HUMAN RELIABILITY ANALYSIS APPLIED TO RIG OPERATIONS USING A COGNITIVE FRAMEWORK AND DEFINED PERFORMANCE INFLUENCING FACTORS

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TESE SUBMETIDA AO CORPO DOCENTE DO INSTITUTO ALBERTO LUIZ COIMBRA DE PÓS-GRADUAÇÃO E PESQUISA DE ENGENHARIA (COPPE) DA UNIVERSIDADE FEDERAL DO RIO DE JANEIRO COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE DOUTOR EM CIÊNCIAS EM ENGENHARIA OCEÂNICA.

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ANÁLISE DE CONFIABILIDADE HUMANA APLICADA A OPERAÇÕES COM SONDAS USANDO UMA ESTRUTURA COGNITIVA E DEFINIÇÃO DE FATORES DE INFLUÊNCIA DE DESEMPENHO

Manoela Teixeira Lopes

Junho/2019

Orientadores: Ilson Paranhos Pasqualino
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Programa: Engenharia Oceânica

Este trabalho apresenta uma abordagem qualitativa e quantitativa para introduzir aspectos de fatores humanos na avaliação de confiabilidade e riscos de operações com sondas. A parte qualitativa compreende a análise de tarefa e a pesquisa por causas potenciais de falhas baseadas em uma estrutura cognitiva. No estágio quantitativo, o efeito combinado de fatores sobre a probabilidade de erro humano é calculado a partir de pesos relativos normalizados e avaliação do denominado grau de conformidade. O modelo é primeiramente elaborado a partir de árvores binárias e posteriormente convertido em uma rede bayesiana para expressar relações condicionais entre fatores humanos e falhas cognitivas. A abordagem foi aplicada para o cenário de desconexão de emergência de sonda e o grau de conformidade pontuado de acordo com revisão de literatura sobre o contexto operacional do *blowout* de Macondo. Os fatores identificados com maior contribuição para o acidente estavam associados a aspectos organizacionais, comunicação de riscos, atenção e colaboração da equipe, que majoritariamente afetaram a consciência situacional da tripulação. Para verificar o modelo, foram efetuadas análises de sensibilidade através de variações nos fatores humanos em duas condições operacionais extremas e nos valores de probabilidade de falha de funções cognitivas. Os resultados obtidos permitiram validar a proposta desenvolvida.

Abstract of Thesis presented to COPPE/UFRJ as a partial fulfillment of the requirements for the degree of Doctor of Science (D.Sc.)

HUMAN RELIABILITY ANALYSIS APPLIED TO RIG OPERATIONS USING A COGNITIVE FRAMEWORK AND DEFINED PERFORMANCE INFLUENCING FACTORS

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This work presents a qualitative and quantitative approach to introduce human factors aspects in the reliability and risk assessment of offshore rig operations. The qualitative part covers the task analysis and searching for potential causes of failures based on a cognitive framework. In the quantitative stage, the combined effect of factors on Human Error Probability is computed from normalized relative weights and evaluation of the called degree of compliance. The model is initially drawn by means of binary trees and subsequently converted into a Bayesian network in order to express conditional relationships between human factors and cognitive failures. The approach was applied to the scenario of rig emergency disconnection and the degree of compliance scored considering a literature review on the operational context of the Macondo well blowout. The main contributors identified for this accident were associated to organizational aspects, risk communication, attention and team collaboration that mostly affected situation awareness of the crew. To verify the model, sensitivity analyzes were performed through variations in the human factors under two extreme operating conditions and in the probability of the cognitive function failures. The results obtained allowed to validate the developed proposal.

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List of Abbreviations and Acronyms

AHP	Analytic Hierarchy Process
AMF	Automatic Mode Function
ANP	National Agency for Petroleum, Natural Gas and Biofuels
ATHEANA	A Technique for Human Error Analysis (NRC, 2000)
BHA	Bottom Hole Assembly
BN	Bayesian network
BOP	Blowout Preventer
BSEE	Bureau of Safety and Environmental Enforcement
BSR	Blind Shear Ram
CC	Common Conditions
CFF	Cognitive Function Failure
CFP	Cognitive Function Probability
Control pod	Assembly of valves and pressure regulators (either hydraulically or electrically operated) that when activated will direct hydraulic power fluid through assigned porting to operate BOP functions (API, 2018a, API, 2018b)
CPC	Common Performance Conditions
CPT	Conditional Probability Table
CREAM	Cognitive Reliability and Error Analysis Method
CSR	Casing Shear Ram
DP	Dynamic Positioning/Positioned
DPO	Operator of the DP control system
EDG	Emergency Disconnection Guidelines
EDS	Emergency Disconnection Sequence
ESD	Event Sequence Diagram
ET	Event Tree
FT	Fault Tree
HEBC	Human Entropy Boundary Conditions
HEP	Human Error Probability
HMI	Human Machine Interface

HPU	Hydraulic Power Unit
IMCA	International Marine Contractors Association
IOGP	International Association of Oil and Gas Producers
LMRP	Lower Marine Riser Package
LNG	Liquid Natural Gas
MATA -D	Multi-attribute Technological Accidents Dataset (MOURA (2015, 2016)
Metocean	Meteorology and Oceanography
MGS	Mud Gas Separator
MMI	Man-Machine Interface
MOF	Management and Organizational Factors
OEM	Original Equipment Manufacturer
OIM	Offshore Installation Manager
PIF	Performance Influencing Factors
PR	Pipe Rams
RIF	Risk Influencing Factors
Risk-OMT	Risk modelling - Integration of Organizational, Human and Technical factors (VINNEM et al., 2012, GRAN et al., 2012, STRAND and LUNDTEIGEN, 2016, 2017)
ROV	Remotely Operated Vehicle
SGIP	Management System of Well Integrity
SPAR-H	Standardized Plant Analysis Risk-Human Reliability Analysis (GERTMAN et al., 2005)
THERP	Technique for Human Error Rate Prediction (SWAIN and GUTTMAN, 1983)
WSOG	Well Specific Operating Guidelines

Chapter 1. Introduction

This chapter describes initially the motivation for the theme of human reliability based especially on the perception of the human contribution in accidents and its repercussions in the international and Brazilian regulation of the oil and gas industry, as well as the characteristics of well and rig activities. The objectives and scope are outlined taking into account this emphasis on human factors and the features of the selected operational scenario. The last section presents how the thesis is organized.

1.1. Background

The investigation of numerous major accidents (e.g. Piper Alpha in 1988, Montara in 2009) demonstrates the importance of the human role as a contributor to identified critical failures, either as an active element or introducing a latent condition (HOLLNAGEL, 2005, LI et al., 2014, STRAND and LUNDTEIGEN, 2017). This perception was even more evident with the technology advances that reduced the frequency of failures attributed strictly to technical issues (GORDON, 1998, HOLLNAGEL, 2005, CHEN et al., 2012). According to HOLLNAGEL (1993), in the 1960's the human contribution was estimated in almost 20% and in the 1990's this number increased to approximately 80%. In literature, authors present a wide range of human contributions to different industries (maritime transportation, offshore, aeronautics, nuclear and etc.), that usually vary from 60% to 90% (TRUCCO et al., 2008, LADAN and TURAN, 2012, CAI et al., 2013a, SMITH et al., 2013, LI et al., 2014).

In the oil and gas industry, the Macondo well blowout is an emblematic case in which a combination of numerous physical and operational barrier losses resulted in a shattering event. The accident occurred in 2010 involving the Deepwater Horizon rig owned by Transocean. The British Petroleum was the leasing operator in the block where the Macondo well was drilled (BP, 2010, TRANSOCEAN, 2011). The accident that started with a well control event and escalated to a blowout, resulted in catastrophic consequences totalizing 11 fatalities and 17 people injured, rig sank, severe environmental and community impact, high financial losses with response operations and liabilities (estimated 40 billion USD in liabilities), impact on company reputation/brand (MOURA et al., 2015), among other critical effects.

This accident motivated a series of changes in regulatory framework and international standards in subsea well operations (MC ANDREWS, 2011, SATTLER, 2013a, 2013b). For example, the revision and reclassification of the publication API 53 from Recommended Practice (RP) to Standard (STD) in 2011 (current version: API, 2018b) and the Well Control Final Rule issued by BSEE (Code of Federal Regulations – 250) in 2016 (BSEE, 2016). The Well Control Final Rule established requirements related to many topics associated to the failures and gaps identified for the Macondo well blowout, for example, real-time monitoring, periodicity and pressure tests of BOP, shear rams capacity, emergency systems, ROV intervention capability (hydraulic power), BOP arrangement and maintenance, training certification, certification of cementing program, among other relevant themes (BSEE, 2016).

In Brazil, the National Agency for Petroleum, Natural Gas and Biofuels (ANP) issued in 2016 the Technical Regulation of the Management System for Well Integrity (ANP, 2016). This resolution aimed to establish the requirements and guidelines for implementation and operation of a Management System of Well Integrity (SGIP) and it should be applied to the whole well life cycle. This document instituted 17 management practices that address topics such as: safety culture; competence management; human factors; contractor management; audits; incidents; information and documentation management; procedures; risk assessment; management of change (ANP, 2016).

The fourth management practice established by ANP is focused on the assessment of human factors in the Well Integrity Management. This explicitly requires development of methodologies to evaluate human factors in the whole well life cycle; implementation of training program focused on non-technical skills; acting in critical aspects in order to ensure suitable work schedules, shift planning and breaks, as well as adequate handover; mitigate aspects related to workplace design that can influence the workforce performance (ANP, 2016). In general, all of the requirements are associated to failures identified in Macondo well blowout.

These regulatory documents encompass topics that are directly or indirectly associated to human factors and most of them affect the requirements of Blowout Preventer (BOP) equipment (ANP, 2016, BSEE, 2016). Subsea BOP is a safety equipment used in activities of well construction and maintenance (API, 2018b). It represents the last line of defense in an emergency scenario in order to avoid injury to personnel, environmental pollution and rig damage, among other severe consequences. It is worth mentioning that all the commands to operate BOP functions depend on manual activation. Furthermore, operational planning and means to keep situation awareness of the operators and supervisors are fundamental aspects to be succeeded in equipment operation. And, consequently, human issues affect considerably BOP performance.

The nature of rig activities, which still leads to many manual tasks, together with the observed scenario of regulatory changes due to accident history, reinforce the importance of dealing with the modelling and analysis of human aspects to allow detailed and complete risk and reliability analyses in design and operation, besides the technical issues.

1.2. Objectives and Scope

The main objective is to propose a reliability/risk analysis approach with emphasis on human aspects feasible for the rig activity domain. In order to get this objective, the following directions were outlined:

- Select or adapt a well-defined framework that allows to describe and model certain operational sequence in a reproducible and systematic way;
- Identify the most representative set of human factors that could characterize rig operations context and determine metrics to evaluate them;
- Build a model that allows taking advantage of updates from field evidences (e.g. near-misses or accident history, audit and drills or other valuable sources).

It is worth mentioning that the scope was delimited to human issues, not including the analysis of equipment failure. This was decided in order to explore techniques for the purpose of human reliability and does not bias the analysis in a system reliability instantiation and structure in a first moment. Moreover, the model was applied to operational phase, not covering Maintenance, Inspection and Testing (MIT) tasks. However, the need for a future model combining technical and human issues and including MIT tasks was mapped for future work.

1.3. Structure of the Thesis

Chapter 2 addresses the description of application scenario detailing the characteristics of Subsea BOP (its main components, functions and critical activation scenarios). Moreover, the main concepts and the high-level description of operational sequence of emergency disconnection scenario are presented.

The literature review on human reliability with applications to oil and gas and other industries are presented in Chapter 3. Chapter 4 presents an introduction about Human Reliability Analysis and a description on the applied techniques for the proposed model: fault trees, Bayesian networks and CREAM.

Chapter 5 presents the whole human factors approach detailing the steps to develop the qualitative and quantitative analysis. The model application for a scenario of rig emergency disconnection is presented in chapters 6 and 7. Chapter 6 comprises the qualitative analysis, preliminary results with fault trees, as well as quantification of weighting factors and scoring of human factors. The main results and discussions on contribution of human factors for each cognitive function and failure probability of tasks and outcome event, besides sensitivity analyses, are detailed in Chapter 7. Conclusions of this work, including recommendations for future work, are presented in Chapter 8. Additional information that gives support to the previous chapters is presented in Appendices A to E.

Chapter 2. Application Scenario

This chapter describes briefly the subsea BOP components, its functions and one critical activation scenario. The emergency disconnection is detailed starting from the context, presentation of basic concepts and high-level description of operational sequence. The features that once more ratify the importance of human reliability analysis for these kind of activities are emphasized.

2.1.Characteristics of Subsea BOP

The subsea BOP is a safety equipment used in well construction and maintenance activities. It is connected to the wellhead or wellhead assemblies in order to contain wellbore fluids, either in the annular space between the casing and the tubulars, or in an open hole condition during well drilling, completion, testing and workover operations (API, 2018b). The Subsea BOP is composed of elements with different characteristics and functions constituting a vertical arrangement of safety barriers. Fig. 1 is a simplified illustration displaying the connection of BOP with the well and the rig, this latter through the marine drilling riser. Fig. 2 illustrates a simplified arrangement of subsea BOP highlighting their main components.

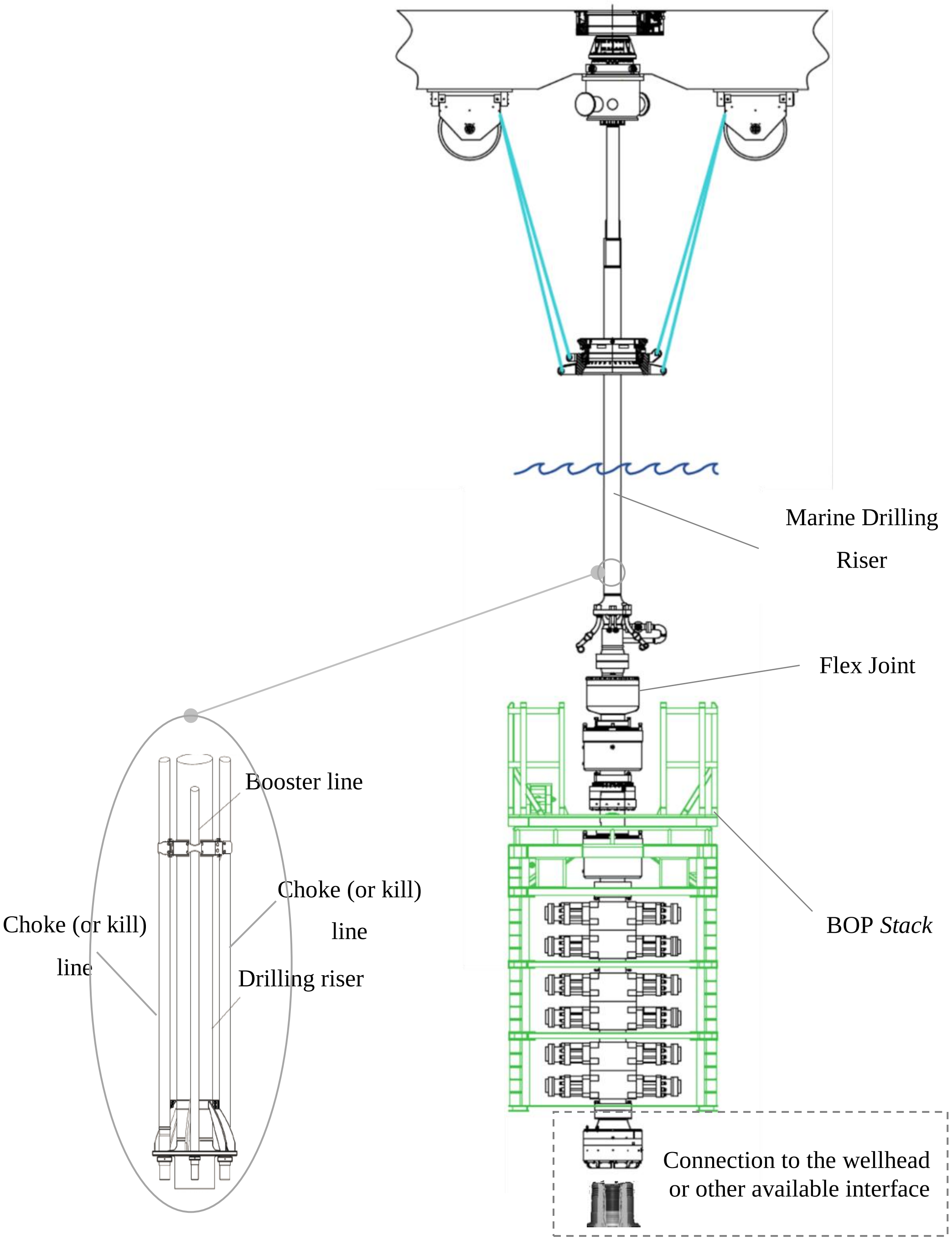


Fig. 1. Overview of Subsea BOP and its connection with the rig through marine drilling riser and with the well via wellhead or other available interface (adapted from API, 2012)

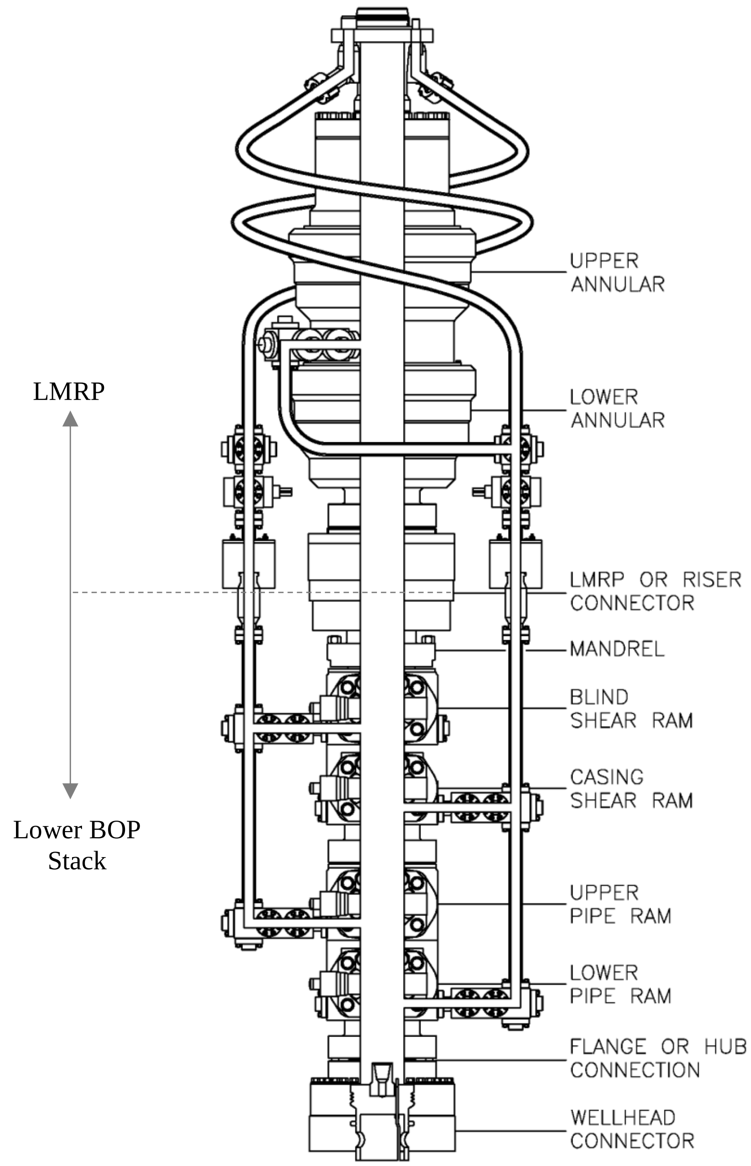


Fig. 2. Example illustration of Subsea BOP Stack (adapted from API, 2018b)

The marine drilling riser represents the link between the subsea equipment assembly and the rig. Among other functions, it conducts the drilling mud up to the surface and helps to guide the work string and the casing to the well (SANTOS, 2013). Attached to the riser, there are two lines called choke and kill line that are used to well control operations (for circulating fluids to balance wellbore pressure) and one booster line to increase circulation of fluid in the riser. In the subsea BOP with a multiplex control system, two additional lines are included for hydraulic supply, named conduit lines.

The BOP stack showed in Fig. 2 is composed of different elements designed to attain specific functions and to operate according to the demand scenarios. Subsea BOP is constituted of an assembly of mechanical barriers that aims to contain wellbore fluids and isolate the well from the external environment. The upper part of the BOP Stack is named Lower Marine Riser Package (LMRP) and encompasses the subsea control pods, subsea accumulators, hydraulic connector, flex joint, riser adapter, flexible choke and kill lines and, at least, one annular preventer (API, 2018a). In an emergency scenario that requires rig disconnection, by default, the LMRP is detached from the Lower Stack. The Lower Stack includes: ram preventers, wellhead connector and can comprise one annular preventer. In an emergency disconnection scenario, the Lower Stack usually remains connected to the well aiming to assure its isolation. The main components of BOP Stack are briefly described below:

- Ram preventers: represent mechanical barriers with the main objective to isolate the well avoiding ascending flow of wellbore fluids to the surface. There are different types of ram preventers, such as: Pipe Rams (PR), Blind Shear Rams (BSR) and Casing Shear Rams (CSR).

  Pipe rams are activated to close and seal around tubulars. For that, PR is designed with a profile that holds and accommodates the tubular with a certain diameter and has sealing elements. The ram remains in position hanging on the tubular by means of pressure and locking mechanism. The profile diameter can be fixed or variable according to the type of ram (API, 2012).

  It is important to mention that there are the called test rams, which in a simplified description is an inverted pipe ram. Such ram is employed to perform tests that demand the isolation of the wellbore avoiding descending flow and, in general, is applied to save time with tripping of work string with test tools.

  Blind Shear Rams have the capacity to shear and seal because they are composed of blades and sealing elements. They can seal after shearing an element passing through BOP (work string, casing, wireline, etc.) and if there is no element, given that they are designed with an overlap between blades. Casing Shear Rams are capable to shear elements, commonly with higher strength than the BSR. CSR is not designed to sealing functions.

- Annular preventers: composed by a central elastomeric element and is closed to isolate the annular space between the work string (or tool) and the well. They can also proportionate sealing functions in case of no elements passing though BOP. The elastomeric element can accommodate different diameters and profiles.

- Hydraulic connectors: provide connection and sealing in interfaces of BOP stack (LMRP and Lower Stack) and the connection with the well. The two main hydraulic connectors are: (i) Wellhead Connector: interface with Lower Stack and the wellhead; (ii) LMRP connector: interface between LMRP and Lower Stack (also called riser connector).

Subsea BOP is controlled by a system that comprises pumps, valves, lines, accumulators and other auxiliary items to activate, to transmit and process signals and to execute the BOP related functions (API, 2012). The so-called main control system is composed of surface equipment (remote control station/panel, umbilical and Hydraulic Power Unit - HPU) and subsea assembly (control pods, subsea accumulators, etc.). In a preliminary classification, the control system can be grouped into two main types, hydraulic or electro-hydraulic/multiplex (API, 2018a).The latter was designed to allow transmission subsea with a short response time in deepwater operations.

In the hydraulic control system, the remote commands are transmitted by means of umbilical hose bundles. There are dual subsea control pods on the LMRP and housing operated valves for directing power fluid to the related BOP functions (API, 2018a). On the other hand, in the electro-hydraulic type, the transmission subsea is directed by multi-conductor cables that have a pair of wires to each function in order to operate subsea solenoid valves, which send hydraulic pilot signals to the control valves that operate the BOP functions (API, 2018a). In multiplex control systems, multiple commands are transmitted over individual conductor wires or fibers, employing serialized communications. Electronic/optical data processing and transmission are implemented to provide safe codifying and to confirm functional signals, avoiding sources of spurious commands (API, 2018a).

In addition to the main control system, emergency and secondary systems are required in view of the role of BOP as the last line of defense in an emergency scenario. The emergency systems are basically formed by the Emergency Disconnection Sequence (EDS) and the autoshear/deadman systems. The secondary systems, also called backup systems, are composed of acoustic and ROV intervention systems (API, 2018b).

An EDS provides a time-regulated sequence of BOP components activation that aims mainly to disconnect the rig and isolate the well. Once manually initiated by the driller, subsea supervisor or other person in charge (e.g. tool pusher), the EDS will proceed with the operation of functions programmed in their software in an automatic way. The EDS is activated when predetermined conditions of DP rig status is reached. These conditions are described in WSOG (Well Specific Operating Guidelines) related to the red or straight red alarm status. These concepts will be discussed in section 2.2.

Each rig has a number of possible sequences of disconnection available, the so-called EDS modes. The EDS modes provide different sequences of BOP items activation that aims to cover a wide range of possible scenarios with the intention to assure a safe disconnection. As will be mentioned in section 2.2, the decision for the suitable EDS mode should be made before beginning a new operation, because the response time has to be fast enough to avoid emergency escalation.

The autoshear and deadman systems are designed to automatically shut in the wellbore, respectively, in an event of LMRP disconnection (when autoshear is armed) or in case of simultaneous absence of hydraulic supply and signal transmission capacity in both subsea control PODs (API, 2018a). Both systems, when activated, direct commands to close blind shear rams.

The backup systems can be employed when the main control system is inaccessible or non-functional. The acoustic control system uses coded acoustic signals for communications having control of some selected BOP critical functions. The ROV intervention system provides interfaces to use hydraulic power supplied by an ROV to operate BOP critical functions (API, 2018a).

It is worth mentioning that all the commands to operate BOP functions depend on manual activation. Furthermore, operational planning and means to keep situation awareness of the operators and supervisors are fundamental aspects to be succeeded in equipment operation and, consequently affect considerably BOP performance. Two critical situations that demand BOP actuation that can be mentioned are: Well control event (kick) and Emergency disconnection.

Usually, well drilling operations are planned to maintain overbalanced conditions, i.e., the wellbore pressure is held higher than the pore pressure of the exposed permeable formation. Such condition is achieved through pumping drilling fluids with adequate density so that can it overcomes pore pressure but do not fracture the exposed formation. If this condition is inadvertently lost due to some issues (e.g. lost circulation, mud cut by gas, swabbing while tripping) it can result in an undesired influx of formation fluids into the wellbore, the well kick. In this situation, a sequence of procedurally actions is implemented, among others, the activation of components of subsea BOP. However, if the kick is not quickly detected and controlled, the condition could be aggravated culminating in a blowout (SANTOS, 2013).

In turn, the emergency disconnection scenario is a risk intrinsic to the operation with Dynamic Positioning (DP) rigs due to the factual possibility of position loss. If pre-established conditions are reached, the EDS is initiated aiming to disconnect the rig and isolate the well. As aforementioned, the EDS is an emergency system, activated manually and operates BOP functions in a preprogrammed time sequence. An unsuccessful emergency disconnection can lead to catastrophic consequences, for instance, total loss of the well, severe damage or rupture of the marine drilling or completion riser, environmental pollution, underground or subsea blowout, among others (PAULA JR and FONSECA, 2013).

Both situations deal with a sequence of human actions according to the related procedures that usually start with the detection of the triggering event until the execution of the suitable BOP functions, as well as additional recovery tasks. The following section will introduce the emergency disconnection scenario selected as an example for application of the approach proposed in this work in light of human factors concepts and methodology.

2.2. Emergency Disconnection Scenario

Dynamic Positioning (or positioned) vessels have automatic control of their position and heading by the use of thrusters with regard to one or more position references (IMCA, 2007). In the case of drilling vessels (offshore rig), the requirement is to maintain the position over the well site for the duration of the well operations (IMCA, 2017). Basically, the DP system comprises the following sub-systems: power system, thruster system (propulsion devices) and DP control system. This latter calculates position and provides thruster commands. An inability to maintain position may result in risks to safety of people and the environment, such as injury to personnel, damage to the rig and to the riser, wellhead, adjacent offshore installations and environmental pollution (IMCA, 2017).

There is a set of documents required for DP rig operations, among others, the Well Specific Operating Guidelines (WSOG). A WSOG defines the operational, environmental and equipment performance limits concerning the well site and the specific activity the rig is undertaking (IMCA, 2017). The performance limits are defined considering the risk level. Moreover, it includes guidance on required actions when the set forth limits are exceeded, such as conditions that require emergency disconnection. A DP rig may have a number of different WSOGs, each applying to different locations, activities and levels of risk (IMCA, 2017).

For dealing with the risks and anticipate actions to be prepared in case of situation aggravation, the concept of DP alert status system was defined by the International Marine Contractors Association (IMCA). A system of lights and audible alarms indicates the DP system status at appropriate operational/control locations. The required actions in case of DP status change is determined by risk assessment and documented in the WSOG (IMCA, 2017). According to IMCA (2017), four status are recommended to deal with different levels of risk to the rig: Normal status (green light), Advisory status, degraded status (yellow light) and emergency status (red light).

The Brazilian company Petrobras has a large experience with DP rigs. The first operations dated from the end of the 1970’s (CRUZ, 2014). According to CRUZ and FONSECA (2017), the current DP operational status classification adopted by Petrobras encompasses the following status: Normal, Advisory, Yellow and Red Status. However, there is a conceptual difference related to the advisory and yellow status in relation to IMCA recommendations as reported by PAULA JR and FONSECA (2013), CRUZ (2014), CRUZ and FONSECA (2017). For Petrobras, the advisory status represents a degraded condition defined by loss of redundancy in the DP system and yellow status corresponds to the loss of station keeping capability due to the overcoming of some boundary parameters (such as offset or riser angle) as defined in WSOG (CRUZ and FONSECA, 2017).

A generic sequence related to emergency disconnection scenario until EDS activation was drawn considering the definition of DP status according to CRUZ and FONSECA (2017) and the description of the main task steps mentioned by PAULA JR and FONSECA (2013). Fig. 3 presents the operational sequence with the main steps of detection, communication of DP status change, preparation to emergency disconnection and EDS activation. Step 0 is related to planning actions accomplished on the rig, before the beginning of each operation. Fig. 4 illustrates the planning activity.

