, 1994). The expert opinions are received according to one of the following approaches (Stewart et al., 1997):

- Aggregated individual method
- Delphi method
- Nominal group technique
- Consensus group method

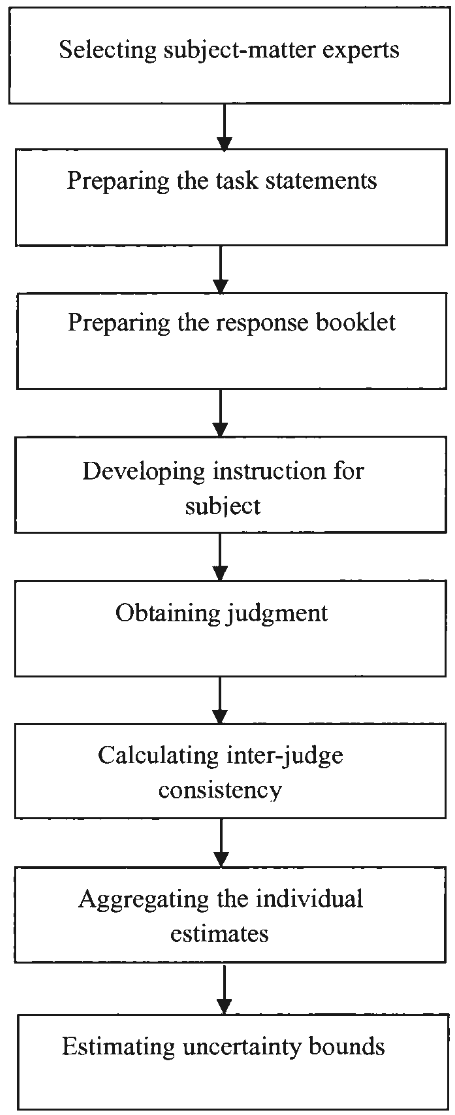

Figure 4.4 APJ procedures to obtain HEP (Kirwan, 1994)

Whenever non-group consensus is used, the Analysis of Variance (ANOVA) is necessary to confirm the significant degree of inter-judge consistency between the experts. Although there is some empirical support for using APJ, the accuracy of this technique for finding very small error rates is not clear (Stewart et al., 1997). The procedure for the APJ method is illustrated in Figure 4.4.

4.7 Paired Comparisons (PC)

Pair wise comparison generally refers to any process of comparing entities in pairs that demonstrates which pair is preferred, or has a greater amount of some quantitative property. PC is a scaling techniques based on expert judgment.

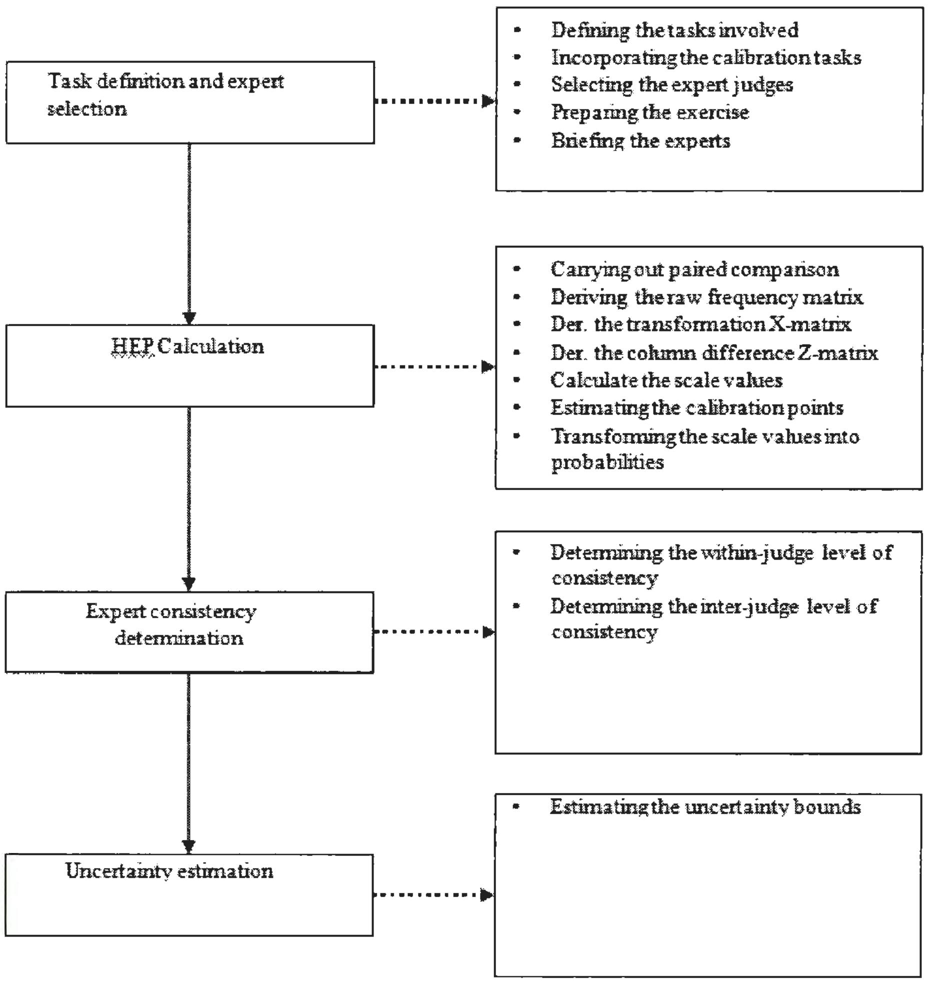

Figure 4.5 PC procedure to obtain HEP (Kirwan, 1994)

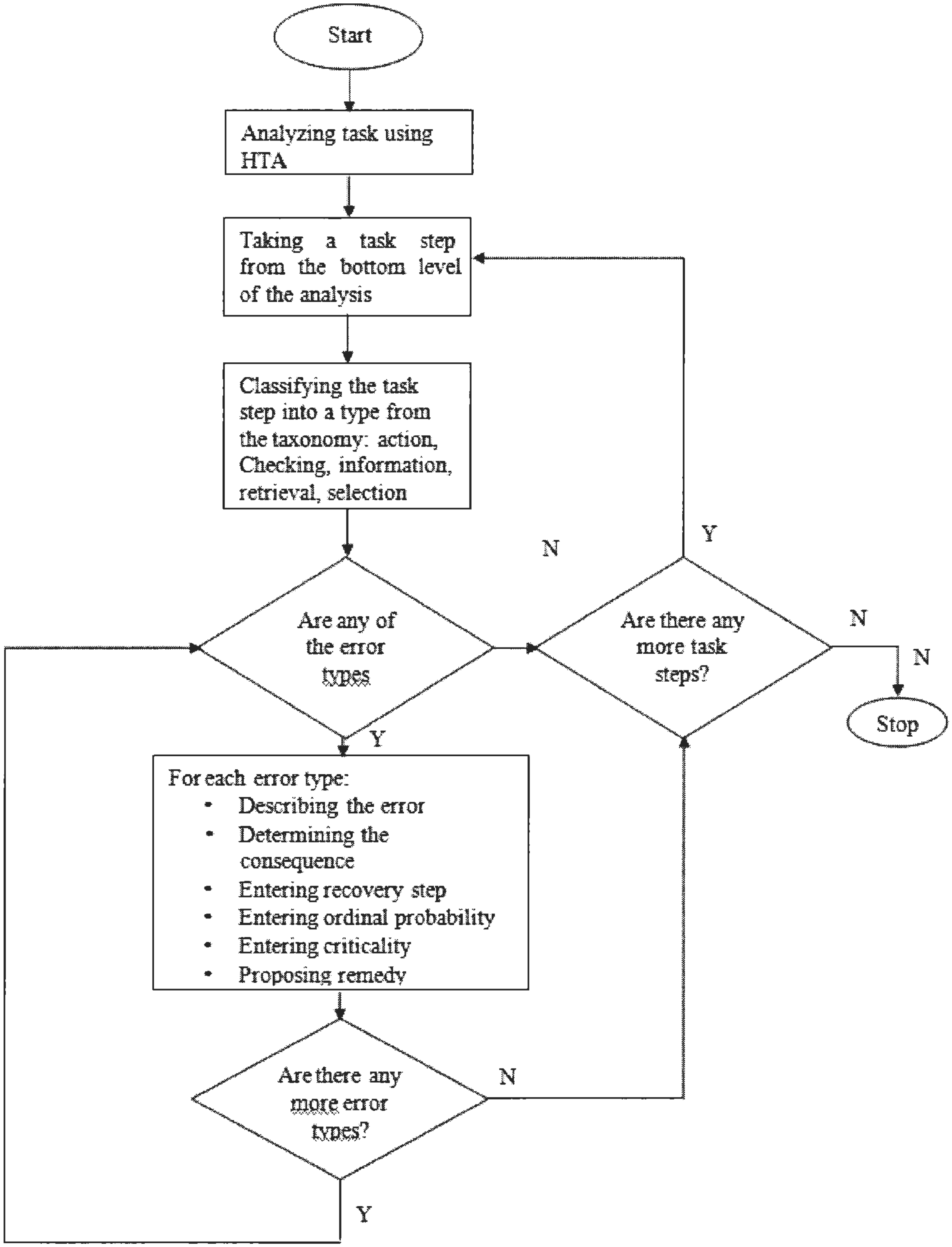

Figure 4.6 Procedure of PHEA methodology for finding HEP (Stanton et al., 2002)

Judges compare one item with another, and determining which is higher or lower in some sort of scale. The technique draws these comparative judgments from different experts, and develops a scaling of the tasks in terms of their relative likelihood of error. Two or more tasks with known HEPs are then used to calibrate the scaling, based on logarithmic transformation for estimating HEPs (Kirwan, 1994). This techniques in extensively used for finding HEPs in a variety of industrial sectors as well as the medical field. (Park et al., 1996). The procedure of PC method may be seen in Figure 4.5.

4.8 Predictive Human Error Analysis (PHEA)

PHEA is a development of Hierarchical Task Analysis (HTA) in that it uses each bottom level task of the hierarchy as its inputs. These tasks are categorized according to a predetermined taxonomy and form the basis of subsequent error identification. Thus, the first step of a PHEA must be to devise an HTA if one is not already available. Human error taxonomy is used to classify tasks into one of five error types (action, retrieval, checking, selection, information communication). The analyst then refers to the taxonomy to assess credible error modes for each task. Ordinal probability and criticality for each potential error is then evaluated consequentiality by the analyst. Then based on the subjective judgment of the analyst, possible remedial actions are presented, as well as recovery steps at which they may be affected. This process occurs for each bottom-level task of the HTA, and the entire procedure is illustrated by means of a flowchart. The procedure of using PHEA is illustrated in Figure 4.6 (Stanton et al., 2002).

The main strengths of the PHEA method are that it provides a structured and comprehensive approach to error prediction, gives an exhaustive and detailed analysis of potential errors and the error taxonomy prompts the analyst for potential errors, however

PHEA is somewhat repetitive and time costly in time to perform (Harris et al., 2005)

4.9 Evaluating the methods to assess HEP

There are different techniques available to obtain HEP, but each is not physically usable via the whole modeling scenarios. Therefore, one should be familiar with the advantages and disadvantages of each technique based on previous investigations to select the suitable methodology for the specific case. SLIM is one of the most flexible techniques which is validated, but it is a sophisticated method for obtaining PSFs from a judgment and it is difficult to ensure about the truly independency of these PSFs. HEART is a quick and simple technique to use with little training, but the reliability of the method is still not proven. Moreover, the lack of existing validation studies and its high dependency on expert opinions are some of HEART's limitations. THEARP was claimed as one of the most accurate techniques to determine HEP, but it is not useful in error reduction and this technique is highly dependent on the assessors. Therefore, choosing the specific level by the assessors may lead to different results. APJ is another technique to obtain HEP and it shows an accurate estimate in different fields. The expert discussion provided in this technique can be classified and can be quantitatively useful. Although, APJ is sometimes prone to certain biases as well as personality/group problems and conflicts. PC is a technique that can estimate the relative importance of different human errors or human events and can be applied quickly to estimate HEPs. But, this method is not suitable for complex predictions of human error and the homogeneity of the events is an assumption in this technique that could be subject to error itself. Finally, in PHEA technique, error reduction strategies offered as part of the analysis, in addition to predicted error. But, this technique does not model cognitive components of error mechanisms. The advantageous and limitations of using these techniques to estimate HEP can be seen through Table 4.1 (Apostolakis et al., 1988; Vestrucci, 1988; Kirwan, 1994; Humphreys, 1995; Kirwan 1996; Kent et al., 1995; Stanton et al., 2002; Salmon et al., 2003; Park et al., 2008).

Table 4.1 Advantages and disadvantages of different techniques for evaluating HEP

Method	Advantages	Disadvantages
SLIM	This is a flexible technique (dealing with the entire range of HE forms without requiring a detailed decomposition of the task is possible). It is validated according to a variety of cases until now. It is usually a highly plausible approach for the assessors (regulators and experts) who participate.	It is a sophisticated method for obtaining PSFs from a judgment. It is difficult to ensure that the PSFs are truly independent The choosing of PSFs is currently somewhat arbitrary and so unsatisfactory affair. There is a lack of selection criteria for choosing good experts. Probabilities of target tasks may be modified by adding a new task to the set. SLIM's PSFs are fairly global in comparison to the more specific PSFs in methods such as HEART
HEART	It is quick and simple to use with little training. Each error-producing condition has a remedial measure related to it. It gives the analyst quantitative output. HEART uses fewer resources in comparison to other techniques such as SHERPA. It is highly flexible and applicable to different areas.	There are some doubts over the consistency of the method. There is a shortage of validation studies. Dependence and EPC interaction is not accounted for by this method. It is subjective, reducing its reliability and consistency. This technique would still require considerable development to be used in different domains. It is strongly based on the expert opinions in the point of probabilities of human error and also in the assessed proportion of EPC effect
THERP	It has been well used in practice over the past three decades. It has good accuracy of performance. It is claimed as one of the most powerful methodologies in HRA	It has limited usefulness in error reduction It has a variable resource used level (In some cases, it can be resource intensive) It is strongly based on the assessors and choosing the specific level by the assessors may lead to different HEPs It does not present sufficient guidance in modeling both scenarios and the impact of PSFs on error It is relatively psychologically opaque, considering external error modes in compare with psychological error mechanisms

APJ	It showed an accurate estimate in different fields (e.g. Weather forecasting) It is quick to use The expert discussion provided in this method can be documented and can often itself be qualitatively useful Expert discussion in this method leads towards the consideration of how to achieve error reduction	It is sometimes prone to certain biases, as well as personality/group problems and conflicts It is often associated with guessing and produces a somewhat low degree of apparent or face validity It is based on the selection of appropriate experts, but there is a lack of selection criteria for choosing good experts
PC	Human judgement evidence is greater than the numerical assessment It can estimate and control part of the system with specific data It can work with a minimum of two empirically estimated HEP values It can estimate the relative importance of different human errors or human events It can be quickly applied	It may not be suitable for complex predictions of human error Homogeneity of the events or tasks is an assumption that could be subject to error Independence of each comparison causes the distortion of results The judges could become tired by the large number of comparisons
PHEA	Structured and comprehensive procedure, yet maintains usability Taxonomy prompts analyst for potential errors Encouraging validity and reliability data Substantial time economy compared to observation. Error reduction strategies offered as part of the analysis, in addition to predicted errors	Can be tedious and time-consuming for complex tasks Extra work involved if HTA not already available Does not model cognitive components of error mechanisms Some predicted errors and remedies are unlikely or lack credibility, thus posing a false economy Current taxonomy lacks generalisability

4.10 Using AHP to choose the optimum method according to the specific case study

The scenario considered in this research is the evacuation of a building in an emergency condition. Five different criteria, as shown in Table 4.2, are considered to compare different methods to obtain HEP for this specific case. These criteria were selected based on previous investigations in HEP techniques comparison (Kirwan, 1988). Description of these criteria is not discussed within this research, as there were described previously (Kirwan, 1988). The criteria demonstrated in Table 4.2, are sorted based on their importance for this scenario. Therefore, individuals who want to find the suitable method for their own case should sort them based on their own limitations and conditions.

In the second step, each of the methods (illustrated in Table 4.1) are compared with another based on each of the criteria listed in Table 4.2. An example of one of the spreadsheet in the second step, each method (illustrated in Table 4.1) is compared with another based on each of the criteria mentioned in Table 4.2. An example of one of the spreadsheets used for this comparison is shown in Table 4.1 of the appendix. Assessing the previous literature about these techniques and their implementation in different case studies and comparing these techniques with another (Bernhard Zimolong, 2003; Park et al., 2008; Kirwan.1996) may help to learn about the advantages and disadvantages of each method and their comparisons respectively.

Finally, following a comparison of these techniques according to characteristics specified for this modeling scenario, Expert Choice software, which is a multi-objective support tool based on analytical hierarchy process, is used to discover a suitable technique to use for this modeling scenario.

Table 4.2 Criteria considered in this comparison based on their priority

No.	Criteria
1	Accessibility
2	Usefulness
3	Validity
4	Accuracy
5	Resource usage

4.11 Results of using AHP

Comparing the six existing techniques based on the criteria mentioned above leads to the following results, as shown in Figure 4.7.

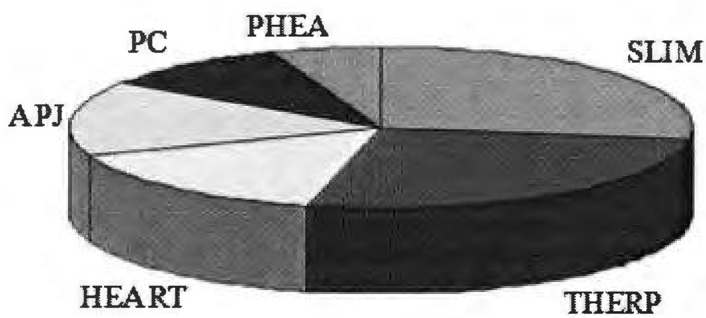

Figure 4.7 Comparing different techniques using AHP

The results show that SLIM is the best option among these techniques according to the specific criteria that are considered in this case study. AHP is highly dependent on the weighting of the selected criteria. Therefore, changing the priority of these criteria based on any other cases may effect on the results. Using AHP in this scenario show priority of each technique and their final ranking percentage based on comparing the technique according to each criteria and weighting the criteria themselves as shown in Table 4.3.

Table 4.3 Priority of techniques received using AHP

Technique	Final value received by AHP
SLIM	0.275
THERP	0.264
HEART	0.152
APJ	0.152
PC	0.098

4.12 Application of SLIM (Case study)

As evaluated in the section, SLIM is selected according to the selected criteria and their priority. Therefore, implementing SLIM to find HEP for the scenario of building evacuation in a fire situation is considered in this research as a case study.

4.13 Scenario description

The scenario considers a business building in a fire evacuation emergency. The alarm detectors are located in different parts of the building in the construction stage. Following the alarm sounding in the building due to fire, staff and visitors are to evacuate the building. During this evacuation, two different scenarios for the staff and visitors are considered. In this research, the evacuation of the building by a visitor to the building is evaluated.

When the alarm sounds, visitors should look for someone who works in the building to identify the type of the alarm. If they find staff, visitors should follow them and evacuate the building. In the case where visitors can not find someone knowledgeable of how to safely evacuate the building, they will have to make egress decisions on their own and likely assist others facing the same situation. Evaluating potential egress paths and selecting the appropriate route by moving along the egress route create the following steps. It should be noted that the quality of the exit route should be assessed while moving to a temporary safe refuge. This modeling scenario is demonstrated in Figure 4.8.

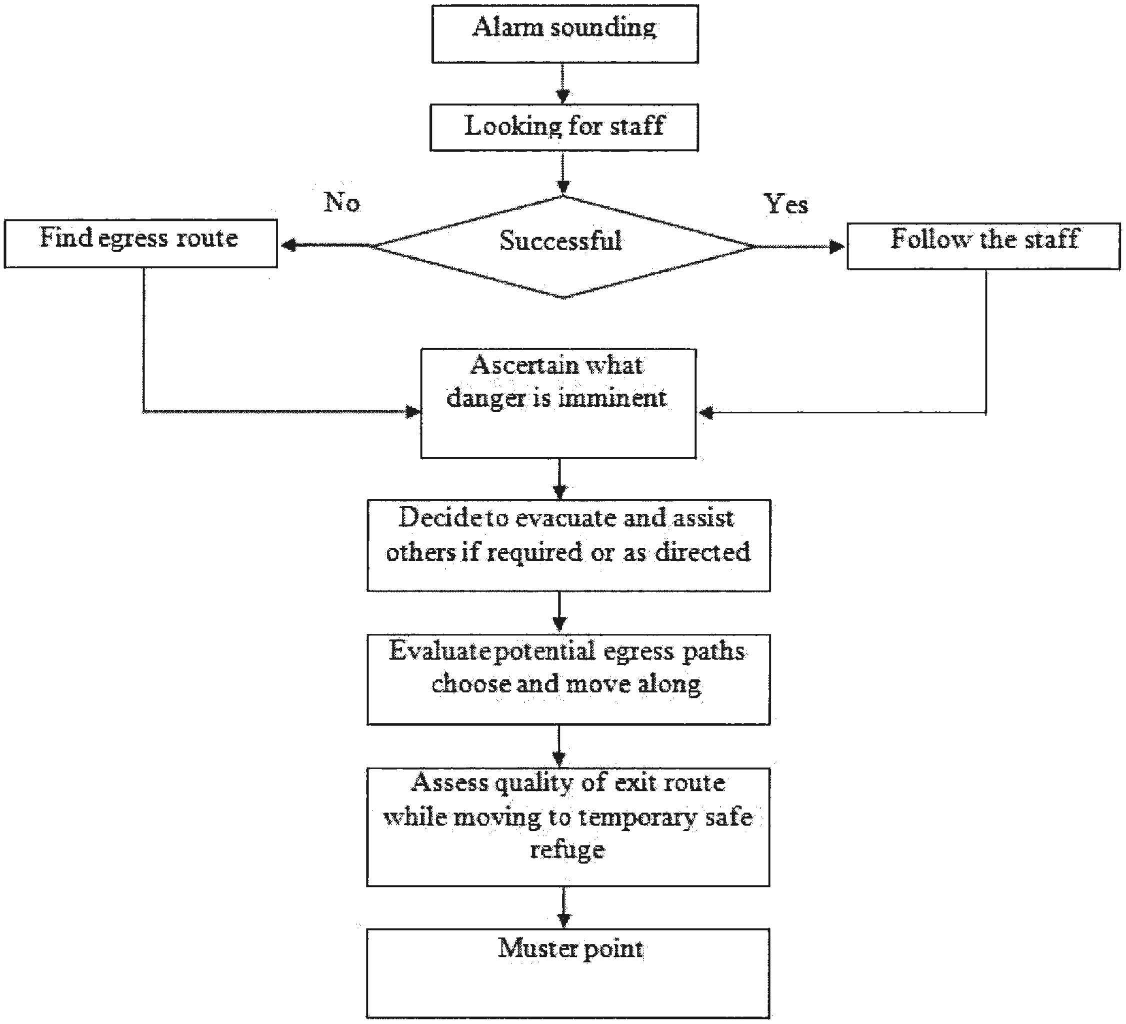

Figure 4.8 Scenario considered for the visitors evacuation

4.14 Evaluating PSFs for this scenario

The performance shaping factors utilized in this case will influence the probability of failure are stress, training, experience, even factors, and time. These factors are described in Table 4.4.

