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The role of human error in risk analysis: Application to pre- and post-maintenance procedures of process facilities

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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, the quantification of human error probabilities in the maintenance phase has not been given the amount of attention it deserves. This paper 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, human error probability is calculated for each activity using the Success Likelihood Index Method (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.
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1. Introduction

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 failure, human fault 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.

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 probabilities. 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.

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]. Human Error Probability (HEP) assessment techniques preliminary have been a focus of the nuclear industry and have developed expert judgment techniques such as SLIM, Technique for Human Error Rate Prediction (THERP), Justified Human Error Data Information (JHEDI), and Human Error Assessment and Reduction Technique (HEART) which are described and validated by Kirwan [2–4]. Incorporating HEPs in the development of operational procedures can significantly improve the overall reliability of the system [7]. There have been efforts to assess HEPs using the aforementioned methods [8–10] while application to risk analysis has been limited [11].

In the second and third generation techniques, Human Reliability Assessment (HRA) methodologies have been utilized in the field of engineering and transportation. The HRA can be estimated by different techniques such as A Technique for Human Error

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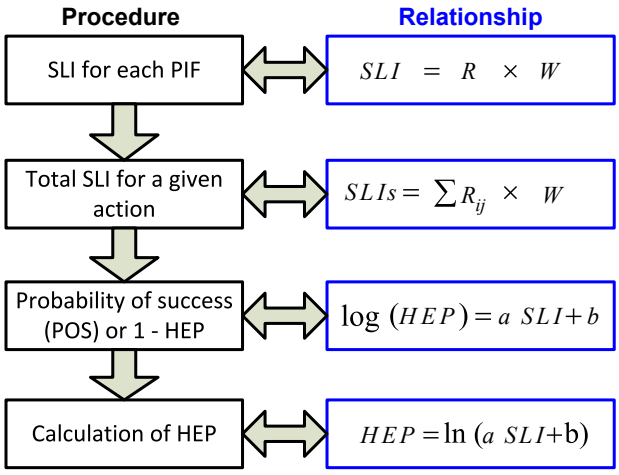


Fig. 1. The SLIM methodology to calculate HEP [30].

Analysis (ATHENA) and Cognitive Reliability Error Analysis Method (CREAM). Konstandinidou et al. have developed a new tool by combining the fuzzy logic principles and the CREAM for the estimation of the HEP and also Dougherty studied forecasting traffic flows using ATHENA method [5,6].

Since most activities in process industries involve human involvement in terms of labor 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 [12], 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 [12]. The importance of training and experience to reduce maintenance errors has been discussed by Dhillon [13]. 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.

Quantification of HEPs 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 [14–17]. Raman et al. [18] developed guidelines to apply hazard identification techniques to maintenance procedures of offshore platforms, while Dhillon and Yang [19] developed a stochastic model to analyze the role of human error in reliability and availability of machines.

Researchers [20] 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 [12,21–30].

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.

2. Background

2.1. SLIM processes

SLIM is a method for probabilistic reliability analysis [31] in which the preference for a set of options is quantified based on an expert judgment. Kirwan [32] proposed SLIM for Human Reliability Assessment (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 Performance Influencing Factor (PIF), are used to assess a human response [33], 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 [34]. 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 [32]. The SLIM procedure is illustrated in Fig. 1. The SLI is calculated for each activity by using the Eq. (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 Eq. (2)), a and b are considered as 0.5 and 10 E−04, respectively.

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

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

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 Fig. 2, including SLIM, Risk Assessment, and Risk Management processes each of which comprises several steps. The HEPs are estimated by applying the SLIM process (Fig. 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 improvement of 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 [36].

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.