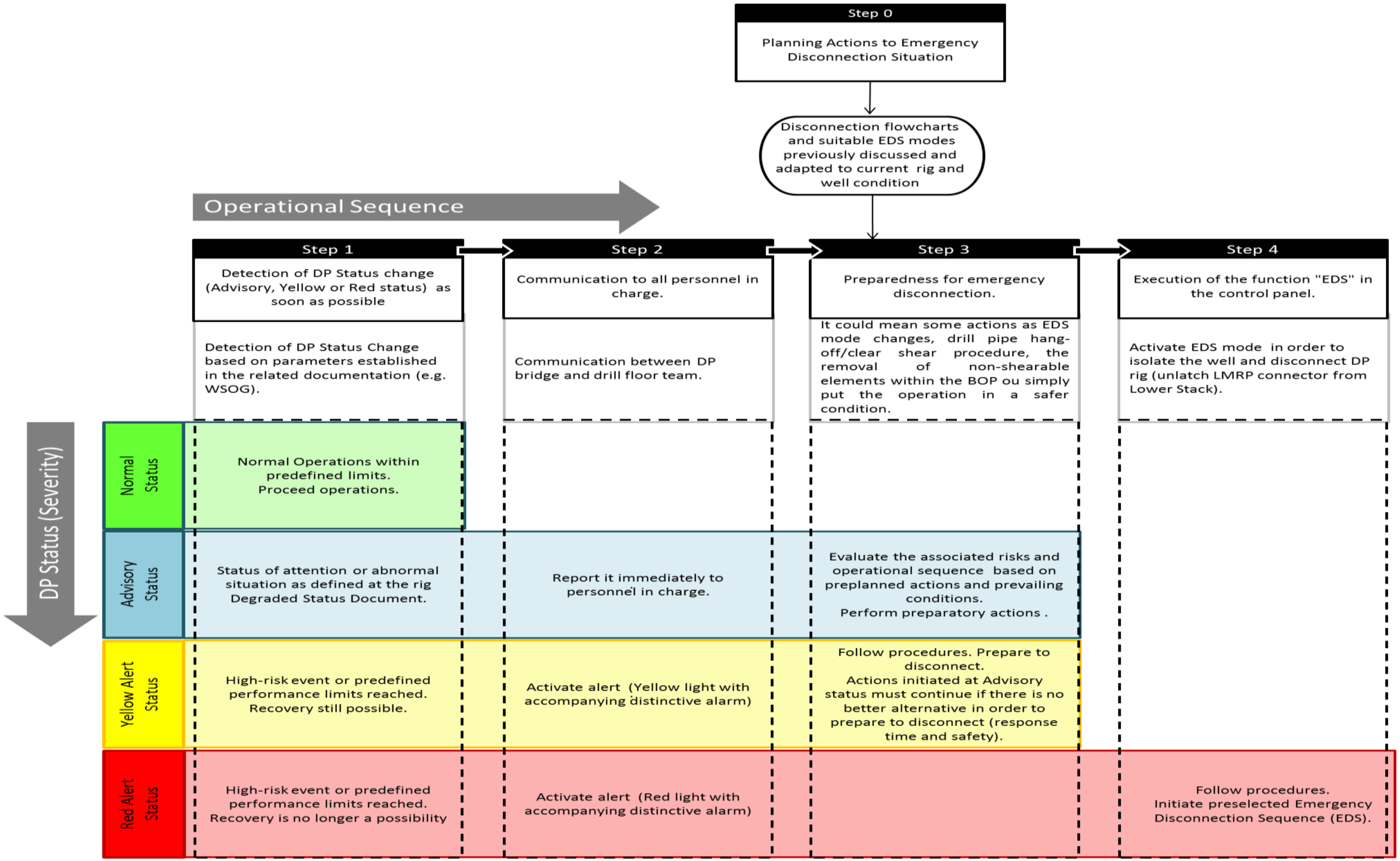


Fig. 3. Generic operational sequence and DP status with required actions (based on PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017)

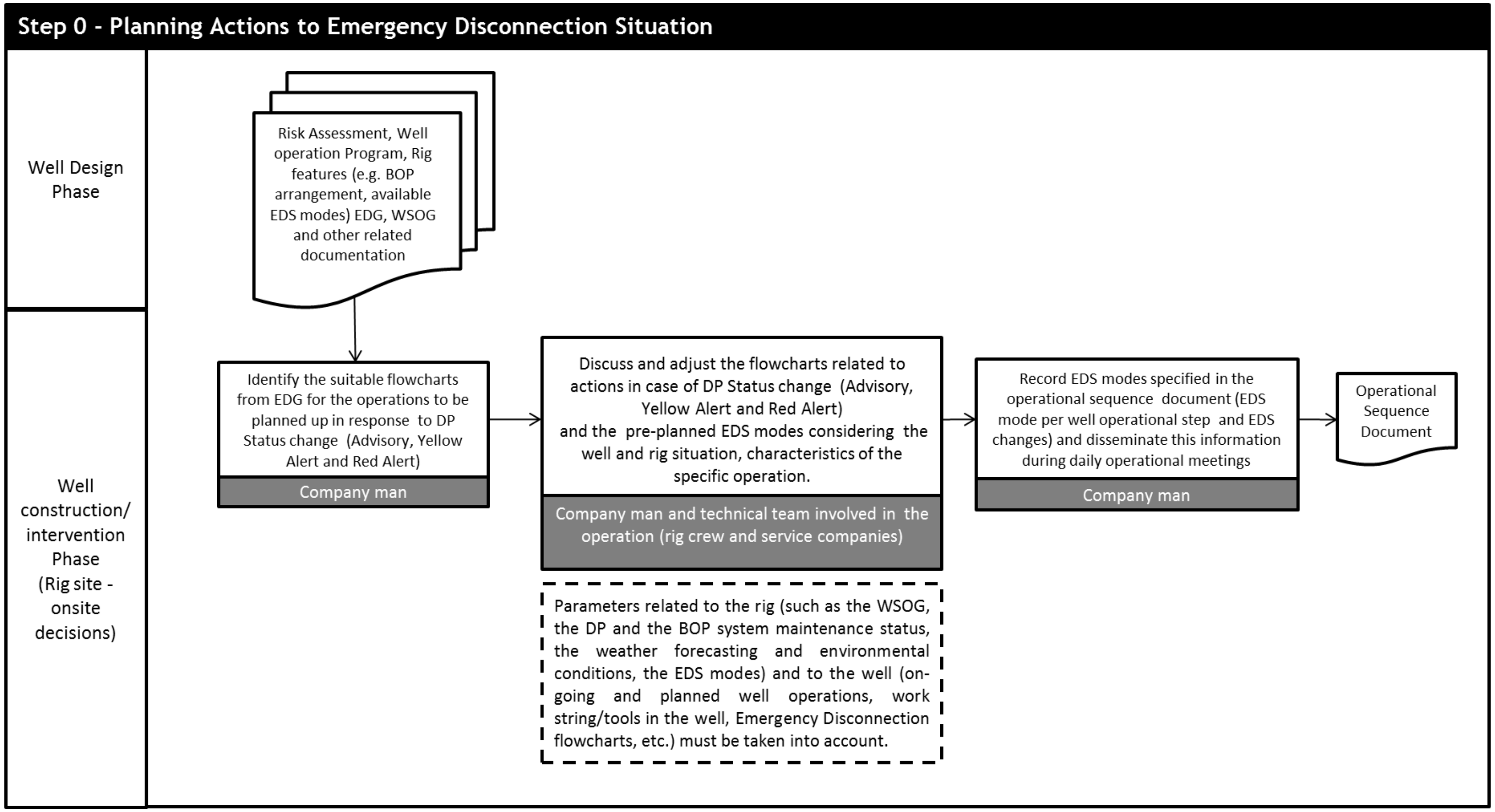


Fig. 4. Planning activities for emergency disconnection scenario (based on PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017)

In a brief description, the planning activity begins with the examination of the work package documentation (e.g. risk assessment, well operation program, rig features, Emergency Disconnection Guidelines, WSOG, etc.). The necessary decisions are made with the leadership of the company man (well owner representative) and participation of the team leaders involved in the operations (rig crew and service companies). The definition of actions in case of DP status change is discussed considering the Emergency Disconnection Guidelines (EDG) taking into account the operation to be initiated. The EDGs contain decision flowcharts for different types of operation for well drilling, completion, workover and well testing activities. They represent a starting point of discussion but need to be customized considering the current conditions of the well and the rig, as well as the particularities of the operation (PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017).

Another important decision is related to the confirmation of the suitable EDS mode for each operation. It depends on numerous variables, such as BOP arrangement, available EDS modes, capacity of shear ram preventers, element passing through BOP (e.g. tubulars, wireline, non-shearable element), heave compensation, etc. This is previously recommended in well program, but should be discussed again in the operation phase taking into account the changes in operations and BOP conditions, as well as the corporate guidelines (internal standards). All these definitions should be recorded in operational sequence by the company man and disseminated during daily operational meetings (PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017).

The conditions of the DP system should be monitored by the DPO. In case of detection of anomalies that represent DP status change, the DPO has to start a series of actions following the pre-established procedure in WSOG. Essentially, one of the subsequent steps is to communicate the current condition to the key personnel involved in operations. For 'yellow' or 'red' status, the communication is more comprehensive and is warned with typical visual and audible alarms (PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017).

In case of advisory status, the well operations are not necessarily suspended, but a risk assessment needs to be done. Preparatory actions can be initiated based on the previous planning with the customized flowchart aiming to take the well to a favorable condition for a safe rig disconnection. These actions can include drill pipe hang off/clear shear procedure, pull out or running in the element within the BOP bore in order to avoid non-shearable element in the position of shear ram blades, etc. Therefore, this step comprises decision-making and execution of preparatory actions. The yellow alert status can also involve preparatory actions that may have been started in advisory status and must continue if there is no better alternative considering response time and safety. In turn, the 'red' status leads to an immediate response of EDS activation because there is no time for additional discussions (PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017).

Besides the four DP status mentioned, there are two additional conditions not necessarily evolved from a previous loss of redundancy, these are the straight yellow and red alert. The straight yellow alert is triggered in the event of a complete loss of propulsive power (blackout or loss of all thrusters). The straight red alert is motivated by the loss of all monitoring systems (drift and angle). In both cases, the yellow or red alarm is immediately activated. These conditions are also covered by the flowcharts of the EDGs and have to be discussed in planning activities (PAULA JR and FONSECA, 2013, CRUZ, 2014, CRUZ and FONSECA, 2017).

Finally, it is worth mentioning that for a successful preparation for the emergency disconnection scenario, it is essential that DP status definitions, the roles and responsibilities of the person in charge and expected response are well defined and understood. Thus, it is possible to ensure fluid communication with common working language and terminology, and also actions to be executed on time. CRUZ and FONSECA (2017) concluded in their paper the importance of fast and clear communication between DP bridge and drill floor crew, well understanding of procedures and periodic drills. All these aspects are associated to human factors.

2.3. Characteristics of the Application Scenario

According to the characteristics of the application scenario presented in this chapter, candidate techniques to develop the model would need to meet the following requirements:

- Ability to deal with dynamic scenario due to the feature of different types of well operations with distinctive conditions per well.
- Consider and represent different teams involved in the operation;

- Ability to model complex relationship between events with conditional nature and with gradual development of scenario, both for safety equipment activation and human tasks;
- Ability to model multistate variables, both for representing degradation when dealing with MIT tasks and different states of human factors.
- Incorporate data from different information sources, including expert opinion in order to compensate some deficiency in the amount and quality of available data, as well as, to obtain estimates on rare events and issues related to human factors.

Chapter 3. Literature Review

Literature review on the incorporation of human factors was performed firstly comprising the applications of offshore operations, subsea BOP reliability, maritime transportation, nuclear industry and other possible sources of information. In a second phase, the search was filtered to the most commonly used methodologies observed, such as THERP, CREAM (including the combination with fuzzy logic) and Bayesian network models. This chapter presents the summary of the relevant publications identified, applied techniques and their contributions.

3.1. Literature Survey

As far as BOP reliability, FOWLER and ROCHE (1994), JORGE (2000) and TANGSTAD (2014) presented studies focused on technical aspects of the equipment. They commented the relevance to encompass human error in the analysis, but did not embrace it mainly because of scarce available data in this area. QUILICI et al. (1998) presented an analysis for evaluation of a new design of BOP and included some manual actions, like EDS activation and switch of active control pod, in an approach for systems reliability. They concluded that in an emergency disconnection scenario, the reluctance of the operator to activate EDS could reasonably affect the operation performance.

Concerning applications on maritime transportation and oil and gas industry, GORDON (1998), SKOGDALEN and VINNEM (2011) and LI et al. (2014) exemplified the progressive incorporation of human factors in accident investigation and risk assessment in the oil and gas industry, as well as recommendations to structure a database for human errors quantification. LADAN and TURAN (2012), ST JOHN (2015a, 2015b) and THEOPHILUS et al. (2017) presented classification systems and taxonomies for application in the marine and offshore domain. LADAN and TURAN (2012) showed a comparison of the so-called Human Entropy Boundary Conditions (HEBC) with the Common Performance Conditions (CPC) from CREAM (HOLLNAGEL, 1998). ST JOHN (2015a, 2015b) proposed an evaluation of human factors barriers, which can be present, absent or may be unknown, considering a structure of bow-tie technique to evaluate the scenario of well control event. THEOPHILUS et al. (2017) included a level of regulatory and statutory influences in their proposed framework for oil and gas industry.

In maritime transportation, TRUCCO et al. (2008) employed Bayesian networks to model organizational factors as an extension of previous analysis with fault trees. The fault trees modelled technical aspects and the BN embraced human factors. The human factors were applied as modifiers to the basic event probabilities (posterior probabilities). The model was applied to an event of vessel collision.

MARTINS and MATURANA (2013) also presented an approach using a BN model applied to an accident of vessel collision. This work complemented a previous study in which the THERP technique and binary trees (FT and ET) were used. The framework in BN was made up by the layers of task, required skills, internal & environmental factors and MOF (Management and Organizational Factors). All the events were assigned as discrete and binary. The data used was gathered by expert elicitation and probability of basic events from the previous work. The CPTs were completed through a linear interpolation algorithm.

CAI et al. (2013a) proposed the evaluation of emergency scenarios in offshore operations using a dynamic BN model. The model was firstly obtained by a conversion of a pseudo-fault-tree (not restricted to binary event) into a BN. The dynamic BN was modelled considering the updating of certain conditional probabilities of some nodes in time intervals. The human factors were assessed in three levels: individual, organizational and group. The CPTs were completed employing the Noisy-Or-gate algorithm (PEARL, 1988). MERWE et al. (2014) and PALTRINIERI et al. (2016) showed applications of HRA for the oil and gas industry by means of the SPAR-H technique in simplified examples for a depressurization system and an emergency disconnection scenario, respectively.

VINNEM et al. (2012) and GRAN et al. (2012) presented an approach of human factors applied to maintenance work in offshore installations during well production phase called Risk-OMT. They proposed a multilevel framework with layers of human actions, human errors, reflecting classification error from REASON (1990, 1997) and Risk Influencing Factors, this latter evaluated in two levels representing operational and management tiers. The framework was modelled first with a hybrid approach using event trees and fault trees. Subsequently, a BN model was built for the entire structure.

STRAND and LUNDTEIGEN (2016, 2017) extended the application of Risk-OMT for the well drilling phase. Some changes were made in the connections between the error classification structure and the Risk Influencing Factors, and also in the set of RIFs in that way to reflect the characteristics of the well construction phase. The approach was applied to the well control event scenario emphasizing the role of BOP. STRAND and LUNDTEIGEN (2016) highlighted the importance of the Risk Influencing Factor HMI, communication and competence as main contributors identified in examination of four accidents in this area. The accidents were described in STRAND and LUNDTEIGEN (2017) where was pointed out the key role of the HMI for situation awareness and, as consequence, some changes were proposed in RIFs structure.

ROBERTS et al. (2016) described a cognitive task analysis focused on the importance of keeping situation awareness for early kick detection. The tasks were detailed remarking technical steps, kick indicators, cognitive steps & components and actions & decisions. The cognitive components were related to perception, comprehension, anticipation and shared information & awareness.

LIU et al. (2015) built a BN model for fault diagnosis based on operation procedures. The BN was structured in three levels: operation procedure, fault layer and fault symptom. The BN was established integrating the three layers that are dependent on each other. The approach was applied to the case of the control system of a subsea BOP. LIU et al. (2018) converted GO models into Bayesian networks considering seventeen basic operators. The methodology was applied to the case of subsea BOP activation in a situation of pump failures. Sensitivity analysis was carried out to define the key influencing factors. CHANG et al. (2018) applied BN to model rig emergency disconnection. The BN was translated from a previous model with FT and ESD (Event Sequence Diagram). The basic events were obtained from expert opinion.

Regarding application of CREAM technique, ZHANG and TAN (2018) used a fuzzy-CREAM approach to represent human factors considering the basic method background from CREAM and combined with a genetic algorithm helping to identify the target membership degree. This was used to decision making for safety promotion of power supply in a LNG (Liquid Natural Gas) terminal.

The combination of CREAM basic method and fuzzy logic was also presented by KONSTANDINIDOU et al. (2006), YANG et al. (2013), UNG (2015), ZHOU et al.

(2017) and ZHOU et al. (2018). Furthermore, YANG et al. (2013) and ZHOU et al. (2018) employed additionally a BN model. Usually, the fuzzy-CREAM association is based on the modelling of level/descriptors of CPCs through linguistic variables and the definition of membership functions for each CPC and control model.

KIM et al. (2006) proposed a probabilistic method to determine the control mode in CREAM using a BN model as an improvement of the deterministic implementation of the basic method. The prior probability distributions were obtained from statistical data and expert judgment. In a subsequent step, the probability was updated by means of considerations, additional information and other expert opinion.

MONFERINI et al. (2013) developed a virtual environment to evaluate the response time of operators in a process plant applied to a situation of gas leakage in order to obtain success/failure probability. Aiming to evaluate the effect of human factors, a sensitivity analysis was performed for each of the nine CPCs from CREAM. The authors employed the ALBA (Artificial Logic Bayesian Algorithm) technique.

XI et al. (2017) presented an approach modifying CREAM methodology in order to overcome the original characteristics of deterministic evaluation for the basic method and equal weights for all CPCs. With this intention, they employed an approach of evidential reasoning and decision making (Decision Making Trial and Evaluation Laboratory (DEMATEL). The case study concerns maritime operations and the data obtained compared with Shanghai coastal. A sensitivity analysis was performed to validate the method.

In turn, WANG et al. (2018) employed the extended method of CREAM and applied to the case of safety inspection in coal mines. Factors were associated to the CPCs and the Analytic Hierarchy Process (AHP) was used, resulting in a modification of the CPC original weights from CREAM. MORAIS et al. (2018a, 2018b) employed the CREAM classification scheme for helping to build a database for major accidents. They employed BNs to represent the connections between categories in a classification scheme with the outcomes related to cognitive function failures.

In the nuclear industry, PINTO et al. (2014) proposed a hybrid approach using DFM (Dynamic Flowgraph Methodology) associated to ATHEANA and fuzzy logic. The methodology was applied to the pressurizer of pressurized water reactor plants. The approach aimed to model the interactions between the control system, the process and the operator. Expert opinion was employed to complement the data found. The approach comprised the modelling of equipment failure, operator errors and human factors. As a result, they determined the event combinations that contribute to system failure.

GOMES et al. (2016) presented a human reliability modelling applied to the case of radiotherapy procedures (brachytherapy and teletherapy) using Bayesian networks. The BN model represented the tasks necessary to deal with the treatment. Equipment failures were not covered. The data were obtained from expert opinion of the personnel involved in this procedure in a hospital. The authors tested two types of probability distributions, normal and lognormal, this latter more commonly used to represent data from expert elicitation. They verified that the normal distribution fitted better to the dispersion of probability values estimated by the experts consulted.

On the development of influence model of human factors, PRANESH et al. (2017) used an approach proposed by KARIUKI (2007) and applied for the case of the Macondo well blowout. The matrix of pairwise comparison was built for each of the five critical events that together contributed to the well blowout. The attributes were rated in a seven-point scale. According to the results, all the failure events remained in the range of poor condition ratifying the context where the referred accident emerged. In the same line, RIBEIRO et al. (2016) applied the KARIUKI's approach (2007) to estimate weights and the degree of implementation of twelve elements, equivalent to human factors and based on ATTWOOD et al. (2007). The element weights were divided into three degrees of evaluation to better represent their different levels of influence. The called degree of implementation was considered as part of an auditing process. The approach was applied to the Tokai-Mura accident and the estimation of the weights and degree of implementation was obtained from expert judgement.

3.2. Conclusions from the literature review

The majority of works identified proposed hybrid approaches combining traditional techniques of system reliability, such as binary trees (fault trees and event trees), with techniques for human reliability analysis like THERP, ATHEANA, SPAR-H and CREAM, as well as fuzzy logic to address issues related to linguistic variables. Table 1 shows a summary of the techniques applied in the works mentioned in this chapter.

Table 1 Summary of the techniques identified in the literature survey

References	Applied Techniques							
	Fault Trees	Event Trees	Bayesian network	THERP	CREAM	ATHEANA	Fuzzy logic	Other
FOWLER and ROCHE (1994)	X							X
QUILICI (1998)	X							X
JORGE (2000)		X	X					
KONSTANDINIDOU et al. (2006)					X		X	
KIM et al. (2006)					X			
TRUCCO et al. (2008)	X		X					
VINNEM et al. (2012)	X	X	X					
GRAN et al. (2012)	X	X	X					
YANG et al. (2013)			X		X		X	
MARTINS and MATURANA (2013)	X	X	X	X				
CAI et al (2013a)	X		X					
MONFERINI et al. (2013)					X			X
TANGSTAD (2014)	X	X						
MERWE et al. (2014)								X
PINTO et al. (2014)						X	X	X
UNG (2015)					X		X	
LIU et al. (2015)			X					
ST JOHN (2015a, 2015b)*				X				X
GOMES et al. (2016)			X					
PALTRINIERI (2016)								X
STRAND and LUNDTEIGEN (2016, 2017)	X	X	X					
ZHOU et al. (2017)					X		X	
XI et al. (2017)					X			X
LIU et al. (2018)			X					X
CHAN et al. (2018)	X		X					X
ZHANG and TAN (2018)					X		X	
ZHOU et al. (2018)			X		X		X	
WANG et al. (2018)					X			

FOWLER and ROCHE (1994) and QUILICI (1998) also used FMEA
MONFERINI et al. (2013) also used the technique ALBA (Artificial Logic Bayesian Algorithm)
PINTO et al. (2014) also used Dynamic Flowgraph Methodology (DFM)
MERWE et al. (2014) and PALTRINIERI (2016) used SPAR-H technique
ST JOHN (2015a, 2015b) used bow-tie technique
XI et al. (2017) also used Decision Making Trial and Evaluation Laboratory (DEMATEL)
LIU et al. (2018) converted BN model from GO models
CHAN et al. (2018) obtain BN model from fault trees and ESD

This combination tries to take the advantages of each technique given the complexity of the analyses in order to get the final result of failure probability. Another conclusion is that Bayesian networks has been widely used, especially for allowing to model conditional relationships between human factors and failure events, as well as for the possibility of updating information with evidences. In many works, the Bayesian networks were obtained from the conversion of the original version in binary trees, exemplifying the decision of many analysts of progressive knowledge and practice, starting from traditional techniques, observing preliminary results and moving up to a subsequent step to some other approaches that provide additional implementation features.

Based on the literature review, the characteristics of the domain described in Chapter 2 and according to the objectives and scope mentioned in Chapter 1, this work proposes an approach to model human actions in rig operations using a cognitive framework based on CREAM methodology (HOLLNAGEL, 1998) and defined Performance Influencing Factors (PIFs) with specific influence model on human error probability. A first step of analysis is performed using fault trees, not considering the PIFs influence. Such preliminary model is further translated into Bayesian network encompassing the conditional relationships between failure events and PIFs, as well as the possibility of including evidences on the status of these factors. Chapter 4 will present the techniques that were employed in order to develop the analyses and the proposed methodology will be detailed in Chapter 5.

Chapter 4. Theoretical Background

This chapter presents a brief introduction on human reliability analysis, including main concepts and the classification in generation techniques. Additionally, the theoretical background is presented with the description of the techniques applied in this work, as well as the main features that justify their use.

4.1. Brief Introduction to Human Reliability Analysis

In the context of human factors introduction to safety analyses, emerged the human reliability study (HOLLNAGEL, 2005). According to HOLLNAGEL (2005), in the 1980's the use of the methodology increased rapidly, when numerous techniques were proposed to address this kind of analysis. This trend could be associated to the accident of Three-Mile Island (1979), which represented a remarkable event to the development of human reliability studies in the nuclear industry (HOLLNAGEL, 2005). Other catastrophic events that can be cited for the same period are the Chernobyl accident in 1986 and the Piper Alpha accident in 1988, which also contributed to the attention and dissemination of the theme (HOLLNAGEL, 2005, LI et al., 2014). Hence, there was a change in risk and reliability analyses that initially focused only on technical issues to the introduction of man-machine or socio-technical aspects (HOLLNAGEL, 2005).

Human reliability can be defined as a set of techniques that help to identify and analyze the contribution of human failures to socio-technical systems failures and can be employed as supporting tools for decision-making (MKRTCHYAN et al., 2015, LI et al., 2014). For the first developed techniques, the main point of the approach was associated to the prediction and reduction of human error probability (HOLLNAGEL, 2005). However, with the progressive development of this field, more attention was given to approaches involving cognitive processes and emphasis on influencing factors, its interactions and dependencies considering the operational context. Moreover, the importance of human factors introduction was verified in reliability and safety analysis for the whole operational cycle. Then, the human reliability analysis should be performed since the design phase (HOLLNAGEL, 2005, SKOGDALEN and VINNEM, 2011).

Two main concepts related to human reliability studies and that are commonly found in the literature are: human error and human factor. According to GORDON (1998), these terms are employed erroneously in an interchangeable way. Human error could be defined as human actions that are considered by a given analyst as deviations from some reference, and, consequently, it would be subjective and dependent on time variable. Conversely, HOLLNAGEL (2005) defined human error as an identifiable human action that is considered as an undesired system outcome. The concept of human factor is defined by GORDON (1998) and SKOGDALEN and VINNEM (2011) as the scientific study of the interaction between human and machine. According to GORDON (1998) and HOLLNAGEL (2005), the human factor could be treated as the cause and the human error as the consequence.

Human factors are commonly evaluated in three levels of influence: individual, group and organization, as referred by GORDON (1998), MOHAGHEGH et al. (2009), MOHAGHEGH and MOSLEH (2009), CAI et al. (2013b) and MKRTCHYAN et al. (2015). Individual level encompasses factors related to competence, experience, emotional state, motivations, and health risks, among others. The group level comprises the relationship between individuals and supervisors, including factors related to leadership, team and open communication between team members and these latter with the local leadership. In the organizational level, factors associated to communication level between worksites, establishment of training programs and clear commitment of high management with safety (GORDON, 1998, CAI et al., 2013b). The organizational factors can be evaluated together with management factors, entitled as Management and Organizational Factors - MOF (MKRTCHYAN et al., 2015).

The set of human factors considered for each analysis and the way they will be used for estimating the human error probability depends on the context and the employed technique (LI et al., 2014). For the first generation techniques, the weights of human factors are usually multiplied by the basic human error probability. However, for more recent techniques, the failure probability or human error may not be directly calculated by means of the frequentist approach and the human factors are not necessarily taken into account as multipliers for the final probability. The selection of human factors can be based on, among other sources, historical data or expert opinion (SKOGDALEN and VINNEM, 2011, LI et al., 2014).

As the majority of available techniques for human reliability analysis were developed for nuclear industry applications, the extension for other industries requires some adaption, such as the definition of influencing factors representative of the domain analyzed and the identification of proper human error database. HOLLNAGEL (2005), MOHAGHEGH et al. (2009), MARTINS (2013), CALIXTO (2013) and ALVARENGA et al. (2014) mentioned in their publications development stages of human reliability techniques and these are grouped in generations in accordance with the main features of each period. Such classification and main characteristics of each generation are presented below:

First generation techniques (1970-1990)[1]: the main feature is related to the focus on prediction of human error probability on execution of prescribed tasks. The human error is assigned in a given task comparing the accomplished action with the expected action regarding a normative reference (for instance, a procedure or corporate standard). Additionally, these techniques include factors that influence human performance (generally called Performance Shaping Factors) and their effects are quantified multiplying factor weights by the basic human error probabilities. Thus, each human factor gives an independent effect on HEP and there is a linear relationship between them. The set of human factors considered may be related to organization, group and individual characteristics. In these techniques, the human error is treated in a similar way to that of a physical component and there is a lack of cognitive structure. Most of the first generation techniques were developed for nuclear industry application. Normally, they encompass mainly omission errors, i.e., errors associated to do not realize the expected action.

Some techniques that can be classified in this group are: THERP (Technique for Human Error Rate Prediction, SWAIN and GUTTMAN, 1983) and HEART (Human Error Assessment and Reduction Technique, WILLIAMS, 1988).

[1] The period defined in parentheses for each generation of human reliability techniques is obtained from CALIXTO (2013) and corresponds to the approximate date that each group of techniques emerged, which had similar characteristics such as objective, approach and scope.

Second generation techniques (1990-2005): the second generation techniques are characterized by the more explicit use of cognitive factors, affecting both the model structure and human error mechanisms. Usually, they encompass omission and commission errors. The techniques also establish human factors related to individual, group and organization. However, a differential feature is the mapping of the human factors that influence certain error mechanisms according to the operational context. Therefore, tables can be built associating information of human factors, error mechanisms and human errors related to a given operational context.
Some techniques that can be classified in this group are: CREAM (Cognitive Reliability and Error Analysis Method, HOLLNAGEL, 1998) and ATHEANA (A Technique for Human Error Analysis, NRC, 2000).

CALIXTO (2013) and ALVARENGA et al. (2014) mentioned also a third generation constituted by techniques that arose from 2005 to the current days. According to ALVARENGA et al. (2014), this generation would be composed of techniques based on adaptions of the first group, such as NARA (Nuclear Action Reliability Assessment, KIRWAN et al., 2005). On the other hand, CALIXTO (2013) mentioned that third generation techniques are focused on performance factors, relationship and dependencies and cited the use of Bayesian networks.

4.2. Applied Techniques

This section describes the techniques used for the methodology proposed in this work. This is a summary of the main characteristics, but the way that they will be applied is explained in chapter 5.

4.2.1. Fault Tree Analysis (FTA)

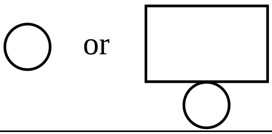
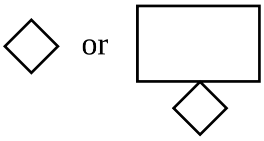
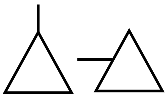
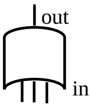
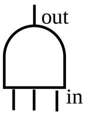
FTA is a technique of deductive analysis used for determination of possible causes of a target event disposed as a top event of the fault tree and can be employed both in reliability and risk analyses (MARTINS, 2013). FTA can be used for qualitative and quantitative assessment. In case of qualitative analysis, the main objective is to explicit the cause-effect relationships that deal with the occurrence of the top event and their logic dependencies (MARTINS, 2013). In quantitative evaluation, beyond the relationships determination, it is possible to estimate the top event probability.

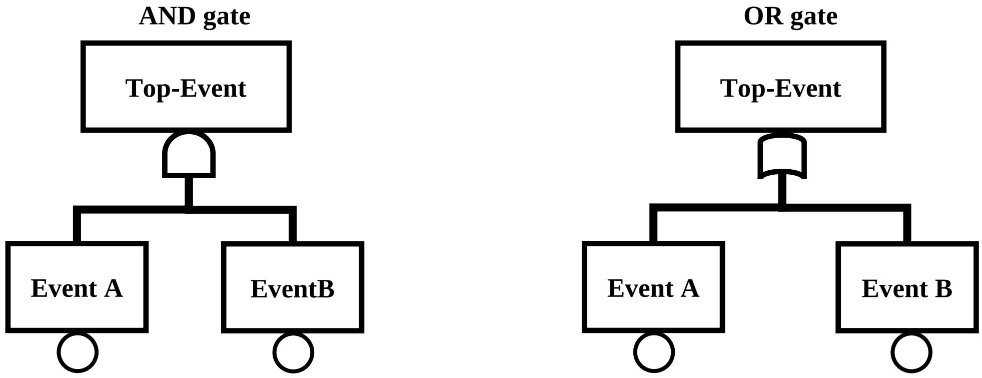
The main steps to elaborate a FTA can be resumed as follows: (i) system definition; (ii) FT drawing; (iii) determination of minimal cut sets; (iv) quantitative assessment (if necessary). The step of system definition includes: physical delimitation and composition, enumeration of associated functions, equipment arrangements and related procedures. The FT is built starting from the top event through a deductive process of causal events and the relationships between events are expressed through logic gates. Table 2 presents the basic symbols used in FTA.

As aforementioned, the FT modelling starts from the top event definition and the related failure events are gradually defined until the basic events. The immediate causes, necessary and sufficient, that deal with the top event are determined (FRUTUOSO e MELO, 2013). The basic events can assume two binary states, that is, they are modelled as Boolean variables (MARTINS, 2013). It is worth mentioning that the analysis resolution depends on the available information.

The determination of cut sets allows identifying the combination of events that leads to the top event and helps to identify the system weaknesses (FRUTUOSO e MELO, 2013). As a subsequent step, the quantitative assessment provides the computation of system unavailability. For such analysis, failure rate of basic events can be input to the model. The probability of the target event is obtained following the operators associated to the logic gates. Fig. 5 shows the probability relationships associated to an OR gate and to an AND gate. The quantitative evaluation allows indicating the minimum cut sets that most contribute to the top event occurrence.

Table 2 Basic symbols for fault tree analysis (QUILICI et al., 1998, MARTINS, 2013)

Symbol	Type	Description
	Basic event	Represents the resolution limit of the model according to the available data.
	Intermediate event	Event that comes from the combination of basic events and/or from other intermediate events.
	Undeveloped event	Undeveloped event due to lack of interest, information or because it is beyond the system delimitation.
	Transfer event	Indicates that a branch of the FT was developed out of the current page in the model. This is a convenient alternative to avoid repeating parts of the FT.
	OR gate	The outcome event happens if at least one of the input events occurs.
	AND gate	The outcome happens if all the input events occur.



Pr(Top-event)=Pr(Event A) . Pr(Event B)

Pr(Top-event)=Pr(Event A) + Pr(Event B) - Pr(Event A ∩ Event B)

Fig. 5. Logic-gates of FTA – probability of top event

The FT model was applied in a first analysis to describe the relationship between task steps of human actions and their links with cognitive function failures as will be explained in Section 5.3.

4.2.2. Bayesian Networks

A Bayesian network, also called opinion network, causal network or graph of probabilistic dependency, is an analysis technique that is mainly based on the straightforward consideration of uncertainties associated to the model in order to obtain the required results. The name comes from the Bayesian probability theorem which deals with inference in uncertainty scenarios and incomplete knowledge about the target system (MARTINS, 2013).

The application of Bayesian networks was firstly introduced by PEARL (1986) and their use has increased throughout the last decades (MKRTCHYAN et al., 2015). In the 1990's, Bayesian networks have been widely used in artificial intelligence analysis to help the task of prediction and abduction (MARTINS, 2013). Nowadays, the BN is extensively applied in risk and reliability analysis (MOHAGHEGH et al., 2009, GROTH et al., 2010, MARTINS, 2013). The main characteristics that have turned BNs a widely used technique are: the intuitive graphical representation, the possibility of combining different sources of information, the use of a probabilistic structure to characterize uncertainties and the capacity to model complex relationships with multiple levels (MKRTCHYAN et al., 2015). These features are especially attractive to applications in human reliability, commonly characterized by the scarcity of available data and, frequently request for incorporating information from different sources (e.g. subjective information) and their associated uncertainties, and whose modelling leads to a combination of factors with complex dependency relationships (MKRTCHYAN et al., 2015).