Table 4.4 PSFs considered in this scenario

PSF	Description
Stress	The inability to complete the task successfully due to anxiety and pressure.
Distraction	PSF that affects the likelihood of a task being completed successfully because of lack of focus due to the extreme mental or emotional disturbance. This, combined with a high level of stress, can make actions that are normally simplistic in nature complicated and/or cumbersome.
Training	Relates to an individual's ability to most effectively identify muster alarm and perform the necessary actions to complete muster effectively.
Experience	Related to how a person will complete the muster task successfully.
Event factors	The location of the individual with respect to the initiating event and/or the magnitude and dimension of the initiating event can dictate the performance of an individual in an emergency situation.
Time	Depending on the definition of the action, the time required may include both the time required to diagnose the problem and the time to physically accomplish the action. The time available would then be measured from the first indication available to the staff and visitor.

In the next step, each PSF is weighted by judges who are considered to this scenario to obtain HEP. The questionnaire filled by these judges can be seen in Table 4.2 of the Appendix. The values of weighting of these PSFs received from judges are described in Table 4.5.

Table 4.5 Weighted values of PSFs

PSF	Weighted Value
Stress	0.3
Distraction	0.1
Training	0.15
Experience	0.2
Time	0.1

In the final stage, HEPs using SLIM for this case study is received as can be seen in Table 4.6.

Table 4.6 HEP for Visitors using SLIM

Events	**HEP (Visitor)**
Alarm Sounding	7.94E-02
Looking for staff/ host to identify type of alarm	4.73E-03
Finding egress route	8.58E-04
Follow the staff	4.99E-01
Ascertain what danger is imminent	2.80E-03
Take decision to evacuate, Assist others if needed or as directed	5.05E-03
Evaluate potential egress paths and choose Move along egress route	1.05E-04
Assess quality of exit route while moving to temporary safe refuge	3.00E-04
Muster point	1.53E-01

4.15 Conclusion

Evaluating some of the well-known techniques based on their advantages and disadvantages, and using AHP for choosing the appropriate techniques to obtain HEP lead to following results:

- A methodology to choose the appropriate technique for specific scenario according to characteristics of each technique and required criteria is necessary
- Using AHP regarding to possible techniques and specific criteria can be a suitable methodology for determining appropriate techniques to obtain HEP
- Although SLIM is selected based on the criteria considered for the case study presented in this research, individuals should compare these techniques based on their own cases and criteria for each specific scenario

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Appendix 4.1 Comparing different techniques based on accuracy of the models

Methods	**Value**									**Methods**
SLIM	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**HEART**
SLIM	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**THERP**
SLIM	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**APJ**
SLIM	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PC**
SLIM	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PHEA**
HEART	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**THERP**
HEART	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**APJ**
HEART	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PC**
HEART	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PHEA**
THERP	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**APJ**
THERP	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PC**
THERP	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PHEA**
APJ	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PC**
APJ	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PHEA**
PC	**5**	**4**	**3**	**2**	**1**	**2**	**3**	**4**	**5**	**PHEA**

Appendix 4.2 The sample of visitor's questionnaire

Visitor's Questionnaire	Stress	Distraction	Training	Experience	Event Factor	Time
The relative importance of hearing or recognize the alarm	4	4		7		
The relative importance of finding the staff	6	7		5	7	6
The importance of finding egress route	6	7	4	8	7	7
How import it is to follow the staff		4			8	
How important it is to identify the risk of human related to the danger (reason for the alarm)	7		7	8		8
The importance of taking decision to evacuate	7		6	7		7
How important it is to make choice of egress Route	8	8	9	7	8	9
How important it is to assess quality of exit route while moving to temporary safe refuge	7	6	7	7	8	
The relative importance of designate muster Point		6	6	5		

5 Determination of human error probabilities in maintenance procedures of a pump[†]

Preface

A version of this manuscript has been published in the *Journal of Process safety and Environmental protection.* Noroozi was the main lead on the work. The co-authors, Drs. Khan, MacKinnon and Amyotte supervised the principal author. They helped to develop the methodology and cross checked the analysis. The co-author Mr. Deacon supplied the list of activities from industry sources. Noroozi, developed the research, analyzed the human reliability, and utilized HEART methodology. Noroozi also prepared the first draft of the manuscript while the co-authors Drs. Khan, MacKinnon and Amyotte reviewed the manuscript and provided the necessary suggestions.

Abstract

The "human factor" constitutes an important role in the prediction of safe operation of a facility. Hence, information about human capacities and behaviors should be applied methodically to increase the safety of a systematic process. This research provides an analysis of human factors in pre- and post- maintenance operations. For possible failure scenarios, this research considers the procedures for removing process equipment from service (pre-maintenance) and returning the component to service (post-maintenance). In this study, a pump is used as the test example. For each scenario, the HEP is calculated for each activity, using the HEART which is commonly implemented technique in industry, can also be applied in the analyses of safety cases. HEART is a reliable

[†] Noroozi et al. Journal of Process Safety and Environmental Protection 2012 (Published).

technique for comparing HEP and its approach is based on the degree of error recovery. Consequences are also assessed for each activity in this methodology. The final value of risk for each activity is assigned by combining error likelihood and related consequences. When the calculated risk is beyond acceptable levels, risk management strategies are provided to increase the safety of the maintenance procedures. The most probable human errors for a considered case study are related to the activities of "draining lines" and "open valves". These two activities have high HEPs, which are 9.57E-01 and 9.62E-01, respectively.

5.1 Introduction

Based on Norman (1981) and Reason (1990), an "error" occurs in situations where an act is committed both intentionally and unintentionally; however, the error itself and the original intention of the act are often viewed separately. Sanders and McCormick (1993) view human errors as inappropriate decisions that have a negative effect on system safety effectiveness and performance. They also argue that providing a classification system may help to organize human error data and provide insight into how errors can be prevented. Several studies have determined that such errors are a major cause of accidents in construction (Suraji et al., 2001) and manufacturing (DuPont Safety Resources, 2000; Lawton and Parker, 1998; Rasmussen et al., 1994; Sanders and McCormick, 1993).

According to Dhillon (2006) poor design factors including issues involving equipment, maintenance, and work layout, and difficulties faced by workers, such as improper work tools, fatigue on overstressed workers and environmental factors, such as humidity, lighting, temperature, etc are the main reasons of error occurrence in maintenance procedures. Improper training, the use of outdated maintenance manuals and a lack of proper experience contribute to high numbers of maintenance errors as well. There are some factors which can improve the work environment such as, providing more experience, ensuring emotional stability and hiring workers who have a greater aptitude for their environment, which can lead to less fatigue, more satisfaction and better team work.

Nelson (1996) argued that accident occurrence due to maintenance activities as well as over speed protection equipment should be a cause for concern in the industry. Balkey (1996), however, asserted that risk based inspection procedures and human error procedures in fossil fuel plants must be taken into account when conducting inspection procedures. Further data is contributed by Eves' (1985) report on accidents which occurred in the chemical manufacturing industry during times of maintenance.

Raman et al. (1991) contributed guidelines to apply Hazop techniques in the application of maintenance procedures conducted on offshore oil and gas platforms, while Underwood (1991) examined the effect of safety systems in the chemical industry through inspecting various case studies on the topic. Further research has been done by Dhillon and Yang (1995) who developed a new stochastic model to analyze the rates of human error and failed system repairs and how they affected reliability and availability of the machines. After examining the ratio estimation of HEP, Park and Jung (1996) suggested that, through linear transformation, and simple techniques of converting ratios, they can determine objective HEP. Further studies were done by Anderson et al. (1998) on reduced manning and how it affects the types of human errors experienced in systems operations and maintenance. Finally, Mcroy (1998) concluded that collecting samples of the different types of errors and interactions one experiences can be helpful in preventing such errors.

Jacob et al. (1997) found that critical human errors were a common cause for failure as a result of repairs done on two unit standby systems. Similarly, Sur and Sarkar (1996) found that redundant systems regularly caused human errors and logic failure and proposed a probabilistic model. Different probabilistic models were developed by Dhillon and Rayapati (1988b) who used supplementary variables method to develop system availability expressions represented by the human errors found in two unit parallel and standby redundant systems.

Further studies have been conducted on the topic of systems failures and human errors by Sridharan and Mohanavadivu (1997), who studied three Markov models of two non-identical unit parallel systems, by Narmada and Jacob (1996) who used a stochastic model representing a three unit system and by Dhillon (1989) who analyzed repairable and non-repairable redundant systems and human errors, establishing a reliability analysis. A basic, but useful, study was done by Reason (1990) who gave an overview of basic error mechanisms and what types of errors occur. In an attempt to deal with the problem of human error, Su et al. (2000) suggested using a knowledge-based system to analyze cognitive types and enhance fault recovery ability using a practical framework, while Gupta et al. (1991) examined overloading effects and critical human error during repair waiting times in a multi-component parallel system.

Chung (1987) examined human error and common-cause failures using a repairable parallel system with standby units. The existence of human error in the form of fault injection was studied by Carr and Christer (2003) who used data on these phenomena to extend the mathematics model of delay-time of inspection maintenance during the inspection process. Ramalhoto (1999) outlined critical safety measures after studying maintenance personnel, while Vaurio (1995), in an attempt to address human errors and common cause failures, supplied a procedure that could be used in various situations to ensure proper maintenance and safety tests for certain systems and also reviewed some earlier models which attempted to address HEPs in a separate researches. Human analysis and repair times in a system were researched by Dhillon and Yang (1993), while Sanders and McCormick (1993) outlined the types of human factors which can contribute to errors in maintenance in direct or indirect ways. Bradley (1995) presented a methodology which can be useful in helping determine the causes of human, design and maintenance errors. Miller and Swain (1986) examined the effects of human errors on system performance, equipment or task characteristics and work potential, and how they can be changed to reduce these errors. In an earlier study, Dhillon (1986) outlined the various aspects present with regards to human factors and maintenance, such as reliability and error, revisiting the topic in a 2002 book. Gramopadhye and Drury (2000) gave their theories behind the increases in maintenance and inspection errors, while Dodson and Nolan (1999) examined the human factors behind field tests, production and man-machine function allocation.

Conclusively, the study of human factors is an important area of process engineering and it includes the systematic application of information about human characteristics and behavior to improve the performance of human-machine systems (McSweeney et al., 2008).

Researchers have suggested different quantitative techniques to estimate the HEPs. SLIM has been used as a methodology to estimate the HEPs in the case of emergency evacuation of an offshore oil and gas platform (DiMattia et al., 2005). Kirwan has also well explained the application of other quantitative techniques such as HEART, and TTHERP to the hypothetical cases (Kirwan, 1996).

Several studies have compared different methods (e.g. SLIM, HEART, and THERP) for finding HEP. These studies considered both the advantages and disadvantages of these techniques with respect to HEP under various scenarios (Stanton et al., 2002; Salmon et al., 2003; Park et al., 2008).

Although modern information database systems can achieve a high degree of automation, human factors still play an important role in process installations, especially maintenance activities (Frank, 1996). One vital consideration is the impact of human error. This research examines pre- and post-maintenance activities of a condenser pump as the context to understand the role of human error. HEPs are evaluated using the HEART. Activities with high HEPs are identified, and mitigation measures are recommended to reduce errors to obtain lower probabilities of poor outcomes as a result of human error.

A risk-based methodology is developed for pre- and post-maintenance in section 2. The HEART methodology explained in section 3. Brief descriptions of the application of HEP for pre- and post-maintenance of a pump with different scenarios are presented in section 4. Section 5 identifies the relevant consequences for each activity. Section 6 shows how to calculate the HEP for each activity. Measuring the risk level for each task and identifying the high risk activities are done in sections 7 and 8. Remedial measure with recommend appropriate mitigation measures for tasks with higher HEP in order to reduce the probability of human error are presented in section 9. The discussion and conclusion with recommendations for future work are presented in sections 10 and 11.

5.2 Developing a risk-based methodology for pre- and post-maintenance

There are different techniques available to obtain HEP, but each method is not physically usable via the whole modeling scenarios. Therefore, one should be familiar with the advantages and disadvantages of each technique based on previous investigations to select the suitable methodology for the specific case.

Individuals who want to find the suitable method for their own case should sort them based on their own limitations and conditions, after comparing each methods based on each of the criteria. Considering different standards, this research suggest HEART methodology as the most applicable technique.

Different human activities occur in pre- and post-maintenance procedures for pieces of equipment. A risk-based methodology can be developed to assess the risks of these activities (see Figure 5.1). The HEPs are estimated by applying the HEART process. After obtaining the HEPs based on a described work activity or scenario, the final value of the risk is calculated by integrating both the HEPs and the consequence analysis results. Whenever the calculated risk exceeds acceptable criteria that are based on specified guidelines, then a risk management approach is employed to minimize the risk.

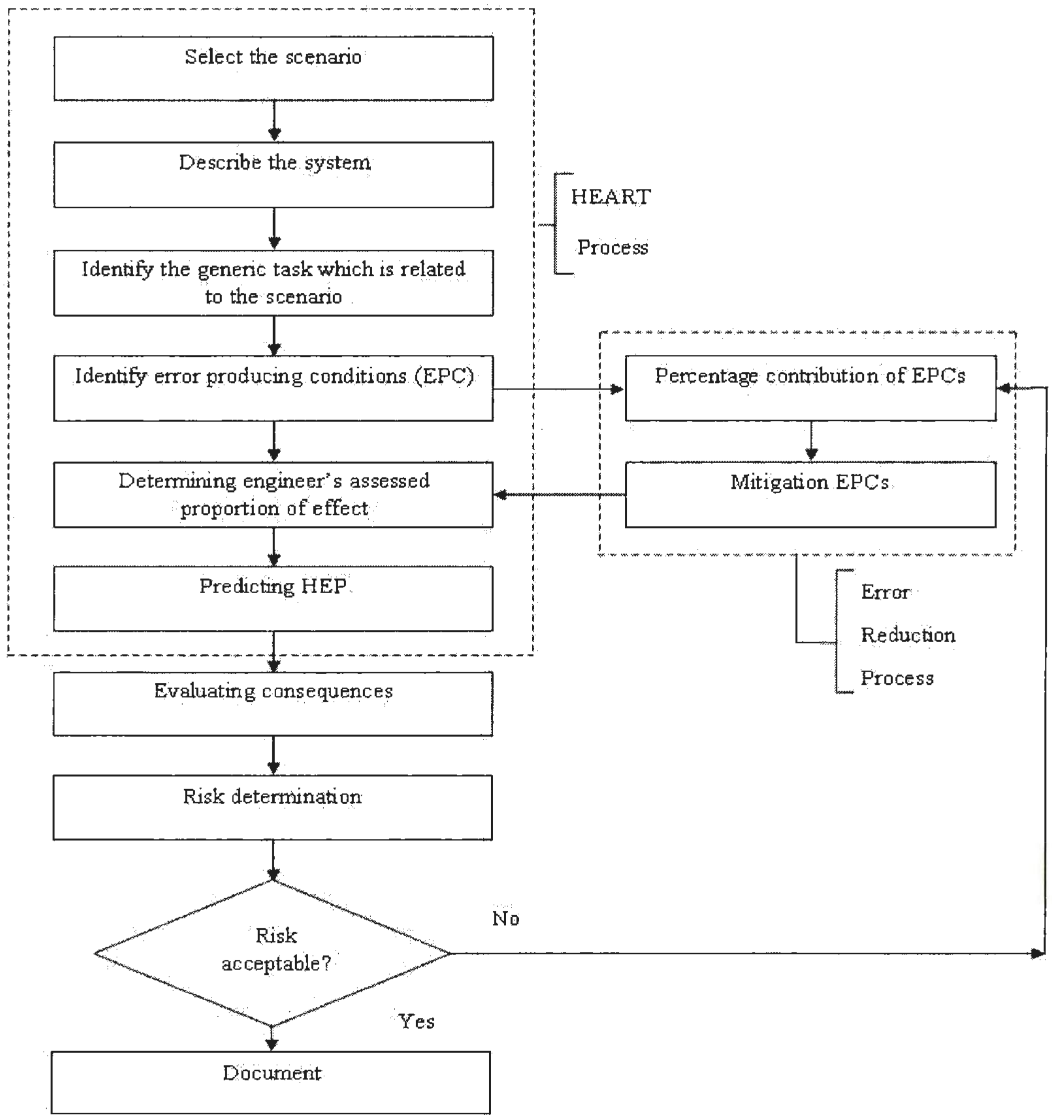

Figure 5.1 Risk - based methodology for minimizing HEP

5.3 HEART approach

HEART is a technique for evaluating HEP, based on the demands of a task, the inherent risk within the task and the opportunities for error recovery. The fundamental basis of this approach lies in reliability and risk equations, with a focus on ergonomic factors that have a large effect on performance. Many studies have examined ergonomic factors and their consequences, even though the studies have a negligible effect on operator performance, factors that do have significant effects on performance are considered in HEART (Kirwan et al., 1996).

The maximum impact of each individual factor (total HEART effect) was determined by various studies of human factors performance over a long period of time. These data come from extensive research on human error in several industries collected by Williams, (1986) who developed the HEART methodology.

The HEART method is easy to understand and is quickly implemented. However, its approach is quite subjective and heavily reliant on the experience of the analyst (Casamirra et al., 2009) this may call into question the method's overall reliability if not applied by competent personnel.

The HEART method utilizes the following steps (Kirwan, 1996):

- Assign step to a generic error category
- Choose generic error probability
- PSFs that apply to the step
- Determine the weight of each applicable PSF on the step
- Calculate the overall HEP

The PSFs are named EPCs in HEART.

The HEART method begins with selecting a generic error category and an associated generic error probability (GEP) within each of the eight generic error categories (Kirwan et al., 1996).

Next, the assessor will determine the factors that influence the HEP, known as EPC. There are 38 EPCs. The first 17 EPCs have the greatest influence on HEP (Kirwan et al., 1996).

Selection of the proper EPC among the 38 possibilities is usually based on developing a scenario for the task under consideration. Each EPC has a maximum nominal amount, which should be inserted in Equation 1 as the error-producing condition representative. The next step is to Assess the Proportion Of Affect (APOA), which is weighted for each chosen EPC based on its importance by the expert judges. In this way, each EPC is individually weighted from 0 to 1 (Williams, 1988).

$$\text{Assessed Effect} = (\text{Maximum effect} - 1) * \text{APOA} + 1 \qquad (1)$$

Equation 1 is used to calculate the effect of each EPC and its relevant APOA on the GEP. The HEP of each task is calculated by multiplying the selected GEP with the nominal amount of APOA related to each EPC (Williams, 1988).

5.4 Application of HEP for pre- and post-maintenance of a pump

5.4.1 Scenario development

This scenario considers pre- and post-maintenance procedures for condensate pumps. These procedures include eight scenarios, one for each of the eight activities. Activities 1 and 2 involve pre-maintenance, and activities 3 to 8 address post-maintenance. These activities were developed in conjunction with Single Buoy Moorings (SBM) Company in Nova Scotia.

The scenarios developed based on maintenance reports of offshore platform in Iran and these were selected based on the most frequent occurring scenario. The accessibility of the data and availability of the experts were the reasons why offshore platform in Iran was chosen.

5.4.2 Pre-maintenance

Pre-maintenance activities have been assigned to the first two activities: "prepare work" and "isolate pump." In the following sections, the sub-activities of each activity and their related scenarios are explained.

5.4.2.1 Prepare work

Work preparedness is the first activity for performing maintenance of a condensate pump which contains of 17 sub-activities as shown in Table 5.1.