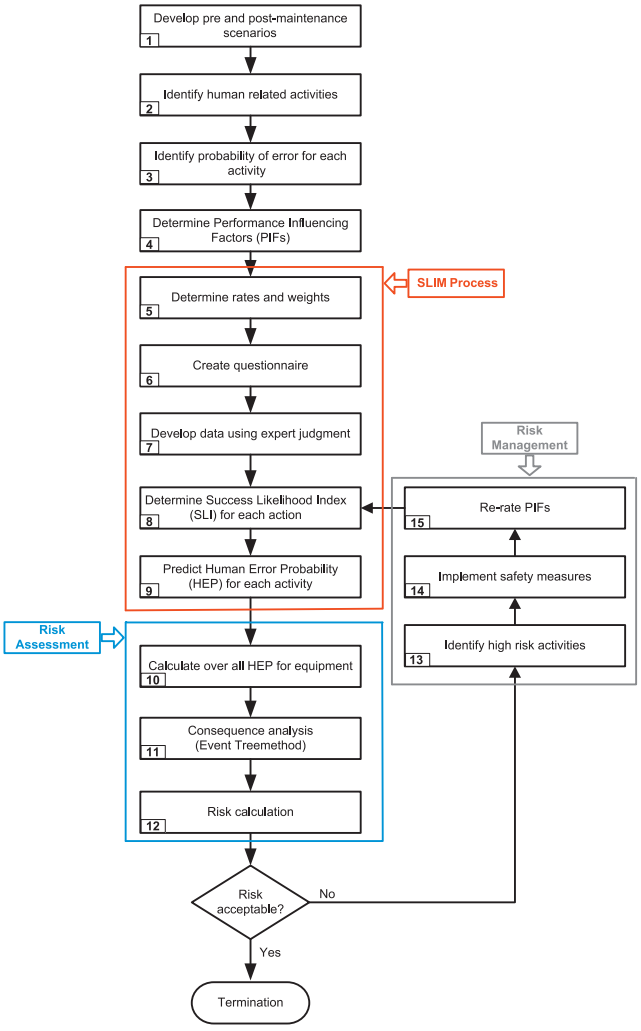


Fig. 2. Risk-based methodology for minimizing human error.

3. Application of the methodology

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 Fig. 2).

The main focus of this paper 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.

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 Fig. 2). Different activities and tasks are identified for pre-maintenance procedure and are presented in Table 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.

Table1
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 center
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

Table 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

3.3. Post-maintenance activities

The next step is to develop post-maintenance activities (Table 2). Activity 3 in Table 2 explains the re-connection of the component to the operating system, while Activities 4–7 explain the preparations for returning the component to active service. Activity 8 describes the re-activation of the component.

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 Fig. 2) to investigate the appropriate PIFs required for the specific task has been previously used by Embery [11]. Baraldi [37] proposed a methodology by combining the CREAM and fuzzy logic principles to estimate HEPs. In their method, anchor points were used to represent prototype conditions of the PIFs, while considering the effect of Expert opinions.

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 3 (Step 5 in Fig. 2).

Table 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	Behavior	4
10	Fatigue	2
11	Time pressure	1
12	Task difficulty (poor design)	1

Table 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

Table 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

According to five experts (considered in this study) who ranked the possible errors, it was observed that the six PIFs demonstrated in Table 4 are the most important ones in pre- and post-maintenance procedure of equipment.

The average values of weights for the considered PIFs received from the experts are presented in Table 5.

Rating the PIFs is another important step in the SLIM procedure. PIFs are rated based on responses collected from questionnaires (Step 6 in Fig. 2). These questionnaires were completed by experts such as maintenance personnel (Step 7 in Fig. 2).

By using Eq. (1), the data which was gathered from the judges were processed and SLIs were obtained for each activity (Step 8 in Fig. 2). Eq. (2) is then used to calculate the HEP for each task and activity (Step 9 in Fig. 2). The results are presented in Table 6.

3.6. Quantitative 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 to estimate risks of envisaged accident scenarios. These approaches are being applied to improve the level of safety in aerospace, nuclear, and chemical process facilities [38–42]. The result of risk analysis is normally considered by decision-makers and safety experts to improve the performance of safety measures in a facility so that the risk can be reduced 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 [40–43], risk-based design of process systems [42,44] and risk-based inspection and maintenance [15,45–49].

To estimate the risk resulting from human error in pre- and post-maintenance procedures of process facilities (Steps 10–12 in Fig. 2), a specific section in offshore process facility including a pump, a separator, and a valve is considered (Fig. 3). Among several techniques available for accident scenario modeling, Event Trees (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 success/failure of top events.

It should be noted that since maintenance procedures of components in Fig. 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.

To this end, considering the maintenance of each component as the initiating event, the event trees are developed (Step 11 in Fig. 2) for the pump and valve (Fig. 4), and the separator (Fig. 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

Table 6
Human error probability.