About their graphical representation, basically the BN is a directed acyclic graph composed by nodes that represent the model variables (discrete or continuous) and by directed arcs that corresponds to causal relationships between variables (MARTINS, 2013, KORB and NICHOLSON, 2011). Two nodes should be connected directly if one affects or causes the other and the arc indicates the direction of the effect (KORB and NICHOLSON, 2011). As a guideline for their construction, it is not possible to reach the same node twice following a sequence that respect the arcs direction (MARTINS, 2013). The structure, or topology, of the network establishes the relationship between variables and these can assume multiple states (MARTINS, 2013).

The dependency between nodes is treated symbolically as a relationship of parents. Parents and child nodes are defined, which means causes/influencing factors and effects, respectively. A node is a parent of a child if there is a directed arc from the former to the latter. Any node without parents is called a root node, while any node without children is named a leaf node (KORB and NICHOLSON, 2011). Fig. 6 presents an example of a BN that illustrates the relationship between nodes. The root node could be considered equivalent to the basic event in the FT, i.e., it represents an initiating event or a basic cause of failure. In Fig. 6, nodes A and C are root nodes and also parent nodes of node B, node B is a parent of node E and this latter is a leaf node.

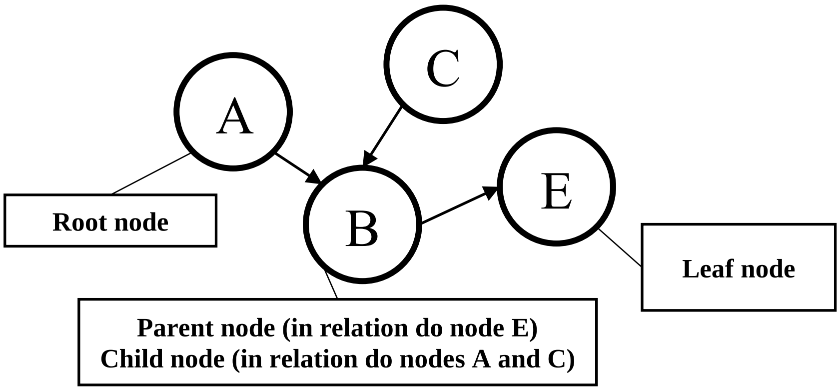


Fig. 6. Example of a Bayesian network

In addition to the graphical representation, the dependency relationships between nodes are described by means of Conditional Probability Tables (CPT) in case of discrete variables and Probability Density Functions (pdf) for continuous variables. Both represent the conditional dependency between nodes. To sum up, a value of conditional probability related to each possible state of parent nodes is assigned to each possible state of child node (MARTINS, 2013). A root node is modelled with marginal probabilities associated to each possible state that can be assumed. Fig. 7 shows an illustration of the Bayesian network with the CPTs and root nodes with binary states. In this example, if it is necessary to obtain the probability of state E1 of node E [P(E=E1)], the calculations will be performed as follows (law of total probability):

$$P(E = E_1) = P(E = E_1|B = B_1).P(B = B_1) + P(E = E_1|B = B_2).P(B = B_2) \qquad (1)$$

where $P(E = E_1|B = B_1)$ and $P(E = E_1|B = B_2)$ are conditional probabilities associating states of node E to the states of node B, its parent node; $P(B = B_1)$ and

$P(B = B_2)$ are marginal probabilities of possible states of node B; these, in turn, are obtained by conditional probabilities related to its parent nodes A and C.

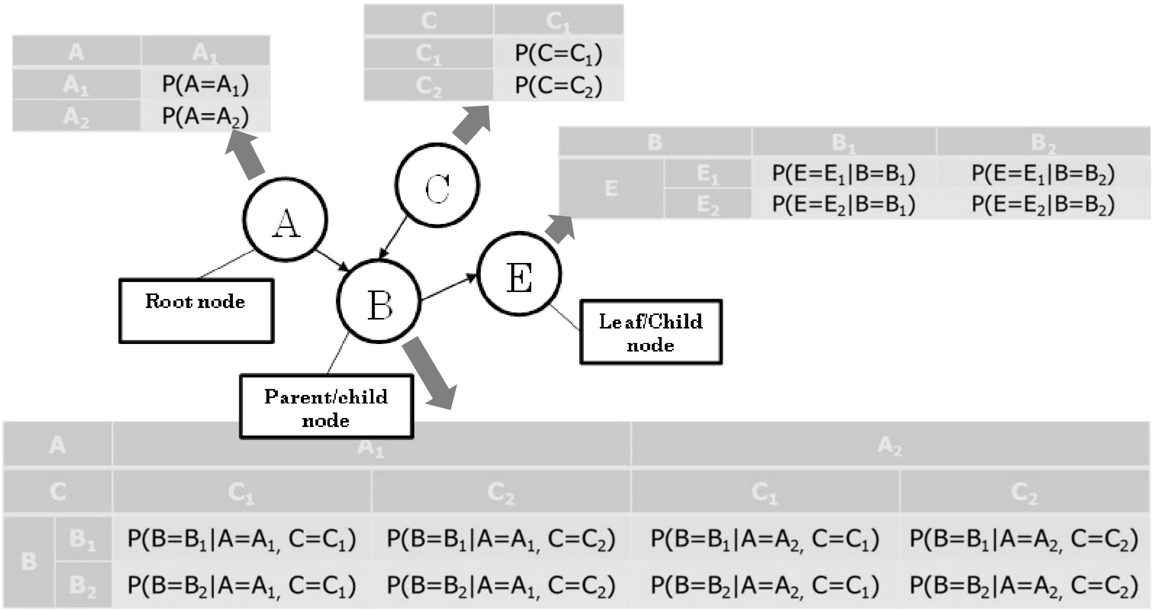


Fig. 7. Example of BN with correlated CPTs

The BN analysis can be used to predictive or diagnostic applications (Fig. 8). In predictive analysis, the probability of each node is calculated from the prior probability of root nodes and conditional probabilities of the remaining ones. It is worth mentioning that the difference between BN and FT for predictive analysis is that in the former the event relationships are treated in a probabilistic way and for the latter, they are considered deterministic (MARTINS, 2013). In case of diagnostic analysis, given evidence on the states of one or more nodes, the posterior probability of each node in the network is calculated (MARTINS, 2013).

The ability to update information also represents an additional advantage of this technique in relation to the traditional ones. The inference can be also applied to cause-effect analysis (probability of effect given the evidence of a causal event) and intercausal (probability of a causal event given the evidence of some other cause of the same event) (MARTINS, 2013).

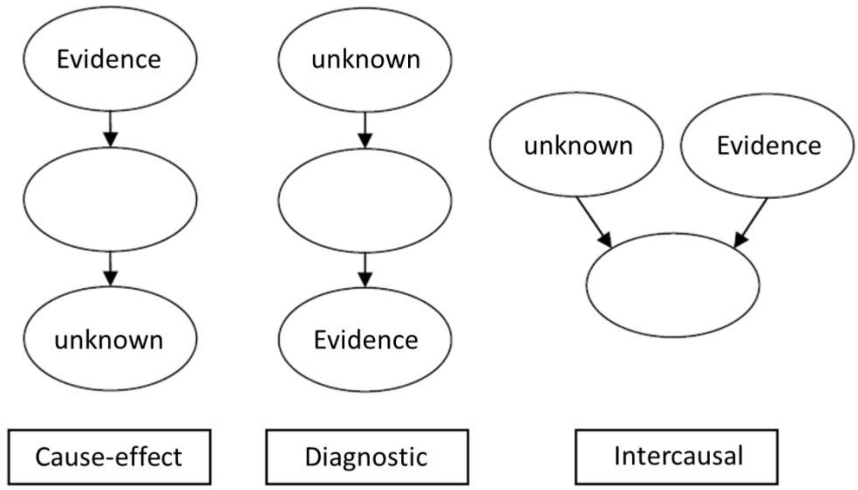


Fig. 8. Possible type of inferences with BN (obtained from MARTINS, 2013)

The resolution of the model development should be limited by the available data. The higher the number of nodes and related states, the higher the amount of data necessary to fill up the CPTs. If there are no data available, the information could be gathered by means of expert elicitation or using algorithms to help filling up the CPTs. Generally, these algorithms can be classified into two groups: adaptations of Noisy-Or-gate algorithm (PEARL, 1988) and other methodologies such as the interpolation of parent nodes states (for example, the linear interpolation applied by MARTINS and MATURANA, 2013). The Noisy-Or-gate algorithm is one of the most widely used for filling up CPTs, but it is based on two strong assumptions: binary events and independent parent nodes (MKRTCHYAN et al., 2015).

In this work, a BN model was employed to model the human task steps and relationships between human factors and the framework of cognition. This choice considered all the features and abilities mentioned above that are also detailed in Section 5.5.2. The CPTs of no binary events were filled up with a specific algorithm that modifies the human error probability by modelling the combined effect of human factors on failure events. This will be detailed in Sections 5.5.1, 5.5.2 and applied in an example in Chapter 7.

4.2.3.CREAM

The Cognitive Reliability and Error Analysis Method (CREAM) is a technique proposed by HOLLNAGEL in 1998. It is commonly classified as a second-generation technique, mainly because of its feature to emphasize the context and cognition as crucial aspects to the human reliability analysis development (CALIXTO, 2013, ALVARENGA et al., 2014). The CREAM framework is composed of three interconnected pillars: Method, Classification scheme and Model. The MCM framework aims to give a consistent support to the application of the technique and to reduce the subjectivity for analysts (HOLLNAGEL, 1998).

Basically, the method describes how to develop the analysis and establishes the principles to decide when it has reached its target result, establishing a stop rule/criterion. The method refers to the categories of the classification scheme and is bidirectional, i.e., the same principles can be applied to carry out retrospective and prediction analysis (HOLLNAGEL, 1998).

Concerning the model adopted in CREAM, it establishes the principles under which the classification scheme is structured. The model connects the description of specific failures to the context in which the observed behaviors occur (HOLLNAGEL, 1998). It is characterized as a functional model rather than structural, this latter usually adopted in the human information processing approach. It means that instead of considering the possible mechanisms of cognition in a fixed structure, the role of cognition to the person is emphasized (HOLLNAGEL, 1998).

The model of cognition is based on a distinction between competence and control. Competence describes the capacity of people of doing their respective duties and control represents the person's level of control over the situation (HOLLNAGEL, 1998). Control is determined by the context and the conditions; it can be described as a combination of three set of factors: individual, technological and organizational factors, also referred to as the triad: Man, Technology and Organization (MTO). According to HOLLNAGEL (1998), one of the common assumptions in all HRA techniques is that the quality of human performance depends on the conditions under which the tasks or activities are developed.

In turn, the classification scheme is an ordered group of categories that defines the data that should be recorded and used to describe the details of an event (HOLLNAGEL, 1998). CREAM establishes a specific classification scheme with groups of categories organized in a non-hierarchical way. The groups are connected through relationships between consequents and antecedents. These definitions are correlated to a distinction between what he has called genotypes (causes) and phenotypes (manifestations). According to HOLLNAGEL (1998), these two concepts need to be clearly differentiated in order to keep consistency of the analysis.

The author highlighted that the classification scheme is necessarily incomplete since it was defined for generic applications (HOLLNAGEL, 1998). However, he opens the opportunity to extend the scheme according to the domain under analysis. To keep coherence, this extension should be performed following the organization in categories and, consequently, creating suitable new links between them.

The classification scheme is divided into three main groups: (i) the consequences of the failure; (ii) the error modes; (iii) the context that can be described in terms of causes and common performance conditions (HOLLNAGEL, 1998). Fig. 9 illustrates these groups and also the categories of classification scheme. Tables 3, 4 and 5 summarize the categories of classification scheme and their related general effects and consequents. The cognitive functions are associated to the 'Man group' labelled as specific functions. Associated to each general effect or consequent, general or specific antecedents can be defined. The specific antecedents have no link with other categories. The general antecedent is found as a general consequent in other category corresponding to the link for carrying on the searching process.

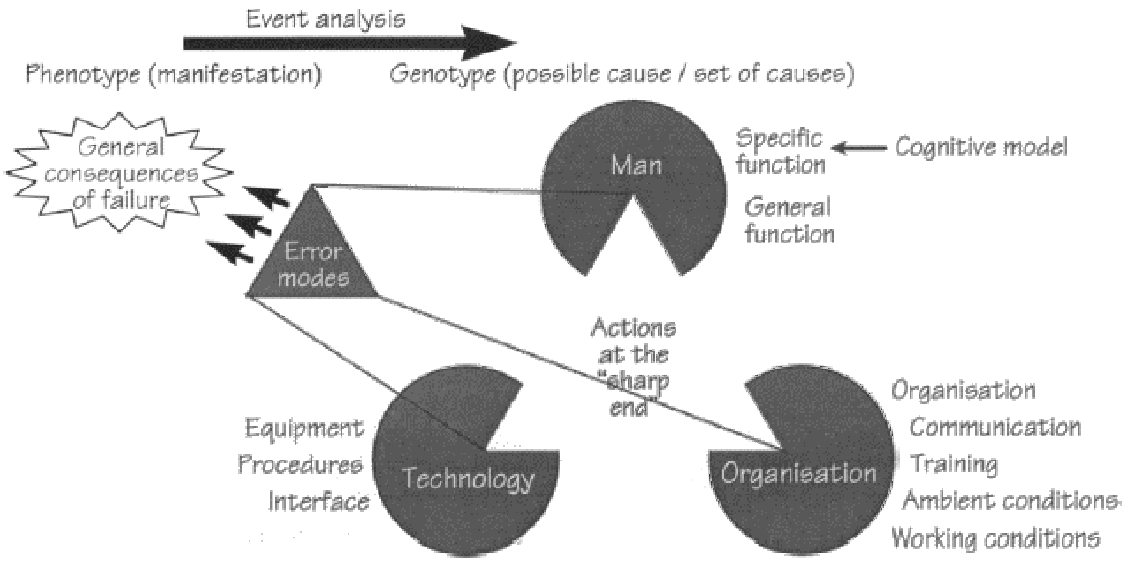


Fig. 9. Three macro-groups (MTO) and categories of CREAM classification scheme (HOLLNAGEL, 1998)

Table 3 Categories of CREAM classification scheme – Error modes (HOLLNAGEL, 1998)

Group	Categories		General effects
Man	Error modes (Basic Phenotypes)	Wrong time	Timing Duration
		Wrong type	Force Distance/magnitude Speed Direction
		Wrong object	Wrong object
		Wrong place	Sequence

Table 4 Categories of CREAM classification scheme – Person-related genotypes (HOLLNAGEL, 1998)

Group	Categories		General consequents
Man			
	Person-related genotypes – Specific cognitive functions	Observation	Observation missed False observation Wrong identification
		Interpretation	Faulty diagnosis Wrong reasoning Decision error Delayed interpretation Incorrect prediction
		Planning	Inadequate plan Priority error
	Person-related genotypes (General functions)	Temporary person-related functions	Memory failure Fear Distraction Fatigue Performance variability Inattention Physiological stress Psychological stress
		Permanent person-related functions	Functional impairment Cognitive style Cognitive bias

Table 5 Categories of CREAM classification scheme – Technology and Organization categories (HOLLNAGEL, 1998)

Group	Categories	General consequents
Technology	Equipment	Equipment failure Software fault
	Procedures	Inadequate procedure
	Man-machine interface – Temporary interface problems	Access limitations Ambiguous information Incomplete information
	Man-machine interface – Permanent interface problems	Access problems Mislabeling
Organization	Communication	Communication failure Missing information
	Organization	Maintenance failure Inadequate quality control Management problem Design failure Inadequate task allocation Social pressure
	Training	Insufficient skills Insufficient knowledge
	Ambient conditions	Temperature Sound Humidity Illumination Other Adverse ambient conditions
	Working Conditions	Excessive demand Inadequate workplace layout Inadequate team support Irregular working hours

Conversely, the Common Performance Conditions (CPCs) describe the contributing factors of performance, consequently the common modes for actions in a context. Nine CPCs are defined in CREAM: Adequacy of organization; Working conditions; Adequacy of Man-Machine Interface and operational support; Availability of procedures/plans; Number of simultaneous goals; Available time; Time of day (circadian rhythm); Adequacy of training and experience; Crew collaboration quality. They are conceived to have a minimum degree of overlapping, but they are not independent of each other (HOLLNAGEL, 1998). The author presents the dependency between CPCs and some alternatives to balance them to determine the combined expected effect on reliability.

According to the author, the main difference of CPCs in relation to Performance Shaping Factors, commonly defined in first generation techniques, is that they are applied since the first step of analysis to characterize the context and not only as a modifier of HEP at a final stage. The CPCs are evaluated according to level/descriptors which, in general, correspond to positive, neutral or negative states. These levels are associated to the expected effect on operator performance reliability. The general principle is that advantageous performance conditions can improve reliability, while bad conditions can reduce it, increasing human error probability (HOLLNAGEL, 1998).

As mentioned above, it is possible to perform retrospective and performance prediction analysis with CREAM. Chapters 7 and 8 of CREAM detail the step-by-step procedure to carry out both type of analysis in a qualitative way. Briefly, retrospective analysis is evolved starting from the description of the context until determination of probable cause(s) for the scenario analyzed. Qualitative performance prediction is developed initially with a task analysis followed by context description (CPCs) and navigating into the classification scheme toward the search for effects in order to describe how the initiating event can be expected to progress (HOLLNAGEL, 1998).

Chapter 9 of CREAM continues the presentation of prediction analysis, but in a quantitative way. Two methods are presented with the purpose of playing a complementary role: basic and extended method. The former has been conceived as a screening method and the context description plays an essential role for obtaining the final probability value. Basically, it comprises the steps of task analysis, assessment of CPCs and determination of control mode. This latter is associated to ranges of general action failure probability.

The extended method was proposed as a step forward aiming to provide a refinement for quantification of the failure probability. In that way, the likely cognitive function failure is identified and the specific action failure probability is defined incorporating the context as a modifier of human error probability. At this stage of the extended method, CPCs play a role similar to the Performance Shaping Factors of first-generation techniques, in which their weights are multiplied by the basic or nominal values of HEP to adjust them according to current conditions. The difference lies in the formulation to modify HEP and the association of different weights according to the cognitive function. In CREAM, the combined effect of CPCs, the global factor, is calculated by multiplying all the individual weights.

HOLLNAGEL (1998) also provided HEP values discriminated into basic value and lower/upper bounds. According to him, it is not feasible to gather specific HEP values for each possible human action in a certain domain due to the amount of data necessary. On the other hand, to limit the error classification into errors of omission and commission (or binary events) as proposed by some first generation techniques do not meet the requirements for HRA since it does not adequately represent cognitive functions and mental actions, such as diagnostics and decision making. Thus, he proposed the categorization of HEPs associated to cognitive function failures equivalent to failure modes in systems reliability. Such proposal aims to provide the degree of resolution necessary to human reliability analysis and at the same time is completely connected to the functional model established in the technique.

BEDFORD et al. (2013) pointed out shortcomings about CREAM, especially incoherencies and inconsistencies between basic and extended methods that, in practice, would not assume a complementary role with each other. Additionally, he argued that the formulation of HEP adjustment is not adequate given that the multiplication of all individual weights deals with high values of global factor. Hence, the modified HEPs can reach values higher than 1 (100%) and frequently need to be truncated. According to BEDFORD et al. (2013), considering all the possible combinations of CPC levels and the whole list of cognitive function failures, approximately 10% will result in HEPs higher than 1. Moreover, this trend of high values of global weight does not meet the intended trade-off with compensation of bad and good conditions of CPCs.

In this work, the CREAM technique was employed considering among other characteristics, the well-defined cognitive framework, the classification scheme with pre-mapped links between causal events and the available HEP data (basic and bound values). Chapter 5 will present the use of the CREAM methodology and some adaptions carried out in order to overcome the issues mentioned by BEDFORD et al. (2013).

Chapter 5. Methodology

An overview of the proposed methodology is presented, encompassing stages of qualitative and quantitative analysis. The qualitative part starts from task description and includes the causal modeling considering the cognitive framework and the classification scheme from CREAM (HOLLNAGEL, 1998). The quantitative part comprises the assessment of Performance Influencing Factors in relation to their degree of influence on HEP and a metric to represent the current conditions for the installation/operation. A preliminary model is built by means of fault trees and posterior converted into Bayesian network adding probabilistic relationships with Performance Influencing Factors.

5.1. Methodology Overview

An overview of the proposed methodology and its main outcomes is illustrated in Fig. 10. The methodology includes an initial qualitative analysis based on the cognitive framework and causal modelling following the CREAM classification scheme (HOLLNAGEL, 1998). Moreover, causal diagrams are drawn expressing graphically the search for causes starting from the cognitive failures. These diagrams help identifying applicable Performance Influencing Factors (PIFs) for each failure in the quantitative stage. As a first quantitative analysis, the relationships between identified failure events are modelled by means of fault trees.

The second part encompasses a quantitative analysis with a mathematical model adapted from KARIUKI (2007) and RIBEIRO et al. (2016). It is organized into four main steps: (i) PIF weighting assignment; (ii) evaluation of degree of compliance; (iii) quantification of PIF contribution for each cognitive function; (iv) HEP Assessment via BN model. In order to obtain the HEP quantification for the outcome event, the prior results from binary trees are converted into a Bayesian network model representing taks steps for operational sequence. Additionally, the BN model embraces the connections between cognitive function failures and PIFs, this allows stating the conditional relationships between them. The PIF nodes are assessed as multistate variables.

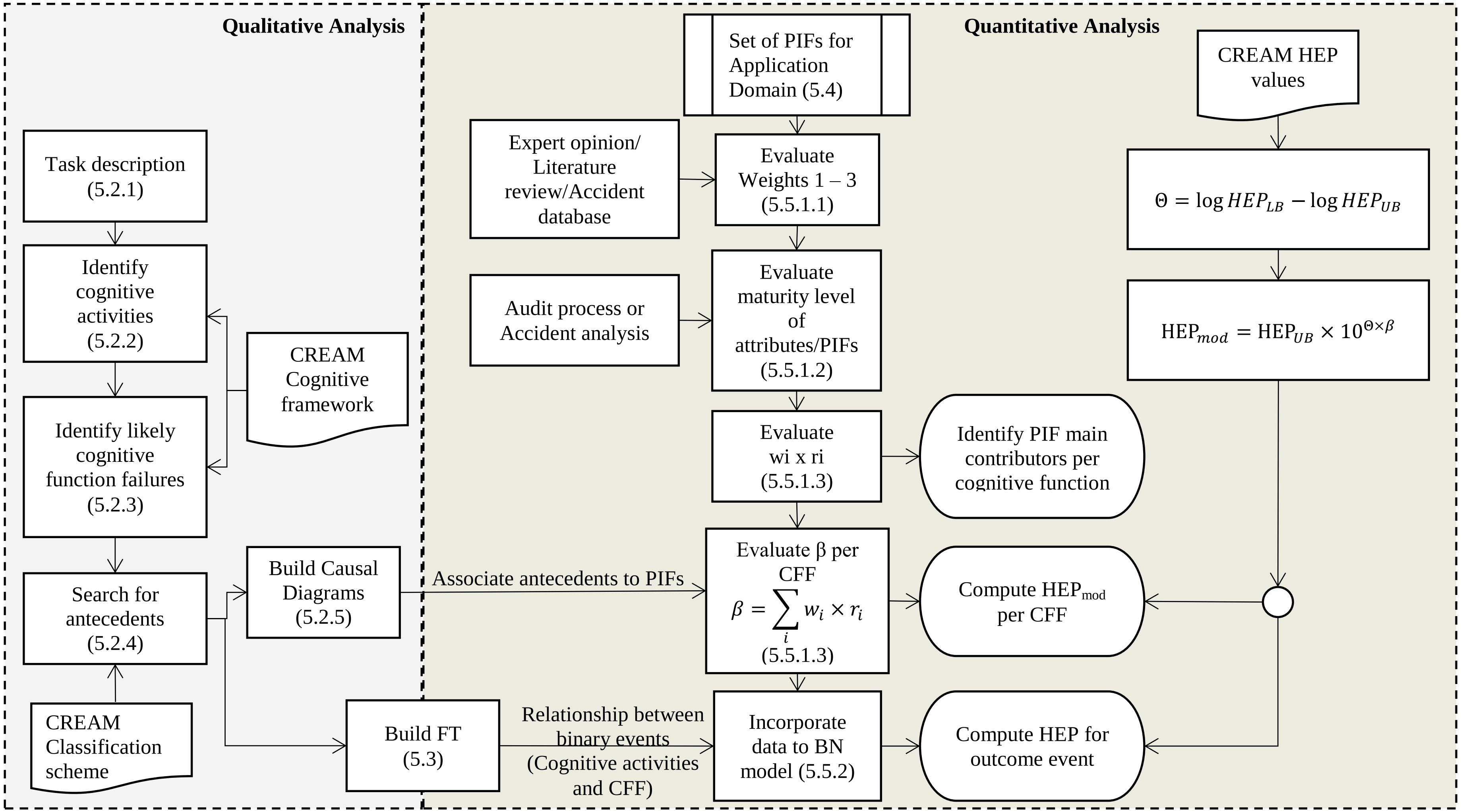


Fig. 10. Flowchart of proposed Human Factors approach. Partially adapted from RIBEIRO et al. (2016)

5.2. Qualitative Analysis

5.2.1. Task Description

The first step is to detail the sequence of tasks regarding the activity under study. The task description is commonly used as part of a task analysis process (FRENCH *et al*, 2019). According to KIRWAN and AINSWORTH (1992), the information concerning an operation/system may be structured in different formats, such as flowcharts and operational sequence diagrams, and can be used as a starting point for further analyzes or directly applied to obtain insights on activity improvements. They listed six groups of techniques for this purpose, among them, charting & network techniques and hierarchical task analysis.

The charting & network group are composed by techniques that allows representing graphically the tasks within a system in a readable and systematic way. KIRWAN and AINSWORTH (1992) exemplified eight techniques in this group that range from process flowcharts to Petri nets (PETRI, 1962, IEC 62551, 2012). Usually, each technique has basic symbols to represent certain type of elements that composes a system/task, such as human tasks, system functions, equipment and etc. Flowcharts can be applied to represent sequential/procedural tasks. KIRWAN and AINSWORTH (1992) pointed out as advantages that they can offer a clear representation of a task and do not need specialist resources for the analysis. As disadvantages, they cannot lead well with an increasing complexity on cognitive content (mental tasks) and with a high amount of information about the system. However, they can feed into other techniques, like event tree and hierarchical task analysis, for advanced evaluation.

Hierachical task analysis allows identifying and organizing hierarchically tasks and subtasks necessary to meet system's goals. The tasks are broken down and described in terms of goals, operations and plans (KIRWAN and AINSWORTH, 1992). The analysis can be represented in a tabular format or using hierarchical diagrams. The level of detail depends on the available information and the stopping rule established by the analyst. As benefits, KIRWAN and AINSWORTH (1992) mentioned the focus on crucial aspects of the task and the delimitation though definition of stopping rule. Also, it can be applied as an initial framework to carry out, for example, other task analysis methods or human factors analysis, including for representing cognitive tasks. On the other hand, they indicated as drawbacks that its development involves the participation of experienced analysts and greatly depends on collaboration of the managerial and technical team of the area under analysis.

For the purpose of the methodology herein described, both groups of techniques may be used. The choice for the suitable technique depends on the complexity of the system under analysis, the data and resource available and the objective/expected outcomes.

5.2.2. Identify cognitive activities

The tasks/subtasks mapped in the previous step are translated into cognitive activities associating them with the definitions described by HOLLNAGEL (1998). A list of fifteen critical cognitive activities is tabulated in HOLLNAGEL's publication (1998) containing their general definition. If a given task step is not fully described by a single cognitive activity, it can be broken down into two or more cognitive activities. Equally to the procedure mentioned in task description step, this breakdown must be decided comparing the benefits with the demanded analysis effort. The result is presented in a tabular format associating the task steps with the list of cognitive activities.

5.2.3. Identify likely cognitive function failures

In order to determine the failure events to be analyzed, the cognitive activities discriminated in the preceding step are described in a downward level through cognitive functions. The functional level was defined following the Cognition Model established by HOLLNAGEL (1998), which assumes that each cognitive activity can be described in terms of the combination of cognitive functions that it requires. Four basic cognitive functions are considered: execution, observation, interpretation and planning. Each cognitive activity is associated with a maximum of two cognitive functions in a predefined and fixed combination.

Once the associated cognitive functions are identified for each cognitive activity, the failure events can be selected considering the list of generic failure type available in CREAM (HOLLNAGEL, 1998) are associated to the categories of person-related genotypes (specific cognitive functions) and error modes (phenotypes). For each cognitive function, there are two or more possible cognitive function failures. These failure events are also described by HOLLNAGEL (1998). The identification of likely cognitive function failures demands the knowledge about the features of the specific domain analyzed and their failure mechanisms, which also involves primarily an adequate task description. The resulting association is also presented in a tabular format showing task steps and cognitive function failures.

5.2.4. Search for antecedents

Aiming to identify the potential causes for the failure events, a search for antecedents is performed guided by the CREAM classification scheme (HOLLNAGEL, 1998). This scheme presents tables of categories generated from the high-level categorization of MTO (Man – Technology – Organization) creating a type of causal network (see Section 4.2.3). The relationship between categories is determined by the links between general consequents – general antecedents inside the scheme (HOLLNAGEL, 1998). Depending on the purpose of the evaluation, the analyst can move on the scheme, searching for causes (retrospective analysis, antecedents direction) or effects (performance prediction, consequents direction).

Some of the categories presented in CREAM were extended to include additional antecedents identified. This extension of categories is mentioned by HOLLNAGEL (1998) as an alternative for possible gaps of causal links not mapped in the original version given that the classification scheme was conceived for a generic application; then it opens the opportunity to extend the scheme according to the domain under analysis, particularly for the organization category whose connections were not completely addressed. Table 6 shows the new links listing the additional antecedents and the extended category.

The identification of potential causes is developed for each task in accordance with the failure types determined in the previous step. These failures are the starting point of the search. From them, the analyst can move on the classification scheme following the direction of general consequent towards general and specific antecedents provided that the objective, in this case, is retrospective analysis. Not all antecedents make sense for the specific failure event and the analysts have to select those most representative for the case study. The stopping rule is reached when the following conditions are met (HOLLNAGEL, 1998):

- there are no general/specific antecedents defined for the general consequent;

- the general consequent has only specific antecedents or general consequent points to a specific antecedent as the most likely candidate cause, then the analysis is stopped because there are no forward links with another category;
- None of the antecedents defined seem feasible for the failure event considered.

Table 6 Categories extended from CREAM classification scheme original version

Category	General consequent	Additional general antecedents proposed
Observation	Wrong identification	Ambiguous information Incomplete information
Interpretation	Faulty diagnosis Wrong reasoning Decision error	Insufficient knowledge
Planning	Inadequate plan	Inadequate procedure
Temporary person-related functions	Fear	Inadequate team support
	Distraction	Excessive demand
	Performance variability Inattention	Irregular working hours
Permanent interface problems	Access problems Mislabeling	Design failure
Communication	Missing information	Ambiguous information Incomplete information Inadequate team support
Training	Insufficient knowledge	Management problem
Ambient conditions	Temperature/Sound/Humidity Illumination/Other/Adverse ambient conditions	Design failure
Working conditions	Inadequate team support Irregular working hours	Inadequate task allocation
Organization	Social Pressure	Insufficient knowledge Inadequate procedure

It is worth mentioning that indirect links were also considered in the search for causes. HOLLNAGEL (1998) defines indirect links as the consideration of general or specific antecedents connected to other general consequents in the same category. According to him, these links were not usually the most representative for the subject, but it is not uncommon or unconceivable, so that they may be explored in the analysis.

5.2.5. Build Causal Diagrams

The potential causes identified for each task and their links were represented graphically by causal diagrams. These causal diagrams are composed of blocks and arrows. The blocks indicate the causal events and the arrows the relationship between them (antecedent-consequent direction). The arrows are differentiated with black or dotted grey symbols denoting respectively direct and indirect links according to the definition mentioned previously. The lower part of the blocks identifies the general/specific antecedent found in the mapping process and the upper part indicates the category to which it belongs. This kind of representation helps visualizing the causal network for each likely cognitive function failure and can be used in more advanced stage as information for determining influencing factors.

5.3. Preliminary Model in Binary Trees

With the task analysis and search for antecedents completed, fault tree model can be built aiming to evaluate the relationship between binary events. This proposal is similar to the approach presented by VINNEM et al. (2012), GRAN et al. (2012) and STRAND and LUNDTEIGEN (2016, 2017) for causal modelling. VINNEM et al. (2012) and GRAN et al. (2012) applied the model for representing well production (maintenance work) and STRAND and LUNDTEIGEN (2016, 2017) for drilling operations. They modelled the operational sequence by event trees and each intermediate event was described by means of fault trees. However, the FT model presented in the above mentioned studies outlined a fixed structure based on the categorization of human errors presented by REASON (1990, 1997) and the FT is connected repeatedly throughout the intermediate ET events.