Table 5.1 Sub-activities considered for activity 1

Activity 1. Prepare work	
1.1	Area Authority (AA) prepare work order
1.2	Apply for permit to work
1.3	Perform equipment diagnostics
1.4	Identify equipment affected and tags used
1.5	Perform risk assessment of activity
1.6	Check work order and ensure no conflict of operation
1.7	Determine and certify required isolations
1.8	Permit to Work Coordinator (PTWC) obtains keys and certificates
1.9	AA authorizes work
1.10	PTWC assigns lockout box and gives keys to supervisors affected by isolation

	1.11	Perform and document initial gas test
	1.12	Rank fluid contained within pump
	1.13	Determine size of inlet and outlet lines from pump
	1.14	Identify most appropriate isolation method
	1.15	Offshore Installation Manager (OIM) approve work activity
	1.16	Workforce Supervisor (WFS) hold toolbox meeting
	1.17	Place Permit to Work (PTW) on permit board with copy displayed at work site

5.4.2.1.1 Describing the Scenario for Activity 1: Prepare for work

This scenario involves running pre-maintenance activities according to the predefined work schedule. This occurs under limited time constraints. Increasing workload within a limited time frame leads to long hours of non-stop work, imposing stress and fatigue and causing problem for personnel. The following scenario descriptors and worker characteristics are defined from maintenance offshore platform team in Iran.

1. Generally, there is insufficient training for the workforce in identifying workplace hazards and working with PTW systems.

2. The supervisor is a new employee who has not passed the related health and safety hazard identification training courses.

3. The testing equipment is not calibrated according to the manufacturer's specifications and there is no new testing equipment available.

4. The operator is inexperienced in isolation methods.

5. The engineer who is training the operators has not approved the standard operating procedures; hence, he or she does not understand the process completely.

6. The supervisor also has little knowledge of potential plant hazards.

5.4.2.2 Isolate pump

Isolation of the pump is the second activity for the pre-maintenance of a condensate pump. It contains 16 sub-activities, as shown in Table 5.2.

Table 5.2 Sub-activities considered for activity 2

2.0	**Isolate Pump**
2.1	Check lines for fluid and pressure
2.2	Check bleeds/vents for obstruction
2.3	Close isolation valves
2.4	Lock and tag isolation valves
2.5	Depressurize lines
2.6	Drain lines
2.7	Purge lines
2.8	Perform pressure test and isolation leak test
2.9	Open all drains of affected equipment possible
2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)
2.11	Re-pressurize lines

	2.12	Isolate, lock and tag motor from control centre
	2.13	Test motor for power
	2.14	Revalidate permit with supervisors
	2.15	Break containment
	2.16	Continue testing pressure and isolation at intervals

5.4.2.2.1 Describing the Scenario for Activity 2: Isolate pump

1- An inexperienced operator is working in an environment with a high level of noise.

2- The manager in charge is known for the emphasis on minimal mean time between failures in order to prevent production delay.

3- The operator is under pressure to address any failure as soon as possible.

5.4.3 Post-maintenance

The post-maintenance activities for a condensate pump are categorized into six topics as shown in Table 5.3.

Table 5.3 Activities of post- maintenance task

3.0	Re-connect pump
4.0	(WFS) Ensure site and equipment left in safe state
5.0	(WFS) Return keys and certificates
6.0	(PTWC) Ensure site ready for reinstatement
7.0	(PTWC & AA) Close Permit to Work
8.0	Open valves and reinstate pump

The following sections describe the sub-activities and their related scenarios.

5.4.3.1 Describing the Scenario for Activities 3, 4, 5, 6, 7

After each maintenance service, the operators and engineers must continue with post-maintenance activities, since production must not be halted for extended periods of time. These activities focus on returning the system to normal operation. In this scenario, characteristics include:

1. Some young operators have logged insufficient training hours. Due to the high amount of work undertaken, the work pressure is high, which leads to intense fatigue for the workers.
2. An inexperienced workforce engineer is responsible for ensuring site readiness for reinstatement. The site engineer is using a poorly written report to perform an inspection and to ensure that the site and equipment are in safe conditions.
3. The responsible incoming assistant lacks adequate information regarding returning keys and supplying certificates.

Table 5.4 shows the sub - activities considered for activities 3, 4, 5, 6, and 7.

Table 5.4 Sub - activities considered for activity 3, 4,5,6,7

Sub Activity	Activity	
3. Re-connect pump	3.1	Check lines and equipment for obstructions
	3.2	Remove mechanical isolation/connect lines to pump
	3.3	Remove locks and tags from valves, leaving valves closed
4. (WFS) Ensure site and equipment left in safe state		

5. (WFS) Return keys and certificates		
6. (PTWC) Ensure site ready for reinstatement	6.1	Return lock-out keys
	6.2	Give worksite authority back to AA
	6.3	(Supervisors) Document reinstatement
7. (PTWC and AA) Close Permit to Work		

5.4.3.2 Describing the Scenario for Activity 8: Open valves and reinstate pump

1- A fairly inexperienced operator takes action, despite the predefined standards and related tasks.

2- The instrumentation is unreliable, which may cause malfunctions in the related procedure.

3- The system feedback is unreliable.

4- The supervisor is too busy to provide complete supervision for the procedure.

5- There is insufficient time, due to the urgency of starting operations to prevent extra costs.

Table 5.5 shows the sub - activities considered for activity 8.

Table 5.5 Sub-activities considered for activity 8

Sub -activity for open valves and reinstate pump	
8.1	Test pressure
8.2	Remove air from lines and pump

8.3	Open valves, fill pump and test for leaks
8.4	Start pump

5.5 Consequence

The consequence analysis of each of the tasks involved in pump removal and reinstatement is shown in Table 5.6. Kletz (2009) was consulted as an aid in determining the possible consequences of error for each task. It is an extensive collection of information and reports of past incidents.

Table 5.6 Consequences considered for each activity

Activities		Consequences
1.0	Prepare work	
1.1	(Area Authority) Prepare work order	• Operators or control room unaware of maintenance work • Serious injury or death
1.2	Apply for Permit to Work	• Operations and maintenance personnel unaware of conflicts • Damage to equipment • Serious injury or death
1.3	Perform equipment diagnostics	• Personnel not completely aware of issue • Damage to equipment
1.4	Identify equipment affected and tags used	• Discrepancy between maintenance team and control room • Operators not aware pump should be removed from service • Serious injury or death
1.5	Perform risk assessment of activity	• Maintenance personnel misunderstand hazard level, unnecessary exposure to risk • Damage to equipment • Injury/death
1.6	Check work order and ensure no conflict of operation or other work	• Operations and maintenance personnel unaware of new developments or conflicts

			• Damage to equipment • Injury/death
	1.7	Determine and certify required isolations	• Operations personnel perform inadequate isolation • Damage to equipment • Injury/death
	1.8	(Permit to Work Co-ordinator) Obtain keys and certificates required	• Maintenance personnel misunderstand hazard level, unnecessary exposure to risk • Damage to equipment • Injury/death
	1.9	(AA) Authorize work	• Maintenance personnel misunderstand hazard level, unnecessary exposure to risk • Damage to equipment • Injury/death
	1.10	(PTWC) Assign lockout box and give keys to supervisors affected by isolation	• Operations or maintenance personnel open valve that should be closed • Damage to equipment • Injury
	1.11	Perform and document initial gas test	• Explosion during hot work • Damage to equipment • Injury
	1.12	Rank fluid contained within pump	• Work order personnel unable to determine most appropriate isolation method • Maintenance personnel exposed to unnecessary risk • Damage to equipment • Injury/death
	1.13	Determine size of inlet and outlet lines from pump	• Work order personnel unable to determine most appropriate isolation method • Maintenance personnel exposed to unnecessary risk • Damage to equipment • Injury/death
	1.14	Identify most appropriate isolation method	• Maintenance personnel exposed to unnecessary risk • Damage to equipment • Injury/death

	1.15	(OIM) Approve work activity	• Maintenance personnel misunderstand hazard level, unnecessary exposure to risk • Damage to equipment • Injury/death
	1.16	(Workforce supervisor) Hold toolbox meeting	• Maintenance and operating personnel unprepared for job, unnecessary exposure to risk • Damage to equipment • Injury/death
	1.17	Place PTW on permit board with copy displayed at work site	• Operators not aware pump should be removed from service • Serious injury or death
2.0	Isolate pump		
	2.1	Check lines for fluid and pressure	• Explosion during hot work • Damage to equipment • Injury/death
	2.2	Check bleeds/vents for obstruction	• Potential for trapped pressure, fluid hazard and/or missiles • Damage to equipment • Injury
	2.3	Close isolation valves	• Personnel exposed to hazards within equipment • Damage to equipment • Injury/death
	2.4	Lock and tag isolation valves	• Operations or maintenance personnel open valve that should be closed • Damage to equipment • Injury
	2.5	Depressurize lines	• Personnel exposed to contents of pipe or pump • Injury/death
	2.6	Drain lines	• Contents of pipes or pump exposed to work area • Damage to equipment • Injury/death
	2.7	Purge lines	• Explosion during hot work • Damage to equipment • Injury/death
	2.8	Perform pressure test & isolation leak test	• Explosion during hot work • Damage to equipment

		• Injury/death
2.9	Open all drains of affected equipment possible	• Inadequate relief from fluid or pressure hazards • Damage to equipment • Injury/death
2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)	• Contents of pipes or pump exposed to work area • Damage to equipment • Injury/death
2.11	Re-pressurize lines	• Damage to equipment • Injury
2.12	Isolate, lock and tag motor from control centre	• Damage to equipment • Injury
2.13	Test motor for power	• Maintenance personnel unaware that motor still has power • Damage to equipment • Injury
2.14	Revalidate permit with supervisors	• Operations and maintenance personnel unaware of new developments /conflicts • Damage to equipment • Injury/death
2.15	Break containment	• Contents of pipes or pump exposed to work area • Damage to equipment • Injury/death
2.16	Continue testing pressure and isolation at intervals	• Conditions in pipes or pump become hazardous • Damage to equipment • Injury/death
3.0	Re-connect pump	
3.1	Check lines and equipment for obstructions	• Obstructions or contaminants in system • Damage to equipment
3.2	Remove mechanical isolation/connect lines to pump	• Damage to equipment • Injury
3.3	Remove locks and tags from valves, leaving valves closed	• Leakage of fluid from pipes, exposure to danger if hot work nearby • Injury/death
4.0	(WFS) Ensure site and equipment left in safe state	• Personnel exposed to uncontrolled workplace hazard

		• Injury
5.0	(WFS) Return keys & certificates	
6.0	(PTWC) Ensure site ready for reinstatement	
6.1	Return lock-out keys	
6.2	Give worksite authority back to AA	
6.3	(Supervisors) Document reinstatement	
7.0	(PTWC & AA) Close Permit to Work	• Damage to equipment • Injury
8.0	Open valves and reinstate pump	
8.1	Test Pressure	• Damage to equipment • Injury
8.2	Remove air from lines and pump	• Damage to equipment
8.3	Open valves, fill pump and test for leaks	• Damage to equipment • Injury
8.4	Start pump	• Damage to equipment • Injury

5.6 HEP calculation

The HEART methodology was used to calculate the HEP for all above activities. A detailed calculation for the sub-activity 1.1, "prepare work order by area authority," is described below as a sample of the procedure. The first step is to determine a Generic Task (GT). According to the classification of generic tasks and associated unreliability estimates in HEART methodology (Kirwan et al., 1996), the GT considered for this sub-activity is "E." For type E task, the nominal unreliability is 0.02. The EPCs and their maximum predicted nominal amounts related to this sub-activity have been selected, based on the scenario illustrated above.

A proportionate weight factor is applied when an EPC is applied. This is shown in the column labeled "Assess Proportion of Effect" in Table 5.7.

According to Table 5.7, the values 0.2, 0.5, and 0.7 are considered for these EPCs, based on the degree of effectiveness of each EPC on human error. Poor information quality is the most important factor contributing to errors. If the information is communicated poorly or if the information is inaccurate, then errors will happen more frequently.

Based on equation (1) the assessed effect of each EPC is calculated:

Assessed effect (for EPC 1) = (17- 1) *0.2 + 1

The same calculation has been done for other EPCs:

HEP of task 1.1= 0.02* 4.2* 3.5* 2.4= 7.06E-01

Table 5.7 The HEP calculation of sub activity No. 1.1

Activity:1.0	Prepare Work				
Sub activity: 1.1	(Area Authority) Prepare work order				
Generic Task	Generic Error Probability	EPCs	Total HEART Effect	Assess Proportion of Effect	Assessed Effect
E	0.02	Unfamiliar with a situation	17	0.2	4.2
		A channel capacity overload	6	0.5	3.5
		Impoverished quality of information	3	0.7	2.4
Total assessed EPC effect					35.28
HEP					7.06E-01

The same calculation has been done for the HEP of other sub-activities. The results are shown in Table 5.8 for pre-maintenance activities and Table 5.9 for post-maintenance activities.

The above method is the simplest formula to be used to obtain HEP. However it would be a great idea to use stochastic models. HEP calculation still used in empirical formulation and more sophistication is needed. Simplistic approach of human error quantification suggested that more quantitative approach such as Markov models could be used. It needs to be considered that human behavior or human actions are highly variable and unpredictable; therefore the use of empirical formulation is superior to statistical technique.

Table 5.8 Probability of error of pre-maintenance activities

Activities			HEP
1.0		**Prepare work**	
	1.1	(Area Authority) Prepare work order	7.06E-01
	1.2	Apply for PTW	3.17E-01
	1.3	Perform equipment diagnostics	7.74E-01
	1.4	Identify equipment affected and tags used	7.74E-01
	1.5	Perform risk assessment of activity	3.58E-01
	1.6	Check work order and ensure no conflict of operation or other work	2.69E-01
	1.7	Determine and certify required isolations	1.49E-01
	1.8	PTWC obtain keys and certificates required	4.73E-01
	1.9	AA authorize work	1.69E-01
	1.10	PTWC assign lockout box and give keys to supervisors affected by isolation	1.39E-01
	1.11	Perform and document initial gas test	9.20E-02
	1.12	Rank fluid contained within pump	5.02E-01
	1.13	Determine size of inlet and outlet lines from pump	1.78E-01
	1.14	Identify most appropriate isolation method	1.92E-02
	1.15	OIM approve work activity	1.73E-01
	1.16	WFS hold toolbox meeting	2.37E-01

Activities			HEP
	1.17	Place PTW on permit board with copy displayed at work site	4.32E-01
	2.0	**Isolate pump**	
	2.1	Check lines for fluid and pressure	8.64E-01
	2.2	Check bleeds/vents for obstruction	5.36E-01
	2.3	Close isolation valves	8.85E-01
	2.4	Lock and tag isolation valves	2.38E-02
	2.5	Depressurize lines	9.09E-01
	2.6	Drain lines	9.57E-01
	2.7	Purge lines	9.09E-01
	2.8	Perform pressure test & isolation leak test	4.66E-01
	2.9	Open all drains of affected equipment possible	2.13E-01
	2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)	5.04E-02
	2.11	Re-pressurize lines	9.24E-03
	2.12	Isolate, lock and tag motor from control centre	5.62E-02
	2.13	Test motor for power	8.47E-01
	2.14	Revalidate permit with supervisors	8.18E-01
	2.15	Break containment	3.36E-01
	2.16	Continue testing pressure and isolation at intervals	3.08E-01

Table 5.9 Probability of error of post-maintenance activities

Activities			HEP
3.0		**Re-connect pump**	
	3.1	Check lines and equipment for obstructions	2.73E-01
	3.2	Remove mechanical isolation/connect lines to pump	7.49E-01
	3.3	Remove locks and tags from valves, leaving valves closed	4.03E-01
4.0		**WFS ensure site and equipment left in safe state**	2.02E-02
5.0		**WFS return keys & certificates**	3.35E-01
6.0		**PTWC ensure site ready for reinstatement**	
	6.1	Return lock-out keys	3.43E-01
	6.2	Give worksite authority back to AA	3.50E-02
	6.3	(Supervisors) Document reinstatement	8.99E-01
7.0		**PTWC & AA close PTW**	7.78E-01
8.0		**Open valves and reinstate pump**	
	8.1	Test Pressure	3.74E-01
	8.2	Remove air from lines and pump	4.91E-02
	8.3	Open valves, fill pump and test for leaks	9.62E-01
	8.4	Start pump	2.30E-01

These results expected to be validated with the industry data.

5.7 Assign consequences and estimate risk level

Sub-activity 2.6, "drain lines," with a HEP equal to 9.57E-01, and sub-activity 8.3, "open valves, fill pump, and test for leaks," with a HEP equal to 9.62E-01, have high HEPs and high consequences, including injury and death.

Risk is a function of the probability of error and the severity of the error consequences. HEP and the severity of the consequences are evaluated for each activity. The overall risk of human error is identified for each activity by integrating the HEP and consequence severity. If the risk of an activity is too high, risk reduction measures are considered to reduce the risk.

According to ISO 17776, DiMattia (2005) proposed a risk matrix that is a function of probability and severity. The color of each block in the matrix shows the level of emergency action needed, ranging from green (no risk), which requires no safety actions, to red (high risk), which needs vital mitigating measures. The acceptable risk is based on the company criteria that accept the levels of risk and the numerical values are shown in table 5.11. Similar to this convention, risk is divided into three categories:

- High risk: red blocks
- Lower risk: yellow blocks
- Lowest risk: green blocks

Table 5.10 shows the consequence categories, and Table 5.11 is the risk table. In Table 5.11, the HEPs are divided into four different ranges of 0.1 to 1, 0.01 to 0.1, 0.001 to 0.01, and 0.0001 to 0.001, subsequently. This table also demonstrates different consequences as well. By having the specific HEP and particular consequence for each activity, this table will assist to estimate the final risk value.

Table 5.10 Consequence categories (DiMattia, et al., 2005)

Severity		Consequence
Critical	(C)	Extremely important because of being or happening at a time of special difficulty, danger, leads to death
High	(H)	Significant physical injury can happen
Medium	(M)	There is a chance of minor to moderate injuries to occur
Low	(L)	Most likely there will be no injuries
Warning	(W)	Lack of implementation

Table 5.11 Risk table (DiMattia, et al., 2005)

Category	**HEP**	**Consequence Severity**				
		Critical (C)	**High (H)**	**Medium (M)**	**Low (L)**	**Warning (W)**
A	0.10 to 1.0	[illegible]	[illegible]	3A	4A	5A
B	0.01 to 0.10	[illegible]	2B	3B	4B	5B
C	0.001 to 0.01	[illegible]	2C	3C	4C	5C
D	0.0001 to 0.001	[illegible]	2D	3D	4D	5D

5.8 The most probable human errors

Two activities with high HEP and high consequences (Block 2A in Table 5.11) were studied in detail in order to reduce the probability of human error occurrence:

- Sub-activity 2.6, “drain lines,” with HEP equal to 9.57E-01;
- Sub-activity 8.3, “open valves, fill pump, and test for leaks,” with HEP equal to 9.62E-01.

5.9 Remedial measures

HEART provides a framework that helps assessors recommend appropriate mitigation measures for tasks with higher HEP in order to reduce the probability of human error. By dividing each of the EPC-assessed effects by the total, the relative contribution to the error probability of each of the EPCs can be evaluated.

The following strategies are provided in order to reduce the probability of human error.

5.9.1 Remedial measure for “drain lines” activity

In this activity, time shortage and unfamiliarity with unknown situations are the highest contributing factors to unreliable modification as shown in Table 5.12. To address situations arising from unfamiliarity with unknown situations, infrequent events should be anticipated, redundancy systems and appropriate tools should be utilized, and operators should be properly trained. These remedial measures will also save time.

Table 5.12 shows the relative contribution made by each of the EPCs for the drain line activity to the value of unreliability modification.

Table 5.12 Contribution of each EPCs to unreliability modification

EPC	% contribution made to unreliability modification
Unfamiliarity with the situation	53

Time shortage	26
Operator inexperienced	7
No independent checking	8
Unreliable instrumentation	6

Table 5.13 shows remedial suggestion for drain lines activity.

Table 5.13 Remedial measure for drain lines activity

Unfamiliarity with a situation (x 17)	• Putting in place a pre-work procedure to analyze the work beforehand to identify infrequent and rare emergency events
Time shortage (x 11)	• Using redundant components to save time • Having maintenance based on prescribed schedule • Posting experienced operators to particular task in order to save time
Operator inexperienced (x 3)	• Completing the training successfully by all the operators • Supporting the inexperienced operators by the expert operators • Not using inexperienced operators for high risk components
No independent checking (x 3)	• Reporting to supervisor by the operator after finishing each task • Rechecking by the supervisor
Unreliable instrumentation (x 1.6)	• Being aware that the equipment which operator is working with is not completely reliable

5.9.2 Remedial measures for "open valves, fill pump, and test for leaks" activity

In this activity, the major contributing factor is time constraints. To improve this situation, maintenance can be conducted based on a prescribed schedule; furthermore,

more experienced operators can be posted to particular tasks in order to save time. The relative contribution of each EPC for the "open valves, fill pump, and test for leaks" activity of unreliability modification is shown in Table 5.14.

Table 5.14 Contribution of each EPCs of unreliability modification

EPC	% contribution made to unreliability modification
Time shortage	38
Ambiguity in standards	17
Poor system feedback	16
Operator inexperienced	10
Impoverished quality of information	11
Unreliable Instrumentation	8

Remedial recommendation shows in Table 5.15.

Table 5.15 Remedial measures of Open valves fill pump and test for leaks activity

Time shortage (x 11)	• To use redundant components to save time • Maintenance based on prescribed schedule • To post experienced operators to particular task in order to save time
Ambiguity in standards (x 5)	• Using comprehensive and update standard • Clarify and rephrase ambiguous statements to simple word for better understanding
Poor system feedback (x 4)	• Effective communication between relevant

	operators and maintenance staff, helping to build proper feedback and thus to prevent the error
Operator inexperienced (x 3)	• Operators must successfully complete the training • The expert operators should support inexperience operators • Do not use inexperienced operators for high risk component
Impoverished quality of information (x 3)	• Effective communication between involved persons, sectors and management for better organizational learning which in turn increases the quality of information
Unreliable Instrumentation (x 1.6)	• Operator should be aware that the equipment operator is working with is not completely reliable

5.10 Discussion

Since its initial development, HEART has proven to be an extremely popular technique, especially within the engineering community. This technique is easy for non-specialists to understand and use, and the EPCs and their multipliers are based on experimental human-performance data. The EPCs selected in this research are the most common factors that influence human performance in maintenance activities. One of HEART's primary strengths is that it contains the appropriate data required to perform human reliability assessments, which can be achieved, by human error identification, human error quantification and human error reduction. In particular, no external databases are required. For this reason, the technique is highly attractive to non-specialist users. HEART is simple to handle, which makes it an attractive proposition.