Activity		HEP	Uncertainty	
			Lower Bound	Upper Bound
1.0				
1.1	(Area Authority) prepare work order	2.67E−04	2.67E−05	7.06E−01
1.2	Apply for permit to work	1.0E−04	7.29E−05	3.17E−02
1.3	Perform equipment diagnostics	1.0E−04	9.84E−06	7.74E−02
1.4	Identify equipment affected and tags used	7.8E−02	9.52E−04	7.74E−01
1.5	Perform risk assessment of activity	6.5E−02	6.71E−04	3.58E−01
1.6	Check work order and ensure no conflict of operation or other work	4.6E−03	1.03E−05	2.69E−02
1.7	Determine and certify required isolations	3.8E−02	5.35E−06	1.49E−01
1.8	(Permit to work coordinator) obtain keys and certificates required	2.9E−02	4.12E−04	4.73E−01
1.9	(AA) Authorize work	3.8E−03	6.51E−04	1.69E−01
1.10	(PTWC) Assign lockout box and give keys to supervisors affected by isolation	1.9E−02	1.64E−04	1.39E−01
1.11	Perform and document initial gas test	2.7E−02	8.45E−04	9.20E−01
1.12	Rank fluid contained within component	1.6E−04	5.28E−06	5.02E−02
1.13	Determine size of inlet and outlet lines from component	3.5E−03	1.12E−05	1.78E−02
1.14	Identify most appropriate isolation method	1.4E−01	6.01E−03	1.05E−01
1.15	(OIM) Approve work activity	5.0E−03	2.81E−06	1.73E−01
1.16	(Workforce supervisor) hold toolbox meeting	2.7E−02	2.11E−04	2.37E−01
1.17	Place PTW on permit board with copy displayed at work site	1.4E−04	5.82E−07	4.32E−02
2.0				
2.1	Check lines for fluid and pressure	3.8E−04	9.21E−07	8.64E−02
2.2	Check bleeds/vents for obstruction	8.5E−02	2.81E−04	5.36E−01
2.3	Close isolation valves	3.8E−02	7.90E−05	8.85E−01
2.4	Lock and tag isolation valves	1.1E−02	6.39E−05	2.38E−01
2.5	Depressurize lines	2.9E−01	3.22E−03	1.09E−01
2.6	Drain lines	6.0E−02	3.45E−05	9.57E−01
2.7	Purge lines	2.1E−02	2.11E−06	9.09E−01
2.8	Perform pressure test & isolation leak test	1.6E−03	3.49E−04	4.66E−01
2.9	Open all drains of affected equipment possible	2.1E−02	3.45E−05	2.13E−01
2.10	Perform mechanical isolation (fit slip plates, disconnect lines, etc.)	1.09E−01	5.61E−04	1.02E−01
2.11	Re-pressurize lines	9.3E−03	2.31E−05	9.24E−02
2.12	Isolate, lock and tag motor from control center	2.9E−02	2.05E−04	5.62E−01
2.13	Test motor for power	3.8E−02	8.31E−05	8.47E−01
2.14	Revalidate permit with supervisors	6.5E−04	6.60E−07	8.18E−02
2.15	Break containment	6.5E−04	3.91E−07	3.36E−02
2.16	Continue testing pressure and isolation at intervals	5.0E−03	1.78E−05	3.08E−01
3.0				
3.1	Check lines and equipment for obstructions	2.9E−02	3.08E−04	2.73E−01
3.2	Remove mechanical isolation/connect lines to component	8.5E−04	3.23E−07	7.49E−02
3.3	Remove locks and tags from valves, leaving valves closed	7.1E−04	7.93E−06	4.03E−02
4.0	(WFS) Ensure site and equipment left in safe state	2.7E−02	4.20E−05	2.02E−01
5.0	(WFS) Return keys & certificates	2.3E−01	1.91E−04	1.15E−01
6.0				
6.1	Return lock-out keys	3.5E−02	1.16E−06	3.43E−01
6.2	Give worksite authority back to AA	6.0E−02	3.88E−05	3.50E−01
6.3	(Supervisors) Document reinstatement	1.7E−04	6.02E−07	8.99E−02
7.0	(PTWC & AA) Close permit to work	6.5E−04	5.31E−06	7.78E−02
8.0				
8.1	Test Pressure	8.5E−03	1.25E−07	3.74E−02
8.2	Remove air from lines	4.6E−02	6.40E−04	4.91E−01
8.3	Open valves, fill and test for leaks	1.3E−03	2.24E−06	9.62E−01
8.4	Start the component	1.3E−02	7.29E−04	2.30E−01

would occur which can be extinguished only if a water sprinkler system is activated by a flame/smoke detector. However, it should be noted that although the event trees of the pump and the valve are similar, both the severities and probabilities of their consequences are different due to differences in the amounts of respective releases and maintenance frequencies. Also, compared to the ET of the pump and valve (Fig. 4), the ET of the separator (Fig. 5) is equipped with more layers of protection (more top events in the corresponding ET). The reason is that the separator is found to cause more severe consequences due to a higher volume of flammable material coupled with high temperature/pressure operational condition.