In this work, the characterization of the causal chain is modified in a more flexible way according to the cognitive structure presented in the previous steps. As described above, the cause-effect links is based on the CREAM classification scheme and the choices of the analyst in terms of the probable antecedents is guided by context knowledge. This feature allows adjusting the causal framework for each specific event analyzed. The fault trees model the relationship between cognitive activity and cognitive function failure described as binary events with deterministic connection. It is important to mention that the antecedents displayed in causal diagrams are not included in the FT model because the links between these events and cognitive function failures are of a conditional nature. Besides, the causal events can assume multiple states.

5.4. Definition of Performance Influencing Factors for Application Domain

In this work, a literature review was carried out in order to search for the most representative set of human factors applicable to the scenario of rig operations. In the sample of works and techniques found, nine sources were mostly considered as candidates to define the Performance Influencing Factors to be used in this work, some of them due to the proximity to the application domain and/or to the cognitive framework (HOLLNAGEL, 1998, KARIUKI, 2007, HOLLNAGEL, 2012, LADAN and TURAN, 2012, VINNEM et al., 2012, GRAN et al., 2012, ALVARENGA et al., 2014, PALTRINIERI et al., 2016, RIBEIRO et al., 2016, STRAND and LUNDTEIGEN, 2016, 2017). Initially, the possibility of choosing the human factors associated to a unique work/technique mapped was considered. Nevertheless, a combination of the influencing factors appeared to be more reasonable to align with the subject of analysis.

Table A-1 in Appendix A contains the set of human factors of each source verified and the last column lists the set of Performance Influencing Factors proposed. The definition of the resulting set of factors is presented in Table 7.

Not all factors found in the literature review were included in the set of PIFs, but some of them were incorporated in an attribute level based on KARIUKI's approach (2007). The attributes defined by KARIUKI (2007) were reorganized between categories and complemented. The number of attributes does not exceed seven per PIF complying with the recommendation for the Analytical Hierarchy Process (SAATY, 2000, KARIUKI, 2007). Table 8 presents the PIFs and the associated attributes.

Table 7 Definition of Performance Influencing Factors (adapted from HOLLNAGEL, 1998, KARIUKI, 2007, HOLLNAGEL, 2012, VINNEM et al., 2012, STRAND and LUNDTEIGEN, 2016)

PIF	Description/Scope
Organizational support	Comprises the quality of the roles and responsibilities of team members, safety culture, safety management systems, additional support, instructions and guidelines for externally oriented activities and the role of external agencies. The quality of the support and resources provided by the organization for the task or work being performed. This includes communication systems, Safety Management System, support for external activities, etc.
Competence	Knowledge, skills and abilities that can contribute to adequate work performance and/or problem solving related to a specific work operation. Encompasses the level and quality of training provided to operators as familiarization to new technology, refreshing old skills, etc. It also refers to the level of operational experience and preparation to emergency response (e.g. kicks and emergency disconnection, among other emergency situations).
Communication	Dissemination of information and knowledge with relevance for correct performance of a specific work operation. This refers both to the technological aspects (equipment, bandwidth) and human or social aspects.
Task Environment	Environmental conditions under which the work takes place and that can affect performance, such as ambient lighting, noise, temperature, vibration, etc.
Workplace Design	Design aspects of working environment with relevance for correct performance of a specific work operation, such as accessibility, layouts, workstation configuration, control room design, interruptions from the task etc.
HMI	Adequacy of Human-Machine Interface in general, including the information available on control panels, computerized workstations, availability of tools, tagging of equipment and operational support provided by specifically designed decision aids with relevance for correct performance of a specific work operation. This is the main point of interaction between the human and the system. Through this interface the operator knows what is going on in the system and can give some input, feedback or controlling measures to the system that in the end will alter its status.
Procedures & Documentation	The availability, dissemination, readability and traceability of procedures, support documentation, guidelines and standards that covers the "work package" for a specific work operation.
Job Design	Small scale planning, coordination, monitoring, follow-up and improvement of daily work operation, with contribution to safety. Job design involves the specification of the contents, method and relationships of jobs to satisfy technological and organizational requirements as well as the personal needs of job holders. The job should also be designed in such a way that risks to worker health and safety are as low as possible especially for manual handling tasks.
Operator & Team Characteristics	The operators' physical and cognitive characteristics, their attention, motivation and fitness for duty will also have an influence on human error. It also includes multiple factors regarding the psychological working environment and interactions between individuals within the team (e.g. cooperation, social support).

Table 8 Performance Influencing Factors and Attributes (Adapted from KARIUKI, 2007)

PIFs	Attributes
Organizational support	1. Human factors policy 2. Organizational & Safety culture 3. Management of change & Risk Assessment [(b)] 4. Organizational learning (audit and reviews) 5. Line management & supervision/Resources Management [(b)] 6. Contractor Management [(a)] 7. Incident investigation & analysis [(a)]
Competence [(a)]	1. Skills & knowledge [(c)] 2. Training & Drills [(b,c)]
Communication [(c)]	1. Organizational Communication Flow and Technological Aspects[(a)] 2. Communication within the team, between teams and shifts (hand-overs) [(a)]
Task Environment	1. Lighting/Illumination 2. Sound/Noise 3. Temperature and Humidity 4. Vibration
Workplace Design	1. Facility layout 2. Workstation configuration 3. Accessibility 4. Control room design
HMI	1. Design of controls & instrumentation [(b)] 2. Displays 3. Control panels 4. Tools (hand) 5. Equipment & valves 6. Labels & Signs [(c)]
Procedures & Documentation [(a)]	1. Documentation - Availability & System [(c)] 2. Procedures/Internal Standards [(c)]
Job Design	1. Staffing 2. Work schedules, shifts & overtime 3. Manual handling
Operator & Team Characteristics [(b)]	1. Fitness for duty 2. Attention/Motivation 3. Crew Collaboration Quality [(a)]

[a] New factors/attributes.
[b] Complementary attributes.
[c] Attributes reorganized.

In the following sections, particularly for the mathematical model used to modify the human error probabilities, the attributes will help to compute the degree of compliance of the PIFs.

5.4.1. Analogy to the Causal Events

The causal events mapped in the qualitative analysis step (general and specific antecedents) are characterized by the following features:

- Conditional relationship with the cognitive function failures, because it was assumed that they can contribute to the failure occurrence, but not completely to determine them;
- Generate combined effects on the cognitive function failures and have internal dependencies between them;
- Not limited to binary states, so that it is possible to assume intermediate states that describe non-compliance or degradation.

The above characteristics associated to the scarcity of available data for the causal events motivated the purpose of modelling them as Performance Influencing Factors. At the same time, this approach reduces the complexity of the network model and allows including these causal events in quantitative analyses.

The description of causal events in CREAM (HOLLNAGEL, 1998) was compared with the PIFs definition providing the analogy showed in Table 9 which associates general consequents/categories from CREAM with equivalent PIFs.

It is worth mentioning that the causal diagrams explained in Section 5.2.5 will be used to define the applicable PIFs for each cognitive function failure, i.e., the influencing factors will be selected from the links mapped in the causal diagrams during the antecedents searching process combined with the above analogy.

Table 9 General consequents from CREAM (HOLLNAGEL, 1998) and equivalence with PIFs

General consequents or Categories (CREAM)	Equivalent PIFs (current work)
Maintenance failure Inadequate quality control Management problem	Organizational Support
Insufficient skills[a] Insufficient knowledge[a]	Competence
Communication failure[b] Missing information[b]	Communication
Ambient conditions[c]	Task Environment
Access limitations Access problems Design failure Inadequate workplace layout	Workplace Design
Ambiguous information Incomplete information Mislabeling	HMI
Inadequate procedure[d]	Procedures & Documentation
Inadequate task allocation Excessive demand Irregular working hours	Job Design
Temporary or permanent person-related functions[e] Social Pressure Inadequate team support	Operator & Team Characteristics

[a] Whole category of Training.
[b] Whole category of Communication.
[c] Whole category of Ambient Conditions.
[d] Whole category of Procedures.
[e] Whole category of Temporary or Permanent Person-related Functions.

5.5. Quantitative Analysis

5.5.1. Mathematical Model for HEP Modifications

The mathematical model herein mentioned refers to the way PIFs are to be computed as modifying elements to HEPs. KARIUKI (2007) proposed the estimation of weighting factors by means of expert opinion using matrices of pairwise comparison. Likewise, a parameter was also introduced to measure the performance of attributes for a specific process plant.

RIBEIRO (2012) and RIBEIRO et al. (2016) adapted the above model, extending the way that factors are evaluated and applied it to the case of the Tokai-Mura accident. According to their approach, the weighting factors were divided into three degrees of evaluation. Additionally, they also assessed the performance of factors in the plant in what they called degree of implementation. The set of factors considered by RIBEIRO et al. (2016) were not the same as KARIUKI's (2007) and was obtained in a document of OGP (nowadays, IOGP – International Association of Oil and Gas Producers, ATTWOOD et al., 2007). Their improved model was adopted in this current work, but the implementation was modified in order to be supported by data from literature review rather than expert opinion.

5.5.1.1. Evaluate Weights 1 – 3

Weight 1 represents the relative importance of the Performance Influencing Factors in relation to the remaining ones. It is evaluated considering the dependencies between CPCs from CREAM (HOLLNAGEL, 1998) and the influence between elements assessed by RIBEIRO et al. (2016). The dependencies reported in these documents were verified and incorporated in this work taking into consideration the different set of PIFs, their definition and scope.

Weight 2 corresponds to the influence weight of each factor on failure event and is measured for each cognitive function. The level of influence estimated was based on the couplings between CPCs and cognitive process established by HOLLNAGEL (1998). The degree of influence is evaluated in three levels: weak, medium and strong, which are distinguished according to the type of cognitive function. Therefore, four different weights per PIF are defined, one for each cognitive function. This is a different approach in relation to what was proposed by RIBEIRO et al. (2016), given that they evaluate a single weight not differentiated per cognitive function.

Weight 3 measures the frequency in which the factors were pointed out as root causes or contributors in accident database for a given installation. According to RIBEIRO et al. (2016), if there is no track record, data from similar installations may be used or, in case of no information, weight 3 would be assigned a value of 1. In this work, a comprehensive database called MATA-D (Multi-attribute Technological Accidents Dataset) published by MOURA et al. (2015, 2016) was consulted. This database was built considering the CREAM classification scheme and the checking of their events/categories as contributors for more than 200 major accidents verified from different industrial segments (refinery, oil and gas, chemical factory, petrochemical, nuclear industry, etc.). The frequency was calculated per Performance Influencing Factor taking into account the grouping of events/categories from CREAM and their analogy with PIFs (see Section 5.4.1 and Table 9).

The table and remarks with the assessment of all weights will be explained and presented in Chapter 6.

5.5.1.2. Evaluate maturity level of attributes/PIFs

The degree of compliance (r_i) represents a score of each PIF regarding the implementation of internal policies, established processes and programs, integration between teams, among others. To sum up, r_i corresponds to a picture showing the current status of comprehensive areas of the installation which influence human actions, that is, the context description. The idea of KARIUKI (2007) and RIBEIRO et al. (2016) is to introduce the assessment of this kind of metric during a periodical auditing process of the installation. However, it was considered that it may also be a helpful tool in a different moment, during an accident analysis.

The quantification of r_i is performed in four steps as described below:

- The available evidences (from auditing processes or accident analysis) are verified and classified according to the attributes listed in Table 8;
- Each attribute is assigned a level of maturity composed by a five-point scale description of rig situation (Level 1 – Level 5). Level 1 represents the worst condition and level 5 corresponds to the best one (Tables B-1 to B-13);
- The total score of each factor is calculated through the sum of attributes

per level (e.g., one attribute assigned with a level 3 and other with a level 4, add a number of 7 to the sum). The final percentage value is calculated with the ratio of the total score of the PIF to the maximum score. The maximum score is obtained multiplying the maximum level (5) by the number of attributes associated to the factor;

- The percentage value is associated to a qualitative ranking of degree of compliance, likewise, for quantification purposes, the r_i factor is correlated to a five-point Likert scale (LIKERT, 1932) as showed in Table 10.

Table 10 Degree of Compliance – Score and Ranking (adapted from KARIUKI, 2007, KARIUKI and LÖWE, 2007, RIBEIRO, 2012, RIBEIRO et al., 2016)

r_i	Ranking	Score – Degree of compliance
0	Bad	0 ≤ Percentage Score ≤ 35%
0.25	Reasonable	35% < Percentage Score ≤ 52%
0.5	Average	52% < Percentage Score ≤ 75%
0.75	Good	75% < Percentage Score ≤ 90%
1	Excellent	90% < Percentage Score ≤ 100%

Table 10 was adapted from the ranges of percentage score adopted by KARIUKI, 2007, KARIUKI and LÖWE, 2007, RIBEIRO, 2012, RIBEIRO et al., 2016. The ranges were calibrated considering all the possible results for PIFs when modifying the evaluation of maturity level of their attributes and also that each PIF may have up to seven associated attributes. More than 700 possible states were analyzed resulting in the aforementioned five-point scale.

The description of the five possible maturity levels for the most part of attributes was obtained directly from KARIUKI (2007), with the exception of thirteen of them whose definitions were complemented with other publications. Appendix B contains these modified descriptions.

Regarding the final calculation of maturity level of PIFs, another relevant aspect is that it was not considered a definition of weights per attribute in order to score the factor. This step was mapped and may be addressed in future work.

5.5.1.3. Evaluate Index of Human Factors Modification

The equation used to modify HEP basic value is presented below (KARIUKI, 2007, RIBEIRO, 2012, RIBEIRO et al., 2016):

$$HEP_{modified} = HEP_{UB} \times 10^{\Theta\beta} \quad (2)$$

where

$$\Theta = \log HEP_{LB} - \log HEP_{UB} \quad (3)$$

and

$HEP_{modified}$ represents the modified HEP basic value.

HEP_{LB} and HEP_{UB} correspond to the lower and the upper bound of the cognitive function probability from CREAM.

β represents the index of human factors modification and is calculated as follows:

$$\beta = \sum_{i=1}^{n} w_i \, r_i \quad (4)$$

where *n* is the number of applicable PIFs for the cognitive function failure.

The terms in Eq. (4) are composed by (adapted from RIBEIRO, 2012, RIBEIRO et al., 2016):

w_i = Weight 1 x Weight 2 x Weight 3, normalized

r_i = degree of compliance of the factor evaluated by auditing or accident analysis.

Weight 1 = relative importance of the factors in relation to the remaining ones;

Weight 2 = influence weight of each factor on the cognitive function failure;

Weight 3 = factor weight as root cause or contributor in rig accident database.

The computation of w_i is normalized according to the set of PIFs applicable for the cognitive function failure. As already mentioned, the applicable PIFs is determined combining the information on the causal events per cognitive function failure (causal diagrams) with the analogy established between categories from CREAM and PIFs.

Additionally, the product w_i x r_i is also applied to compare the PIFs with major importance for each cognitive function and help decision-making process for areas that need more investment for better results in terms of safety and reliability.

It is important to highlight that the mathematical model adopted allows obtaining the modification of HEP combining the characteristics of the installation analyzed, but keep the final value between the lower and upper bound. If all the attributes are assigned with level 5 (best case), the index of human factors modification (β) will assume the value of 1 and the $HEP_{modified}$ becomes equal to HEP_{LB}. On the other hand, if all the attributes are considered with level 1 (worst case), β will be null and $HEP_{modified}$ becomes equal to HEP_{UB}. The aforementioned feature avoids the issues found in CREAM formulation after CPCs evaluation (BEDFORD et al., 2013, see Section 4.2.3).

5.5.2. Incorporate Data to Bayesian Network Model

A Bayesian network model is used considering the following main characteristics valuable for this analysis:

- Allows modelling in straightforward way conditional relationships and complex interactions between events. In this work, its capability applies to cover the links between cognitive function failures and PIFs;
- Not limited to binary events, multistate nodes can be easily modelled. PIFs are evaluated in five levels and need to be described as multistate variables;
- It is possible to develop predictive and retrospective analysis. This is in alignment with CREAM that allows the two options of application (HOLLNAGEL, 1998) through the searching for effects or causes and correspondingly, moving forward or backward in its classification scheme (consequents ↔ antecedents);
- Allows incorporating observations and update the data with a posterior probability. This is an important feature to insert new data from cognitive function failures or evidences of PIFs from accident analysis or auditing processes, as well as adding information from different sources, such as expert opinion;
- It is possible to be built through conversion of models developed in other traditional techniques (e.g. fault trees, event trees, etc.).

The BN model is built from two previous frameworks: the binary trees described in Section 5.3 and the causal diagrams mentioned in Section 5.2.5. These diagrams indicate the causal events for each cognitive function failure which, in turn, are associated to PIFs according to the analogy established in Table 9. It is worth mentioning that the conversion of events in the classification scheme from CREAM into PIFs helps to reduce the complexity of the network and the amount of data required to perform the quantitative analysis. Moreover, this increases the readability of the whole network.

Fig. 11 illustrates the basic framework of the BN model. The nodes related to task steps and cognitive function failures are modelled as binary events. On the other hand, the PIFs are represented as multistate nodes that can assume one of the five levels of the degree of compliance. Consequently, the Conditional Probability Tables for the task steps are filled up according to the deterministic relationships following the preliminary model in binary trees. The CPTs for cognitive function failures are determined using the equations from the mathematical model adopted (see Section 5.5.1.3). It is important to mention that the equations from the mathematical model play the role of the called filling-up algorithm (MKRTCHYAN et al., 2015). Such equations help filling CPTs in a straightforward way encompassing all the domain of possible PIF states.

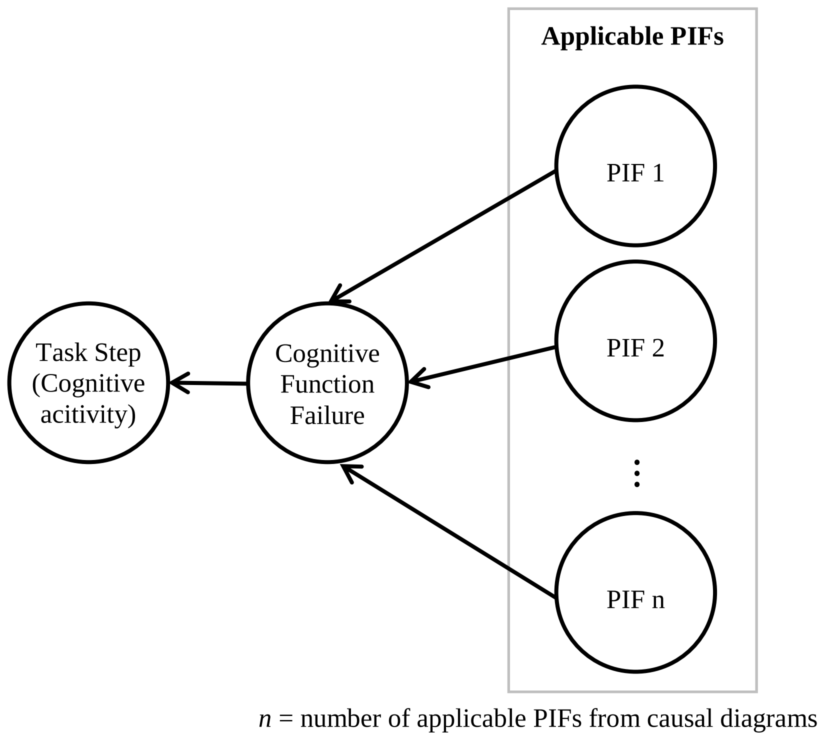


Fig. 11. Basic framework of the Bayesian network model.

Chapter 6. Model Application

An application of the methodology proposed in chapter 5 is presented for the rig emergency disconnection scenario. This chapter comprises the whole stage of qualitative analysis and part of the quantitative analysis up to the evaluation of weights and score of degree of compliance. The Performance Influencing Factors defined in the previous chapter for the domain analyzed are quantitatively evaluated in order to compute their effect on HEP values. The degree of compliance was characterized considering a major accident in the oil and gas company, the Macondo well blowout. Some preliminary quantitative results are presented using a FT model anticipating analyses and allowing further comparisons with the BN model. The major part of quantitative analysis and the associated results is described in chapter 7.

6.1. Task Description

The task description was developed considering the charting and network technique. A flowchart was drawn based on the high-level description of the operational sequence represented in Fig. 3 and Fig. 4 in Section 2.2. Fig. 3 shows the generic operational sequence and the different required actions depending on the DP operational status. Aiming to evaluate a scenario of gradual escalation of DP operational status, two conditional events were considered: the loss of minimum redundancy in DP system and the evolution until red status, i.e., the demand for Emergency Disconnection Sequence activation. Fig. 12 illustrates the resulting flowchart.

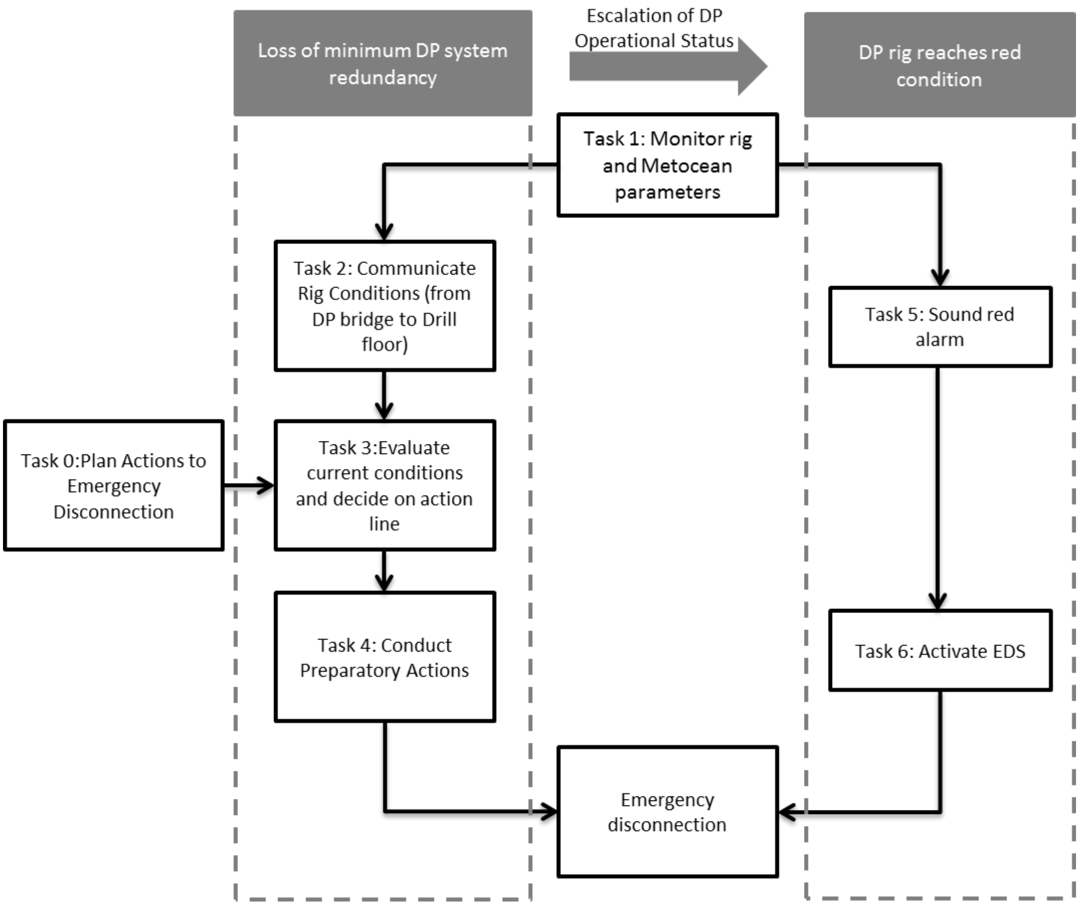


Fig. 12. Flowchart of the main task steps under DP operational status change evolved gradually from loss of minimum DP system redundancy to red status condition.

It is recommended in a future version to apply hierarchical task analysis with breakdown of the main task steps in order to analyze specific well operations according to the guidelines presented in emergency disconnection flowcharts.

6.2. Identification of Cognitive Activities

The task steps are described in terms of cognitive activities. This association is performed considering the list of critical cognitive activities described by HOLLNAGEL (1998). As an example, considering the task 1 identified as ‘Monitor Rig and Metocean parameters’, the cognitive activity that seems predominant is ‘Monitor’ which is defined by HOLLNAGEL (1998) as follows: “Keep track of system states over time, or follow the development of a set of parameters”. The comparison between the task steps and the descriptions of cognitive activities was performed for each human action mentioned in Fig. 12.

Table 11 presents the proposed correlation between task steps (ordered in a time-logic sequence) and the associated cognitive activities.

Table 11 Translation of operational sequence of emergency disconnection scenario into cognitive activities

Task Step	Cognitive Activity	Description
Task 0: Plan Actions to Emergency Disconnection	Plan	Planning actions to emergency disconnection scenario coordinated by company man and discussed/validated with the participation of rig team and company services representatives
Task 1: Monitor Rig and Metocean parameters	Monitor	Detection of DP operational status change according to the parameters established in the WSOG document
Task 2: Communicate Rig Conditions (from DP bridge to Drill floor)	Communicate	Communicate the DP operational status change to all personnel in charge according to the directions established in the WSOG document
Task 3: Evaluate current conditions and decide on action line	Evaluate	Evaluate risks considering well and rig situation and decide on actions to be initiated in order to get a better condition for disconnecting rig in a safe way
Task 4: Conduct Preparatory Actions	Regulate	Execute actions to prepare to disconnect, such as repositioning work string for assuring shearable element in front of shear rams, changing EDS mode, etc.
Task 5: Sound Red alarm	Communicate	Sound red alarm warning rig personnel about the moment to disconnect the rig
Task 6: Activate EDS	Execute	Driller (or other personnel in charge) execute function EDS in the driller control panel

The activity of communication includes two actions, which happen in different moments, the first related to sharing information about DP system redundancy loss and the second one to warning the escalation of DP system status that reaches the red alarm condition defined in WSOG (see Section 2.2). The task ‘Conduct Preparatory Actions’ has been described in terms of the cognitive activity ‘Regulate’, instead of ‘Execute’, given that it can comprise adjustments in work string, equipment and other components in preparation to emergency disconnection. For instance, these regulations can include pull out or running in hole the work string aiming to position non-shearable components out of shear rams (BSR, CSR) depth. The final objective is to assure well isolation by means of BOP shut-in. Comparing to the definitions of the cognitive activities, ‘Regulate’ fit better: “Alter speed or direction of a control (system) in order to attain a goal. Adjust or position components or subsystems to reach a target state” (HOLLNAGEL, 1998).

6.3. Related Cognitive Function Failures

According to the cognitive framework established by HOLLNAGEL (1998), the cognitive activities are described in terms of cognitive functions in a predefined combination. For example, the activity ‘Monitor’ calls for the following functions: ‘Observation’ and ‘Interpretation’. The cognitive functions associated to each task step are listed in the second column of Table 12.

Table 12 Association between cognitive activities, cognitive functions and related failure types

Task Step (cognitive activity)	Cognitive Function	Cognitive Failure Types	Some examples of possible failures
Task 0: Plan Actions to Emergency Disconnection (Plan)	Planning	Inadequate Plan/ Priority error	Not explicit the necessary EDS mode changes throughout operation or not define required actions in case of DP operational status change
Task 1: Monitor Rig and Metocean parameters (Monitor)	Observation	Observation missed/ Wrong identification	Lost signal or event that represents DP operational status change according to WSOG document
	Interpretation	Faulty diagnosis	Does not diagnose the DP operational status change
Task 2: Communicate Rig Conditions from DP bridge to Drill floor (Communicate)	Execution	Missed action	Not communicate the new condition to the personnel in charge
Task 3: Evaluate current conditions and decide on action line (Evaluate)	Interpretation	Decision error/ Incorrect prediction	Wrong decision about the actions to be conducted in preparation to emergency disconnection or incorrect prediction on the condition development
	Planning	Associated to Task 0	
Task 4: Conduct Preparatory Actions (Regulate)	Observation	Observation missed	Lost signal or event crucial to conduct the preparatory actions, such as the position of work string how planned
	Execution	Wrong type/Wrong time/Action out of sequence	Delay on initiating actions; errors on the overpull applied to the work string; erroneous EDS mode selections and etc.
Task 5: Sound red alarm (Communicate)	Execution	Wrong time	Delay in red status conditions announcement
Task 6: Activate EDS (Execute)	Execution	Wrong type/Wrong time/Action out of sequence	Reluctance of the driller in activating EDS function; not follow the correct procedure to active EDS function; activate incorrect EDS mode

Once the correlation between cognitive activities and functions is completed, the cognitive function failures are identified considering the features of the operational scenario and the descriptions presented by HOLLNAGEL (1998). Following the same example of task 1, the likely failure event selected was ‘faulty diagnosis’ for interpretation function. It can be characterized as a specific event of wrong diagnosis ("The diagnosis of the situation or system state is incorrect") or an incomplete diagnosis ("The diagnosis of the situation or system state is incomplete"). For the scenario under analysis, it means an issue with the interpretation of the DP operational status change that can be incorrectly or incompletely done; consequently, the DPO may not diagnose the loss of minimum redundancy or the escalation to red status. This interrupts the continuity of actions in order to communicate and conduct preparatory actions.

The likely cognitive function failures are presented in the third column of Table 12. The fourth and fifth column presents a description of what kind of failure event is expected to observe to justify the chosen cognitive branch. It is important to mention that some task steps are associated to more than one cognitive function, such as task 1 (observation and interpretation), task 3 (interpretation and planning) and task 4 (observation and execution). Consequently, it is possible to find two or more cognitive function failures related to them.

Task 3 comprises interpretation and planning functions. The latter is linked to task 0 that represents the planning actions before the operations have been initiated. Therefore, the development of potential causes for task 3 for the branch associated to the planning function will be directly connected to the analysis of task 0.

The cognitive demand profile for operational sequence is presented in Fig. 13. The frequency was obtained counting how many times that a given cognitive function is associated with task steps. The execution function presents the highest frequency and the other functions have the same representativeness. For the execution function, half of the frequency is associated directly to execution activities and the remaining part to the communication activity; if subdivided, considering five groups, the bars in the histogram would remain constant with 20% (observation, interpretation, planning, execution, communication). Thus, the cognitive demand is relatively equilibrated between cognitive functions. This was obtained based on a high-level description of the operational sequence. In case of a detailed version, considering subtasks, the cognitive demand may be modified.