The results of this research demonstrate that the calculated HEPs for pump pre- and post-maintenance tasks are in the range of 9.24E-03 and 9.62E-01. The maximum HEPs are related to the "open valves, fill pump, and test for leaks" and "drain lines" activities, due to their time shortages and the operators' unfamiliarity with those situations. Applying consequence analysis and calculating the risk value showed that the risk values for these activities are extremely high. Using redundant components, experienced operators, and scheduled maintenance to save time and to identify emergency events beforehand are helpful remedial actions in these situations, which will reduce the risk value. Application of a risk-based decision-making process to manage the HEPs was investigated previously, by DiMattia (2004), who used the SLIM to calculate the HEPs. The risk values for other tasks applied in this research are below the acceptable limit since they belong to the lower and lowest risk categories. This demonstrated that the probabilities of conducting errors when performing these tasks are acceptable, and no remedial actions should take place.

5.11 Conclusion

In this study, a human reliability analysis for the pre-maintenance and post-maintenance activities of a pump was analyzed, utilizing HEART methodology. To perform this study, a scenario was developed for each category of activities. Based on these scenarios, the nominal amount of HEP was calculated for each sub-activity. According to the results, two activities had high HEPs: "drain lines" and "open valves, fill pump and test for leaks." In order to reduce the probability of human error, required remedial measures were recommended for these activities. Related injuries and deaths could be decreased by optimizing the design and utilization of some equipment and devices and by hiring more experienced operators or improving the level of their training. This study identified the high risk activities and discussed ways to prevent failure.

The ultimate future work is to improve variability and minimizing uncertainty. Also testing and validating methodologies to have better understanding of the calculation of HEPs and possible improvement of the techniques.

5.12 References

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6 Human Error Probability Assessment during the Maintenance Procedures of Offshore Oil and Gas Facilities by Using an Integrated Method†

Preface

A version of this manuscript has been submitted to the *Journal of Reliability Engineering and System Safety*. Noroozi was the main lead on the work. The co-authors Drs. Khan and MacKinnon supervised the principal author. They helped to develop the methodology and cross-checked the analysis. The co-author Dr. Abbassi cross-checked and helped collect data from industry. Dr. Khandoker helped test the model results and was the contact with industry. Noroozi performed the analysis and prepared the first draft of the manuscript while the co-authors Drs. Khan and MacKinnon reviewed the manuscript and provided the necessary suggestions.

Abstract

The research presents a novel approach for HEP assessment by integrating the Success Likelihood Index Method (SLIM) with the THERP. In this approach, the SLIM has been embedded within the THERP framework to generate the nominal HEP data when it is unavailable. The developed methodology has been implemented in an offshore condensate pump maintenance task. In the first step of this study, the human error has been estimated considering all the standard tools and procedures which are in place. In the second step, as an additional measure, RFID based tools have been utilized and HEP has been recalculated. Without the application of RFID tools, the HEP value is estimated as 5.72% and with RFID tools, it has been reduced to 4.63%, which yields a net HEP reduction of 1.09%.

† Noroozi et al. Journal of Reliability Engineering and System Safety 2012.

6.1 Introduction

Human error management is receiving growing interest in industries to reduce the risk associated with the production loss, asset damage, and fatality. Over the last few years, a number of major accidents occurred in different industries as a result of incorrect operations, and maintenance. Human error is directly or indirectly related to a number of factors which are called PSF. The PSFs are commonly categorized as external, internal, psychological and physiological factors. External PSFs are the factors associated with the situational and equipment characteristics, procedural and perceptual requirements and quality of the work environment. Internal PSFs are related to the individual characteristics such as skills, motivation, experience, mental strength etc. The psychological factors are the factors which directly affects the mental stress such as task load, task speed, task type etc. Physiological factors are those which affect the physical stress such as discomfort, hunger, thirst, extreme temperature etc. [1].

In maintenance activities, PSFs are considered as the major contributors to human error [2-4]. Therefore, in reducing human error attempts have been taken to analyze the PSF factors involved in a specific maintenance activity. In order to improve the PSF factors, the industries have taken initiatives in three major directions: i) change of equipment, tools, or process ii) change of procedure and iii) change of management system [5]. Change of equipment or tool has brought simpler deigns of the equipment and use of more accurate and easy handling tools in maintenance. The procedural change has involved more comprehensive research to introduce the simple and systematic procedure to carry out a complex task, team involvement rather than individual accomplishment. Administrative control is focused on the management of human activity and skill, stress, and work environment. Researchers investigated factors related to Situation Awareness (SA) in aviation maintenance teams at a major airline [6]. The analysis recommended a training program is important to improve the SA in maintenance.

Some studies have linked mental workload to be an important factor to human work performance [7-10]. The European Joint Aviation Authority depicted that error rates may increase when the technicians or engineers undertake more or less workload than the usual. This is a particular feature of some industry areas, such as line and base maintenance [11].

To reduce the human error in maintenance activity, the use of work permit is very common in different industries [12-13]. It is a detailed document that authorizes certain people to carry out specific work at a particular time, which demonstrates the hazards associated with the work and the precautions to be taken in particular situations. However, the typical work permits cannot provide detailed information and do not meet user expectations [14-15].

Computer-based procedure (CBP) and computer-based training (CBT) and aiding programs have been developed for inspection and maintenance. These replace the use of research based work permits. CBP/CBT provides detailed information along with graphical presentation which is easy to follow and update. Researches has been carried out on the computer-based aiding approach in maintenance activity [5; 16-17]. Researchers have proposed an online aiding system for human error management [5]. In addition to the computer based training and aiding, the online aiding system provides the list of potential errors in each step of a task and provides with the quantitative human error risk index for each error type. This creates the risk informed awareness among the individuals and makes them careful to carry out the task without error.

Along with the procedural development, significant effort has been made to simplify the design of the equipment and tools to reduce human error in maintenance activity. Improper selection of equipment, component and spare parts is also a significant contributor to human error in maintenance activity. Therefore, research has been carried out to develop the computerized inventory management and asset tracking system.

The emergence of RFID system is replacing the technology based on barcode based identification systems. RFID tag is accurately readable by RFID reader from near or far locations. This helps to have the updated information of the tagged items at any specific time [18-19]. The usefulness of RFID system has been demonstrated through wide case studies in asset or item tracking, inventory control, personal identification, time and attendance system, and process control in numerous facilities [18]. However, so far, no case study is available to demonstrate the applicability of the RFID technology in industrial operations and maintenance to reduce the human error. Alongside the improvement of the PSF factors, significant effort has been devoted to develop approaches to quantify the HEP in industrial activities. The approach should be reasonably accurate to predict the HEP value; the underestimation might lead to a severe accident.

In this research, the HEP in an offshore pump maintenance activity has been estimated using the THERP technique. THERP is a well-known technique to estimate the HEPs, which conceived mainly for the nuclear industry [1; 20] and validated repeatedly by applying to different cases in industries [21; 22].

In this research, a new methodology is developed to solve one of the main challenges of using THERP to estimate HEPs, which is unavailability of nominal error data for all types of tasks. To demonstrate the application of the new methodology, a case study of estimating HEPs in maintenance procedures of offshore oil and gas condensate pump is considered. In the first step of this case study, the HEPs are quantified considering all the standard tools and procedures which are in place. In the second step, as an additional measure, RFID based tools have been incorporated and HEPs have been recalculated. The difference demonstrates the applicability of the RFID to reduce HEP in maintenance activity.

6.2 Major Human Error Probability Assessment Methods

The human error quantification techniques are based on two principles: i) subjective judgment and ii) human error data base. The techniques employs subjective judgments depend on a number of experts having complete knowledge about the task for which HEP will be evaluated. The experts analyze the task and the relevant PSFs and provide their opinion; which are manipulated within the framework of a specific method to obtain the HEP value. The common methods in this category are: i) APJ, ii) PC, iii) SLIM and iv) AHP-SLIM. The major problems associated with the expert judgments are the inconsistencies of the results among different experts. The absolute judgment method based on direct judgment of experts without manipulating the opinion further in any specific framework [23]. This method is relatively quick; the results could be qualitatively useful to take the improvement measures to reduce the human error. The PC technique involves the paired comparison of the judgment of experts, which are further manipulated to develop a HEP scale [24]. It uses at least two empirically estimated known HEP values for calibration and with the help of logarithmic correlation; the final HEP values are obtained. This method can estimate the relative importance of different human error specific to a task. PC may not be suitable for predicting the human error in a complex situation.

SLIM is the most flexible technique and widely used among the methods those uses expert judgment. In the SLIM approach, the judges identify the important PSF factors associated with a specific task; the contribution of each PSF factor to cause the human error is judged and a relative weight is assigned [25]. This PSF rating is used to calculate a success likelihood index, which is calibrated with two known HEP values and with the help of a logarithmic equation, the desired HEP value is estimated. SLIM places no constraints on the analyst in terms of the factors that are assumed to influence error probability in the task being assessed. The analyst is also able to take into account the differential weights or levels of influence that each Performance Influencing Factor (PIF) may have in a particular situation. The technique allows the effects of changes in the quality of the PIFs and also assumptions about their relative influence to be evaluated as part of a cost-effectiveness analysis designed to achieve the greatest improvements in human reliability at minimum costs. However, since the analyst needs to construct a model of the factors influencing performance in the situation being assessed, some degree of human factors knowledge will be necessary to use the technique effectively. The technique is therefore likely to be less favored by engineering users than by human factors specialists. The technique also requires that calibration data are available, preferably from the domain in which the technique is being applied, although expert judgment can be used for this purpose if no hard data are available [26]. Moreover, the inconsistency may arise during the PSF rating, and the PSF evaluation might not be very straightforward when the PSF conditions are difficult to understand or not constant. To reduce the inconsistency in the judgments of PSFs, AHP-SLIM has been developed. The analytical hierarchy approach is used to check consistency among the experts and induce failure likelihood, while the SLIM approach is used to convert the likelihood into HEPs [27]. This helps to improve the quality of judgment through the use of the structured framework associated with AHP. However, in cases of SLIM or AHP-SLIM one major disadvantage is that the choice of anchor point is very critical and the calibration equation does not have sufficient evidence to conclude that it is well established. One of the common issues with all the aforementioned method is the selection of judges. It becomes a challenge to have the required number of judges available who can evaluate the situation adequately. The common methods which use the available human error data as a basis are HEART, Justification of Human Error Data Information (JEHDI), and THERP. These techniques could be easily implemented by a single assessor.

In the HEART, a task is classified into one of the generic task categories. Then the nominal HEP value is assigned to the task. In the next step, the EPC or PSFs are determined and the maximum proportion of effect of each PSF on the nominal HEP is determined [28]. In the final step, the final HEP is calculated using a simple mathematical formula considering the nominal HEP, number of EPC and the maximum effect of proportion. The technique has some specific features such as easy understanding and use by non-specialists, and the EPCs and their multipliers are provided based on experimental data on human performance [29]. However, the major problem of the HEART technique is that the assessment of the proportion of affect is highly judgmental which is a potential source of inconsistency and may affect the reliability of the technique.

The JEHDI is a computerized method developed by [30], which is not available in public domain. The selection of the most similar error descriptor and the answering of the questions are the primary area for potential inconsistency.

In the THERP technique, the task is decomposed into different task levels. For each task level, the nominal human error data is collected from the THERP handbook. The nominal HEP of each task level is modified by considering the effects of PSF. In the next step, the dependency between different HEPs is considered [1]. The final HEP is calculated using an ET relationship. The THERP technique is very established technique and is used extensively in industrial applications in comparison to other techniques [21]. The major problems associated with the THERP technique is the unavailability of nominal error data for all types of tasks. The determination of the effects of PSF factor is highly judgmental, which may significantly affect the final value of the estimated HEP. However, integrating of SLIM and THERP as a part of a methodology developed in this research overcomes the existing problem. As a result, wherever nominal error data is unavailable in the THERP handbook, the SLIM has been used to estimate the HEP value for a specific task element.

6.3 Case Study: Scenario

The case study investigates pre and post-maintenance procedures for a condensate pump, which is typically used on offshore platforms. A condensate pump is used to pump condensate water produced in heating or cooling, refrigeration, condenser boiler furnaces, or steam systems. It may be also used to pump the condensate produced in many applications such as refrigerated air in cooling and freezing systems, steam in heat exchangers and radiators, and the exhaust steam of very-high-efficiency furnaces. Maintenance operations for a condensate pump can be divided into three steps: i) pre-maintenance, ii) maintenance and post-maintenance However, the focus of this study is on pre- and post-maintenance and for each category, different activities (or main-tasks) are assessed.

There is an array of responsibilities involved with pre and post-maintenance activities. Responsibilities are given to a range of different workers, who specialize in different aspects of maintenance activities and bring with them different HEPs relevant to their tasks. The following types of people are considered to be directly or indirectly involved in this maintenance activity: i) maintenance manager, ii) technician, iii) supervisor, iv) inventory manager. The field maintenance team is considered to be consisted of three members. The workers in this study are considered to be working 8 hours per day. The weather conditions on an offshore platform are considered to be harsh, especially in the winter (thunderstorms, and heavy precipitation).

6.4 Task Analysis

6.4.1 Analysis of pre-maintenance activities

The first step in HEP analysis is to identify the activities necessary in the pre-maintenance of a pump. Such activities are mentioned in Table 6.1. The first category involves the preparations needed before the removal of the pump, while the second category involves the removal of the pump so that it may be serviced.

Table 6.1 Activities during pre-maintenance of a pump

1.0	**Prepare work**	
	1.1	Perform equipment diagnostics
	1.2	Identify equipment affected and tags used
	1.3	Perform and document initial gas test
	1.4	Rank fluid contained within pump
	1.5	Identify the most appropriate isolation method
	1.6	Hold a toolbox meeting
2.0	**Isolate pump**	
	2.1	Check lines for fluid and pressure
	2.2	Check bleeds/vents for obstructions
	2.3	Close isolation valves
	2.4	Lock and tag isolation valves
	2.5	Depressurize lines
	2.6	Drain lines
	2.7	Purge lines
	2.8	Perform pressure test & isolation leak test
	2.9	Open all drains of affected equipment possible
	2.10	Perform mechanical isolation (fit slip plates, disconnect lines)
	2.11	Re-pressurize lines
	2.12	Isolate, lock, and tag motor from control center
	2.13	Test motor for power
	2.14	Continue testing pressure and isolation at intervals

6.4.2 Analysis of post-maintenance activities

The next step is developing post-maintenance activities. Activity 3.0 explains the reconnection of the pump to the operating system. While activities 4.0 and 5.0 explain the preparations needed to return the pump back to an active position. Table 6.2 explains items 3.0 to 5.0, which concern post-maintenance pump procedure.

Table 6.2 Activities during post-maintenance of a pump

3.0	Re-connect pump
	3.1 Check lines and equipment for obstructions
	3.2 Remove locks and tags from valves, leaving valves closed
4.0	Ensure the site and equipment are left in a safe state
5.0	Open valves and reinstate pump
	5.1 Test pressure
	5.2 Remove air from lines and pump
	5.3 Open vales, fill pump and test for leaks

6.4.3 Identify the probability of pre-maintenance errors

Once all of the activities have been identified for pre and post-maintenance activities, the next phase is to decompose each main activity into different task elements. The importance of dividing the main tasks into elements is so that HEPs can be made more accessible. Furthermore, performance-shaping factors may also be identified that would mostly affect the performance of a task. The nominal HEP value of each task element has been collected from [1]. Table 6.3 illustrates the breakdown of few main tasks to their task elements.

Table 6.3 Main tasks accompanied with task elements

Main Tasks	Task Elements
Identify equipment affected and tags used	• All affected equipment not identified • Equipment not tagged properly • Tag not clear • Failure to keep record of tagged equipment
Hold a toolbox meeting	• Toolbox meeting was not held • Failure to identify all required tools • Failure to list required tools properly

Close isolation valves	• Feed valves to pump were not closed properly • Failure in closing valves properly lead to valves left partially opened • Failure to close all valves when check list is used • Failure to close all valves when check list is not used
Test pump pressure	• Failure in testing lines or pump for pressure • Failure to use a checklist • Failure in interpreting data correctly • Failure in recording the test data

6.4.4 Nominal HEP values and Modifications

Once task elements are produced for each main task, nominal HEPs must be attained for each task element. It is important to note that at this point for assigning task elements, it is nearly impossible to predict all errors of commission. However, a competent analyst should be able to predict most erroneous acts by maintenance workers. The nominal human error data from Tables in the THERP handbook were then assigned to each task element. From these HEPs, the analysis used the lower bounds of all nominal values in attempts of accounting for the age of the handbook [1]. Since being published in 1983, it would be more sensual to use these values because of updated safety practices and industry standards in the last 28 years. For HEP values that could not be found in the handbook, SLIM has been used to generate the HEP data. The nominal error data collected from the THERP handbook needs to be modified considering simultaneous error of the team members, dependency among them and various PSF factors.

6.4.4.1 Simultaneous Error

Simultaneous error is perhaps one of the simpler modifications to implement. This type of error arises when there is more than one operator working on the same task. Since there is more than one operator assigned to the same task it, is obvious that the probability of error for a given task would be significantly less due to two or more individuals thinking independently of each other. To calculate simultaneous error, the nominal HEP value is raised to the power of the number of people attempting a task. For example, the nominal value for failure to follow a written procedure is 0.5. However it is assumed that three people in a maintenance team will influence each other to follow written procedure, therefore the value is modified to 0.5^3 or roughly 0.001.

6.4.4.2 Dependence

Another modification used in this step is dependency. When the Probability Of Success (POS) or failure in one task directly affects the POS in another, then the tasks are said to be dependent on each other. In this study, a dependency model has been used to modify the nominal HEP value. The model utilizes different degrees of dependency, varying from zero dependence to complete dependence.

It is very difficult to judge which intermediate state is most appropriate to use and often times the expertise of the analyst is relied on. However the basic rule of thumb is that low dependence is used when the level of dependence between two tasks is slightly higher than zero, moderate dependence is used when an intermediate level of dependence is present, and high dependence is used when the level of dependency between two tasks is slightly less that complete dependence.

For each level of dependency, there are different equations used to calculate a new HEP value with the exception of zero and complete dependency. This is due to the fact that if there is zero dependency between tasks, then they are independent of each other and the nominal HEP values should be a sufficient representation of human error. Below are the equations use to assess dependency where "n" is the nominal HEP value [31].

Table 6.4 The set of dependency equations

[ZD] = n
[LD] = (1 + 19n)/20
[MD] = (1 + 6n)/7
[HD] = (1 + n)/2
[CD] = n = 1.0

In a team work, the dependency among team members is calculated based on these dependency equations. The first operator does not depend on other operators. However, the dependency of the next operator on the first operator needs to be assessed. The second operator, for example could be following direct orders from the first operator who is not dependent, possibly affecting the actions of the second operator (especially, if the first operator is wrong in his task). A similar approach is taken in the case of the third operator, who may be dependent on the second operator, who is similarly dependent on the first operator, giving the third operator the highest degree of dependency. Once the case is judged, the nominal value needs to be substituted into the appropriate equation and a new HEP value for the task evaluated to account the dependency.

6.4.4.3 Performance shaping factors

Once the nominal HEP values are collected and modified for accounting the simultaneous error and dependency effects, data is further modified to account the effect of performance shaping factors specific to the task. Performance shaping factors addresses how an operator will perceive what is required of him or her and how he will handle his tasks given external, internal, and stressor influences [32]. Generally, PSF factors are divided into three groups. These groups are: 1) external PSFs, 2) internal PSFs, and 3) stressors.

External PSFs encompass the conditions that affect the work environment. They are global and can be related to many tasks. However, they may be related to a specific job or a set of procedures. Below are some common external PS factors that are used in HEP analysis:

- Temperature, humidity, and air quality
- Hours worked
- Availability of tools, and supplies
- Organization
- Procedures required
- Perceived requirements
- Decision making
- Memory
- Written and oral communication

Internal PSFs considers the individuals' characteristics, such as their skills, motivations, and attitude etc. that influence their performance. Listed below are some common internal PS factors used in HEP analysis.

- Experience
- Skill
- Intelligence
- Motivation
- Attitude towards his/her work
- Knowing acceptable standards

Stressors are otherwise known as specific conditions that affect an operator mentally or physically and in most cases contribute to an error in performing the task. However, if there is little or no stress, then task performance also may decrease due to many factors like carelessness, and overconfidence. Therefore, a certain degree of stress is required in most tasks to maintain an optimal degree of task performance. Listed below are some common stressor PS factors used in HEP analysis:

- Duration of stress
- Task load
- High risk
- Monotonous/ meaningless work
- Sensory deprivation
- Fatigue
- Hunger/ thirst

- Radiation

6.4.4.4 Calculating modification factors for PSF

PSFs are the major determiners of HEP. Researchers recommend multiplying the nominal HEPs by modifying factors to account the effect of PSFs [1]. Unlike dependency, there is no straightforward equation to calculate PSF influences. This is because these factors will interact and influence each other making each case unique to the factors present. Previous studies [33] used the percentile score concept to evaluate the quality of each PSF which is combined with the relative weight of each PSF to obtain the composite quality score.

Researchers analyzed the PSF quantitatively [32]; the relative weight of each PSF is combined with the performance rating of the human for determining the human factor index. In both cases a mapping method is used to modify the nominal HEP and the relative weights of PSF are determined using analytical hierarchy method [34]. The above studies did not address how to rate the performance of the operators when the task is performed in a team.