As such, a temperature gage and a relief valve are devised to monitor and release the high temperature/pressure. Also, a hydrocarbon (HC) detector is provided to make personnel aware of any possible release of HC pursuant to possible high temperature/pressure. Therefore, any released HC could be cleaned up prior to meeting an ignition source. As can be seen from Fig. 5, according to these additional safety barriers, the number of consequences increases while their probabilities decrease. The potential consequences resulting from the foregoing accident scenarios along with their descriptions are presented in the first and second columns of Table 8.

The probabilities of the top events of the event trees in Figs. 4 and 5 are indicated in Table 7 [48]. However, the probability of the first top event, Human error, has been derived using the probabilities of the sub-activities in Table 6, assuming that these activities and sub-activities are independent (the worst-case scenario). Thus, the probability of human error, HEP_T, for maintenance procedure of the equipment can be calculated using

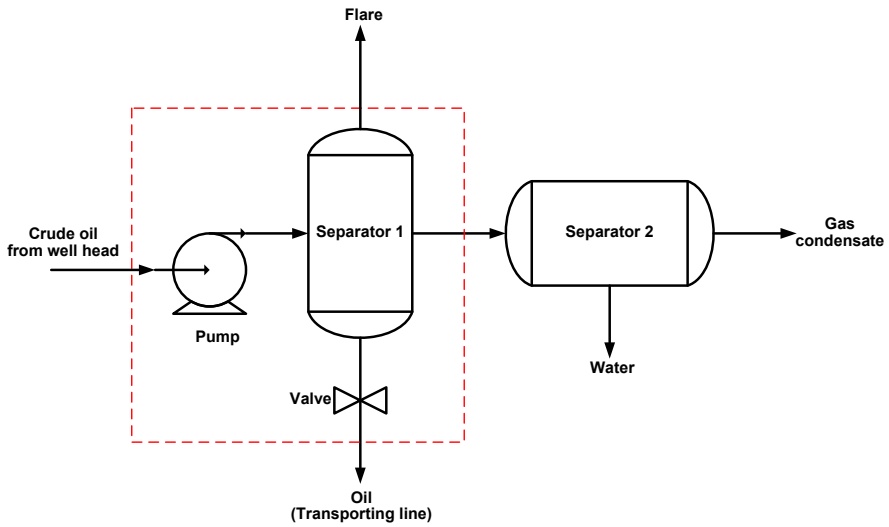


Fig. 3. Schematic of an offshore process facility including a pump, separators and a valve. The components used in this study are enclosed by dashed line.

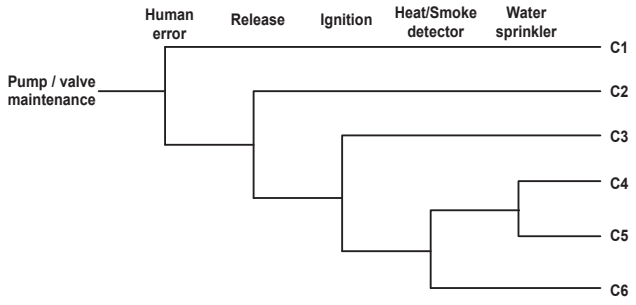


Fig. 4. Event tree developed for pump and valve maintenance risk analysis.

Table 7
Probabilities of event tree's top events [49].