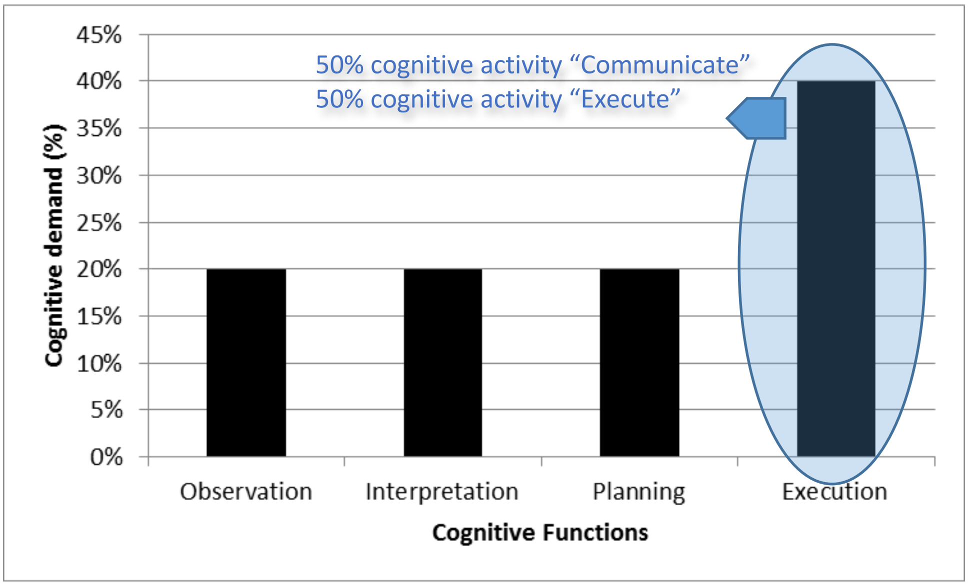


Fig. 13. Cognitive demand profile for the operational sequence

6.4. Search for Antecedents and Causal diagrams

Fig. 14 shows the worksheet created for this work containing the whole classification scheme from CREAM and the extended categories proposed. The hyperlinks are used for moving on the classification scheme throughout the search for antecedents. Each hyperlink edited for consequent is associated to the correspondent antecedent in other category. The extension of categories is highlighted in green color. Specific antecedents have no hyperlinks since they do not have connection with other categories. The indirect links are composed of general antecedent connected to general consequents in the same category. They can be explored since it seems reasonable for the general consequent under analysis

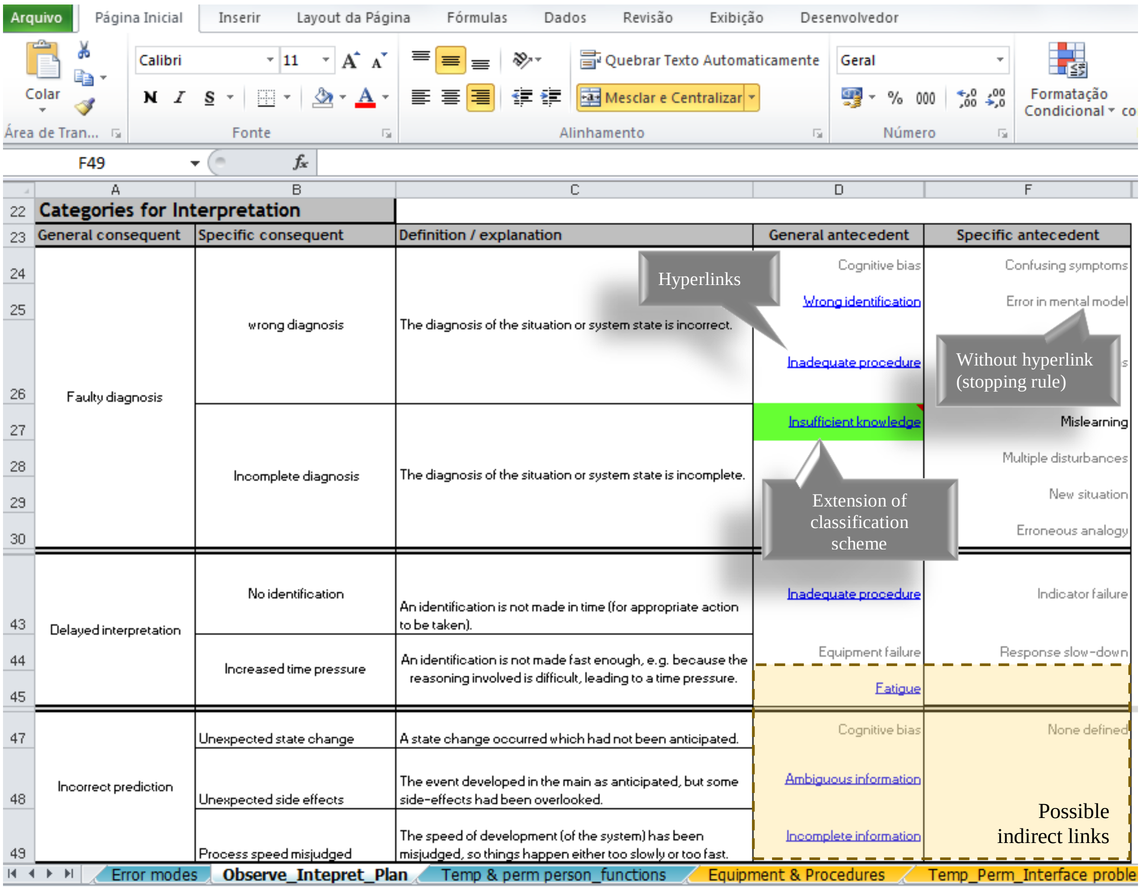


Fig. 14. Worksheet showing partially the Interpretation Category (additional antecedents in green representing category extension, hyperlinks in blue color and possible indirect links bounded in yellow color)

Fig. 15 illustrates an example of the searching process for task 1, cognitive function failure: ‘faulty diagnosis’, moving on the consequents to antecedents direction. Searching was interrupted when the antecedents from organization category were found as the candidate causes since no antecedents have been defined for these events.

After identification of the potential causes, diagrams are drawn for each cognitive function failure. The causal diagrams are displayed in Appendix C. Fig. C-3 represents the causal diagram for task 1. The cognitive function failures are circled in red color and the indirect links represented by dotted gray arrows.

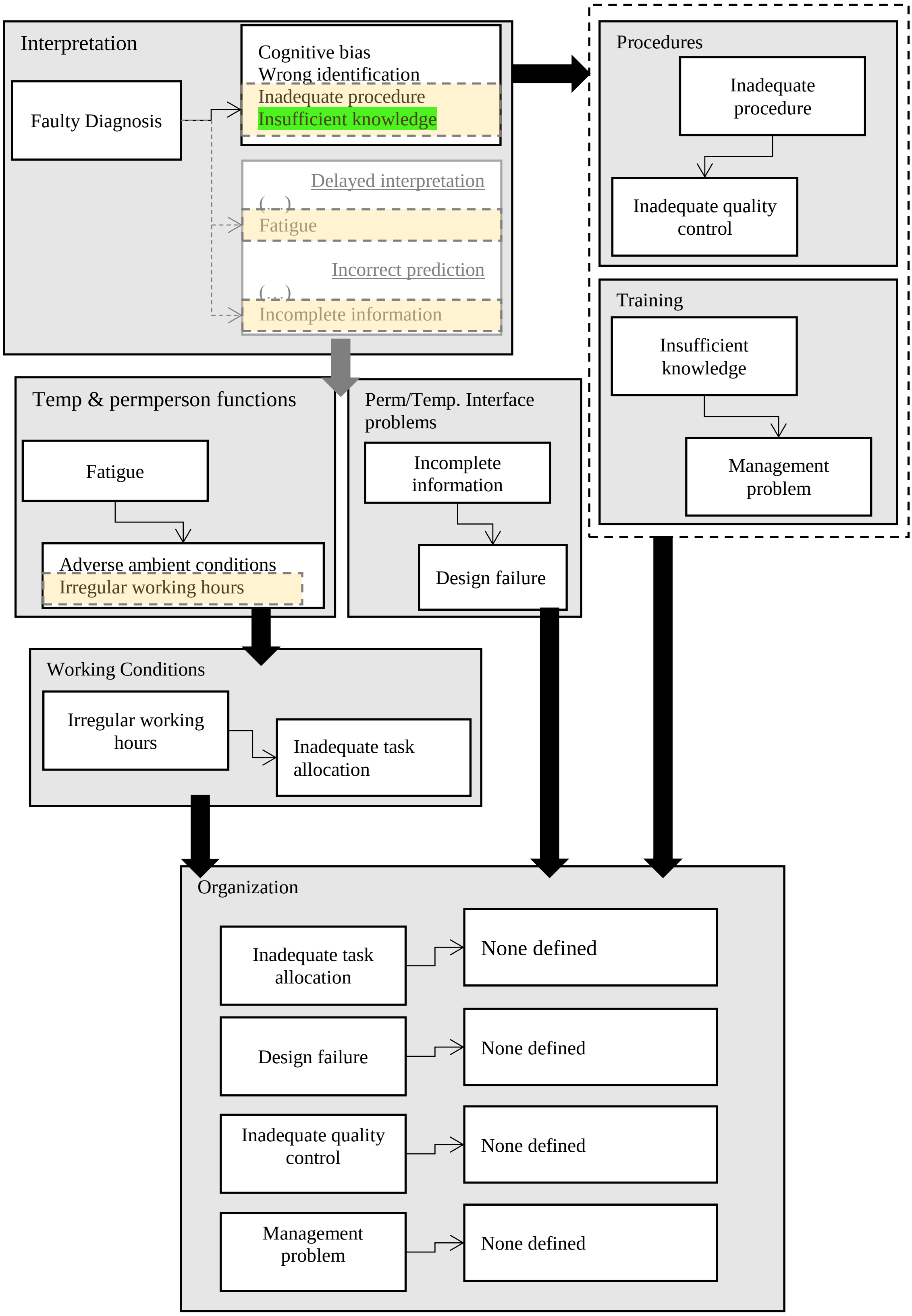


Fig. 15. Example of search for causes throughout CREAM classification scheme for task 1, cognitive function failure: faulty diagnosis

6.5. FT model

The fault tree model was developed based on the flowchart presented in Fig. 12 representing the high-level description of the human actions in scenario of emergency disconnection. The model was built using the CARA FaultTree software (Sydvest Software, 2013) and the generic outcome was assumed as the 'Human error in operational sequence' because equipment failures were not evaluated. Conservative hypotheses were assumed in the model development and recovery actions were not considered. Furthermore, the relationship between events was modelled with an OR-gate in which any forward step has a positive state only if the preceding events in operational sequence and the cognitive function failures are successful. In practice, it implies that any failure event in the model deal with a negative state of the generic outcome.

The FT representing the task steps and cognitive function failures are displayed below. Besides the fault trees, figures illustrate on the right side: the preceding step, the cognitive functions and cognitive function failures associated with each task step.

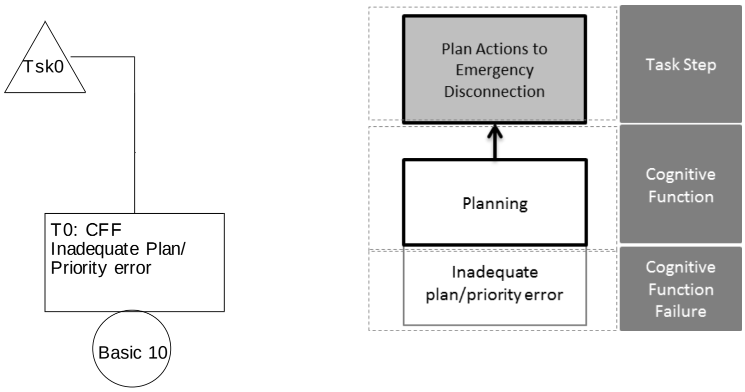


Fig. 16. Fault Tree for task 0: Plan Actions to Emergency Disconnection

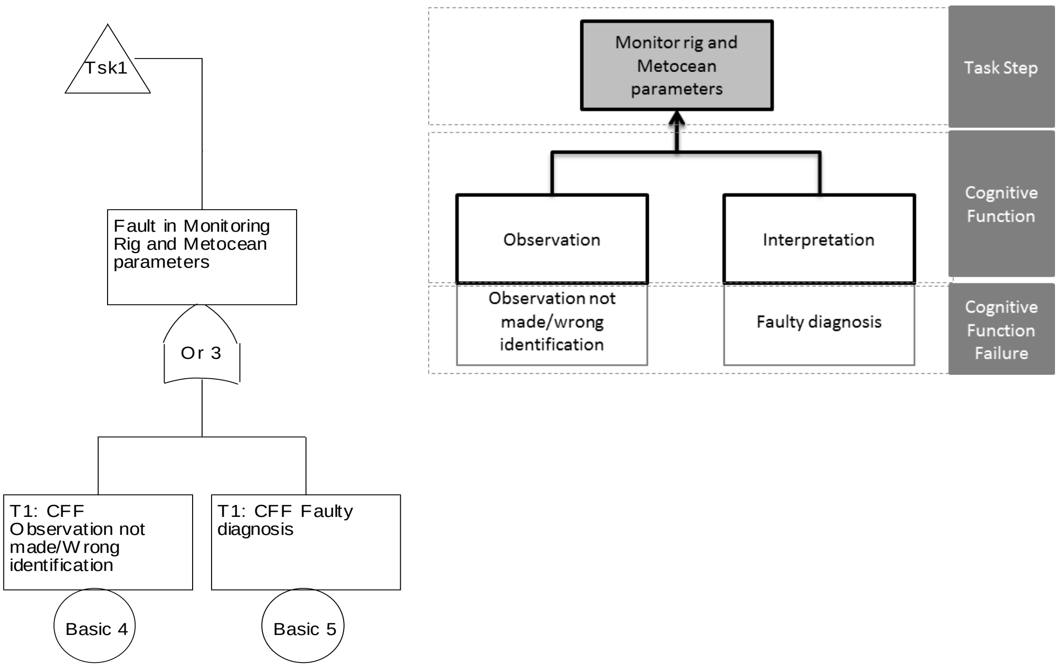


Fig. 17. Fault Tree for task 1: Monitor Rig and Metocean parameters

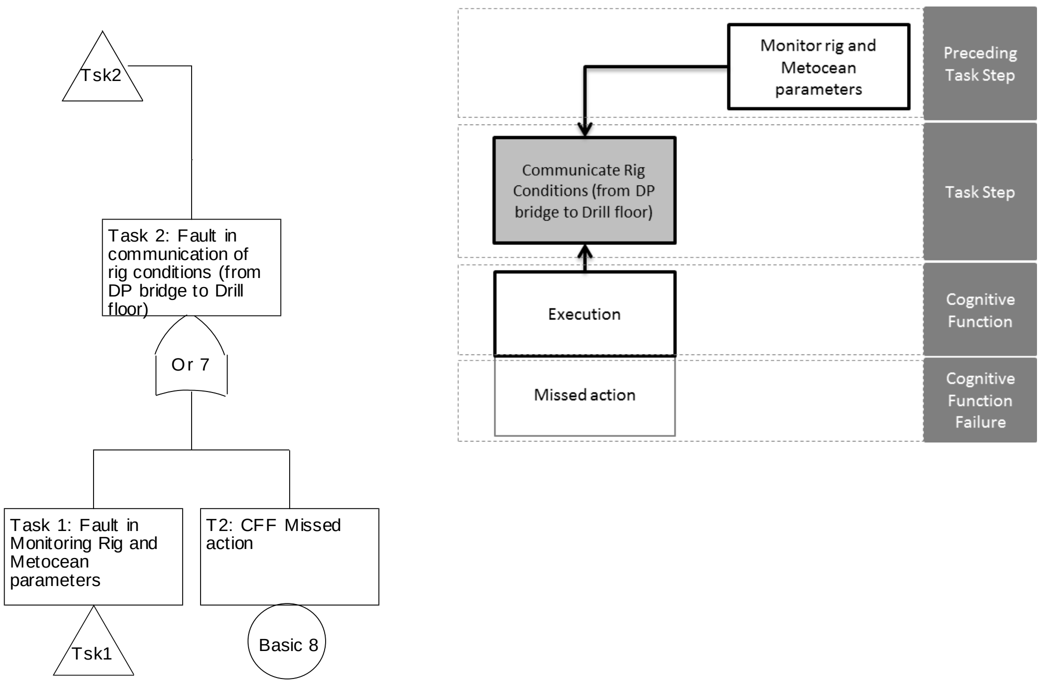


Fig. 18. Fault Tree for task 2: Communicate Rig Conditions from DP bridge to Drill floor

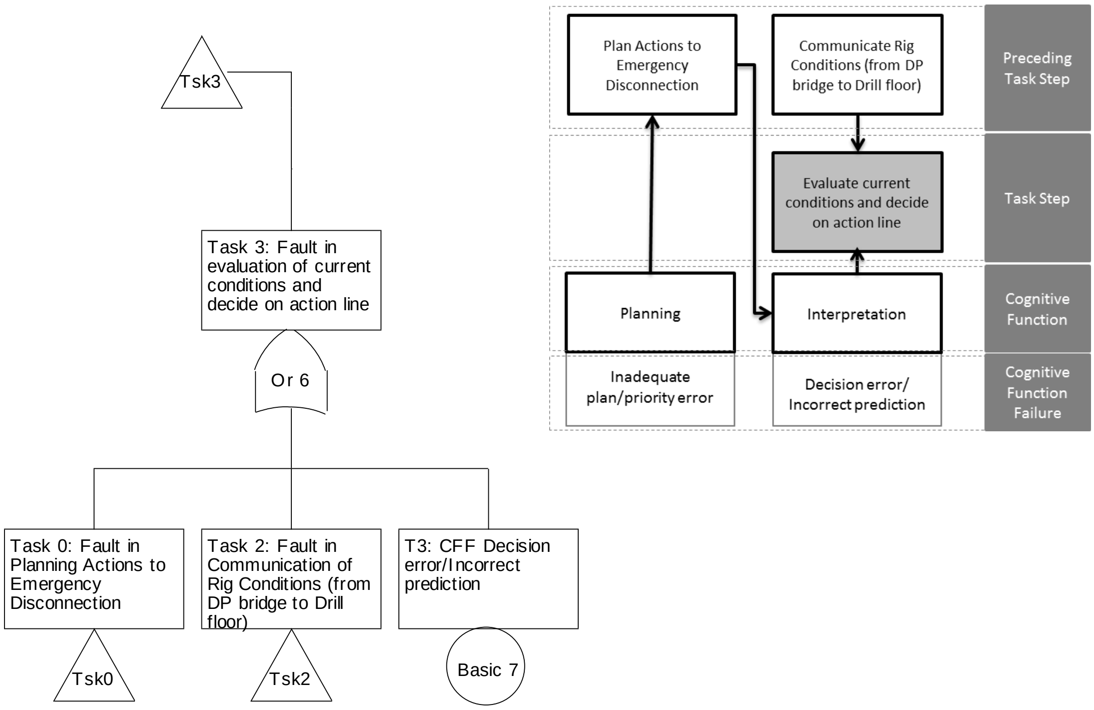


Fig. 19. Fault Tree for task 3: Evaluate current conditions and decide on action line

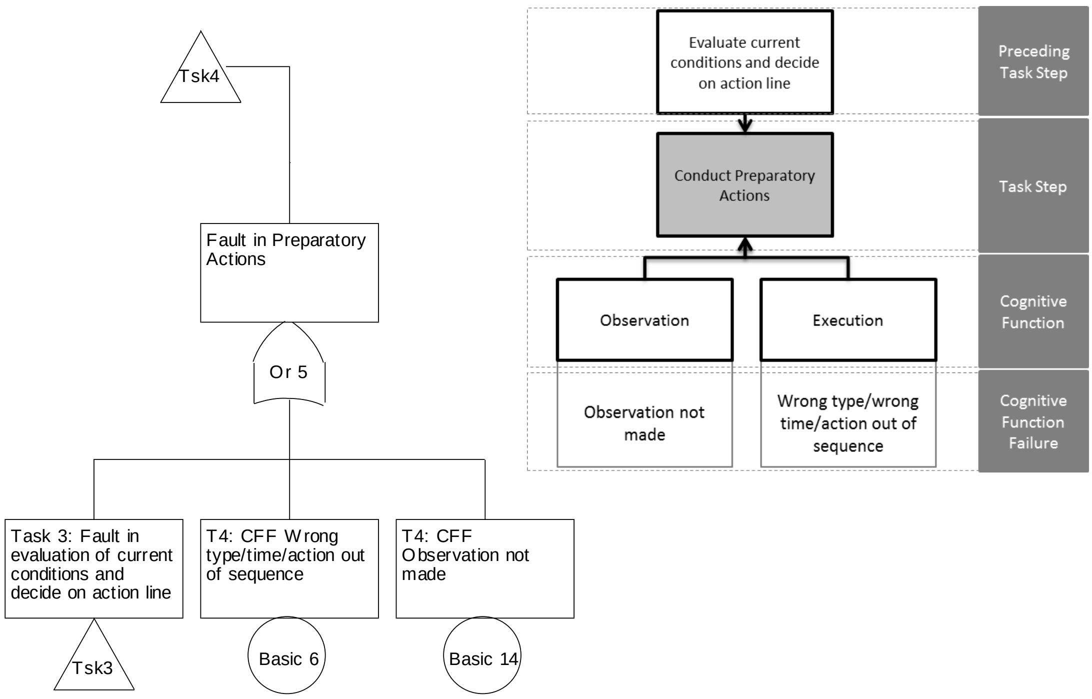


Fig. 20. Fault Tree for task 4: Conduct Preparatory Actions

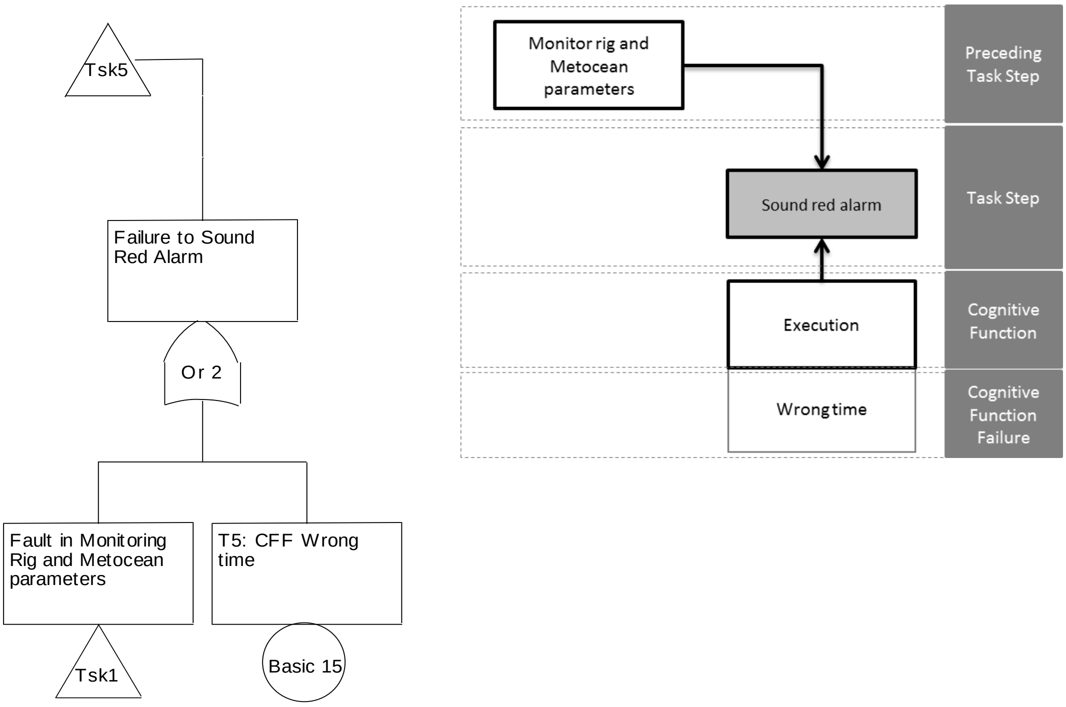


Fig. 21. Fault Tree for task 5: Sound red alarm

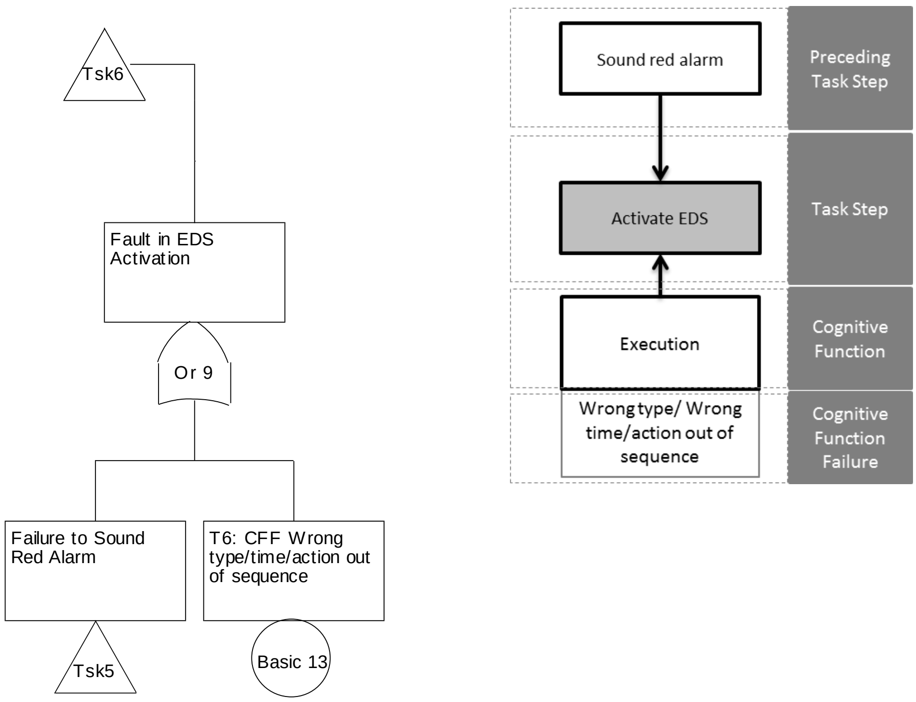


Fig. 22. Fault Tree for task 6: Activate EDS

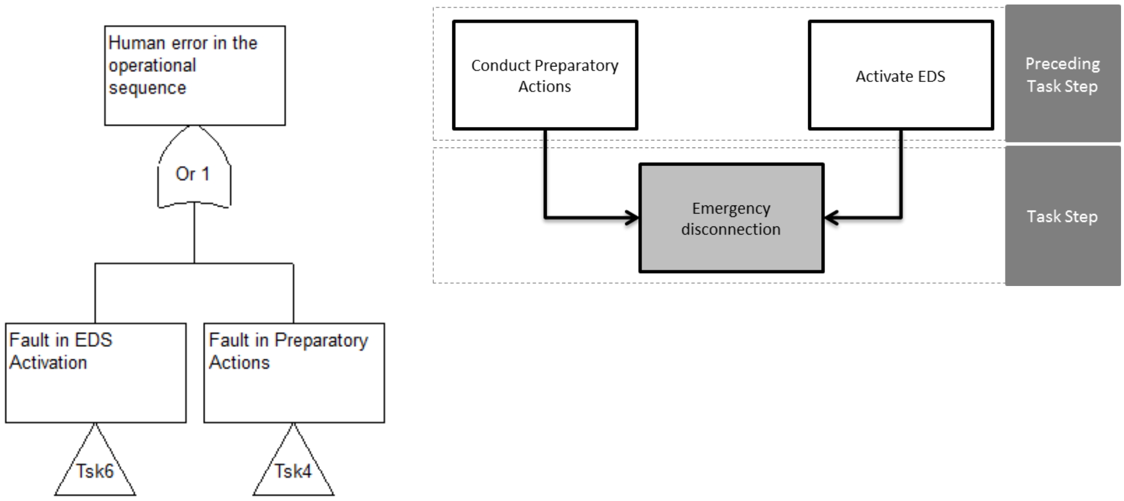


Fig. 23. Fault Tree for generic outcome: Human error in operational sequence

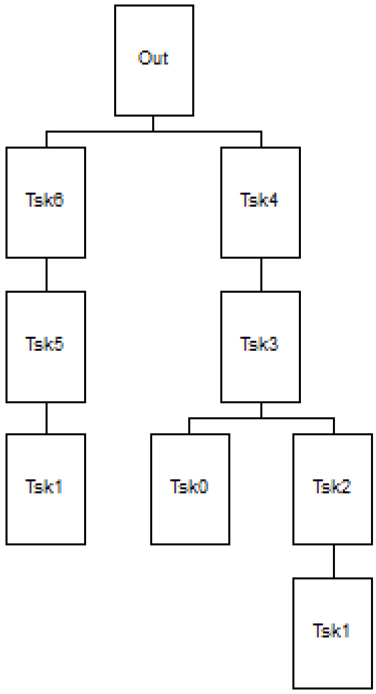


Fig. 24. Overview of the FT model

In order to evaluate consequences quantitatively and compare the influence of events, HEP basic data from CREAM (HOLLNAGEL, 1998) were inserted into the aforementioned FT model. The input data of HEP are presented in Table 13.

Table 13 HEP data for cognitive function failures (HOLLNAGEL, 1998)

Failure Types	Lower Bound	HEP (basic value)	Upper Bound
T0: Fault in Planning (Inadequate Plan/Priority error)	1.0E-3	1.0E-2	1.0E-1
T1: Fault in observation (Observation not made/Wrong identification)	2.0E-2	7.0E-2	2.45E-1
T1: Faulty Diagnosis	9.0E-2	2.0E-1	6.0E-1
T2: Missed Action	2.5E-2	3.0E-2	4.0E-2
T3: Decision error/Incorrect prediction	1.0E-3	1.0E-2	1.0E-1
T4: Observation not made	2.0E-2	7.0E-2	2.45E-1
T4: Wrong type/time or action out of sequence	1.0E-3	3.0E-3	9.0E-3
T5: Wrong time or action out of sequence	1.0E-3	3.0E-3	9.0E-3
T6: Wrong type/time or action out of sequence	1.0E-3	3.0E-3	9.0E-3

The failure probability of each task is presented in Table 14. The final probability value of the generic outcome event is conceived to represent the detection of failure in any event throughout the operational sequence. Hence, the general outcome has a negative state in case of failure in any task step and disregarding recovery actions. Therefore, it is worth emphasizing that this final value does not mean a complete failure for the emergency disconnection operation because other complementary analyzes would need to be performed, such as recovery actions, equipment reliability and the probability of the triggering events: loss of minimum DP system redundancy and red condition. Moreover, the HEP for observation (observation not made/wrong identification) and interpretation (faulty diagnosis) functions have high values and is based on a generic database from CREAM. This can be revisited and calibrated to better represent the characteristics of rig operations domain.

Table 14 Failure probability per emergency disconnection task step

Task Step	Failure Probability
Task 0: Plan Actions to Emergency Disconnection	1.00E-2
Task 1: Monitor Rig and Metocean parameters	2.56E-1
Task 2: Communicate Rig Conditions from DP bridge to Drill floor	2.78E-1
Task 3: Evaluate current conditions and decide on action line	2.93E-1
Task 4: Conduct Preparatory Actions	3.44E-1
Task 5: Sound Red Alarm	2.58E-1
Task 6: Activate EDS	2.60E-1
Outcome: Human Error in Operational Sequence	3.48E-1

Cut sets and component importance analyses have also been compiled through CARA FaultTree software (Sydvest Software, 2013). All the cut sets identified are composed of one component which corresponds to each basic event. This is in alignment with the modelling with OR-gate for all task steps. The component importance was estimated considering Birnbaum's reliability method. The result is presented in Table 15 organized in ascending order. The list with the degree of importance coincided with the order of magnitude of the HEP basic values in Table 13. Hence, the failures related to interpretation and observation functions have major influence because of the high values of probability.

Table 15 Component importance in ascending order

Order	Task Step
1	T1: Faulty diagnosis
2	T4: Observation not made
3	T1: Fault in observation (Observation not made/Wrong identification)
4	T2: Missed Action
5	T0: Fault in Planning (Inadequate Plan/Priority error)
6	T3: Decision error/Incorrect prediction
7	T4: Wrong type/time or action out of sequence
8	T6: Wrong type/time or action out of sequence
9	T5: Wrong time

6.6. Weights 1 - 3 Quantification

Each weight is quantified according to the previous description presented throughout Section 5.5.1.1. As previously mentioned, Weight 1 represents the importance weight of a given factor in relation to the remaining ones. It was quantified considering some equivalence with dependencies between CPCs described in CREAM (HOLLNAGEL, 1998) and influences between elements mapped by RIBEIRO et al. (2016), as well as adding the features of the new set of PIFs established. Table 16 shows the result of this evaluation. The cross-relation of PIFs was marked with an ‘x’ when a factor in a given row influences the factor in a given column. The diagonal of the table is completely filled given that it represents the PIF autocorrelation.

For instance, it was assumed that the factor ‘Organizational support’ influences the whole set of PIFs through programs and policies, superior guidelines, organizational goals and every decision that demonstrates what direction the company is pointing out at the moment of the assessment and its priorities. Such written and perceived decisions reflect in all areas. Another example, PIF ‘Communication’ influences the dissemination of organizational policies and helps their implementation, can cause delays or advances in knowledge and experience sharing, affects verbal and written records that are important to tasks documentation, allows identifying distortions in job design and has consequences in individual and team response, such as collaboration and motivation. In turn, PIF ‘Competence’ impacts the implementation of policies and programs established by the organization; influences the communication flow; helps to improve the quality of procedures and documentations; has positive consequences on job design and create a favorable environment for crew collaboration quality and motivation.

The column influence in Table 15 is computed by means of the sum of factors that are affected by the PIF represented in a given row. Weight 1 is calculated for each PIF as the ratio of the influence to the total score. Organizational support is the most representative because it affects all PIFs.

Weight 2 measures the influence of the PIF on the cognitive function failure. As mentioned in Section 5.5.1.1, this is discriminated for each kind of cognitive function following the directions on couplings between CPCs found in CREAM (HOLLNAGEL, 1998) and adapting them for the PIFs considered. Three levels of influence could be assigned: weak, medium and strong. Table 17 displays this relationship between PIFs and cognitive functions in a qualitative way and Table 18 presents this information in a numeric scale converted as follows: weak →1, medium → 2 and strong → 3. Finally, four different weights per PIF are defined, one for each cognitive function. Weight 2 is calculated as the ratio of the degree of influence to the sum of the total influence of all factors.

It is worth mentioning that Table 17 shows some differences in relation to dependencies of equivalent CPCs presented in CREAM. Some of links became stronger than suggested in CREAM. Two of them are mentioned here:

- The CPCs ‘Adequacy of MMI’ and ‘availability of procedures/plans’ had been assigned with weak influence in CREAM while PIFs ‘HMI’ and ‘Procedures & Documentation’ were considered with strong influence on the interpretation function. This is because the type and amount of data available in control panels and displays were considered valuable information for situation awareness. Furthermore, standards, procedures and documentation can establish critical information for interpretation tasks, such as important criteria for identifying equipment/systems conditions. One example is the WSOG and degraded status document, which establishes the parameters that helps to determine each DP operational status.