The THERP handbook provides guidelines for estimating HEPs for four levels of stress: very low task load, optimum task load, heavy task load, and threat stress. However, only a few modifiers (multiplication factors of 1, 2, or 5) are available and it is not a systematic and elaborate method [33].

In this research, the important PSFs specific to a task are screened out from a large number of PSFs. The modifying factor (MF) for each important PSF specific to an operator is determined based on the subjective judgment, which are averaged for the team members. The MF for all PSFs are then multiplied together to obtain the overall MF which are used to modify the nominal HEP of the task element.

Table 6.5 below shows that for task A, three PSFs are considered to be important: i) training, ii) experience, and iii) knowledge. For task B, also three PSF are considered: i) knowledge, ii) time/pressure, and iii) stress. The HEP assessors then judge, by what percentage each operator will increase the HEPs of task element A and B. Since it is more realistic to judge under the basis that each operator may have different levels of training, experience, and knowledge specific to a task, it was assumed that among them there would be a supervisor who would contribute little to no extra error, an operator of medium contribution and a third operator of medium to high contribution. Their contributions specific to a PSF are averaged to obtain the modifying factor for that PSF.

Table 6.5 The nominal HEPs

Task A
Training – (1.05 + 1.00 + 1.05)/3 = 1.03 (increases the nominal HEP by 3%)
Experience – (1.10 + 1.05 + 1.0)/3 = 1.05 (increases the nominal HEP by 5%)
Knowledge – (1.05 + 1.0 + 1.10)/3 = 1.05 (increases the nominal HEP by 5%)
Overall multiplying factor: 1.03 x 1.05 x 1.05 = 1.13
Task B
Knowledge – (1.10 + 1.00 + 1.05)/3 = 1.05 (increases the nominal HEP by 5%)
Time/ pressure – (1.10 + 1.05 + 1.15)/3 = 1.10 (increases the nominal HEP by 10%)

Stress – (1.10 + 1.10 + 1.05)/3 = 1.08 (increases the nominal HEP by 8%)

Overall multiplying factor: 1.05 x 1.10 x 1.08 = 1.24

The overall multiplying factors 1.13 and 1.24 are used to multiply the nominal HEPs of the tasks A and B, respectively.

6.5 Calculating the HEP value

After modifying the nominal HEP values, they are combined with the help of ET relationship to obtain the HEP value for each main task of the pump maintenance activity. Table 6.6 lists the HEP values for each main task of the condensate pump maintenance after taking account of simultaneous errors, dependency, PSFs.

Table 6.6 Final HEP values for maintenance tasks

		Main Activities	HEP
1.0	**Prepare work**		
	1.1	Perform equipment diagnostics	7.41×10^{-4}
	1.2	Identify equipment affected and tags used	1.00×10^{-5}
	1.3	Perform and document initial gas test	1.363×10^{-3}
	1.4	Rank fluid contained within pump	2.25×10^{-3}
	1.5	Identify the most appropriate isolation method	9.39×10^{-3}
	1.6	Hold a toolbox meeting	2.346×10^{-3}
2.0	**Isolate Pump**		
	2.1	Check lines for fluid and pressure	2.09×10^{-3}
	2.2	Check bleeds/vents for obstructions	1.69×10^{-3}
	2.3	Close isolation valves	5.66×10^{-4}
	2.4	Lock and tag isolation valves	1.09×10^{-4}
	2.5	Depressurize lines	1.30×10^{-3}
	2.6	Drain lines	1.28×10^{-4}
	2.7	Purge lines	1.28×10^{-4}
	2.8	Perform pressure test & isolation leak test	7.62×10^{-3}
	2.9	Open all drains of affected equipment possible	6.06×10^{-4}
	2.10	Perform mechanical isolation (fit slip plates, disconnect lines)	1.11×10^{-3}

2.11	Re-pressurize lines	2.52×10^{-4}
2.12	Isolate, lock, and tag motor from control center	1.66×10^{-3}
2.13	Test motor for power	7.27×10^{-3}
2.14	Continue testing pressure and isolation at intervals	8.022×10^{-3}
3.0	**Re-connect pump**	
3.1	Check lines and equipment for obstructions	1.69×10^{-3}
3.2	Remove locks and tags from valves, leaving valves closed	1.125×10^{-3}
4.0	Ensure the site and equipment are left in a safe state	1.21×10^{-3}
5.0	Open valves and reinstate pump	
5.1	Test pressure	1.85×10^{-3}
5.2	Remove air from lines and pump	3.08×10^{-3}
5.3	Open vales, fill pump and test for leaks	8.08×10^{-4}

6.5.1 Bounding Analysis

Uncertainty bounds are used because of the involvement of some degree of subjective judgment to estimate the effect of PSF factors and uncertainties in nominal HEP data. Uncertainty bounds help to include all possible inconsistency resulting from random sources and differences between operators. The case study has considered that for the uncertainty, the lowest considerable limit of uncertainty should be 5×10^{-5}. For evaluating uncertainties of the HEP value, the guidelines prescribed in the THERP handbook as shown in Table 6.7 is followed in this study. If an HEP value falls within a certain range, then the lower and upper bounds can be attained from simple division and multiplication of the original HEP value.

Table 6.7 Guidelines followed to calculate uncertainty bounds

Guide Line	Lower Bounds	Upper Bounds
Estimated HEP < 0.001	HEP/ 10	HEP x 10
Estimated HEP from 0.001 - 0.01	HEP/ 3	HEP x 3

Estimated HEP > 0.01	HEP/ 5	HEP x 5

For example, the final HEP value for the task of "checking lines for fluid and pressure" is 2.09×10^{-3}. Given that this value is greater than 0.001 and less than 0.01, therefore according to the guide line, to calculate the uncertainty of this task, the HEP value must be divided by 3 to find the lower bound, and must by multiplied by 3 to find the upper bound. This gives the values of the uncertainty for the main task to be $6.96 \times 10^{-4} - 6.27 \times 10^{-3}$.

6.5.2 Calculating total human error probability

The final step is to aggregate HEP values of each major task according to an ET. This final calculation represents the total HEP in the pump maintenance activity. Upon doing this, the final total HEP value is found to be 5.7244×10^{-2}. This indicates that during the process of the pre and post-maintenance, the probability of an error occurring that would lead to the eventual failure in restoring a pump back to the service is roughly 5.72% with an uncertainty bound of $1.1448 \times 10^{-2} - 1.1452 \times 10^{-1}$.

6.6 Incorporation of RFID

In this step, the RFID technology is incorporated in the present case study in order to study the applicability of RFID technology to reduce the human error. The assessor reviewed the applications of the RFID technology with respect to the present case study and identified the potential areas where it could be successfully applied. Table 6.8 lists the tasks where RFID technology was used; the reduction of the nominal HEP was judged subjectively considering the features of the RFID technology. The recalculated HEP values are also shown in Table 6.8.

Table 6.8 Final HEP values after considering RFID system

		Main Activities	HEP
1.0		**Prepare work**	
	1.2	Identify equipment affected	1.00×10^{-5}
	1.4	Rank fluid contained within pump	2.25×10^{-3}
2.0		**Isolate Pump**	
	2.2	Check bleeds/vents for obstructions	1.69×10^{-3}
	2.3	Close isolation valves	5.66×10^{-4}
	2.6	Drain lines	1.28×10^{-4}
	2.7	Purge lines	1.28×10^{-4}
	2.9	Open all drains of affected equipment possible	6.06×10^{-4}
	2.12	Isolate, lock, and tag motor from control center	1.66×10^{-3}
3.0		**Re-connect pump**	
	3.1	Check lines and equipment for obstructions	1.69×10^{-3}
	3.2	Remove locks and tags from valves, leaving valves closed	1.125×10^{-3}

The new total HEP value calculated considering these reductions is 4.6342×10^{-2} or 4.63% error with an uncertainty of bound of 2.145×10^{-2} - 2.089×10^{-1}. Therefore, in this case study, the use of RFID technology yields a net human error reduction of 1.09%.

6.7 Conclusions

An integrated new approach to quantify the human errors occurred in maintenance procedures of an offshore condensate pump has been developed. A developed methodology solves one of the most important challenges of using THERP solely which is the availability of nominal HEPs in the THERP guidelines for all of the considered task elements. As a result, wherever these data are unavailable, the SLIM has been used to generate the required data. In the first step, the human error in the pump maintenance task is quantified without utilizing the RFID technology based tools which is estimated as 5.72%. Afterwards, the application of RFID technology is considered in order to minimize the probability of human error and to investigate the applicability of the system in maintenance procedures. The total HEP of the pump maintenance task with the incorporation of RFID technology is calculated as 4.63%, which yields a net of HEP reduction of 1.09%. The result demonstrates the potential of RFID technology to human error management in the maintenance activity. Although the reduction is not very significant in the present case study, the higher degree of HEP reduction may be possible depending on the maintenance activity in offshore oil and gas facilities. Application of a developed methodology to a considered case study in this research also demonstrates that the proposed integration of SLIM in the THERP framework has made the application of THERP much quicker and simpler.

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7 Effects of Cold Environments on Human Reliability Assessment in Offshore Oil and Gas Facilities†

Preface

A version of this manuscript has been accepted for publication in the Journal of *Human Factors and Ergonomics Society.* Noroozi was the first author and the main lead on the work. The co-authors Drs. Khan and MacKinnon supervised the first author. They helped to develop the methodology and cross-checked the analysis of the manuscript. The co-author Dr. Abbassi cross-checked and helped collect data from industry while the co-author Dr. Khakzad helped developing event tree and doing the event tree analysis. Noroozi performed the analysis and prepared the first draft of the manuscript while the co-authors Drs. Khan and MacKinnon reviewed the manuscript and provided the necessary suggestions.

Abstract

This research focuses on the effects of cold, harsh environments on the reliability of human performance. As maritime operations move into cold arctic and Antarctic environments, decision makers must be able to realize how human performance is affected by cold, and adjust management and operational tools and strategies accordingly. This research provides a proof of concept that the risk of operations in cold environments is greater than those performed in temperate climates, and develops guidance regarding how this risk can be assessed. A methodology by application of HEART is developed to

assess the effects of cold on the likelihood of human error in offshore oil and gas facilities. This methodology is applied to the post-maintenance tasks of a pump in offshore oil and gas facility to investigate as to how management, operational and equipment issues must be considered in risk analysis and prediction of human error in cold environments. The present work demonstrates a significant difference between the HEPs and related risk in normal conditions, as opposed to cold and harsh environments. This study also highlights that the cognitive performances of human is the most important factors affected by the cold and harsh conditions.

7.1 Introduction

The study of human factor is an important area of process engineering which includes the systematic application of information related to human characteristics and behavior to improve the performance of human-machine systems (McSweeney et al., 2008). According to Dhillon & Liu (2006), poor design factors in equipment, maintenance, and work layout, and difficulties faced by workers, such as improper work tools and overstressed-induced fatigue are the main factors contributing to error occurrence in maintenance procedures. Other contributing factors include environmental factors such as humidity, lighting, and temperature,. Improper training, the use of outdated maintenance manuals and lack of proper experience also cause a high numbers of maintenance errors. On the other hand, there are few factors to improve the work environment such as training the personnel, ensuring emotional stability and hiring workers with a greater aptitude for their environment, improving team work, and boosting morale.

Nelson (1996) argued that accident occurrence due to maintenance activities as well as over speed protection equipment should be taken into consideration in the industry. Balkey (1996), however, asserted that risk-based inspection procedures and human error procedures in fossil fuel plants must be considered when conducting inspection procedures. Further data is provided by Eves (1985) on accidents in the chemical manufacturing industry during maintenance.

Researchers concluded that collecting samples of the different types of human errors and interactions can be helpful in preventing such errors in future. In this way, investigations on human error have been carried out to explain the role of human error in maintenance, repairable systems, inspection process and system performance (Carr & Christer, 2003; Gramopadhye & Drury, 2000; Ramalhoto, 1999; Dhillon & Yang, 1993). Human errors in maintenance procedures cannot be neglected and several methodologies have been developed to estimate the human error in maintenance procedures. However, there is no study available at present to quantify the HEPs of maintenance activities at arctic conditions. The dissimilar characteristics of arctic regions and their effect on human performance during maintenance procedures can be a considerable motivator to develop a methodology to account for the effect of cold and harsh environments in final HEPs estimation.

Numerous challenges related to the operation of equipment, the systems, the structure and the safety equipment performed under cold and harsh environments have been previously explained (Strauch, 2004; Parsons, K. (2003). Some of the effects of cold temperatures and harsh environments on human performance are listed in Table 7.1. However, there is a lack of methodology at present to fully consider the effects of cold on the probabilities of human error. This will lead to underestimating the values of human error probabilities (HEPs) by neglecting the essential factors that should be evaluated because of the cold conditions, and to decline of the overall reliability in process facilities.

Table 7.1 General Cold Environmental Factors Affecting Human Performance (Bercha et al., 2003; 2004; Forsius et al., 1970)

Stressors	Details
Cold Temperature	Breathing difficulty
	Muscular stiffness
	Frost bite
	Lowered metabolism
	Hypothermia
	Bulky clothing
	Stiffness of suits impairing movement
Ice Ad-freeze	Incapacitates mechanisms
	Slippery surfaces
	Adds weight/mass
Combined Weather Effects	Wind, snow, waves-impair HP
Marine Ice	Precludes rapid decent to sea level
	Unstable for locomotion
Low visibility	Ice, fog, lack of solar illumination
	Frost on windows, visors, glasses
Stress	Fear of unknown
	Disorientation

When deep body temperatures begin to fall below the normal resting values, hypothermia starts (Makinen, 2006). Metabolism is increased to produce more body heat, and as cooling continues, a person will start to shiver, which is a visible sign that body cooling has continued beyond a comfortable level. By increasing metabolic rates, the amount of time a person can sustain work will be reduced (Legland et al., 2006). Motor control becomes impaired as a body cools, making an operator vulnerable to physical injuries. Extremely cold conditions adversely affect mental skills and cognition (Bourne & Yaroush, 2003). As operational temperatures decrease, the frequency of cognitive error increases. Operations at cold temperatures coupled with physical distracters such as noise or moving environments will affect the quality of perception, memory, and reasoning, further increasing the risk of error in decision-making (Legland et al., 2006). Specific effects of extreme environments on human performance are highlighted in Karwowski, 2001 and Hoffman, 2002, and must be considered when assessing task performance, operating procedures and equipment design.

Physical performance decrements because of exposure to cold weather can have profound effects upon the way a task is completed. Direct deficits include loss of strength, mobility and balance. While thermal protective clothing may mitigate the neurophysiologic responses, indirectly protective clothing could affect manual performance due to reduced strength producing capacity, a decrease in mobility, and inability to perceive external elements or cues. Investigations have reported minimal decreases in simple reaction time (except in the most extreme conditions) (Enander, 1987; Hoffman, 2002). However, for more complex tasks, cold environments have resulted in poorer performances. It is reported that reduced in reaction speed were observed among subjects beginning at an ambient temperature of –26°C with a wind speed of 10 mph or greater (Hoffman, 2002). Outcomes also included: an increased number of errors, increased speed of reporting incorrect responses, increased numbers of false alarms and a decreased ability to inhibit incorrect responses. Visual-motor tracking performance is markedly and immediately impaired in the cold. Upon exposure of a person fully dressed in arctic clothing to extremely cold air temperatures, a significant reduction in performance is occurred compared to the exposure to the normal temperatures (Parsons, 2003). Extreme cold stress may produce confusion and impaired consciousness. Researchers demonstrated the increase in the number of errors when performing at the temperature of 5°C, compared to the performance in 22°C ambient temperature (Olden & Benoit, 1996; Hoffman, 2002; Pilcher et al., 2002; Wright et al., 2002). One of the major consequences of working in cold and harsh environments includes fatigue, both physical and cognitive. Fatigue continues to be either a main cause or a contributory factor to casualties and damage to the environment and property. Fatigue impacts on individual's skills to react, recognize and interpret stimuli in the work environment. Fatigue also encourages the apathy status and decreases motivation at work contributing consequently toward poor performance (Xhelilaj & Lapa, 2010).

Considering the effects of cold on various features of human performance, a methodology is developed in this research by particularization of the HEART for cold environments. The proposed methodology will help the assessors to investigate the probabilities of human error more accurately in cold conditions understanding of which will help to improve the overall reliability of offshore oil and gas facilities in cold and harsh environments.

7.2 A developed methodology applied in cold environments

HEART is a technique widely used in human reliability assessment to compare HEPs, based on the degree of error recovery. In a standard HEART methodology, the specification of a particular scenario based on the present conditions of a facility (or a part of the facility) is required. Thus, observing the specific conditions such as cold temperature, high speed wind, lack of visibility, and slippery is required for describing an accurate scenario to be applicable in cold and harsh environments. Considering the above factors is one of the reasons that which distinguishes the methodology of this work from the standard HEART methodology. HEART methodology has been previously used extensively to estimate the HEPs in normal operating conditions (Kirwan et al., 2007; Casamirra et al., 2009; Noroozi et al., 2012). For using this methodology, after considering a particular scenario, all of sub-tasks that would be required by the operator to complete within each task in the considered scenario will be investigated. Subsequently, a nominal human unreliability score (Kirwan et al., 1996) for the particular task is determined. In the standard HEART, the estimator used recommended values ranging from 5th to 95th percentile boundaries of nominal human unreliability for a particular task (typically the mean values). However, because of the harsh and cold conditions, the modified methodology used the values of the 95th percentile, which is considered as a worst case scenario.

By identifying the particular scenario, the assessor will determine the factors that influence the HEP, known as Error Producing Conditions (EPCs). For illustration purposes, only three to four EPCs of higher nominal amounts, according to the considered scenario, have been selected to estimate the final HEPs. In the developed methodology, the EPCs are divided into four different categories of physical, cognitive, instrumentations, and management (Table 7.2). These four major categories have been derived based on previous work on the effect of cold and harsh conditions on producing errors in human performances (Bourne & Yaroush, 2003; Forsius et al., 1970; Hoffman, 2002; Mekjavic et al., 1988; Orden & Benoit, 1996; Staal, 2004). The EPCs, related to each category in the modified methodology is added to the main EPCs which are similar to the normal conditions and then used in the final estimation of HEPs.

Table 7.2 EPCs in HEART methodology (**P:** Physical C: Cognitive. **I:** Instrumentations. **M:** Management) [1]

Error-producing condition		Maximum predicted nominal amount by which unreliability might change going from 'good' conditions to 'bad'
1	Unfamiliarity with a situation which is potentially important but which only occurs infrequently or which is novel	17
2	**A shortage of time available for error detection and correction (P)**	11
3	**A low signal-to-noise ratio (C)**	10
4	A means of suppressing or overriding information or features which is too easily accessible	9
5	No means of conveying spatial and functional information to operators in a form which they can readily assimilate	8
6	**A mismatch between an operator's model of the world and that imagined by the designer (C, M)**	8
7	No obvious means of reversing an unintended action	8
8	A channel capacity overload, particularly one caused by simultaneous presentation of non-redundant information	6
9	A need to unlearn a technique and apply one which requires the application of an opposing philosophy	6
10	**The need to transfer specific knowledge from task to task without loss (C)**	5.5
11	Ambiguity in the required performance standards	5
12	A mismatch between perceived and real risk	4
13	**Poor, ambiguous or ill-matched system feedback (C, I)**	4
14	No clear direct and timely confirmation of an intended action from the Portion of the system over which control is to be exerted	3
15	Operator inexperienced (e.g. a newly qualified tradesman, but not an 'expert')	**3**
16	An impoverished quality of information conveyed by procedures and person-person interaction	3

17	**Little or no independent checking or testing of output (P, I, M)**	3
18	A conflict between immediate and long-term objectives	2.5
19	No diversity of information input for veracity checks	2.5
20	A mismatch between the educational achievements level of an individual and the requirements of the task	2
21	**An incentive to use other more dangerous procedures (P, C)**	2
22	Little opportunity to exercise mind and body outside the immediate confines of the job	1.8
23	**Unreliable instrumentation (I, M)**	1.6
24	**A need for absolute judgments which are beyond the capabilities or experience of an operator (C)**	1.6
25	Unclear allocation of function and responsibility	1.6
26	No obvious way to keep track of progress during an activity	1.4
27	**A danger that finite physical capabilities will be exceeded (P)**	1.4
28	Little or no intrinsic meaning in a task	1.4
29	High-level emotional stress	1.3
30	**Evidence of ill-health amongst operatives, especially fever (P)**	1.2
31	**Low work force morale (C, M)**	1.2
32	Inconsistency of meaning of displays and procedures	1.2
33	**A poor or hostile environment (below 75% of health or life-threatening severity) (P)**	1.15
34	Prolonged inactivity or highly repetitious cycling of low mental workload tasks	×1.1 for first half hour ×1.05 for each hour there after
35	**Disruption of normal work-sleep cycles (C, M)**	1.1
36	Task pacing caused by the intervention of others	1.06
37	Additional team members over and above those necessary to perform task normally and satisfactorily	× 1.03 per additional man
38	Age of personnel performing perceptual tasks	1.02

[1]*The following variables were assessed for impact due to operations in cold environments. These variables were considered to influence operator physical or cognitive performance and/or effect management decision-making.*

Each EPC has a maximum nominal amount, which should be inserted in Equation 1 as the Maximum effect. The next step is to assess the proportion of affect (APOA), which is weighted for each chosen EPC based on its importance. Accordingly, each EPC is individually weighted from 0 to 1 (Williams, 1988).

$$\text{Assessed Effect} = (\text{Maximum effect} - 1) * \text{APOA} + 1 \qquad (1)$$

Equation 1 can be applied to calculate the effect of each EPC and its relevant APOA on the HEP. The HEP of each task is calculated by multiplying the selected HEP with the nominal amount of APOA related to each EPC (Williams, 1988). The methodology developed in this research to tailor the HEART methodology to cold and harsh environments is demonstrated in Figure 7.1.