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

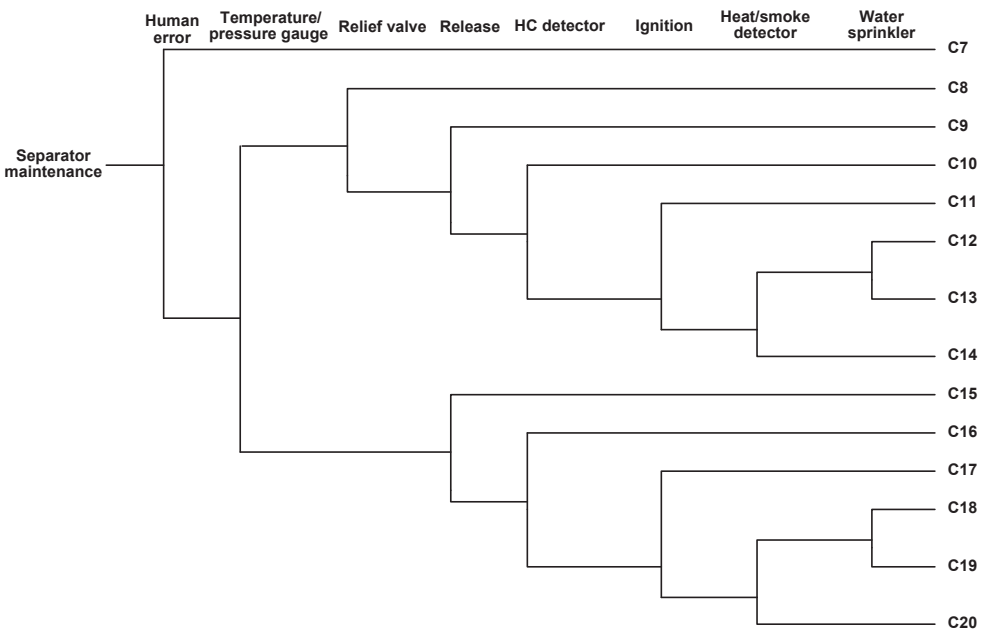


Fig. 5. Event tree developed for separator maintenance risk analysis.

Eq. (3) (Step 10 in Fig. 2):

$$HEP_T = 1 - \prod_{i=1}^{N} (1 - HEP_i) \quad (3)$$

where HEP_i is the probability of each activity (Table 6).

Applying the probabilities of top events, the probabilities of consequences can be calculated for the pump, valve and the separator (Table 8). It should be noted that in Table 8, for C1–C6, the first values refer to the pump while the second values are for the valve. Using the consequence severity matrix (Table A1,

Table 8
Risk analysis of maintenance-induced accidents.

Index	Description	Probability	Severity class	Damage (S)
C1	Safe condition	6.00E−02, 5.00E−02	1, 1	0, 0
C2	Mishap	2.16E−01, 1.80E−01	1, 1	0, 0
C3	Near miss	2.16E−02, 1.80E−02	2, 1	5E+03, 0
C4	Fire; successful extinguishment of fire, minor property damage, minor injury	2.28E−03, 1.9E−03	3, 2	25E+04, 5E +03
C5	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of death	9.5E−05, 7.92E−05	5, 3	25E+06, 25E +04
C6	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of death	2.38E−03, 1.98E−03	5, 3	25E+06, 25E +04
C7	Safe condition	1E−01	1	0
C8	Mishap	3.75E−01	1	0
C9, C15	Near miss	6.91E−03, 1.44E−02	1	0
C10, C16	Release of hydrocarbon; successful control of release; no fire	6.14E−04, 1.28E−03	2	5E+03
C11, C17	Release of hydrocarbon; unsuccessful control of release; no fire	1.38E−04, 2.88E−04	3	25E+04
C12, C18	Fire; successful extinguishment of fire; major property damage, multiple major injury	1.46E−05, 3.04E−05	4	25E+05
C13, C14, C19, C20	Fire; unsuccessful extinguishment of fire; major property damage, major injury, possibility of fatalities	6.08E−07, 1.54E−07, 1.27E−06, 3.2E−07	6	25E+07

Table A1
Consequence severity matrix [49].

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	0.01K–10K	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	10K–500K	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	500K–5M	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	5M–50M	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	50M–500M	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	>500M	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

Appendix I), the severity of each consequence can be determined (Column 4 of Table 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), the total amount of envisaged risk for the accident scenario can be estimated as $ 68,615 (Step 12 in Fig. 2).

It is worth noting that in this study, the Risk Management process (Steps 13–15 in Fig. 2) via re-designing the activities or implementing safety measures to reduce the risk is not discussed. 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 by $ 68,615.

4. Conclusion

The majority of the tasks in pre- and post-maintenance procedures are currently being done by automated systems. However, the likelihood of human error has not completely eliminated. We developed a methodology to investigate the role of human error in maintenance procedures of process facilities using the SLIM and event tree diagram. After the human error probability is estimated using SLIM method, it is coupled with existing safety barriers in an event tree to estimate the probabilities of potential outcomes originating from a human error. As a result, the role of human error probability in risk analysis can be better investigated, and the overall reliability and safety of the process system increase.

We applied the methodology to pre-and post-maintenance procedures of equipment in offshore facilities. The results show that ignoring human error in quantitative risk analysis of pre-and post-maintenance procedures can result in noticeable difference in the amount of envisaged risk. For example, it was illustrated that in the case of a simple process facility comprising a pump, a valve, and a separator, including the human error in the risk analysis could add $ 68,615 to the risk value. The results also show although maintenance procedures are aimed at increasing the reliability and availability of a system, the occurrence of human errors in pre- and post-maintenance procedures is likely to increase the overall risk.

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Appendix I

Table A1.

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