- PIFs ‘Workplace Design’ and ‘Procedures & Documentation’ were assumed to strongly influence execution functions. Fundamentally, accessibility to the workplace, general layout and well-established procedures are important issues for error modes.

Weight 3 represents the observed frequency in which the factor was identified as a contributor or root cause for accident occurrence. As already mentioned, the MATA-D database (MOURA et al., 2015, 2016) was used in order to obtain the related frequencies considering the PIFs and their analogies with the CREAM classification scheme (Table 9). Table 19 shows the obtained value of Weight 3. The column named ‘frequency’ contains the number of accidents in a sample of 238 in which the PIF (equivalent to the CREAM category) was considered as a contributor. Weight 3 is calculated as the ratio of the frequency to the total number of cases found. The four most representative considering the sample of MATA-D and the set of defined PIFs were: Organizational Support, Workplace Design, Job Design and Competence.

Table 16 Weight 1 quantification

PIF	Organizational Support	Competence	Communication	Task Environment	Workplace Design	HMI	Procedures & Documentation	Job Design	Operator & Team Characteristics	Influence	Weight 1
Organizational Support		x	x	x	x	x	x	x	x	9	0.169811
Competence	x		x				x	x	x	6	0.113208
Communication	x	x					x	x	x	6	0.113208
Task Environment			x					x	x	4	0.075472
Workplace Design			x	x		x	x	x		6	0.113208
HMI			x	x			x	x		5	0.094340
Procedures & Documentation	x	x	x					x	x	6	0.113208
Job Design	x	x	x						x	5	0.094340
Operator & Team Characteristics	x	x	x				x	x		6	0.113208
									Total	53	1

Table 17 Qualitative evaluation of Weight 2

PIFs	Cognitive Function			
	Observation	Interpretation	Planning	Execution
Organizational Support	Weak	Weak	Medium	Medium
Competence	Medium	Strong	Strong	Medium
Communication	Strong	Strong	Strong	Strong
Task Environment	Medium	Weak	Weak	Medium
Workplace Design	Medium	Weak	Weak	Strong
HMI	Strong	Strong	Weak	Strong
Procedures & Documentation	Medium	Strong	Strong	Strong
Job Design	Strong	Strong	Strong	Strong
Operator & Team Characteristics	Strong	Strong	Strong	Strong

Table 18 Weight 2 quantification

PIF	Cognitive Function							
	Observation		Interpretation		Planning		Execution	
	Influence	Weight 2	Influence	Weight 2	Influence	Weight 2	Influence	Weight 2
Organizational Support	1	0.047619	1	0.047619	2	0.10	2	0.083333
Competence	2	0.095238	3	0.142857	3	0.15	2	0.083333
Communication	3	0.142857	3	0.142857	3	0.15	3	0.125
Task Environment	2	0.095238	1	0.047619	1	0.05	2	0.083333
Workplace Design	2	0.095238	1	0.047619	1	0.05	3	0.125
HMI	3	0.142857	3	0.142857	1	0.05	3	0.125
Procedures & Documentation	2	0.095238	3	0.142857	3	0.15	3	0.125
Job Design	3	0.142857	3	0.142857	3	0.15	3	0.125
Operator & Team Characteristics	3	0.142857	3	0.142857	3	0.15	3	0.125
Total	21	1	21	1	20	1	24	1

Table 19 Weight 3 quantification

PIF	Frequency	Weight 3
Organizational Support	163	0.181111
Competence	129	0.143333
Communication	69	0.076667
Task Environment	21	0.023333
Workplace Design	161	0.178889
HMI	48	0.053333
Procedures & Documentation	105	0.116667
Job Design	148	0.164444
Operator & Team Characteristics	56	0.062222
Total	900	1

6.7. Degree of Compliance Quantification

6.7.1. Brief Description of Macondo Well Blowout

The Macondo well was located in Mississippi Canyon Block 252 in the Gulf of Mexico (GoM). BP Exploration and Production Inc. (BP) was the leasing operator of the block and shared the ownership with two other companies. The drilling operations started in October 2009 with the semi-submersible Marianas rig owned by Transocean. The rig was moved away the well site due to Hurricane Ida in November of the same year and had to be replaced for dock repairs. Deepwater Horizon rig also owned and operated by Transocean was selected to continue Macondo well construction. The drilling activities recommenced on February 2010 (BP, 2010, TRANSOCEAN, 2011).

Macondo well was designed for exploratory purposes, but with an infrastructure to be completed in case of confirming reservoir with sufficient potential of hydrocarbons production. Some changes were necessary in relation to the initial design given the observed differences in input parameters, such as pore pressures and fracture gradients, consequently resulting in alterations in mud weights and well casing setting depths (BP, 2010). Some remarkable events were found during the drilling activity, for example, lost circulation zones and well control event. This latter resulted in drill pipe stuck and abandonment of the lower part of the wellbore, which had to be bypassed to continue the drilling activities (BP, 2010, TRANSOCEAN, 2011).

The reservoir intervals potential were evaluated through logging the well and decided to complete it for production purposes. The temporary abandonment of the well would be concluded with the rig Deepwater Horizon and another unit would be designated for completion activities. The well control event that aggravated culminating in a scenario of uncontrolled influx (blowout) occurred during the final activities in preparation for the temporary abandonment on April 20, 2010 (BP, 2010, TRANSOCEAN, 2011).

A number of investigation reports were issued by the companies involved in the operations, government entities, third parties and independent researches (SUTTON, 2013). In the investigation report published by the leasing operator BP (BP, 2010), eight key findings were pointed out as contributors that together led to the accident. These issues were identified from fault tree analysis. Fig. 25 illustrates the model of Swiss cheese from REASON (1990), where the slices represent the physical and operational barriers, while the holes correspond to the failures or weaknesses in these barriers. The combined failures (alignment of holes) can lead to the general consequence, in this case, a blowout scenario. Moreover, in the upper part of Fig. 25, four critical factors were highlighted considering that eliminating one or more of them, the event or their consequence could be prevented or mitigated (BP, 2010). The critical factors and key findings are also listed in Table 20 with topics of potential vulnerabilities attributed in this report (BP, 2010).

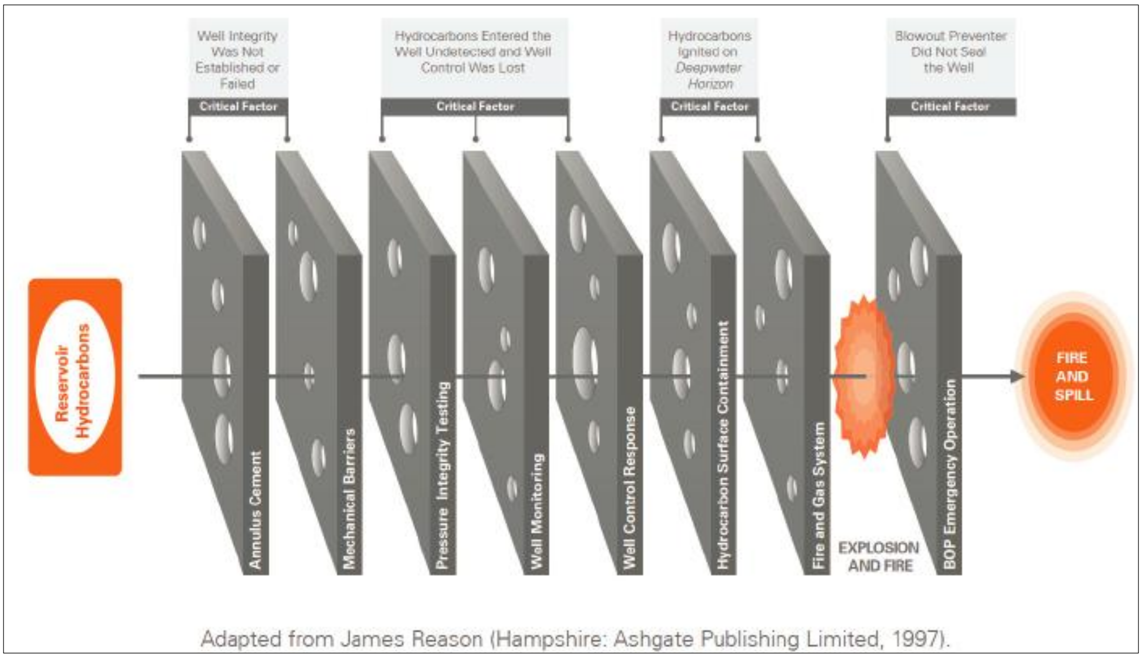


Fig. 25. Physical and Operational barriers identified and critical factors for the Macondo well blowout occurrence (obtained from BP, 2010, MC ANDREWS, 2011)

Table 20 Critical factors and key findings for Macondo well blowout and main topics associated (based on BP, 2010, TRANSOCEAN, 2011)

Critical Factor	Key Findings	Some Topics Associated
Well integrity not established or failed	Annulus cement barrier did not isolate the hydrocarbons	Problem with cement slurry design (issues related to the stability of the foamed composition for narrow margin between pore pressure and fracture gradient/incomplete tests for attesting adequate composition/issues related to risk communication) Cement placement (lower number of centralizers than estimated by simulation/position of top of cement, problems with circulation parameters – low volume and flow rate) Evaluation of cementing operation quality (decision for not conducting a cement evaluation log contrary to internal standards)
	Shoe track barriers did not isolate the hydrocarbons	Possible failure of the float collar (possible damage during circulation establishment/failure of check valves/not conversion of float collar) Possible failure of shoe track cement (contamination from annulus cement or mud in the wellbore/inadequate design)
Hydrocarbons entered the well undetected and well control was lost	Acceptance of negative-pressure test	Not well established definition of monitoring line, unfamiliarity with the procedure and issues with test interpretation
	Influx not recognized until hydrocarbons entering in the riser	Parallel activities in preparation to conclude the abandonment operation (specially mud transferring to supply vessel)/possible vulnerabilities in monitoring capacity/failure in communication
	Well control response failure	Delayed and not effective actions did not allow isolate the well
Hydrocarbons ignited	Diversion to the Mud gas separator system	Mud gas separator not prepared to process the high-pressure and high flow wellbore fluids/decision of not directing fluid to the overboard line/Flow-lines from MGS could have directed gas onto the rig
	Fire and gas system did not prevent hydrocarbon ignition	Fans and dampers not designed to trip automatically upon gas detection, what did not avoid migration of gas to not electrically classified areas
BOP did not seal the well	Subsea BOP did not isolate the well	Failure in isolating the well by means of subsea BOP either via EDS activation, Automatic Mode Function (AMF)[1] and ROV intervention

[1] The Automatic Mode Function (AMF) from the OEM Cameron is an emergency system that activates the Blind Shear Ram when communications, electrical and hydraulic power are lost to both control pods.

6.7.2. Evaluation of Degree of Compliance

As briefly described above, the Macondo well blowout encompassed two critical scenarios of BOP activation: well control event (well kick) and EDS activation. However, in this situation, the emergency disconnection was not originated at a first moment by a DP system issue, but in an escalation of unsuccessful well control procedure. This case was widely studied and evaluated supporting important changes in international standards and regulatory statements as mentioned in Chapter 1. Most of the publications indicated human aspects with high contribution to the accident, consequently it offers valuable subject of study.

The first step in order to estimate the degree of compliance was to examine the reports of investigation aiming to figure out the context behind this major accident. Some limitations in this type of evaluation using accident analysis lie in the scope of the reports, which obviously emphasizes the contributors to the accident; consequently not all factors are covered in the reports. Besides, as the objective of the investigation is to explore the weaknesses found in the installation, the positive aspects are rarely mentioned. Another point is that human aspects were not the focus in that moment, so they need to be inferred by the descriptions. On the other hand, this can be partially compensated by numerous papers found in the literature (SMITH et al., 2013, SUTTON, 2013, ROBERTS et al. 2015, ST JOHN, 2015a, 2015b, STRAND and LUNDTEIGEN, 2017, PRANESH et al., 2017).

After reports and papers examination, the preceding events with some contribution for the accident were listed and associated with the Performance Influencing Factors and their attributes. This is reported in Table. E-1. This association allows rating each attribute with a level of maturity (graduated from level 1 – worst condition to level 5 – best condition) according to the descriptions mentioned in Tables B-1 to B-13 in Appendix B and in KARIUKI’s (2007) publication.

Tables 21 to 29 display the assessment of level of maturity of each attribute. The total and percentage score is computed in accordance with the procedure described in Section 5.5.1.2. Finally, the ranking and degree of compliance is defined according to Table 10. Attributes not evaluated due to lack of information were not computed to the total score of the factor and were assigned with ‘Not applicable/Not evaluated’ status.

Three PIFs were scored with a null degree of compliance: ‘Organizational support’, ‘Communication’ and ‘Operator & Team Characteristics’. Indeed, safety culture, Management of change/Risk assessment, risk communication, attention and team collaboration had been pointed out as critical conditions and main contributors to the accident in many publications on this subject. Another important aspect widely mentioned in papers about this accident is the competence issue. Although, the crew has been certified for the functions they assumed, a lack of preparation to deal with the dynamic characteristics of the operations was identified, mainly for leadership

(PRANESH, 2017). For that reason, it was assigned the level 2 for the attributes related to the PIF ‘Competence’ (‘Skills and knowledge’ and ‘Training & Drills’) This is one of the topics that stimulate changes for all the industry, some of them established by BSEE in the US (Well Control Final Rule – CFR 250, BSEE, 2016) and ANP in Brazil (Technical Regulation of the Management System for Well Integrity, ANP, 2016).

It is worth mentioning that the attributes related to the PIF ‘Task Environment’ were not evaluated because there is no sufficient information in the reports to score them. For further quantitative analyses in the BN model (Section 7.2), level 3 for ‘Task Environment’ was assumed, considering that all the possible states have the same chance.

Table 21 Degree of compliance quantification – Organizational Support

Factor: Organizational Support

Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Human factors policy	X					
Organizational and Safety culture	X					
Management of change/Risk Assessment	X					
Organizational learning (audit and reviews)		X				
Line management and supervision/Resources Management		X				
Contractor Management		X				
Incident investigation and analysis		X				
Score: 11		(%) 31%		r_i: 0		Bad

Table 22 Degree of compliance quantification – Competence

Factor: Competence						
Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Skills and knowledge		X				
Training & Drills		X				
Score: 4		(%) 40%		r_i: 0.25		Reasonable

Table 23 Degree of compliance quantification – Communication

Factor: Communication						
Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Organizational Communication Flow and Technological Aspects	X					
Communication within the team, between teams and shifts (hand-overs)		X				
Score: 3		(%) 30%		r_i: 0		Bad

Table 24 Degree of compliance quantification – Task Environment

Factor: Task Environment						
Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Lighting/Illumination						X
Sound/Noise						X
Temperature and Humidity						X
Vibration						X
Score: NA		(%) NA		r_i: NA		NA

Table 25 Degree of compliance quantification – Workplace Design

Factor: Workplace Design						
Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Facility layout		X				
Workstation configuration						X
Accessibility						X
Control room design						X
Score: 2		(%) 40%		r_i: 0.25		Reasonable

Table 26 Degree of compliance quantification – HMI

Factor: HMI						
Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Design of controls and instrumentation		X				
Displays		X				
Control panels			X			
Tools (hand)						X
Equipment and valves		X				
Labels and Signs		X				
Score: 11		(%) 44%		r_i: 0.25		Reasonable

Table 27 Degree of compliance quantification – Procedures & Documentation

Factor: Procedures & Documentation

Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Documentation - Availability and System		X				
Procedures/Internal Standards		X				
Score: 4		(%) 40%		r_i: 0.25		Reasonable

Table 28 Degree of compliance quantification – Job Design

Factor: Job Design

Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Staffing			X			
Work schedules, shifts and overtime		X				
Manual handling						X
Score: 5		(%) 50%		r_i: 0.25		Reasonable

Table 29 Degree of compliance quantification – Operator & Team Characteristics

Factor: Operator & Team Characteristics

Attribute	Level 1	Level 2	Level 3	Level 4	Level 5	Not applicable/Not evaluated
Fitness for duty		X				
Attention/Motivation	X					
Crew Collaboration Quality	X					
Score: 4		(%) 27%		r_i: 0		Bad

Chapter 7. Results and Discussions

This chapter presents quantitative results from the model application for the rig emergency disconnection scenario, including the BN modelling. This evaluation is carried out by the quantification of influence weights and measure of the status of the PIF set for each cognitive function and per cognitive function failure identified. Sensitivity analyses are performed considering the base case of Macondo well blowout and variation in PIFs under two extreme conditions, as well as the situation of not considering PIF effects. Additional analysis is also carried out considering variations in Human Error Probability per cognitive function failure.

7.1. PIFs Evaluation per Cognitive Function

After the quantification of the metrics to weight and score the PIFs, their representativeness in relation to each cognitive function was measured. Tables 30 to 33 list the weights and the evaluation of the product of normalized weight and degree of compliance for each cognitive function.

Table 30 Weighting and degree of compliance for the Macondo well blowout analysis – Observation cognitive function (adapted from RIBEIRO et al., 2016)

Observation function

PIF	**Weight 1**	**Weight 2**	**Weight 3**	w_i	$w_{i,n}$* (%)	r_i	$w_{i,n}.r_i$
Organizational Support	0.1698	0.0476	0.1811	0.001465	12,7%	0	0
Competence	0.1132	0.0952	0.1433	0.001545	13,4%	0.25	0.03346
Communication	0.1132	0.1429	0.0767	0.001240	10,7%	0	0
Task Environment	0.0755	0.0952	0.0233	0.000168	1,5%	NA	NA
Workplace Design	0.1132	0.0952	0.1789	0.001929	16,7%	0.25	0.04176
HMI	0.0943	0.1429	0.0533	0.000719	6,2%	0.25	0.01556
Procedures & Documentation	0.1132	0.0952	0.1167	0.001258	10,9%	0.25	0.02724
Job Design	0.0943	0.1429	0.1644	0.002216	19,2%	0.25	0.04799
Operator & Team Characteristics	0.1132	0.1429	0.0622	0.001006	8,7%	0	0
Sum	1	1	1	0.011545	100%		

*$w_{i,n}$ represents normalized weight.

Table 31 Weighting and degree of compliance for the Macondo well blowout analysis – Interpretation cognitive function (adapted from RIBEIRO et al., 2016)

Interpretation function

PIF	**Weight 1**	**Weight 2**	**Weight 3**	w_i	$w_{i,n}^*$ **(%)**	r_i	$w_{i,n}.r_i$
Organizational Support	0.1698	0.0476	0.1811	0.001465	12,3%	0	0
Competence	0.1132	0.1429	0.1433	0.002318	19,5%	0.25	0.04870
Communication	0.1132	0.1429	0.0767	0.001240	10,4%	0	0
Task Environment	0.0755	0.0476	0.0233	0.000084	0,7%	NA	NA
Workplace Design	0.1132	0.0476	0.1789	0.000964	8,1%	0.25	0.02026
HMI	0.0943	0.1429	0.0533	0.000719	6,0%	0.25	0.01510
Procedures & Documentation	0.1132	0.1429	0.1167	0.001887	15,9%	0.25	0.03964
Job Design	0.0943	0,1429	0.1644	0.002216	18,6%	0.25	0.04656
Operator & Team Characteristics	0.1132	0,1429	0.0622	0.001006	8,5%	0	0
Sum	1	1	1	0.011899	100%		

$^*w_{i,n}$ represents normalized weight.

Table 32 Weighting and degree of compliance for the Macondo well blowout analysis – Planning cognitive function (adapted from RIBEIRO et al., 2016)

Planning function

PIF	**Weight 1**	**Weight 2**	**Weight 3**	$\mathbf{w_i}$	$\mathbf{w_{i,n}^{*}}$ **(%)**	$\mathbf{r_i}$	$\mathbf{w_{i,n}.r_i}$
Organizational Support	0.1698	0.1	0.1811	0.003075	22,7%	0	0
Competence	0.1132	0.15	0.1433	0.002434	18,0%	0.25	0.04498
Communication	0.1132	0.15	0.0767	0.001302	9,6%	0	0
Task Environment	0.0755	0.05	0.0233	0.000088	0,7%	NA	NA
Workplace Design	0.1132	0.05	0.1789	0.001013	7,5%	0.25	0.01871
HMI	0.0943	0.05	0.0533	0.000252	1,9%	0.25	0.00465
Procedures & Documentation	0.1132	0.15	0.1167	0.001981	14,6%	0.25	0.03661
Job Design	0.0943	0.15	0.1644	0.002327	17,2%	0.25	0.04300
Operator & Team Characteristics	0.1132	0.15	0.0622	0.001057	7,8%	0	0
Sum	1	1	1	0.013528	100%		

$^{*}w_{i,n}$ represents normalized weight.

Table 33 Weighting and degree of compliance for the Macondo well blowout analysis – Execution cognitive function (adapted from RIBEIRO et al., 2016)

Execution function							
PIF	**Weight 1**	**Weight 2**	**Weight 3**	w_i	$w_{i,n}^*$ **(%)**	r_i	$w_{i,n}.r_i$
Organizational Support	0.1698	0.0833	0.1811	0.002563	20,1%	0	0
Competence	0.1132	0.0833	0.1433	0.001352	10,6%	0.25	0.02646
Communication	0.1132	0.1250	0.0767	0.001085	8,5%	0	0
Task Environment	0.0755	0.0833	0.0233	0.000147	1,1%	NA	NA
Workplace Design	0.1132	0.1250	0.1789	0.002531	19,8%	0.25	0.04953
HMI	0.0943	0.1250	0.0533	0.000629	4,9%	0.25	0.01231
Procedures & Documentation	0.1132	0.1250	0.1167	0.001651	12,9%	0.25	0.03230
Job Design	0.0943	0.1250	0.1644	0.001939	15,2%	0.25	0.03794
Operator & Team Characteristics	0.1132	0.1250	0.0622	0.000881	6,9%	0	0
Sum	1	1	1	0.012778	100%		

$^*w_{i,n}$ represents normalized weight.

With the purpose of better visualize the importance weight of PIFs for cognitive functions showed previously in tabular format, colour-coded radar charts were drawn. The regions with hot colors (red and orange) and near to the origin represent the major contributors to failures. They can also be interpreted as the areas that need more investment to reduce failure probability. The peripheral regions in tones of green correspond to the less impacting PIFs for this analysis. The yellow ones have an intermediate effect. This interpretation is in alignment with the meaning of the index of human factors modification (β). If the index of human factors modification is low (bad conditions), the modified HEP is high (near to upper bound). Conversely, if context is improved (higher β), modified HEPs tend to the lower bound of failure probability.

In general, Figs. 26 to 29 display that the PIFs with relevant impact are those with worse results (bad score) in the degree of compliance mentioned in Section 6.7: 'Organizational support', 'Communication' and 'Operator & Team Characteristics'. The fourth PIF in degree of importance was HMI.

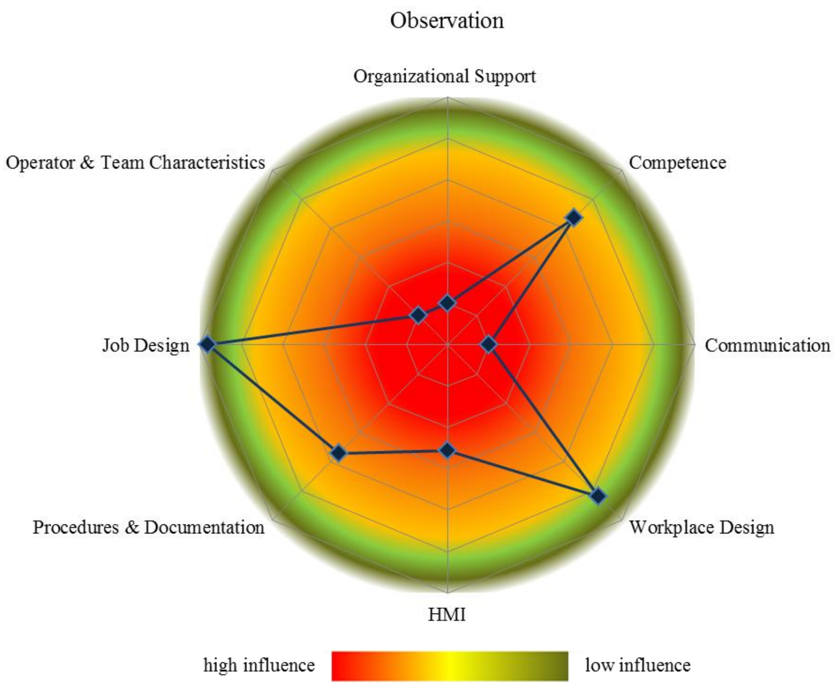


Fig. 26. Radar chart - Cognitive function Observation for Macondo well blowout (adapted from RIBEIRO et al., 2016)

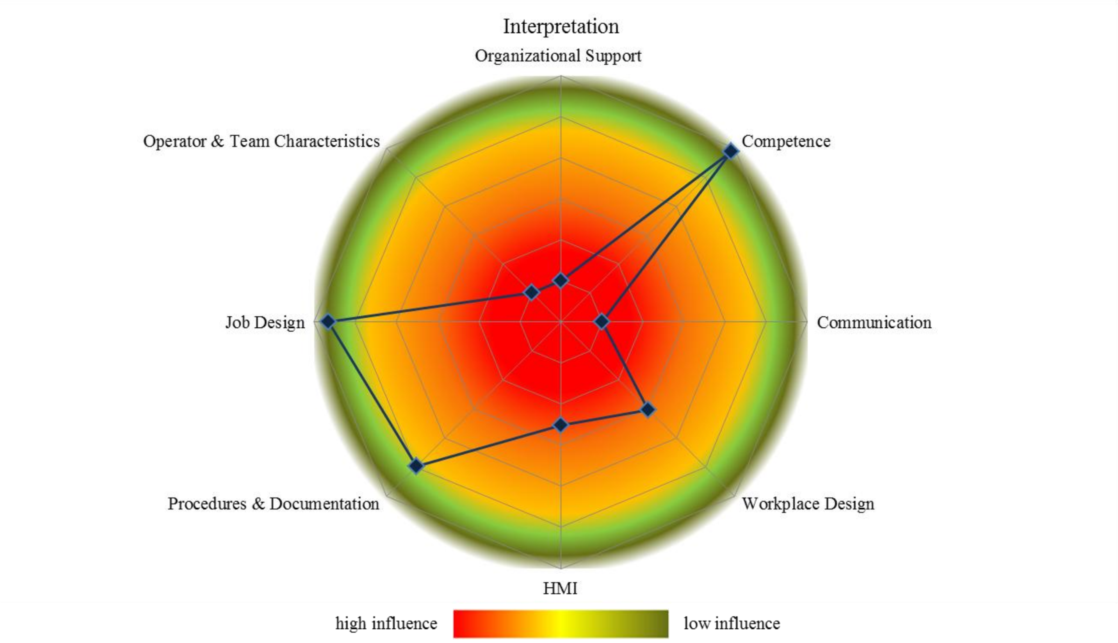


Fig. 27. Radar chart - Cognitive function Interpretation for Macondo well blowout (adapted from RIBEIRO et al., 2016)

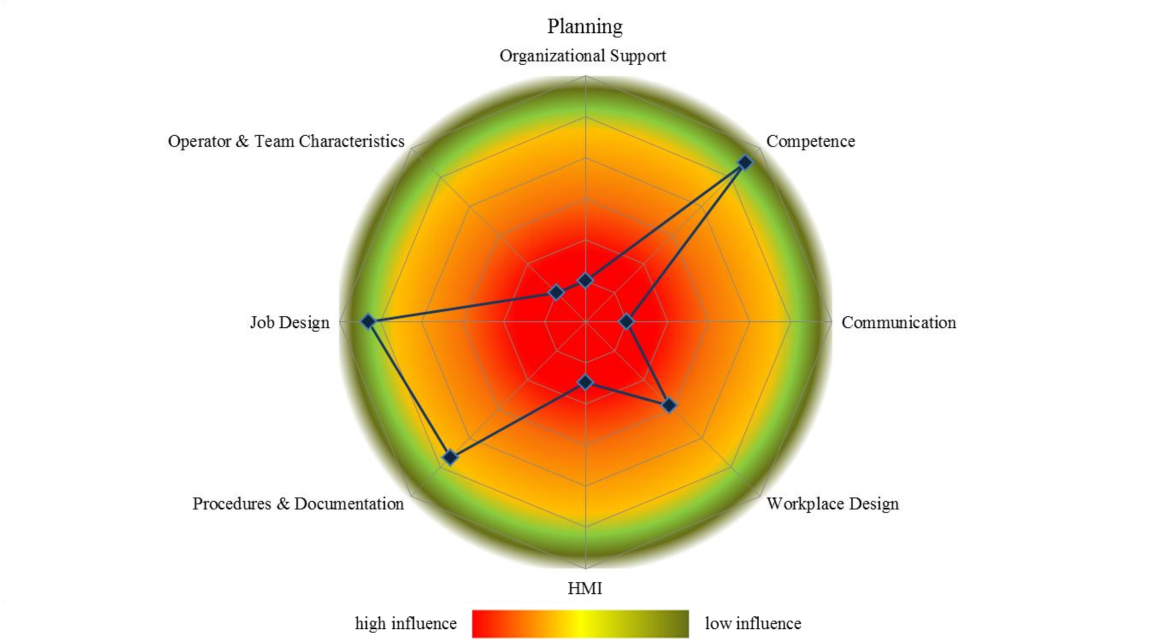


Fig. 28. Radar chart - Cognitive function Planning for Macondo well blowout (adapted from RIBEIRO et al., 2016)

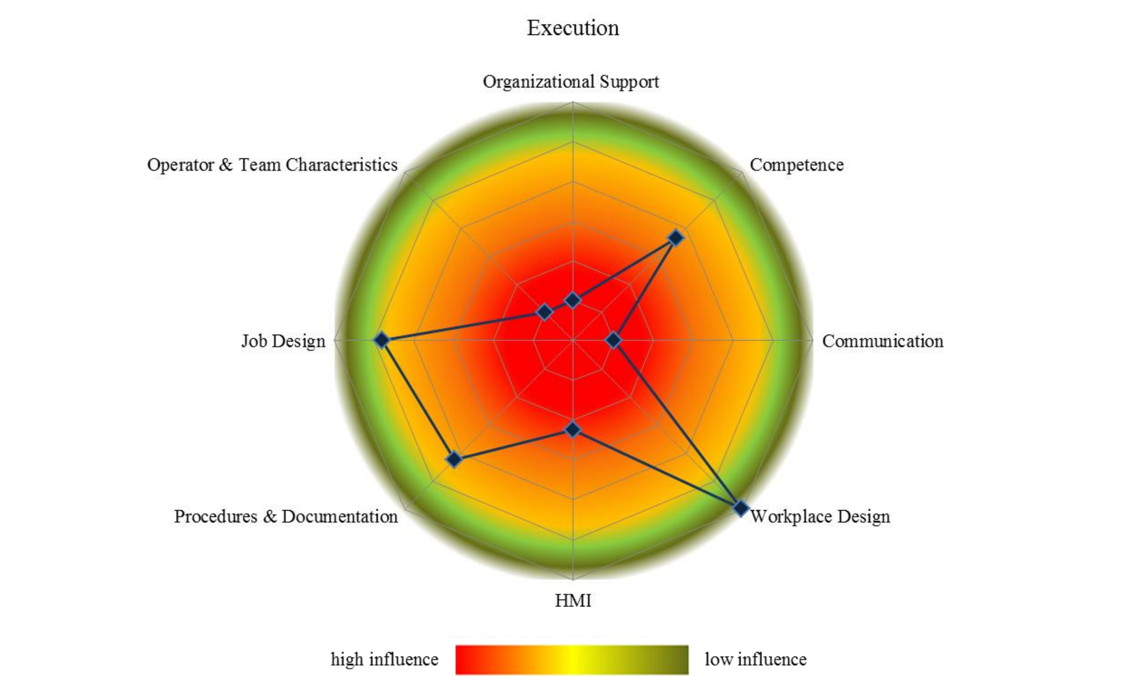


Fig. 29. Radar chart – Cognitive function Execution for Macondo well blowout (adapted from RIBEIRO et al., 2016)

7.2. Evaluation of Index of Human Factors Modification

The quantification data obtained in Section 7.1 was incorporated into Eq. (4) of the mathematical model adopted (see Section 5.5.1.3). The Performance Influencing Factors that impact each cognitive function failure were determined from the links mapped in the causal diagrams during the antecedents searching process combined with the analogy of CREAM categories as explained in Section 5.4.1 and demonstrated in Figs. 30 and 31.