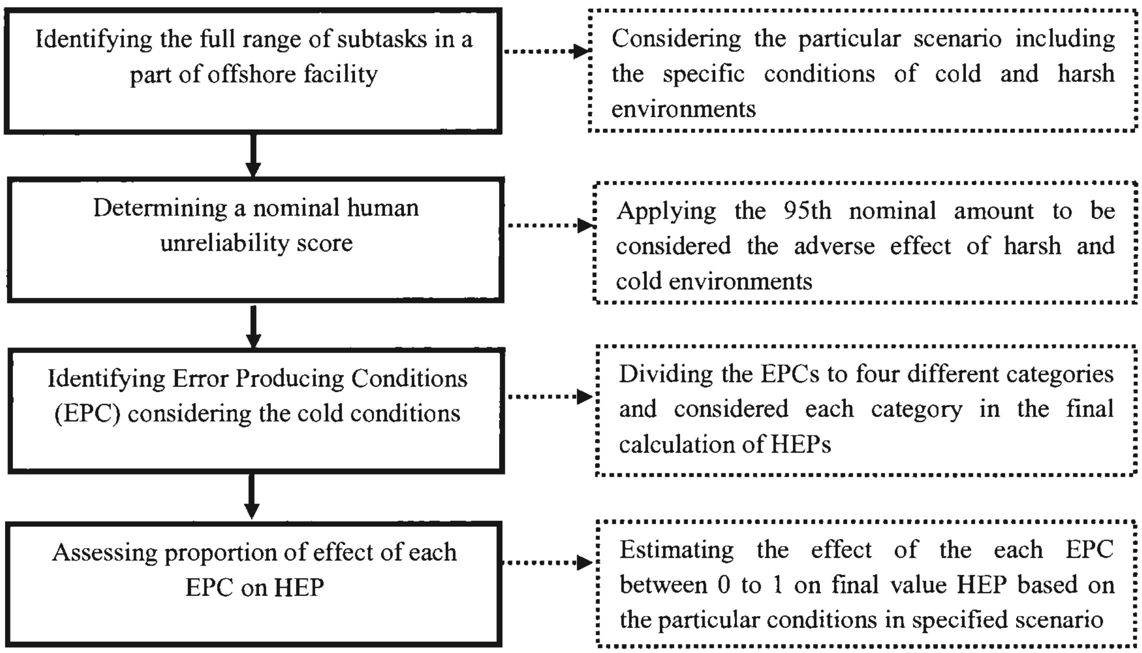

Figure 7.1 A modified methodology developed to calculate the HEP

7.3 Application of the developed methodology

To demonstrate the variation in HEPs by using the developed methodology, both in harsh and cold environments and the normal conditions, it is applied to post-maintenance procedures of a condensate pump in offshore oil and gas facility. It is a particular type of pump applied to the condensate water produced in an HVAC (heating or cooling), condensing boiler furnace or steam system. The regular maintenance activities of a pump in offshore oil and gas can be divided using three different categories namely pre-maintenance, maintenance, and post-maintenance. The focus of the case considered in this study is on the post-maintenance activities. These activities have been developed in conjunction with the Single Buoy Moorings (SBM) Company, Nova Scotia, Canada. The scenarios were developed based on maintenance reports of the offshore platform selected based on the most frequent occurring scenarios.

7.3.1 Selected scenario for post maintenance activities

After each maintenance service, the operators and engineers must continue with post-maintenance activities, since production must not be halted for extended periods of time. These activities focus on returning the system to normal operation. The following information provides characteristics of the selected scenario in this work:

1. Some junior operators have logged insufficient training hours. Because of the high amount of work undertaken, the pressure is high, leading to intense fatigue for the workers;
2. An inexperienced workforce engineer is responsible for ensuring site readiness for reinstatement. The site engineer is using a poorly written report to perform an inspection and to ensure that the site and equipment are in safe conditions;
3. The responsible incoming assistant lacks adequate information regarding returning keys and supplying certificates;
4. The system feedback is unreliable;
5. The supervisor is too busy to provide complete supervision for the procedure;
6. There is insufficient time, due to the urgency of starting operations to prevent extra costs.

Generally, there are time constraints related to further extending the shutdown activities.

The above mentioned scenario is considered in the calculation of the HEPs in normal conditions. The similar scenario is applied to calculate the HEPs in cold and harsh environments. The particular specifications of these regions listed in Table 7.1 have been included. Post-maintenance work requires sequentially executed activities. Factors such as operator experience, time constraints, administrative procedures, and high work demands can lead to task error. The post-maintenance scenarios for the considered procedures of a condensate pump are indicated in Tables 7.3 and 7.4.

Table 7.3 Activities required during post-maintenance

Sub Activity	Activity	
1. Re-connect pump	1.1	Check lines and equipment for obstructions
	1.2	Remove mechanical isolation/connect lines to pump
	1.3	Remove locks and tags from valves, leaving valves closed
2. Workforce Supervisor (WFS) ensure site and equipment left in safe state		
3. WFS return keys and certificates		
4. Permit to Work	4.1	Return lock-out keys
	4.2	Give worksite authority back to AA (Area

Coordinator (PTWC) ensure site is ready for reinstatement		Authority)
	4.3	(Supervisors) Document reinstatement
5. **PTWC & AA finalize PTW**		
6. Open valves and reinstate pump	6.1	Test pressure
	6.2	Remove air from lines and pump
	6.3	Open valves, fill pump and test for leaks
	6.4	Start pump

Table 7.4 The HEP calculation of sub-activity 1.1 due to the effect of cold and harsh environments on physical performances

Activity: 1.0	**Re-connect Pump**					
Sub-activity 1.1	***Check lines and equipment for obstruction (arctic conditions: effect on physical performances)***					
Generic task	Generic error probability	NO.	EPCs	Total HEART effect	Assess proportion of effect	Assessed effect
E	0.045	2	Time shortage	11	0.01	1.1
		11	Ambiguity in standards	5	0.01	1.04
		17	Little or no independent checking	3	0.05	1.1
		21	An incentive to use other more dangerous procedures	2	0.05	1.05
		27	A danger that finite physical capabilities will be exceeded	1.4	0.05	1.02
		30	Evidence of ill-health amongst operatives	1.2	0.05	1.01
		33	A poor or hostile environment	1.15	0.05	1.0075
Total assessed EPC effect						1.371433
HEP						**6.17E-02**

7.3.2 HEP calculation

The developed methodology is applied to calculate the HEPs for all of the above activities in a considered scenario. A detailed calculation for the sub-activity 1.1, "Check lines and equipment for obstructions" because of the effect of cold on physical performances of employees during maintenance procedures of a pump is explained in Table 7.4 as an example.

Table 7.5 Human error probabilities in normal conditions

	Activities	HEP
1.0	**Re-connect pump**	
1.1	Check lines and equipment for obstructions	8.01E-03
1.2	Remove mechanical isolation/connect lines to pump	1.45E-01
1.3	Remove locks and tags from valves, leaving valves closed	8.93E-03
2.0	**WFS ensure site and equipment left in safe state**	8.98E-04
3.0	**WFS return keys & certificates**	6.55E-02
4.0	**PTWC ensure site ready for reinstatement**	
4.1	Return lock-out keys	7.06E-02
4.2	Give worksite authority back to AA	8.90E-04
4.3	(Supervisors) Document reinstatement	1.57E-01
5.0	**PTWC & AA finalize PTW**	6.73E-02
6.0	**Open valves and reinstate pump**	
6.1	Test Pressure	8.01E-03
6.2	Remove air from lines and pump	9.16E-04
6.3	Open valves, fill pump and test for leaks	7.93E-03
6.4	Start pump	6.30E-02

The first step is to determine a Generic Task (GT). The upper-bond values of GT considered for sub-activity 1.1 is "E". For the type "E" task, the nominal unreliability is 0.045. Based on Table 7.2, the EPCs and their maximum predicted nominal amounts related to this sub-activity have been selected based on the scenario illustrated above. The EPCs from Table 7.2 related to the effect of cold and harsh environments on the major human performances (cognitive and physical), as well as management and instrumentations, have been adopted for each category and added to the related EPCs. A proportionate weight factor is applied when an EPC is considered. This is demonstrated in the column labelled "Assess Proportion of Effect" in Table 7.4 for the sub-activity 1.1. As illustrated in Table 7.4, the values of 0.01 for the EPCs of 2 and 11, and 0.05 for the other EPCs, are selected based on the degree of effectiveness of each EPC on human error.

Based on Equation 1, the assessed effect of each EPCs is calculated. Finally, the HEP is calculated based on the effect of cold and harsh environments on physical performances for sub-activity 1.1 as 6.17 E-02. The similar process is adopted to estimate the HEPs of different sub-activities in normal condition (Table 7.5), and also by considering the effect of cold and harsh environments on human performances (cognitive and physical), decision making (management), and instrumentation (Table 7.6) used in post-maintenance activities of a pump.

Table 7.6 Human error probabilities in cold conditions

	$HEP_{physical}$	$HEP_{cognitive}$	$HEP_{instrumentations}$	$HEP_{management}$
1.0				

1.1	6.17E-2	1.54E-1	6.71E-2	8.79E-2
1.2	4.05E-1	7.46E-1	4.4E-1	5.77E-1
1.3	6.88E-2	1.18E-1	7.48E-2	9.81E-2
2.0	1.21E-2	3.01E-2	1.32E-2	1.72E-2
3.0	1.7E-1	4.23E-1	1.85E-1	2.42E-1
4.0				
4.1	1.83E-1	4.56E-1	1.99E-1	2.61E-1
4.2	1.2E-2	2.99E-2	1.3E-2	1.71E-2
4.3	5.65E-1	7.67E-1	5.81E-1	7.61E-1
5.0	1.75E-1	4.35E-1	1.9E-1	2.49E-1
6.0				
6.1	7.32E-2	1.54E-1	6.71E-2	8.79E-2
6.2	1.44E-2	3.01E-2	1.32E-2	1.72E-2
6.3	7.25E-2	1.52E-1	6.64E-2	8.71E-2
6.4	1.64E-1	4.07E-1	1.78E-1	2.33E-1

The above method is the simplest formula to be used to obtain HEPs. HEP calculation still uses the empirical formula, where more sophistication is required. Simplistic approach of human error quantification suggested that more quantitative approach such as Markov models could be used (Sridharan & Mohanavadivu, 1997). However, it should be noted that human behaviour or human actions are highly variable and unpredictable. Therefore, the use of empirical formula is still preferred to statistical technique.

7.3.3 HEP Comparison

7.3.3.1 Statistical Comparison

To examine the impressions cold and harsh environments might leave on HEPs, if any, the normalized relative differences in HEP values calculated in cold and normal environments are obtained (Table 7.7) and appropriate statistical analyses are applied. To this end, the normality of the HEPs in each column is checked. As the HEPs in each column are not distributed normally, the Wilcoxon Signed-Rank test is applied to define the significant difference between each column of the HEPs, which resulted from harsh environments with those which resulted from normal conditions.

Table 7.7 Relative human error probabilities in cold and normal conditions ((HEP_{cold} - HEP_{normal}) / HEP_{normal})

	$HEP_{physical}$	$HEP_{cognitive}$	$HEP_{instrumentations}$	$HEP_{management}$
1.0				
1.1	6.7	18.2	7.37	9.97
1.2	1.79	4.14	2.03	2.97
1.3	6.7	12.21	7.37	9.98
2.0	12.47	32.5	13.69	18.15
3.0	1.59	5.45	1.82	2.69
4.0				
4.1	1.59	5.45	1.81	2.69
4.2	12.48	32.5	13.6	18.21
4.3	2.59	3.88	2.7	3.84
5.0	1.6	5.46	1.82	2.69
6.0				

6.1	8.1	18.22	7.37	9.97
6.2	14.7	31.8	13.4	17.77
6.3	8.1	18.16	7.37	9.98
6.4	1.6	5.46	1.82	2.69

It is a non-parametric statistical hypothesis used to compare two related groups of data to assess whether their populations mean ranks differ (Vaughan, 2001). The statistical analysis is also used to define the difference between the columns of HEPs including the effect of cold on human performance (cognitive and physical), instrumentations, and management. Thus, the Friedman Test (with considering post-hoc tests) was used to investigate the differences between the four considered categories. The Friedman test compares the mean ranks between the related groups and indicates how the groups differ, although not demonstrating exactly where those differences lay. As a result, to examine where the differences occur, the Wilcoxon Signed-Rank Test was used to combine of the considered groups (cognitive with physical, cognitive with management, etc.)

The results obtained by applying the Wilcoxon Signed Ranks Test to the Z-scores and P-values (Devore, 2008) demonstrate that there are statistically significant differences between the HEPs received from the effect of cold on physical performance and normal condition ($Z = -3.180$, $P = 0.001$), cognitive performances and normal conditions ($Z = -3.181$, $P = 0.001$), management and normal conditions ($Z = -2.691$, $P = 0.007$), and also instrumentations with normal conditions ($Z = -3.181$, $P = 0.007$). These results highlight the necessity of re-evaluating the human errors due to the effect of cold and harsh conditions, increasing the overall reliability of maintenance procedures in arctic and sub-arctic regions. The results obtained from the Fiedman Test show that there is a statistically significant difference in HEPs depending on which type of effects are considered due to the cold and harsh conditions ($\chi2(2) = 32.908$, $P = 0.00$). Post-hoc analysis with Wilcoxon Signed-Rank Tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $P < 0.0125$. Median (IQR) perceived effort levels for the physical, cognitive, instrumentations, and management include 7.32 E-02 (3.81 E-02 to 1.79 E-01), 1.54 E-01 (7.41 E-02 to 4.56 E-01), 7.48 E-02 (3.98 E-02 and 1.95 E-01), and 8.79 E-02 (4.66 E-02 and 2.46 E-01), respectively. There are no significant differences between HEPs received from the effect of cold on physical performance and management ($Z = -2.272$, $P = 0.023$), physical performance and instrumentations ($Z = -2.064$, $P = 0.039$), and instrumentations and management ($Z = -2.273$, $P = 0.023$). However, there are statistically significant differences between the HEPs received from the effect of cold on physical and cognitive performances ($Z = -3.180$, $P = 0.001$), cognitive performances and management ($Z = -3.182$, $P = 0.001$), and also between cognitive performances and instrumentations ($Z = -3.185$, $P = 0.001$).

7.3.3.2 Risk-based Comparison

Quantitative Risk Analysis (QRA) has played an important role in identifying major risks and maintaining safety in process facilities. QRA includes several steps such as hazard identification, accident modeling, consequence analysis, and risk estimation. The results of QRA can either be used in assisting decision-makers with risk levels of different plans or to improve the safety measures of facilities. Event tree is a technique widely used in QRA to explore and calculate the probabilities of potential consequences of an initiated undesired event given subsequent failures/successes of safety barriers (Khakzad et al, 2012; Khakzad et al, 2013). In this study, to investigate the effect of cold and harsh environments on HEPs, a risk assessment has been conducted to compare the values of risks, which resulted from human-error-induced accidents both in normal and cold environments. It should be noted that for cold conditions, the risk analysis is separately performed for physical, cognitive, instrumentations, and management, resulting in four different values, respectively.

Considering the pump post-maintenance as the initiating event, the event tree in Figure 7.2 is developed. Based on field studies and expert opinions, the most probable accident scenario following a human error in post-maintenance procedure of the pump would be a release of flammable liquid. Meeting an ignition source, a pool fire would occur which can be extinguished only if a water sprinkler system is activated by a flame/smoke detector (Figure 7.2).

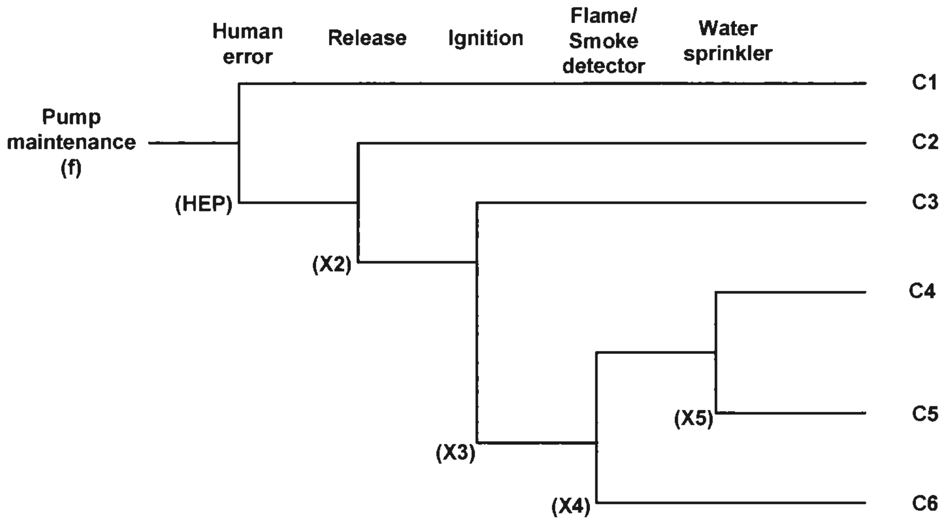

Figure 7.2 Event tree of pump post- maintenance

The probabilities of the components of the event tree have been indicated in Table 7.8 (Khakzad et al, 2012; Khakzad et al, 2013). However, it is worth noting that the probability of the top event "Human error", HEP, in Figure 7.2 for normal and cold conditions has been derived using Tables 7.5 and 7.6, respectively, assuming that the activities and sub-activities are independent and act like a series system (the worst-case scenario). Thus, HEP can be calculated using Equation 2.

$$HEP = 1 - \prod_{i=1}^{n} (1 - P_i) \qquad (2)$$

Where P_i is the probability of each activity (sub-activity).

Table 7.8 Probabilities of event tree's components (Khakzad et al, 2012; Khakzad et al, 2013)

Top event	Description	Probability
F	Frequency of pump maintenance	0.3
HEP	Human error probability for normal conditions and cold conditions including physical, cognitive, instrumentation, and management	Normal: 0.472 Cold: 0.913, 0.997, 0.926 and 0.982
X2	Occurrence probability of Release given a Human error	0.1
X3	Occurrence probability of Ignition given a Release	0.1
X4	Failure probability of Flame detector given a fire	0.01
X5	Failure probability of Water sprinkler given the operation of Flame detector	0.04

Having the probabilities of top events, the probabilities of consequences can be calculated as demonstrated in the last five columns of Table 7.9. Using the consequence severity matrix (Appendix 7.1), the severity of each consequence can be determined (Column 3 of Table 7.9) based on the extent of its adverse effects such as causalities, environmental, and property damage. Assigning according monetary values to each consequence (column 4 of Table 7.9), the total amount of envisaged risk for the accident scenario in normal and cold conditions can be estimated (last raw of Table 7.9).

Table 7.9 Risk analysis of pump post-maintenance accident in normal and cold conditions

Index	Description	Severity class	Damage (USD)	Normal condition P (Ci)	Cold Condition P (Ci)			
					Physical	Cognitive	Instrument	Management
C1	Safe condition	1	0	1.584 E-01	3.06 E-01	3.34 E-01	3.10 E-01	3.29 E -01
C2	Mishap	1	0	1.274 E-01	2.46 E-01	2.68 E-01	2.50 E-01	2.64 E-01
C3	Near miss	2	5 E +03	1.274 E-02	2.46 E-02	2.68 E-02	2.50 E-02	2.64 E-02
C4	Fire; Successful extinguishment; Minor property damage; Minor injury	3	250 E +03	1.35 E-03	2.61 E-03	2.84 E-03	2.65 E-03	2.8 E-03
C5	Fire; Unsuccessful extinguishment; Major property damage; Major injury; possibility of death	5	25 E +06	5.61 E-05	1.085 E-04	1.183 E-04	1.099 E-04	1.165 E-04
C6	Fire; Unsuccessful extinguishment; Major property damage; Major injury; possibility of death	5	25 E +06	1.4 E-03	2.71 E-03	2.95 E-3	2.75 E-03	2.9 E-03

Total risk analysis based on dollar value	36,854	71,238	77,649	72,135	76,463

It should be noted that C5 and C6 are of a similar severity; however, different probabilities arise from different causes. According to the event tree in Figure 7.2, C5 would be a result if the Flame detector works, trying to activate the Water sprinkler. However, the Water sprinkler would not work due to its respective failure modes. On the other hand, in C6, the Water sprinkler would not work since it has not been activated because of the Flame detector failure as Water sprinkler is conditionally dependent on Flame detector. Thus, in either case, i.e., C5 and C6, a major accident would occur due to unsuccessful fire extinguishment.

These results confirm that the cold and harsh conditions may have significant effects on producing human errors due to the effects on people's cognitive performance. The effects of repeated exposure of people to cold on cognitive performance have previously been discussed by Enander (1987), Pilcher (2002) and Makinen et al. (2006).

7.4 Conclusion

Investigation of the attributes of people in cold regions is required to accurately calculate the probability of error in human activities. A new methodology is developed in this research to estimate the HEPs in arctic environments for a specific task. In the new methodology, the upper bond values of human unreliability can be applied for the extreme environmental conditions. Also, the existence of specific EPCs related to arctic conditions such as high level emotional stress and a poor hostile environment may add more value to the methodology to calculate the HEPs. In the current study, HEPs in arctic environments are calculated for each task for four different categories based on people's different attributes.

Application of the methodology to post-maintenance of a pump demonstrated that the HEPs in arctic conditions are in the higher ranges as opposed to the normal conditions. Statistical analysis indicated that there exist significant differences between the HEPs in cold and harsh conditions and normal conditions. This is more evident for tasks for which cold temperatures, wind, ice, and visibility are able to decrease human performance. Further, the statistical analysis showed the effect of cold on people cognitive attributes such as attention, decision making, diagnosis, memory, and problem solving. This study confirmed that re-evaluating the HEPs is required for any scenario that occurs in harsh environments since the HEPs calculated in normal conditions are not compatible with similar scenarios in harsh and cold conditions. Comparing the risk of the normal and cold conditions including physical, cognitive, instrumentations, and management, the cognitive category is shown to have the highest risk values. Cognitive impairment can increase the HEP, and subsequently the risk.

7.5 References

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Appendix 7.1 Consequence severity matrix (Kalantarnia, 2009)

Severity Class	Dollar value equivalent	Asset Loss	Human Loss	Environmental Loss	Confidence or Reputation Loss
1	0	No significant asset loss	Minor mishap, No injury	No remediation required	Get noticed by operating unit only
2	0.01 K - 10 K	Short term production interruption	Minor injury, first aid attention required	Around the operating unit, Easy recovery and remediation	Get noticed in the operation line/ line supervisor
3	10 K - 500 K	Equipment damage of one unit requiring repair/medium term production interruption	One injuries requiring hospital attention however no threat to life	Around the operating line, Easy recovery and remediation	Get noticed in plant
4	500 K - 5 M	Equipment damage of more than one unit requiring repair/ long term production interruption	More than one injuries requiring hospital attention however no threat to life	Within plant, Short term remediation effort	Get attention in the industrial complex. Information shared with neighboring units
5	5 M – 50 M	Loss of one operating unit/ product	Multiple major injuries, potential disabilities, potential threat to life	Minor offsite impact, Remediation cost will be less than 1 million	Local media coverage
6	50 M – 500 M	Loss of major portion of equipment/ product	One fatality and/or multiple injuries with disabilities	Community advisory issued, Remediation cost remain below 5 million	Regional media coverage a brief note on national media
7	> 500 M	Loss of all equipment/ products	Multiple fatalities	Community evacuation for	National media coverage, Brief note

longer period, Remediation cost in excess of 5 million	on international media

8 The role of human error in risk analysis: application to pre and post-maintenance procedures of process facilities[†]

Preface

A version of this manuscript has been submitted to the Journal of *Reliability Engineering and System Safety.* Noroozi was the first author and the main lead on the work. The co-authors Drs. Khan and MacKinnon supervised the principal author. They helped to develop the methodology and cross-checked the analysis of the manuscript. The co-author Dr. Abbassi cross-checked and helped collect data from industry. The co-author Dr. Khakzad helped developing the event tree and performed the relevant analysis. Noroozi performed the analysis and prepared the first draft of the manuscript while the co-authors Drs. Khan and MacKinnon reviewed the manuscript and provided the necessary suggestions.

Abstract:

Human factors play an important role in the safe operation of a facility. Human factors include the systematic application of information about human characteristics and behavior to increase the safety of a process system. A significant proportion of human errors occur during the maintenance phase. However, evaluating human error in the maintenance phase has not been given the amount of attention it deserves. This research

focuses on a human factors analysis in pre- and post- pump maintenance operations. The procedures for removing process equipment from service (pre-maintenance) and returning the equipment to service (post-maintenance) are considered for possible failure scenarios. For each scenario, HEP is calculated for each activity using the SLIM. Consequences are also assessed in this methodology. The risk assessment is conducted for each component and the overall risk is estimated by adding individual risks. The present study is aimed at highlighting the importance of considering human error in quantitative risk analyses. The developed methodology has been applied to a case study of an offshore process facility.

8.1 Introduction

Human failure, human fault and human error all refer to different concepts; thus, it is necessary to differentiate among them to minimize their adverse effects. Human failure is due to massive errors that have far reaching consequences, often moral in nature and entirely inexcusable. Human fault refers to errors caused by negligence or intentional behavior, often punishable. Human error refers to common mistakes that are easily identified, diagnosed and generally excusable. An understanding of raw data, relevant data, and productive data and of what differentiates among them is important to understand these concepts.

Human error is an important consideration in process industry. It includes the systematic application of information about human characteristics and behaviors to improve the performance of human-machine systems (1). HEP assessment techniques preliminary have been a focus of the nuclear industry and have developed expert judgment techniques such as SLIM, THERP, and Human Error Assessment and Reduction Technique

(HEART). Incorporating HEPs in the development of operational procedures can significantly improve the overall reliability of the system (2). There have been efforts to assess HEPs using the aforementioned methods (3-5) while application to risk analysis has been limited (6).

Since most activities in process industries involve human involvement in terms of labour force, monitoring, inspection, maintenance, supervision, management, and decision-making, human errors seem inevitable. Errors can occur at any phase due to the performance of a wrong action or the failure to perform a necessary action. There are different sources for human error, including lack of training, poor equipment design, inadequate lighting, loud noise, inadequate work layout, improper tools, and poor operating procedures. As discussed by Dhillon (7), human error can be classified into six categories as: operation, assembly, design, inspection, installation, and maintenance. However, the effect of human errors on system maintenance via pre- and post-maintenance procedures and their contribution to the induced risk are the focus of this study. The particular area of application is offshore oil and gas process facility.

There are several reasons why maintenance errors occur and include: poor work layout, poorly written maintenance procedures, complex maintenance tasks, harsh environments (i.e., temperature, humidity, and noise), fatigue, outdated maintenance manuals and inadequate training and experience (7). The importance of training and experience to reduce maintenance errors has been discussed by Dhillon (8). People with more experience, higher aptitude, greater emotional stability, fewer reports of fatigue, greater satisfaction with the work group and higher moralities have less probability of making errors.

Human error in maintenance activities has not received much attention. Recent studies have illustrated that most human errors occur in the inspection and maintenance phase, where workers clearly have an important role in keeping equipment in good working order (9-12). Raman et al. (13) developed guidelines to apply hazard identification techniques to maintenance procedures of offshore platforms, while Dhillon and Yang (14) developed a stochastic model to analyze the role of human error in reliability and availability of machines.

Sanders and McCormick (15) outlined the types of human factors directly and indirectly related to errors in maintenance. Further studies have also been conducted on the topic of system failure and human errors, using Markov models, stochastic models, and reliability models (7, 16-25).

In the present study, a risk-based approach is presented and applied to offshore process facilities to investigate the role of human error in pre- and post-maintenance procedures. In the context of risk-based maintenance, the main focus has been on the application of risk as a tool to prioritize or optimize the maintenance plans and schedules which consequently helps to reduce the overall risk. This study is aimed at illustrating the role of human error in maintenance, which is likely to make a significant contribution to the overall risk by endangering the safety of the facility.

8.2 Background

8.2.1 SLIM processes

SLIM is a method for probabilistic reliability analysis (26) in which the preference for a set of options is quantified based on an expert judgment. Kirwan (27) proposed SLIM for HRA models. The applicability of SLIM in assessing human reliability has been derived via human performances affected by various factors. The additive influences of these factors, which are called PIF, are used to assess a human response (28), which is subsequently transformed into a HEP. The basic principle of this method is that the likelihood of a particular error occurring in a specific situation is associated with the combined effect of a relatively small set of PIFs (29). SLIM is a feasible approach and overcomes the problems of the potential inconsistency of multiple expert judgments or the problem with the systematic consideration of PIFs, and has been considered in different forms such as the SLIM-MAUD method (27). The SLIM procedure is illustrated in Figure 8.1. The SLI is calculated for each activity by using the Equation 1, in which SLI_s is the SLI of activity S. R_{ij} is the scaled rating of task j on the PIF and W_i is the importance weight for the i_{th} PIF. In SLIM error estimation (see Equation 2), a and b are considered as 0.5 and 10 E -04, respectively.

$$SLI_s = \sum R_{ij} W_i \tag{1}$$

$$Log(HEP) = a\,SLI + b \tag{2}$$

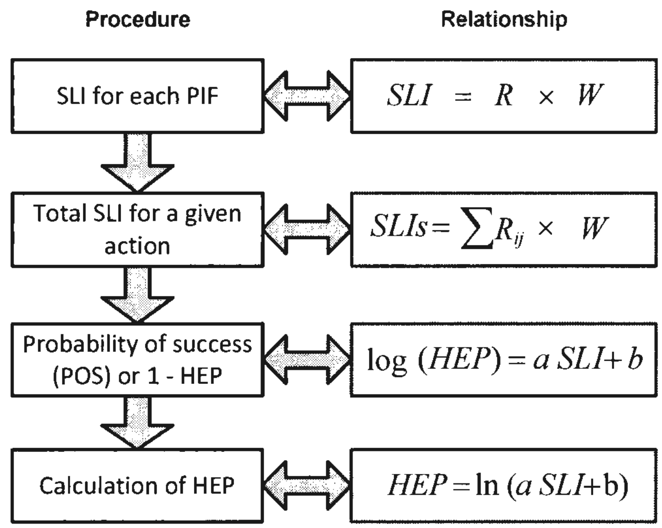

Figure 8.1 The SLI methodology to calculate HEP (30)

8.2.2 A risk-based approach

Different human activities are carried out in pre- and post-maintenance procedures of a piece of equipment. A risk-based methodology is developed to assess the risk of these activities as illustrated in Figure 8.2, including SLIM, Risk Assessment, and Risk Management processes each of which comprises several steps. The HEPs are estimated by applying the SLIM process (Figure 8.1). After obtaining the HEPs based on a specific scenario, the final value of the risk is calculated by integrating the HEPs and consequence analysis results (Risk Assessment). If the risk exceeds predefined acceptable criteria, it will be reduced through either implementation of additional safety barriers or improving the performance of existing safety measures while re-quantifying the risk (Risk Management). This can also be accomplished by reducing the HEPs through re-designing the activities (31).

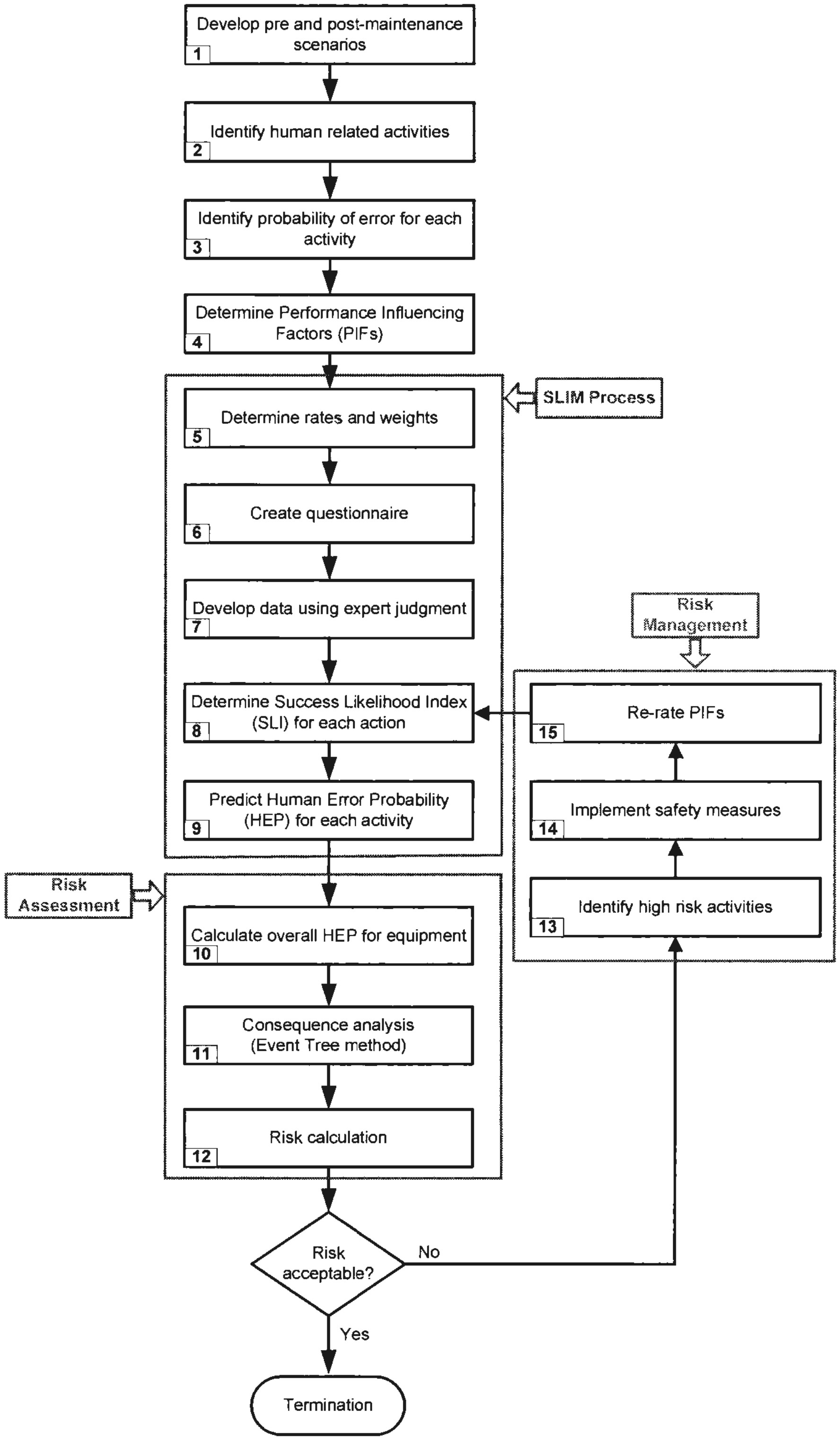

Figure 8.2 Risk-based methodology for minimizing human error.

The risk-based methodology developed in this study provides a tool for decision makers to investigate the severity of human error present in process facilities. Application of this methodology and redesigning of the activities which have high values of human errors may help to reduce the risk occurred due to the human performances in each pre- and post maintenance task. This finally increases the overall safety and reliability of the process facilities. However, it should be noted that the Risk Management process has not been considered in this present study.

8.3 Application of the methodology

8.3.1 Scenario development

This section investigates the effect of human error on the risk analysis via a case-study from offshore process facility including a pump, a separator, and a valve during maintenance procedures. Generally, maintenance procedures can be divided into pre-maintenance, maintenance, and post- maintenance (Step 1 in Figure 8.2).

The main focus of this research is on pre- and post-maintenances which are the same for all the above-mentioned components. For each category, different activities should be assessed to calculate HEPs. The most frequent scenarios are developed based on maintenance reports of offshore platform.

8.3.2 Pre-maintenance activities

When the scenario is developed, the human related activities and the probability of error for each activity is identified (Steps 2 and 3 in Figure 8.2). Different activities and tasks are identified for pre-maintenance procedure and are presented in Table 8.1. The first major activity involves the preparation tasks which require removing the component from service. The second activity describes the tasks involved in removing the component from service, so that maintenance can take place.

Table 8.1 Activities during pre-maintenance

1.0	Prepare work
1.1	(Area Authority) Prepare work order
1.2	Apply for permit to work
1.3	Perform equipment diagnostics
1.4	Identify equipment affected and tags used
1.5	Perform risk assessment of activity
1.6	Check work order and ensure no conflict of operation or other work
1.7	Determine and certify required isolations
1.8	(Permit to work coordinator) Obtain keys and certificates required
1.9	(Area Authority) Authorize work
1.10	(PTWC) Assign lockout box and give keys to supervisors affected by isolation
1.11	Perform and document initial gas test
1.12	Rank fluid contained within component
1.13	Determine size of inlet and outlet lines from component
1.14	Identify most appropriate isolation method

	1.15	(OIM) Approve work activity
	1.16	(Workforce supervisor) Hold toolbox meeting
	1.17	Place PTW on permit board with copy displayed at work site
2.0	Isolate the component	
	2.1	Check lines for fluid and pressure
	2.2	Check bleeds/vents for obstruction
	2.3	Close isolation valves
	2.4	Lock and tag isolation valves
	2.5	Depressurize lines
	2.6	Drain lines
	2.7	Purge lines
	2.8	Perform pressure test & isolation leak test
	2.9	Open all drains of affected equipment possible
	2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)
	2.11	Re-pressurize lines
	2.12	Isolate, lock and tag motor from control centre
	2.13	Test motor for power
	2.14	Revalidate permit with supervisors
	2.15	Break containment

	2.16	Continue testing pressure and isolation at intervals

8.3.3 Post-maintenance activities

The next step is to develop post-maintenance activities (Table 8.2). Activity 3 in Table 8.2 explains the re-connection of the component to the operating system, while Activities 4 to 7 explains the preparations for returning the component to active service. Activity 8 describes the re-activation of the component.

Table 8.2 Activities during post-maintenance

3.0	Re-connect	
	3.1	Check lines and equipment for obstructions
	3.2	Remove mechanical isolation/connect lines
	3.3	Remove locks and tags from valves, leaving valves closed
4.0	(WFS) Ensure site and equipment left in safe state	
5.0	(WFS) Return keys & certificates	
6.0	(PTWC) Ensure site ready for reinstatement	
	6.1	Return lock-out keys
	6.2	Give worksite authority back to Area Authority
	6.3	(Supervisors) Document reinstatement
7.0	(PTWC & Area Authority) Close Permit to Work	

8.0	Open valves and reinstate	
	8.1	Test Pressure
	8.2	Remove air from lines
	8.3	Open valves, fill and test for leaks
	8.4	Start

8.3.4 Performance Influencing Factors (PIFs)

PIFs may be described as basic human error tendencies and the creation of error- likely situations. They help to describe the likelihood of error or ineffective due to human performance. PIFs such as the quality of procedures, level of stress, and effectiveness of training will vary on a continuum from the best practicable (e.g. an ideally designed training program based on a proper training needs analysis) to worst possible (corresponding to no training program at all). There is a direct correlation between the PIFs and performance, meaning that if PIFs are optimal, performance will be optimal and consequently the likelihood of error will be minimized. The list of PIFs can be identified and associated with the problem areas that will increase error potential. In the process of incident investigations, PIFs are also studied to establish the underlying causes of error for each activity. PIFs are important in the redesign of the process necessary to minimize the potential of error and to maximize utility. This can be achieved through effective presentation of information in control rooms, or by using clear operating instructions. Expert judgments are also applied to clarify the PIFs for different tasks and the causes of failure as a part of the HEPs methodology. Application of the expert judgment (Step 4 in

Figure 8.2) to investigate the appropriate PIFs required for the specific task has been previously used by Embery (6).

8.3.5 Rate and weights of PIFs

One of the most important steps in SLIM is to determine the weight of PIFs for calculating SLIs. Weights are assigned by the same experts who assess the PIFs to calculate HEPs. Weights are assessed based on the significance of the PIF based on the specific scenario. In this assessment, the PIFs with highest ranks are considered as the relevant PIFs, listed in Table 8.3 (Step 5 in Figure 8.2).

Table 8.3 Ranking of PIFs

No.	PIF	Rank
1	Training	10
2	Experience	9
3	Stress	9
4	Work Memory	8
5	Physical capability and condition	7
6	Work environment	6
7	Access to equipment	5
8	Distraction	5
9	Behaviour	4
10	Fatigue	2
11	Time pressure	1
12	Task difficulty (poor design)	1

According to five experts (considered in this study) who ranked the possible errors, it was observed that the six PIFs demonstrated in Table 8.4 are the most important ones in pre- and post-maintenance procedure of equipment.

Table 8.4 PIFs consider in this scenario

PIF	**PIF Description**
Training	Related to an individual's ability to most effectively identify each action and perform the necessary actions to complete activities
Experience	Related to how a person will complete the activities successfully
Stress	The inability to complete the task successfully due to anxiety and pressure
Work Memory	Related to short and long term memory of the maintenance operators
Physical capability and condition	Related to functional capabilities and the conditions of working environment of the operators who maintain the components
Work Environment	Related to how operators identified the conditions of the place used for maintenance

The average values of weights for the considered PIFs received from the experts are presented in Table 8.5.

Table 8.5 Weights of PIFs

PIF	**Weight**
Training	0.25
Experience	0.20
Work memory	0.15
Stress	0.15
Work environment	0.15
Physical capability and condition	0.10

Rating the PIFs is another important step in the SLIM procedure. PIFs are rated based on responses collected from questionnaires (Step 6 in Figure 8.2). These questionnaires were completed by experts such as maintenance personnel (Step 7 in Figure 8.2).

By using Equation 1, the data which was gathered from the judges were processed and SLIs were obtained for each activity (Step 8 in Figure 8.2). Equation 2 is then used to calculate the HEP for each task and activity (Step 9 in Figure 8.2). The results are presented in Table 8.6.