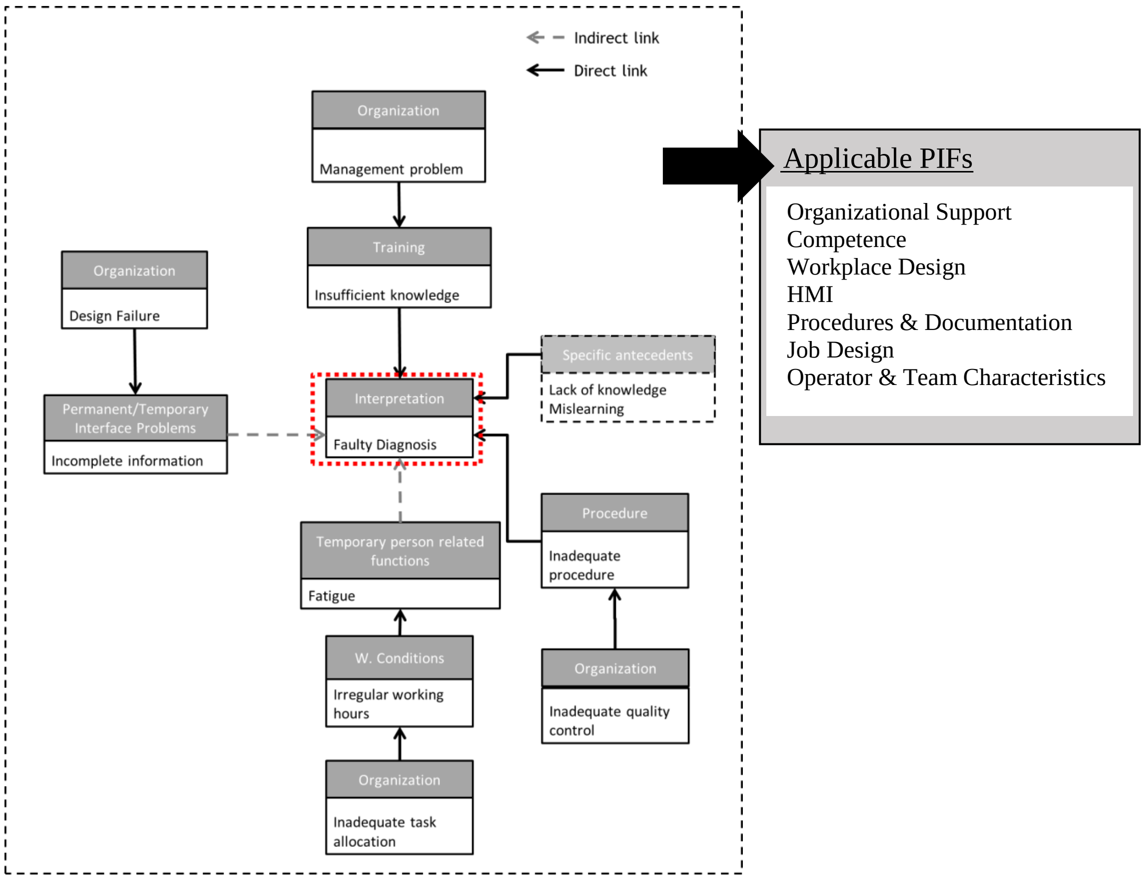


Fig. 30. Example of search for causes for task 1: 'Monitor Rig and Metocean parameters', Cognitive Function Failure: Faulty diagnosis, and the applicable PIFs

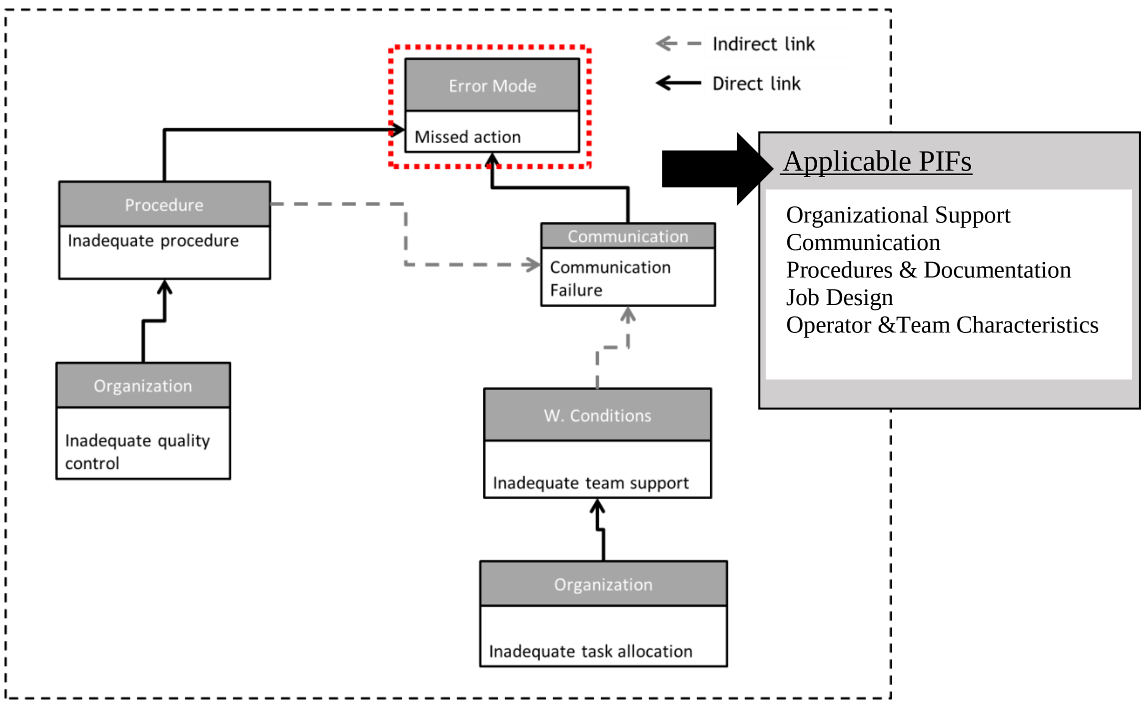


Fig. 31. Example of search for causes for task 2: 'Communicate Rig Conditions from DP bridge to Drill floor' and the applicable PIFs

The applicable Performance Influencing Factors per Cognitive Function Failure is presented in Table 34.

Table 34 Applicable PIFs per cognitive function failure

Cognitive Function Failure	Organizational Support	Competence	Communication	Task Environment	Workplace Design	HMI	Procedures & Documentation	Job Design	Operator & Team Characteristics
T0: Fault in Planning (Inadequate Plan/Priority error)	x	x	x				x	x	x
T1: Fault in observation (Observation not made/Wrong identification)	x		x	x	x	x	x	x	x
T1: Faulty Diagnosis	x	x			x	x	x	x	x
T2: Missed Action	x		x				x	x	x
T3: Decision error/Incorrect prediction	x	x	x		x	x	x	x	x
T4: Observation not made	x		x	x	x	x	x	x	x
T4: Wrong type/time or action out of sequence	x	x	x	x	x	x	x	x	x
T5: Wrong time or action out of sequence	x		x				x	x	x
T6: Wrong type/time or action out of sequence	x	x	x		x	x	x		x

Tables 35 to 43 present the computation of index of human factors modification (β) for each cognitive function failure. As already mentioned, for quantification purposes, the degree of compliance for the PIF 'Task Environment' was considered 'average'. The related equations were presented in Section 5.5.1.3.

Table 35 Index of human factors modification (*β*) for task 0 (adapted from RIBEIRO et al., 2016)

Applicable PIFs	Weights	Normalized weights	r_i		$w_{i,n}.r_i$
Organizational Support	0.003075	0.252583	0		0
Competence	0.002434	0.199897	0.25		0.049974
Communication	0.001302	0.106921	0		0
Procedures & Documentation	0.001981	0.162707	0.25		0.040677
Job Design	0.002327	0.191116	0.25		0.047779
Operator & Team Characteristics	0.001057	0.086777	0		0
Sum	0.012176	1		β	0.138430

Table 36 Index of human factors modification (β) for task 1/T1: Fault in observation (Observation not made/Wrong identification) (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	$\mathbf{r_i}$	$\mathbf{w_{i,n}.r_i}$
Organizational Support	0.001465	0.146451	0	0
Communication	0.001240	0.123989	0	0
Task Environment	0.000168	0.016771	0.50	0.008386
Workplace Design	0.001929	0.192872	0.25	0.048218
HMI	0.000719	0.071878	0.25	0.017969
Procedures & Documentation	0.001258	0.125786	0.25	0.031447
Job Design	0.002216	0.221623	0.25	0.055406
Operator & Team Characteristics	0.001006	0.100629	0	0
Sum	0.01	1	β	0.161426

Table 37 Index of human factors modification (β) for task 1/T1: Faulty Diagnosis (adapted from RIBEIRO et al., 2016)

Applicable PIFs	Weights	Normalized weights	r_i	$w_{i,n}.r_i$
Organizational Support	0.001465	0.138488	0	0
Competence	0.002318	0.219201	0.25	0.054800
Workplace Design	0.000964	0.091192	0.25	0.022798
HMI	0.000719	0.067969	0.25	0.016992
Procedures & Documentation	0.001887	0.178420	0.25	0.044605
Job Design	0.002216	0.209572	0.25	0.052393
Operator & Team Characteristics	0.001006	0.095157	0	0
Sum	0.010575	1	β	0.191589

Table 38 Index of human factors modification (β) for task 2 (adapted from RIBEIRO et al., 2016)

Applicable PIFs	Weights	Normalized weights	r_i	$w_{i,n}.r_i$
Organizational Support	0.002563	0.315688	0	0
Communication	0.001085	0.133635	0	0
Procedures & Documentation	0.001651	0.203357	0.25	0.050839
Job Design	0.001939	0.238864	0.25	0.059716
Operator & Team Characteristics	0.000881	0.108457	0	0
Sum	0.008118	1	β	0.110555

Table 39 Index of human factors modification (*β*) for task 3 (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	r_i	$w_{i,n}.r_i$
Organizational Support	0.001465	0.123954	0	0
Competence	0.002318	0.196198	0.25	0.049049
Communication	0.001240	0.104943	0	0
Workplace Design	0.000964	0.081622	0.25	0.020406
HMI	0.000719	0.060837	0.25	0.015209
Procedures & Documentation	0.001887	0.159696	0.25	0.039924
Job Design	0.002216	0.187579	0.25	0.046895
Operator & Team Characteristics	0.001006	0.085171	0	0
Sum	0.011815	1	*β*	0.171483

Table 40 Index of human factors modification (β) for task 4/T4: Observation not made (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	r_i	$w_{i,n}.r_i$
Organizational Support	0.001465	0.146451	0	0
Communication	0.001240	0.123989	0	0
Task Environment	0.000168	0.016771	0.50	0.008386
Workplace Design	0.001929	0.192872	0.25	0.048218
HMI	0.000719	0.071878	0.25	0.017969
Procedures & Documentation	0.001258	0.125786	0.25	0.031447
Job Design	0.002216	0.221623	0.25	0.055406
Operator & Team Characteristics	0.001006	0.100629	0	0
Sum	0.01	1	β	0.161426

Table 41 Index of human factors modification (β) for task 4/T4: Wrong type/time or action out of sequence (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	$\mathbf{r_i}$	$\mathbf{w_{i,n}.r_i}$
Organizational Support	0.002563	0.200574	0	0
Competence	0.001352	0.105824	0.25	0.026456
Communication	0.001085	0.084906	0	0
Task Environment	0.000147	0.011485	0.50	0.005742
Workplace Design	0.002531	0.198113	0.25	0.049528
HMI	0.000629	0.049221	0.25	0.012305
Procedures & Documentation	0.001651	0.129204	0.25	0.032301
Job Design	0.001939	0.151764	0.25	0.037941
Operator & Team Characteristics	0.000881	0.068909	0	0
Sum	0.012778	1	β	0.164274

Table 42 Index of human factors modification (β) for task 5 (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	r_i	$w_{i,n}.r_i$
Organizational Support	0.002563	0.315688	0	0
Communication	0.001085	0.133635	0	0
Procedures & Documentation	0.001651	0.203357	0.25	0.050839
Job Design	0.001939	0.238864	0.25	0.059716
Operator & Team Characteristics	0.000881	0.108457	0	0
Sum	0.008118	1	β	0.110555

Table 43 Index of human factors modification (β) for task 6 (adapted from RIBEIRO et al., 2016)

Applicable PIFs	**Weights**	**Normalized weights**	r_i	$w_{i,n}.r_i$
Organizational Support	0.002563	0.239706	0	0
Competence	0.001352	0.126471	0.25	0.031618
Communication	0.001085	0.101471	0	0
Workplace Design	0.002531	0.236765	0.25	0.059191
HMI	0.000629	0.058824	0.25	0.014706
Procedures & Documentation	0.001651	0.154412	0.25	0.038603
Operator & Team Characteristics	0.000881	0.082353	0	0
Sum	0.010692	1	β	0.144118

7.3. BN model

The Bayesian network was modelled with the help of the Netica software (Norsys Software Corp., 2017). The framework follows the cognitive model starting from the task step, breakdown in cognitive function and identification of cognitive function failures. Lastly, the respective applicable Performance Influencing Factors (root nodes) are added to the structure. Figs. 32 to 40 illustrate the framework in BN model per task step.

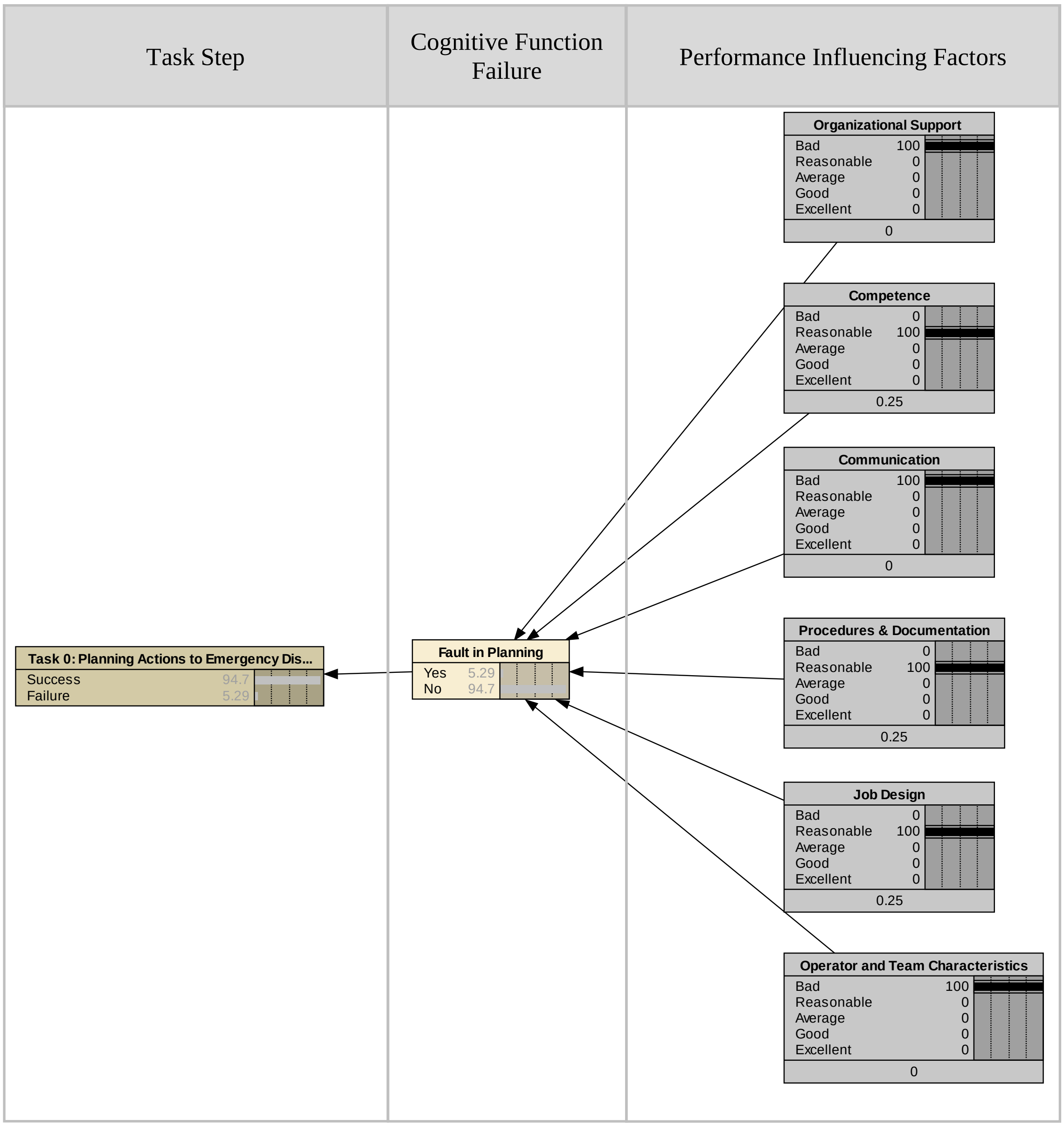


Fig. 32. BN framework for task 0: Plan Actions to Emergency Disconnection.

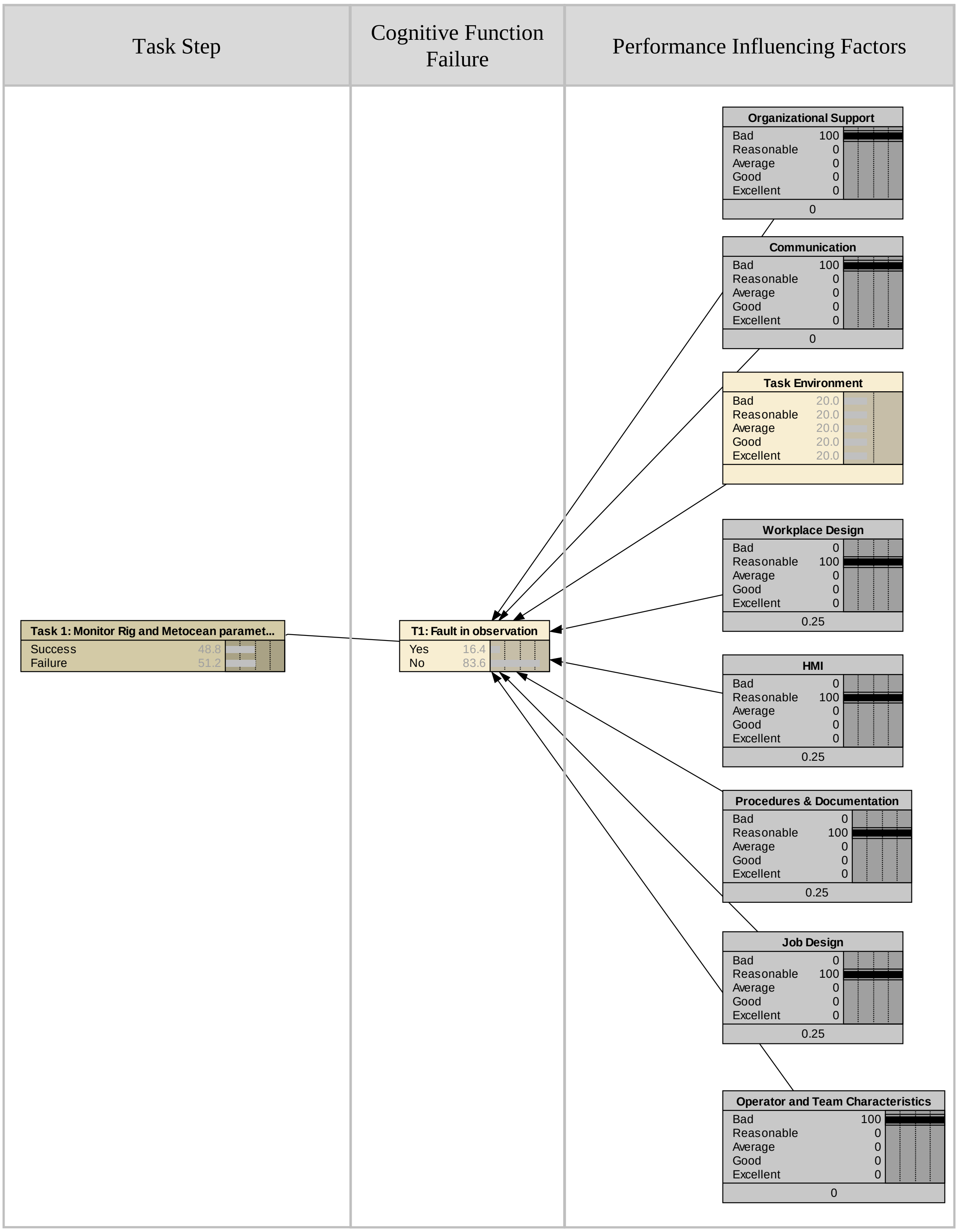


Fig. 33. BN framework for task 1: Monitor Rig and Metocean parameters – Fault in Observation

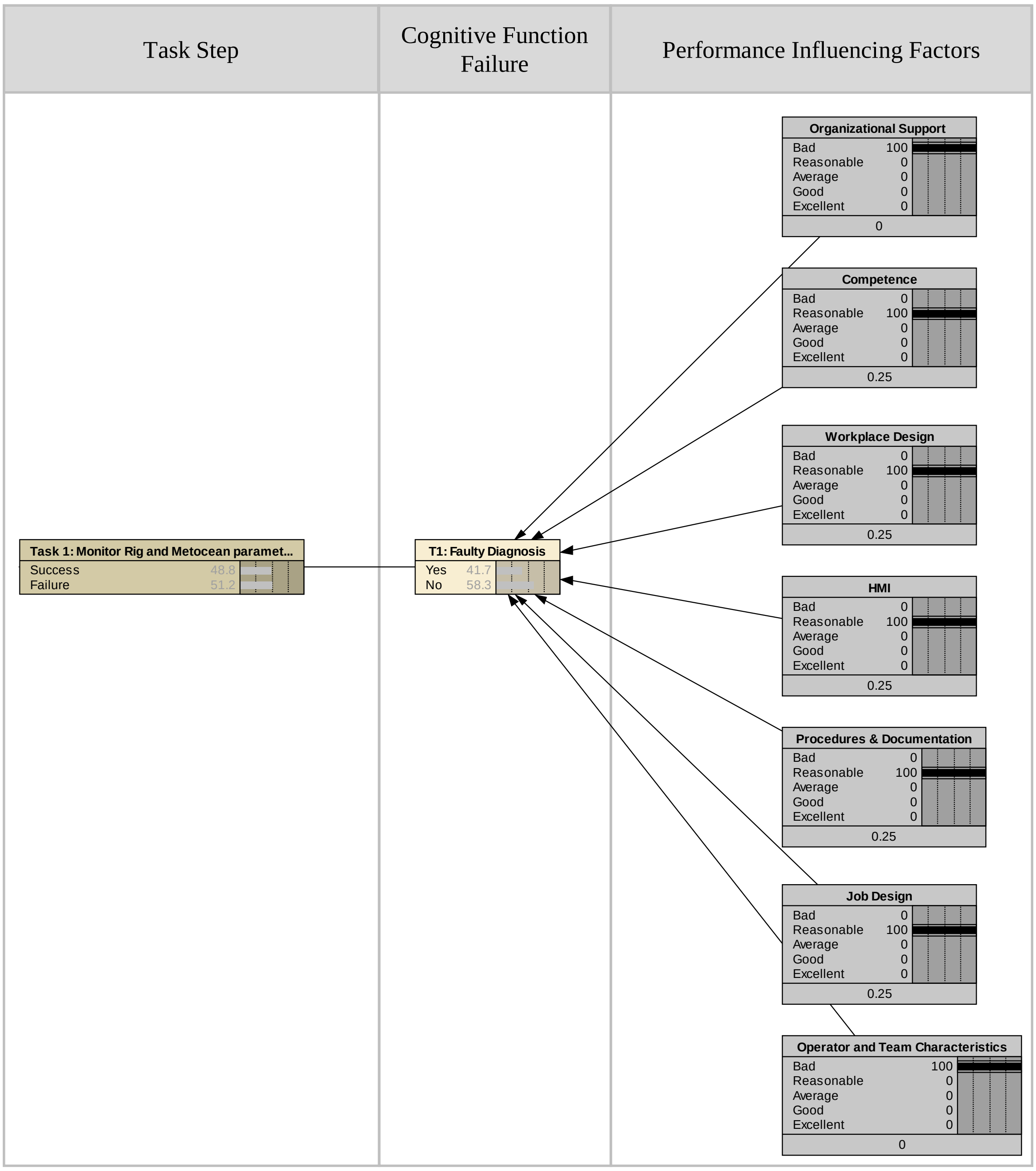


Fig. 34. BN framework for task 1: Monitor Rig and Metocean parameters – Faulty Diagnosis

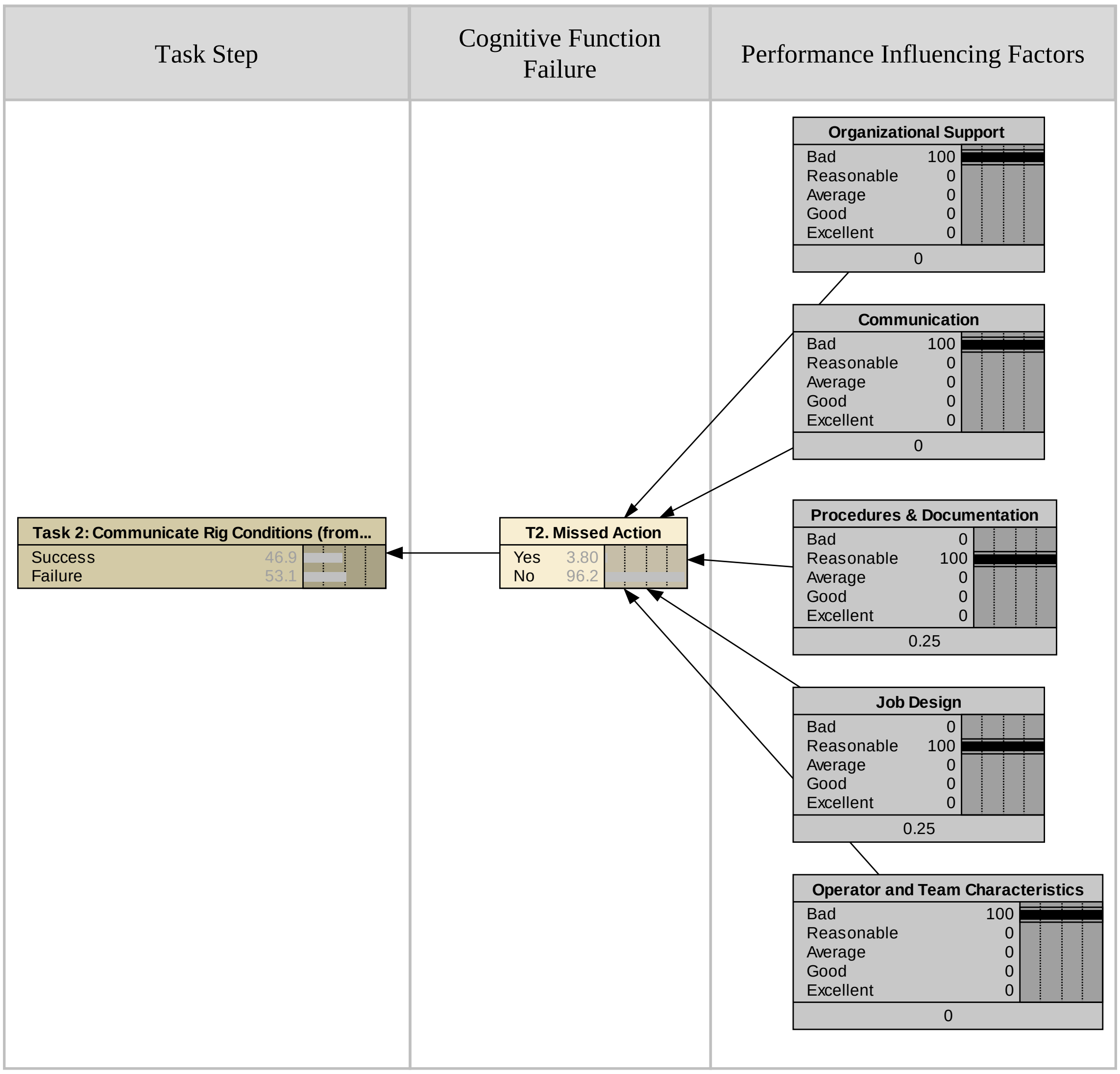


Fig. 35. BN framework for task 2: Communicate Rig Conditions from DP bridge to Drill floor

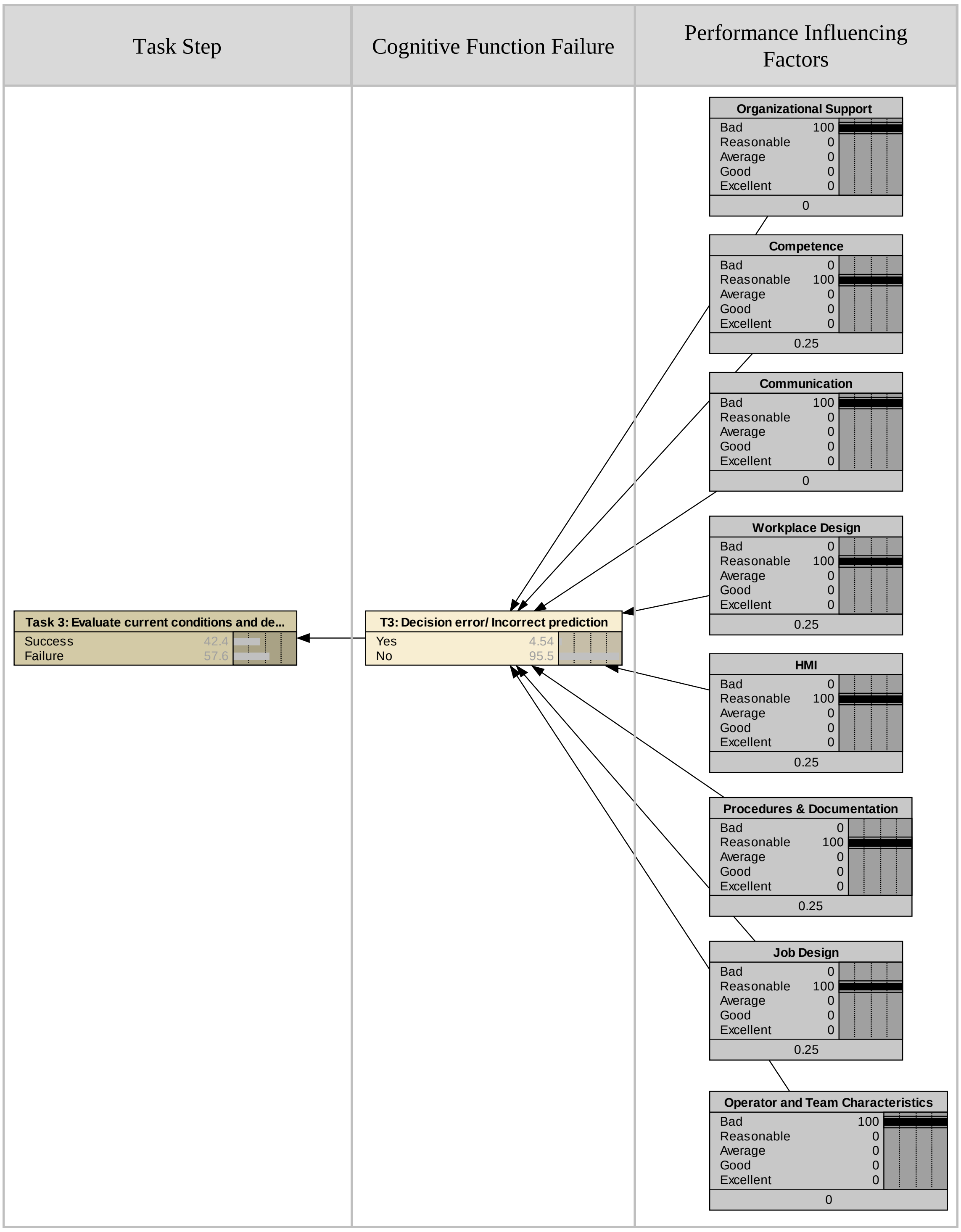


Fig. 36. BN framework for task 3: Evaluate current conditions and decide on action line