Table 8.6 Human error probability

Activity		HEP
1.0	Prepare work	
1.1	(Area Authority) Prepare work order	2.67E-04
1.2	Apply for Permit to Work	1.0E-04
1.3	Perform equipment diagnostics	1.0E-04
1.4	Identify equipment affected and tags used	7.8E-02
1.5	Perform risk assessment of activity	6.5E-02
1.6	Check work order and ensure no conflict of operation or other work	4.6E-03
1.7	Determine and certify required isolations	3.8E-02
1.8	(Permit to Work Coordinator) Obtain keys and certificates required	2.9E-02
1.9	(AA) Authorize work	3.8E-03
1.10	(PTWC) Assign lockout box and give keys to supervisors affected by isolation	1.9E-02

	1.11	Perform and document initial gas test	2.7E-02
	1.12	Rank fluid contained within component	1.6E-04
	1.13	Determine size of inlet and outlet lines from component	3.5E-03
	1.14	Identify most appropriate isolation method	1.4E-01
	1.15	(OIM) Approve work activity	5.0E-03
	1.16	(Workforce supervisor) Hold toolbox meeting	2.7E-02
	1.17	Place PTW on permit board with copy displayed at work site	1.4E-04
2.0			
	2.1	Check lines for fluid and pressure	3.8E-04
	2.2	Check bleeds/vents for obstruction	8.5E-02
	2.3	Close isolation valves	3.8E-02
	2.4	Lock and tag isolation valves	1.1E-02
	2.5	Depressurize lines	2.9E-01
	2.6	Drain lines	6.0E-02
	2.7	Purge lines	2.1E-02
	2.8	Perform pressure test & isolation leak test	1.6E-03
	2.9	Open all drains of affected equipment possible	2.1E-02
	2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)	1.0E-01
	2.11	Re-pressurize lines	9.3E-03

	2.12	Isolate, lock and tag motor from control centre	2.9E-02
	2.13	Test motor for power	3.8E-02
	2.14	Revalidate permit with supervisors	6.5E-04
	2.15	Break containment	6.5E-04
	2.16	Continue testing pressure and isolation at intervals	5.0E-03
3.0			
	3.1	Check lines and equipment for obstructions	2.9E-02
	3.2	Remove mechanical isolation/connect lines to component	8.5E-04
	3.3	Remove locks and tags from valves, leaving valves closed	7.1E-04
4.0		(WFS) Ensure site and equipment left in safe state	2.7E-02
5.0		(WFS) Return keys & certificates	2.3E-01
6.0			
	6.1	Return lock-out keys	3.5E-02
	6.2	Give worksite authority back to AA	6.0E-02
	6.3	(Supervisors) Document reinstatement	1.7E-04
7.0		(PTWC & AA) Close Permit to Work	6.5E-04
8.0			
	8.1	Test Pressure	8.5E-03
	8.2	Remove air from lines	4.6E-02

	8.3	Open valves, fill and test for leaks	1.3E-03
	8.4	Start the component	1.3E-02

8.3.6 Quantitative risk analysis

Different approaches are used in risk analysis such as QRA and PSA to identify major hazards and risks of potential accident scenarios. These approaches are being applied to improve the level of safety in aerospace, nuclear, and chemical process facilities (32-35). The result of risk analysis is normally considered by decision-makers safety experts to improve the performance of safety measures in a facility to reduce the risk within an acceptable range.

Risk analysis techniques have been integrated into design, inspection, and maintenance scheduling of process systems, resulting in risk-based design of safety measures (34-36), risk-based design of process systems (35,37) and risk-based inspection and maintenance (10,38-42).

To estimate the risk resulting from human error in pre- and post-maintenance procedures of process facilities (Steps 10 to 12 in Figure 8.2), a specific section in offshore process facility including a pump, a separator, and a valve is considered (Figure 8.3). Among several techniques available for accident scenario modeling, ETs have widely been used to explore the probability of consequences resulted from an initiating event. Considering the initiating event, the occurrence probability of each consequence is calculated based on the occurrence/nonoccurrence of a set of events or success/failure of components.

It should be noted that since maintenance procedures of components in Figure 8.3 are assumed to be performed at different times, while each component is separated and isolated from the others, it is not possible to consider all components in an entire accident scenario. Thus, the risk assessment is conducted for each component and then the overall risk is estimated by adding individual risks.

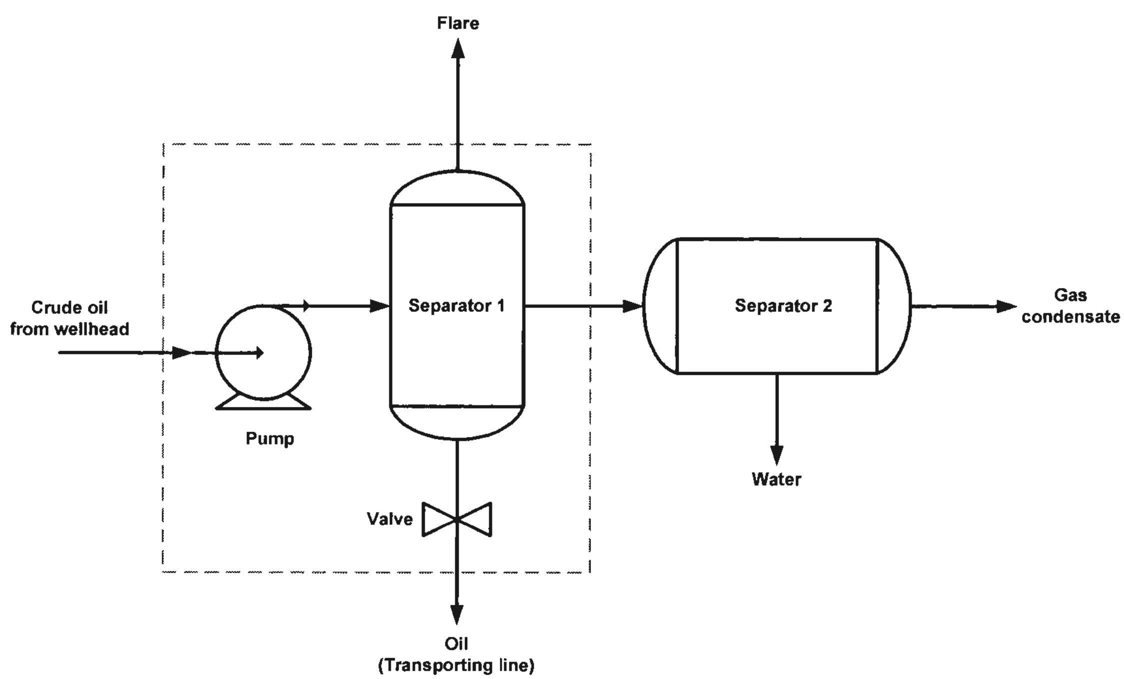

Figure 8.3 Schematic of an offshore process facility including a pump, separators and a valve. The components used in this study are enclosed by dashed line.

To this end, considering the maintenance of each component as the initiating event, the ETs are developed (Step 11 in Figure 8.2) for the pump and valve (Figure 8.4), and the separator (Figures 8.5), respectively. Based on field studies and expert opinions, the most probable accident scenario following a human error in maintenance procedure of the above-mentioned components would be a release of flammable liquid. Meeting an ignition source, a pool fire would occur which can be extinguished only if a water sprinkler system is activated by a flame/smoke detector. Also, it is worth noting that although the ETs of the pump and the valve are similar, both the severity and probability of their consequences are different due to the different amounts of respective releases and maintenance frequencies.

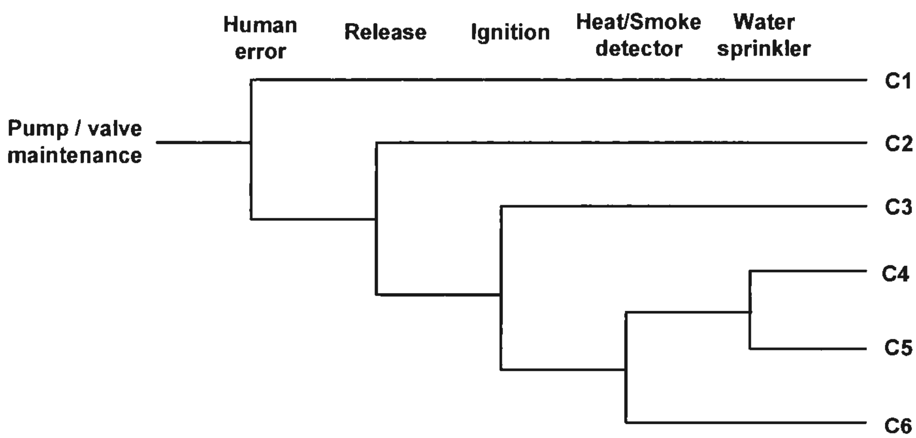

Figure 8.4 Event tree developed for pump and valve maintenance risk analysis

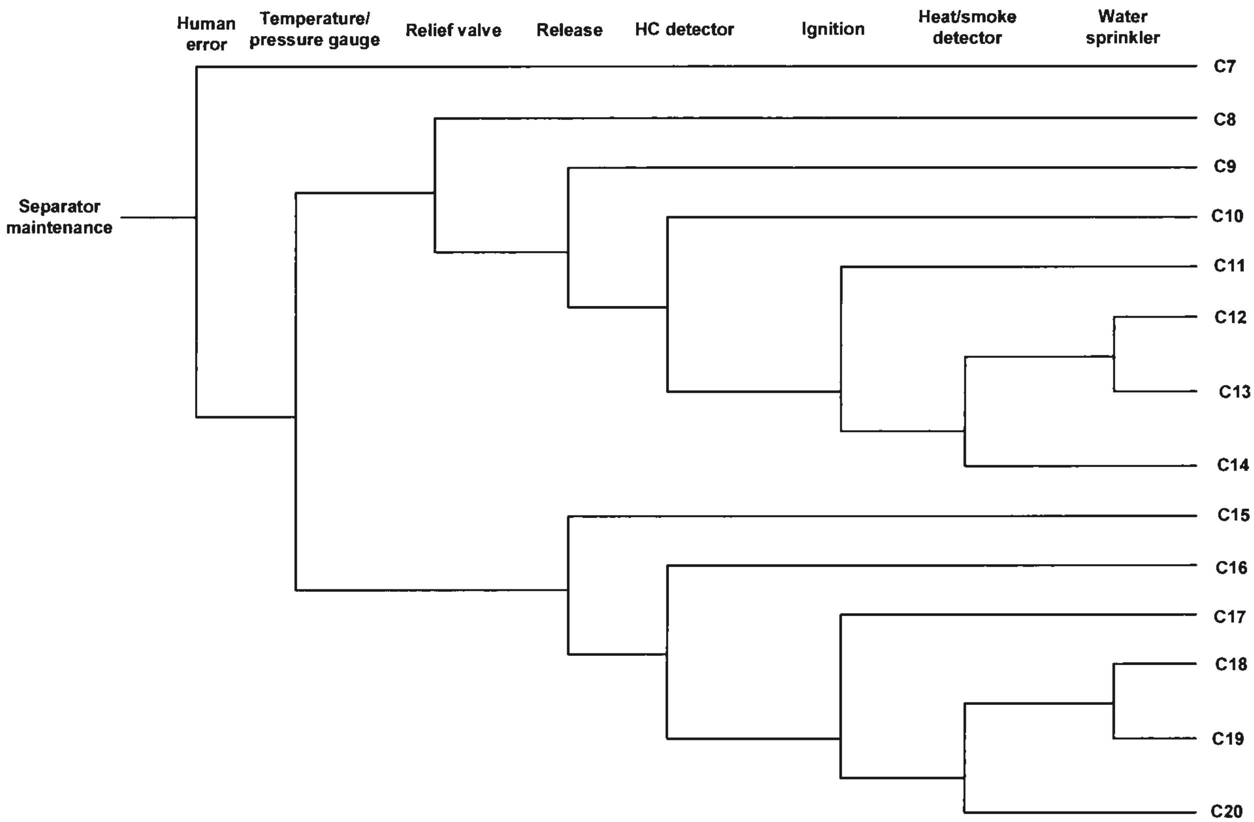

Figure 8.5 Event tree developed for separator maintenance risk analysis

The probabilities of the top events of the ETs in Figures 8.4 and 8.5 are indicated in Table 8.7 (43). However, the probability of the first top event, i.e., Human error, can be derived using the probabilities of the sub-activities in Table 8.6, assuming that these activities and sub-activities are independent, and acting like a series system (the worst-case scenario). Thus, the probability of Human error, HEP_T, for maintenance procedure of the equipment can be calculated using Equation 3 (Step 10 in Figure 8.2):

$$HEP_T = 1 - \prod_{i=1}^{n} (1 - HEP_i) \tag{3}$$

where HEP_i is the probability of each activity (Table 8.6).

Table 8.7 Probabilities of event tree's top events (43)

Initiating/Top event	Probability
Maintenance frequencies of pump, valve, and separator	0.3, 0.25, and 0.5
Human error (HEP_T)	0.8
Release	0.1
Ignition	0.1
Heat/ smoke detector	0.01
Hydrocarbon detector	0.2
Temperature/ pressure gauge	0.04
Relief valve	0.02
Water sprinkler	0.04

Applying the probabilities of top events, the probabilities of consequences can be calculated for the pump, valve and the separator (Table 8.8). It should be noted that in Table 8.8, for C1 to C6, the first values refer to the pump while the second values are for the valve. Using the consequence severity matrix (Appendix 8.1), the severity of each consequence can be determined (Column 4 of Table 8.8) based on the extent of its adverse effects such as causalities, environmental, and property damage. Assigning corresponding monetary values to each consequence (column 5 of Table 8.8), the total amount of envisaged risk for the accident scenario can be estimated as $68615 (Step 12 in Figure 8.2).

It is worth noting that in this study, the above-mentioned risk is not further considered in the Risk Management process (Steps 13 to 15 in Figure 8.2) aiming at re-designing the activities or implementing safety measures to reduce the risk. However, it is evident that if the role of human error in pre- and post-maintenance is neglected, the total amount of estimated risk is likely to be underestimated at least $68615.

Table 8.8 Risk analysis of maintenance-induced accidents

Index	Description	Probability	Severity class	Damage ($)
C1	Safe condition	6.00 E-02, 5.00 E-02	1, 1	0, 0
C2	Mishap	2.16 E-01, 1.80 E-01	1, 1	0, 0
C3	Near miss	2.16 E-02, 1.80 E-02	2, 1	5 E+03, 0
C4	Fire; successful extinguishment of fire, minor property damage, minor injury	2.28 E-03, 1.9 E-03	3, 2	25 E+04, 5 E+03
C5	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of death	9.5 E-05, 7.92 E-05	5, 3	25 E+06, 25 E+04
C6	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of death	2.38 E-03, 1.98 E-03	5, 3	25 E+06, 25 E+04
C7	Safe condition	1 E-01	1	0

C8	Mishap	3.75 E-01	1	0
C9, C15	Near miss	6.91 E-03, 1.44 E-02	1	0
C10, C16	Release of hydrocarbon; successful control of release; no fire	6.14 E-04, 1.28 E-03	2	5 E+03
C11, C17	Release of hydrocarbon; unsuccessful control of release; no fire	1.38 E-04, 2.88 E-04	3	25 E+04
C12, C18	Fire; successful extinguishment of fire; major property damage, multiple major injury	1.46 E-05, 3.04 E-05	4	25 E+05
C13, C14, C19, C20	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of fatalities	6.08 E -07, 1.54 E-07, 1.27 E-06, 3.2 E-07	6	25 +07

8.4 Conclusion

The majority of the tasks in pre- and post-maintenance procedures are currently being done by automated systems. Thus, the human error likelihood is expected to be lower. The methodology developed in this research can be applied to maintenance procedures of any equipment or process facility in onshore and offshore. This could help to better investigate the role of HEP in risk analysis and consequently to increase the overall reliability and safety of the process system.

A risk-based methodology is developed to determine the HEPs and applied to the case of pre- and post-maintenance procedures in offshore facilities. The results illustrate that human error should be considered in risk analyses of process systems as an important contributor. Although maintenance procedures are aimed at increasing the reliability and availability of the system, the occurrence of human errors in pre and post-maintenance procedures is likely to increase the overall risk.

Appendix 8.1 Consequence severity matrix (44)

Severity Class	Dollar value equivalent	Asset Loss	Human Loss	Environmental Loss	Confidence or Reputation Loss
1	0	No significant asset loss	Minor mishap, No injury	No remediation required	Get noticed by operating unit only
2	0.01 K - 10 K	Short term production interruption	Minor injury, first aid attention required	Around the operating unit, Easy recovery and remediation	Get noticed in the operation line/ line supervisor
3	10 K - 500 K	Equipment damage of one unit requiring repair/medium term production interruption	One injuries requiring hospital attention however no threat to life	Around the operating line, Easy recovery and remediation	Get noticed in plant
4	500 K - 5 M	Equipment damage of more than one unit requiring repair/ long term production interruption	More than one injuries requiring hospital attention however no threat to life	Within plant, Short term remediation effort	Get attention in the industrial complex. Information shared with neighboring units
5	5 M – 50 M	Loss of one operating unit/ product	Multiple major injuries, potential disabilities, potential threat to life	Minor offsite impact, Remediation cost will be less than 1 million	Local media coverage
6	50 M – 500 M	Loss of major portion of equipment/ product	One fatality and/or multiple injuries with disabilities	Community advisory issued, Remediation cost remain below 5 million	Regional media coverage a brief note on national media

7	> 500 M	Loss of all equipment/ products	Multiple fatalities	Community evacuation for longer period, Remediation cost in excess of 5 million	National media coverage, Brief note on international media

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9 Summary, Conclusions, and Recommendations

9.1 Summary

The present study developed risk-based methodologies to identify the role of human errors in pre and post-maintenance of process facilities and established mechanism to reduce their contribution to the risk, different methods of HEPs were reviewed and evaluated. Among the existing methods, HEART and SLIM were used to develop methodologies..

HEART technique was used to calculate the HEP in different scenarios and to identify the high-risk activities in pre and post maintenance of a pump. Also the HEART methodology was revised to study HEPs and estimate risk in normal and cold conditions. SLIM technique was used to calculate the HEPs of the same scenario. To estimate the risk, the consequences were also assessed in this methodology. This research focused on the importance of considering human error in quantitative risk analyses. Further, the SLIM and the THERP were integrated to generate the nominal HEP data when it is unavailable.

9.2 Conclusions

The main conclusions of this study are as follow:

9.2.1 Evaluation of Human Error Probability Assessment Techniques

SLIM is one of the most flexible techniques to obtain performance shaping factors from an expert although failing to model the interdependencies among them. HEART, on the other hand, is a quick and simple technique to use with little training; however, the reliability of the method is not yet proven. Lack of existing validation studies and the method's high dependency on expert opinions are just some of HEART's limitations. THEARP is claimed as one of the most precise techniques to determine HEP; however, it is not useful for error reduction and is highly dependent on the assessors. Therefore, choosing the specific level by the assessors may lead to different results. APJ is another technique to make precise estimates of HEP in different fields. Likewise, PC can be used to estimate the relative importance of different human errors or human events and also to estimate HEPs. However, this method is not suitable for complex predictions of human error.

9.2.2 A new methodology to assess the HEPs in maintenance procedures

Human reliability analysis for the pre-maintenance and post-maintenance activities of a pump was analyzed using HEART methodology. The nominal HEP was calculated for each activity. According to the results, two activities had high HEPs: "drain lines" and "open valves, fill pump and test for leaks." This study identified the high risk activities and discussed ways to prevent failure. To reduce the probability of human error, required remedial measures were recommended for these activities. Related injuries and fatalities could be decreased by optimizing the design and utilizing some of the equipment and devices and by selecting more experienced operators, and improving the level of their training.

9.2.3 Human Error Probability Assessment during the Maintenance Procedures by Using an Integrated Method

An integrated new approach to quantify the human errors occurred in maintenance procedures of an offshore condensate pump has been developed. The developed methodology solves one of the most important challenges encountered in application of THERP, i.e., the availability of nominal HEPs for the considered tasks. Wherever data were unavailable; the SLIM has been used to generate the required data. This study demonstrated that RFID technology can effectively be applied to minimize the probability of human error in the maintenance operation. Although the reduction is not very significant in the present case study, the higher degree of HEP reduction may be possible depending on the maintenance activity in offshore oil and gas facilities. Application of the developed methodology to a considered case study in this research also demonstrates that the proposed integration of SLIM in the THERP framework has made the application of THERP much quicker and simpler.

9.2.4 A new methodology to estimate the HEP in harsh and cold environments

In this study it was illustrated that human performance is adversely affected by harsh and cold conditions. The extreme conditions (the extremely cold temperature with high speed wind) lead to higher chances of human error in their activities. Extreme conditions affect the cognition, physiology, and psychology of personnel.

In this research, a new methodology is developed to estimate the HEPs in harsh environments for a specific task. The results showed the effect of cold on cognitive attributes of people such as attention, decision-making, diagnosis, memory and problem solving is significant. This study confirmed that re-evaluation of HEPs is required for any scenario that occurs in harsh environments since the HEPs calculated in normal conditions are not compatible to a similar scenario in harsh and cold conditions. Comparing the human error risks in the normal condition and the cold conditions, it was demonstrated that the cognitive category has the highest risk among physical, instrumentations, and management. Cognitive impairment increases the HEP and subsequently the human error risk.

9.2.5 Application of Human Error Probability methods in Quantitative Risk Analysis

In this research, a risk-based methodology was developed and applied to determine the HEPs in the case of pre- and post-maintenance procedures in offshore facilities. The results illustrate that human error should be considered in risk analysis of process systems as an important contributor. Although maintenance procedures are aimed at increasing the reliability and availability of the system, the occurrence of human errors in pre and post-maintenance procedures is likely to increase the overall risk.

9.3 Recommendation

The present work attempts to introduce new methodologies to assess and include HEP in the risk analysis of maintenance procedures in offshore oil and gas industries. This study can be further extended as follows.:

9.3.1 HEP of entire maintenance procedure

Since this study was aimed at introducing a new methodology to assess the HEPs, it merely focused on the pre and post-maintenance procedures. However, the methodology developed in this study can be applied to entire maintenance activities to increase the overall reliability of process facilities during maintenance procedures.

9.3.2 Application and validation of HEP in QRA

The present study has introduced a new methodology based on application of HEP methods in QRA. The methodology developed in this research is mainly based on the application of event tree, considering the maintenance as an initiating event. However, it is recommended that bow-tie approach be used to model the effect of HEPs not only in the consequence analysis but also in the cause analysis of an initiating event.

9.3.3 Consideration of dependence and HEP updating

Due to the variation of operational and environmental conditions of process facilities, particularly with respect to offshore activities or harsh environments, it is recommended that HEPs be updated when new information become available. This updating can be performed using Bayesian techniques as operational parameters vary over time and space.

Bayesian techniques also provide a good opportunity to consider interdependency of performance shaping factors in human error probability estimation. Use of Bayesian approaches in HEP and human factor risk analysis would improve overall reliability of the risk analysis.