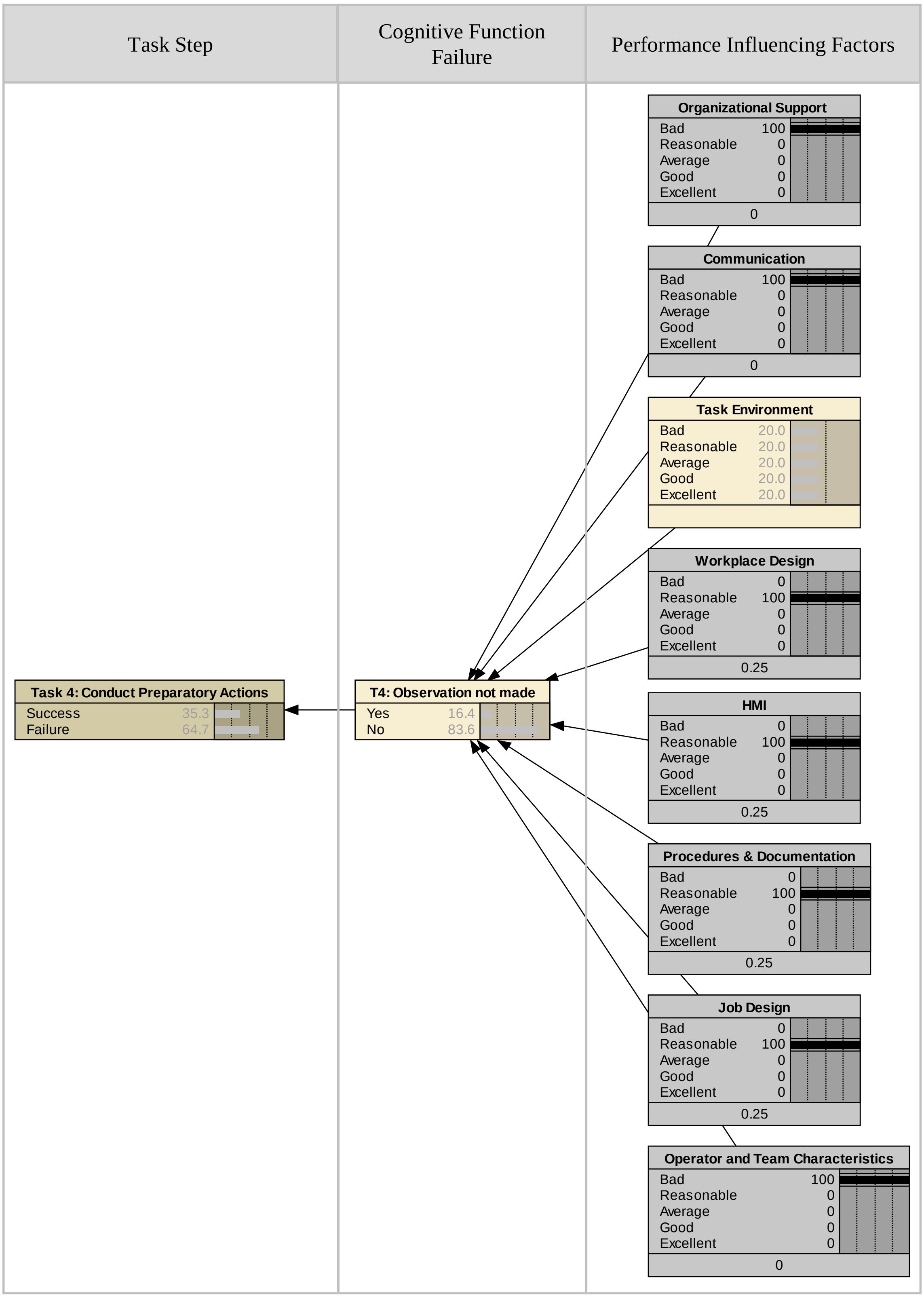


Fig. 37. BN framework for task 4: Conduct Preparatory Actions – Observation not made

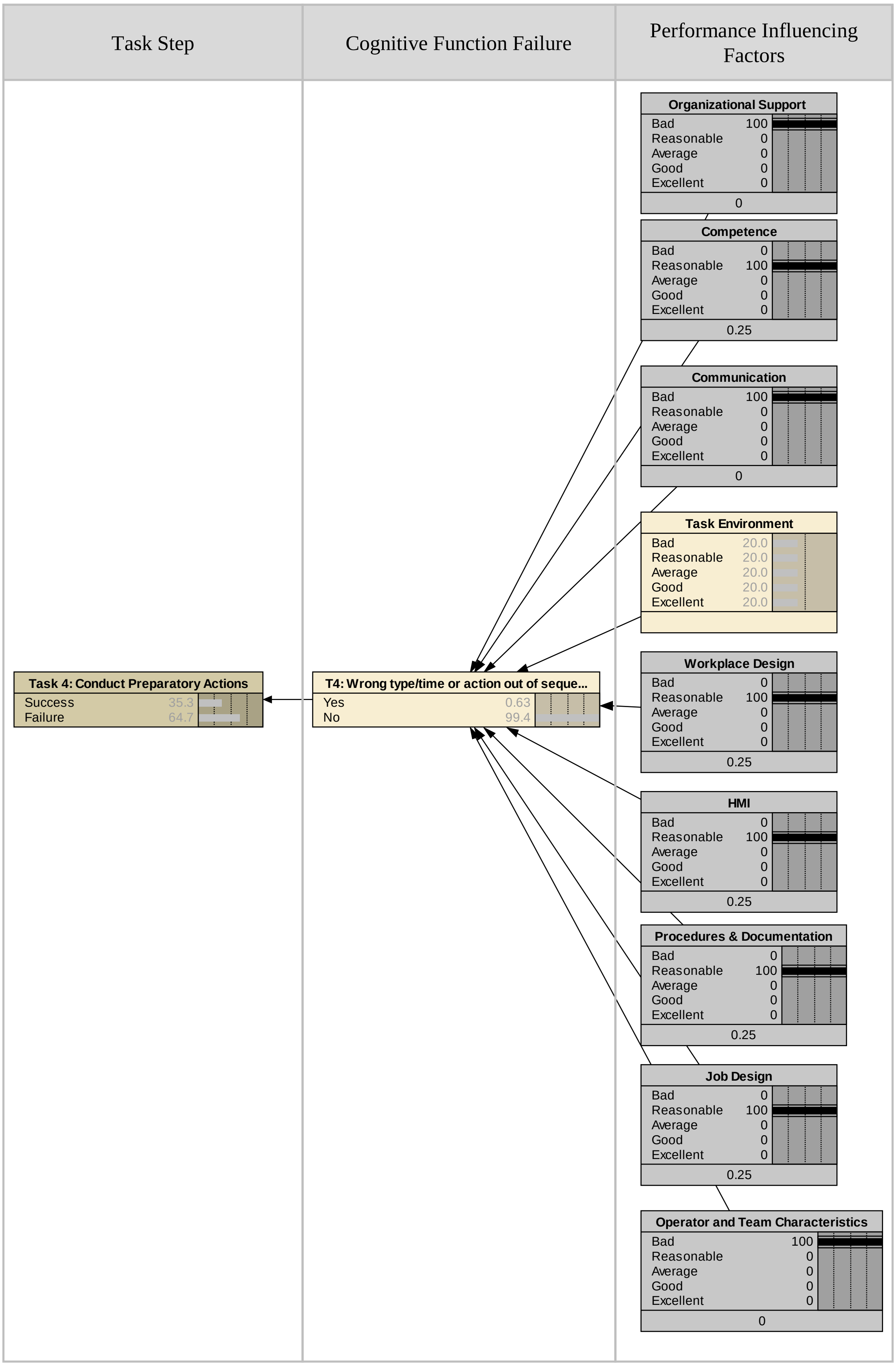


Fig. 38. BN framework for task 4: Conduct Preparatory Actions – Wrong type/wrong time/Action out of sequence

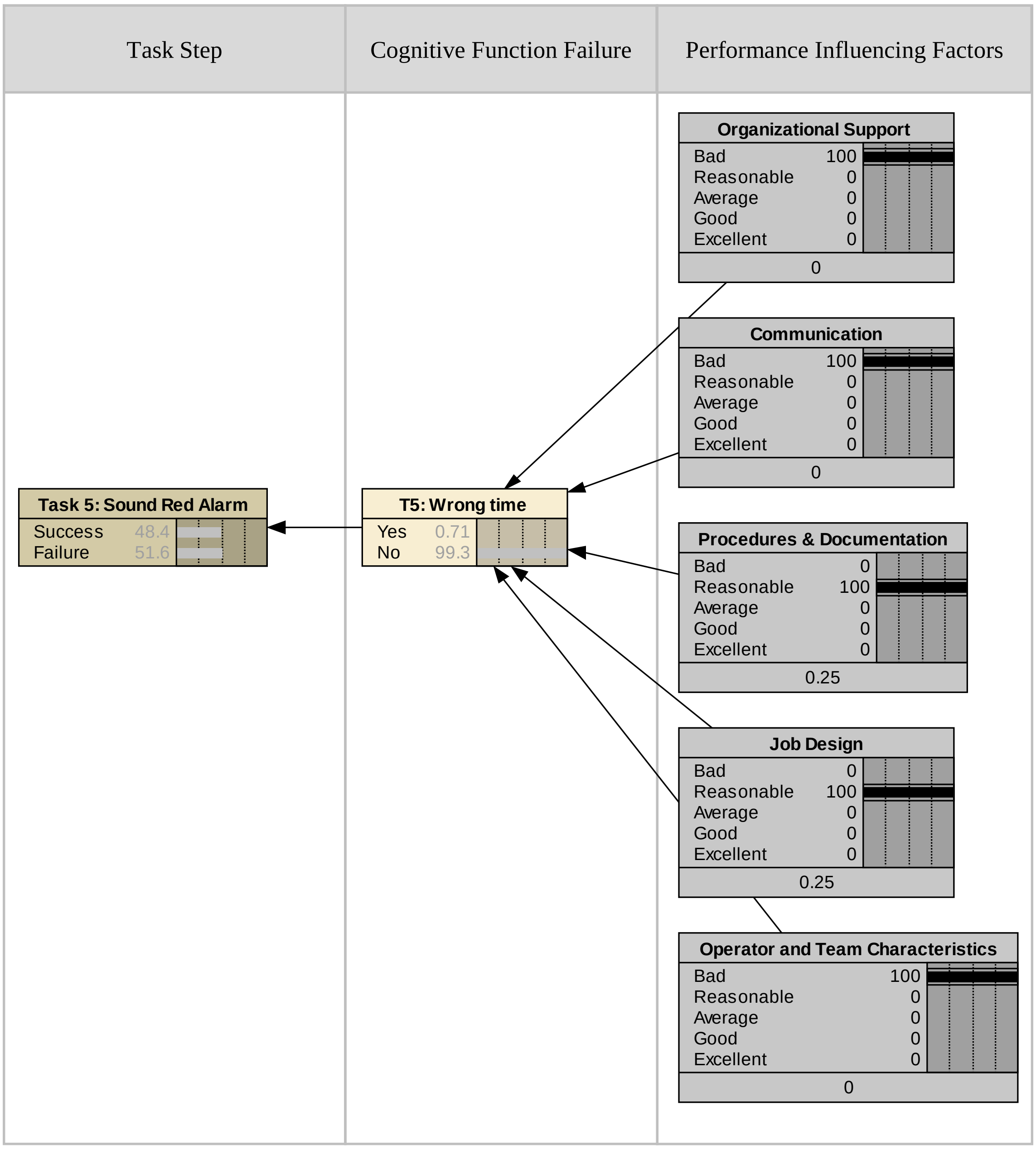


Fig. 39. BN framework for task 5: Sound Red Alarm

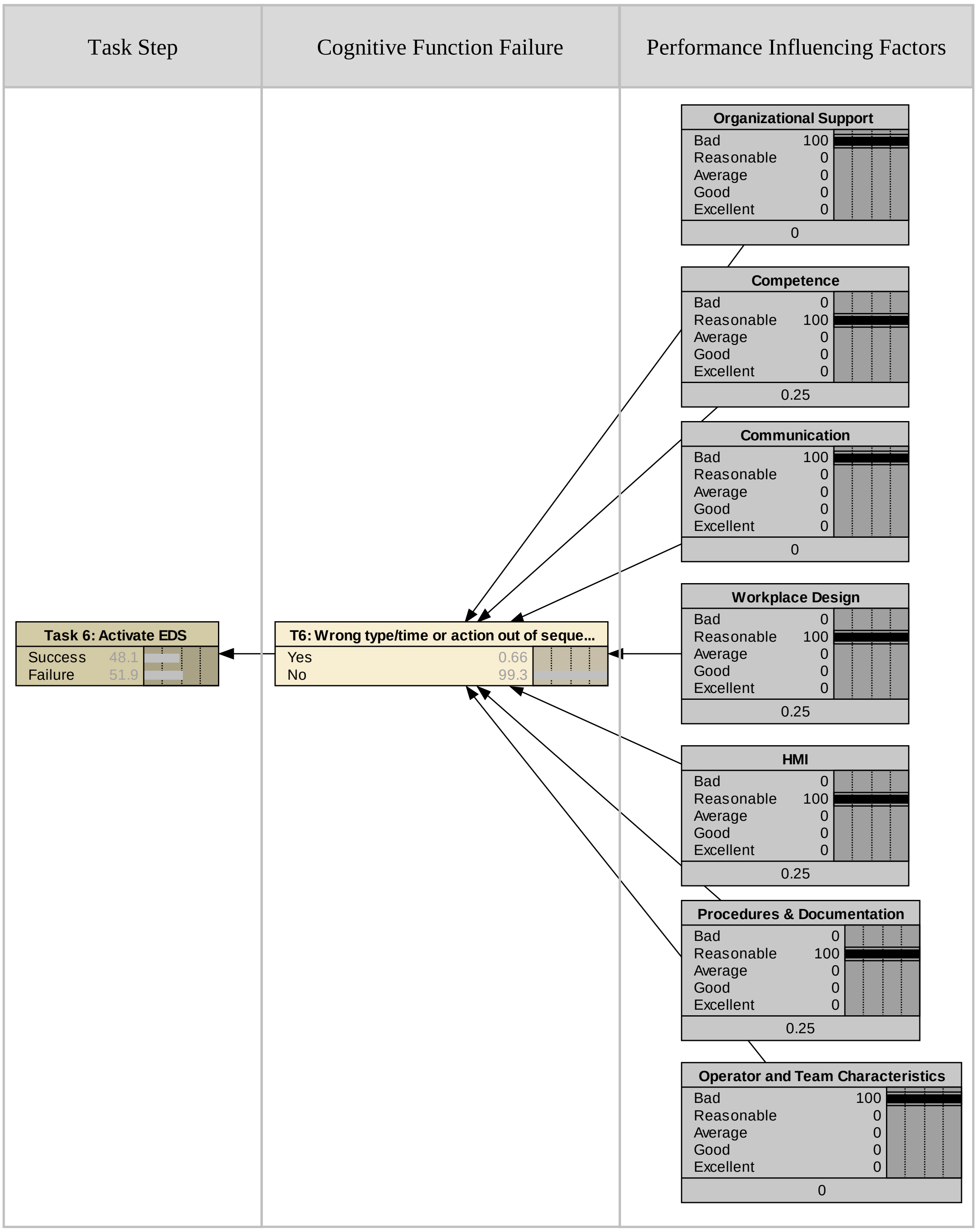


Fig. 40. BN framework for task 6: Activate EDS

With the aim of conducting a quantitative analysis, the Conditional Probability Tables are filled using deterministic and probabilistic relationships. The CPTs related to the task steps are deterministic following the type of logic gates established in the fault tree model (OR gate). The CPTs for the Cognitive Function Failures are determined in a probabilistic way using the equations from the mathematical model [Eqs. (2) to (4)].

Typing the equations in the Netica software, the CPTs for cognitive function failures are filled up automatically. In turn, the PIFs are root nodes and their state is entered manually according to the scored degree of compliance.

Fig. 41 displays an example of a CPT related to the generic outcome event translated from fault trees and, consequently, treated as a deterministic relationship.

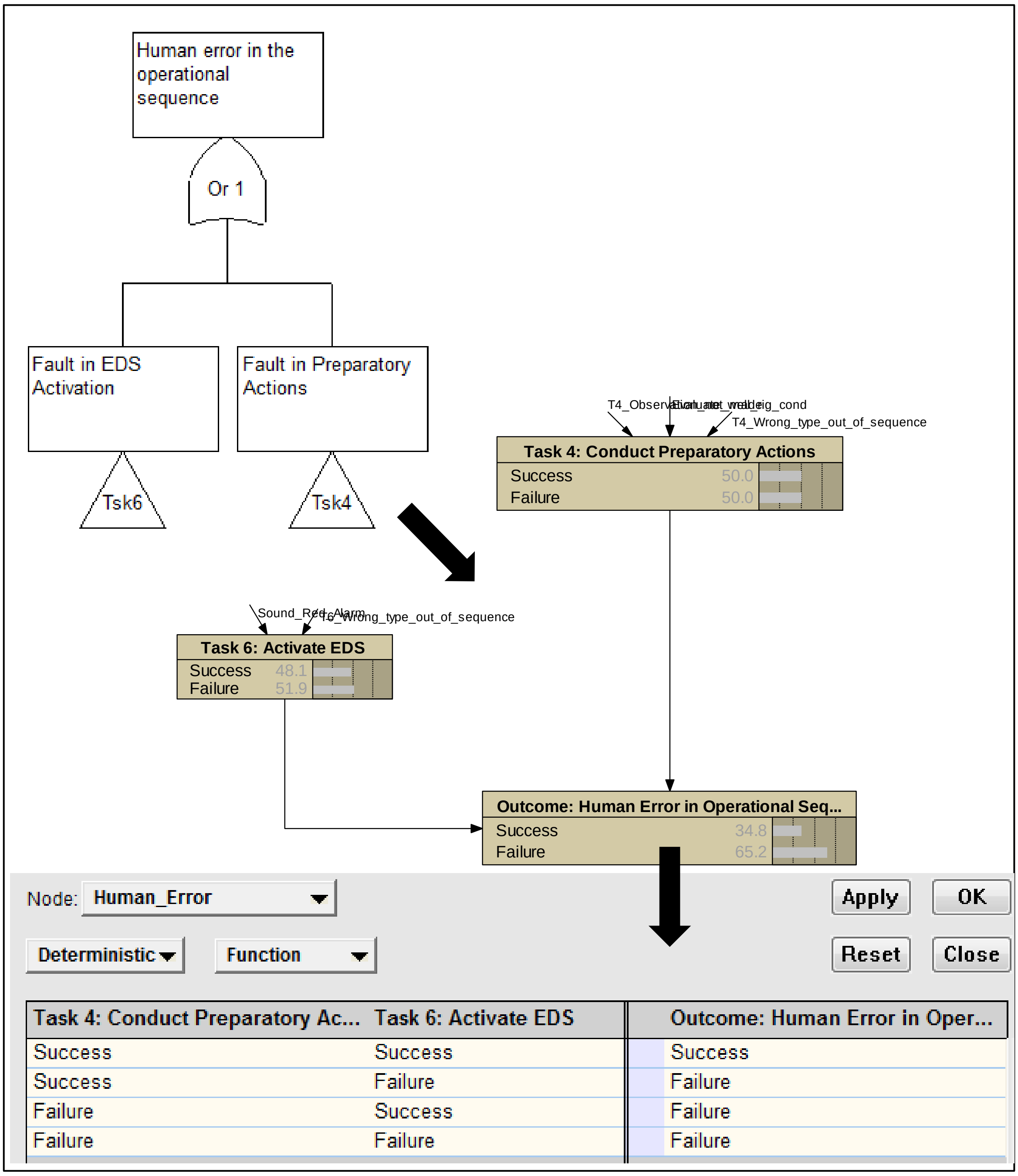


Fig. 41. Example of filled CPT with deterministic relationship for outcome event: 'Human error in operational sequence'

It is worth mentioning that, in practice, the final result of human error in operational sequence is not adequately represented by a deterministic relationship. Indeed, the influence of the states of preparatory actions and EDS activation has a probabilistic relationship with the outcome event of human error. However, given that a generic operational sequence was considered, conservative hypotheses were assumed and the final positive result is dependent on the successful states of the both preceding steps. In case of a specific analysis with detailed description of tasks/subtasks of a given type of well operation and for a particular rig, the CPT can be filled up with probability values instead of deterministic functions.

Fig. 42 illustrates the application of the equations for filling-up CPTs related to the cognitive function failures.

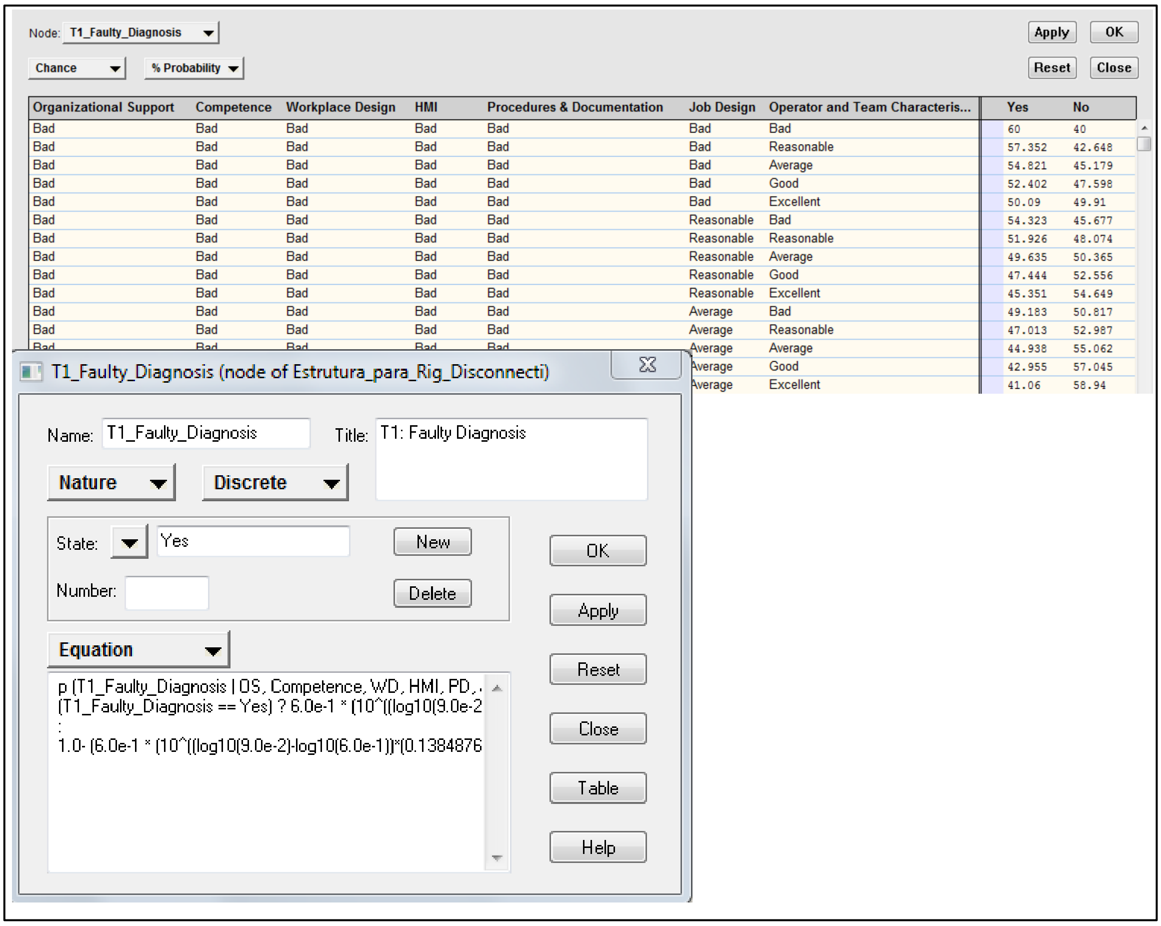


Fig. 42. Example of filled CPT with probabilistic relationship for task 1, CFF Faulty diagnosis, following the established equations

Fig. D-1 in Appendix D illustrates the BN framework with three regions representing the operational sequence. The first two regions represent the triggering events - ‘Loss of minimum DP system redundancy’ and ‘DP rig reaches red condition’ – until the intermediate events of ‘Activate EDS’ and ‘Conduct Preparatory Actions’. The third region is the outcome event: ‘Human Error in Operational sequence’. The complementary part is related to the relationship between cognitive function failures and PIFs. Fig. D-2 in Appendix D shows the overview of the BN model proposed. This structure helps to visualize the multiple levels of analysis.

7.4. Comparison with CREAM Influence Model

The main characteristic of the CREAM methodology is to point out the importance of the context and cognition to the resulting performance of the operator at the sharp end. The context is described in terms of the entitled Common Performance Conditions (CPCs). The nine CPCs prescribed in such technique are assessed in levels that represent the positive, negative or neutral influence on cognitive function failures. In CREAM, the CPCs influence is computed multiplying a global factor by HEP basic value. In turn, the individual weighting factors are modified according to the CPC level and the cognitive function associated. The global factor is obtained from the product of all individual weighting factors.

For comparison purposes between the CREAM influence model and the mathematical model adopted in this work, an analysis was carried out considering the available information about the Macondo well blowout. The CPCs from CREAM were scored based on the evaluation of the degree of compliance per PIF and considering an analogy between them. The equivalence was based on the definitions and links between CPCs and PIFs.

Table 44 presents the corresponding weighting factors for the nine CPCs (differentiated per cognitive function) considering the associated definitions from CREAM (HOLLNAGEL, 1998). Note that in some cases the assignments of two PIFs generate a unique evaluation of analogous CPCs, and the opposite is also true, a PIF can be break down into two or more CPCs with different levels attributed. It is worth mentioning that there is no an exact comparison between CPC levels and degree of compliance of PIFS due to the different number of levels that characterize them and because there are no definition about CPC levels in CREAM. Therefore, this is an approximation for example purposes.

Table 44 Rating of attributes for Deepwater Horizon rig (degree of compliance) and CPC levels (HOLLNAGEL, 1998)

PIFs evaluated (degree of compliance)		Analogous CPC		Weighting factors (HOLLNAGEL, 1998)			
ID	rating	ID	Level	Obs	Int	Plan	Exe
Organizational Support	Bad	Adequacy of organization	Deficient	1	1	2	2
Competence	Reasonable	Adequacy of training and experience	Inadequate	2	5	5	2
Communication	Bad	No correspondence	-	-	-	-	-
Task Environment	Not evaluated	Working Conditions	Incompatible	2	2	1	2
Workplace Design	Reasonable						
HMI	Reasonable	Adequacy of HMI and operational support	Tolerable	1	1	1	1
Procedures & Documentation	Reasonable	Availability of procedures/plans	Inappropriate	2	1	5	2
Job Design	Reasonable	Number of simultaneous goals	More than capacity	2	2	5	2
		Available time	Temporarily inadequate	1	1	1	1
		Time of day (circadian rhythm)	Night-time (unadjusted)	1.2	1.2	1.2	1.2
Operator & Team Characteristics	Bad	Crew collaboration quality	Deficient	2	2	2	5
		Total influence of CPCs ($\prod \omega_i$)		38.4	48	600	192

The subsequent step according to CREAM methodology is to multiply the individual weighting factors by every CPC evaluated so as to obtain a global factor for each type of cognitive function. The global weighting factors were computed and the result is presented in the last row of Table 44. The global factor is multiplied by the cognitive function probabilities in an attempt to get a modified HEP demonstrated in Table 45. As can be observed, the global factor reaches high values and can impact significantly the HEP.

Table 45 Modified HEPs using global factor for each CFP. Adapted from CREAM (HOLLNAGEL, 1998)

Failure Types	HEP (basic value)	Global factor	Adjusted HEP	Final value
T0: Fault in Planning (Inadequate Plan/Priority error)	1.0E-2	600	6 [a]	1.0
T1: Fault in observation (Observation not made/Wrong identification)	7.0E-2	38.4	2.688 [a]	1.0
T1: Faulty Diagnosis	2.0E-1	48	9.6 [a]	1.0
T2: Missed Action	3.0E-2	192	5.76 [a]	1.0
T3: Decision error/Incorrect prediction	1.0E-2	48	4.8E-1	4.8E-1
T4: Observation not made	7.0E-2	38.4	2,688 [a]	1.0
T4: Wrong type/time or action out of sequence	3.0E-3	192	5.76E-1	5.76E-1
T5: Wrong time	3.0E-3	192	5.76E-1	5.76E-1
T6: Wrong type/time or action out of sequence	3.0E-3	192	5.76E-1	5.76E-1

[a] For some cases, the modified HEP was truncated because it exceeded the maximum allowable value of probability.

The adjusted data was input to the BN model and the results are shown in Table 46. As the global factors are excessively high, the modified HEP provided high values, consequently most of the failure probabilities for each task becomes equal to 100%. Finally, the probability of the general consequence ‘Human error in operational sequence’ follows this trend and was computed with a probability of 100%.

Table 46 Failure probability per emergency disconnection task modified by CPCs

Task Step	Failure Probability
Task 0: Planning Actions to Emergency Disconnection	1.00
Task 1: Monitor Rig and Metocean parameters	1.00
Task 2: Communicate Rig Conditions from DP bridge to Drill floor	1.00
Task 3: Evaluate current conditions and decide on action line	1.00
Task 4: Conduct Preparatory Actions	1.00
Task 5: Sound Red Alarm	1.00
Task 6: Activate EDS	1.00
Outcome: Human error in operational sequence	1.00

The aforementioned result demonstrated an issue already emphasized by BEDFORD (2013). The influence model proposed by HOLLNAGEL (1998) to incorporate the effect of CPCs deal with high values of probability generating results near or higher than unity (100%). As will be demonstrated in the following section, the proposed approach helps to overcome the shortcomings identified throughout this first analysis, especially the limitation to incorporate conditional links and multi-state events of antecedents found in the mapping process (Section 6.4) and the high values found for probability failures.

7.5.Quantitative Results and Sensitivity Analysis

As a primary test, the network was compiled considering the same data and framework used in section 6.5 for the FT model, entering only the HEP basic value from CREAM (excluding PIFs evaluation). It results in the same value of failure probabilities pointed out in Table 14 for each task and for the outcome event. The referred results are presented in the last column of Table 47.

Additionally, three cases were analyzed aiming to observe the sensitivity to variations in Performance Influencing Factors states: (i) base case from Macondo well blowout considering the degree of compliance scored in Section 6.7.2; (ii) worst case considering all the PIFs in bad state; (iii) best case with every PIF in excellent conditions. In the context of excellent conditions, the index of human factors modification tends to reach unit value and the HEP approximates to the lower bound value. On the other hand, in completely bad conditions, the index reaches null value and the HEP tends to the upper bound value. The failure probability for each task and outcome event is presented in Table 47.

Table 47 Failure probability per emergency disconnection task

Task Step	Best case (Excellent conditions)	Base Case (Macondo)	Worst case (Bad conditions)	Without context description
Task 0: Plan Actions to Emergency Disconnection	1.000E-3	5.286E-2	1.000E-1	1.000E-2
Task 1: Monitor Rig and Metocean parameters	1.082E-1	5.125E-1	6.980E-1	2.560E-1
Task 2: Communicate Rig Conditions (from DP bridge to Drill floor)	1.305E-1	5.310E-1	7.101E-1	2.783E-1
Task 3: Evaluate current conditions and decide on action line	1.322E-1	5.759E-1	7.652E-1	2.927E-1
Task 4: Conduct Preparatory Actions	1.504E-1	6.475E-1	8.243E-1	3.442E-1
Task 5: Sound red alarm	1.091E-1	5.159E-1	7.007E-1	2.582E-1
Task 6: Activate EDS	1.100E-1	5.191E-1	7.034E-1	2.605E-1
Outcome: Human error in operational sequence	1.521E-1	6.523E-1	8.274E-1	3.481E-1

The consideration of rig context (PIFs) increases the failure probability of outcome event almost twice when compared with the base case of Macondo, i.e., it returns a more conservative and realistic result. The sensitivity to alterations in PIFs is significant. PIFs in excellent conditions can reduce the failure probability to less than a quarter of the original value of the base case and bad conditions can increase it approximately by 30%.

Once more, it is worth emphasizing that the high values of failure probability found, even for the best case of PIF states, may be related to the first assumption of conservative hypotheses applying OR-gate relationships throughout the model in fault tree and Bayesian network and disregarding recovery actions. Such recovery actions range from supervisory roles, double-check in operators actions, possibility of using redundant equipment, back up and secondary systems (acoustic control system, ROV intervention panel), possibility of changing the EDS mode for safer disconnection condition, among others.

Additionally, as mentioned in Section 7.3, the consideration of deterministic relationship for outcome event may not be realistic. The human error in operational sequence is dependent on a probabilistic relationship between preparatory actions and EDS activation what could be analyzed considering specific well operation and rig. Moreover, it is important to further combine the results with analyses regarding equipment failure and the probability of triggering events: loss of minimum DP system redundancy and red alarm condition.

Additional sensitivity analysis was performed considering variations in human error probability of the cognitive function failures since it was used a generic database from CREAM (HOLLNAGEL, 1998). Such analysis was performed changing the HEP for a given cognitive function failure, one at a time, and observing the result for the outcome event by means of the BN model. Two different groups of analysis were made, one considering only the variation on HEP basic value in the network (not considering influence of PIFs) and the other modifying the lower and upper bounds encompassing PIFs evaluation for the base case of Macondo. Figs. 43 and 44 display the resulting graphs. Each colored curve represents a specific cognitive function failure discriminated in the caption at the bottom of the figure. In Fig. 44, the flat region on the right side of line representing the cognitive function failure ‘faulty diagnosis’, is explained since the maximum allowable value for the upper bound is reached and cannot be exceeded.

Both figures demonstrate the high influence of the cognitive failures related to observation function and faulty diagnosis, what can be somewhat explained by the high HEP basic values attributed to interpretation and observation cognitive functions. The HEP for ‘observation not made’, ‘wrong identification’ and ‘faulty diagnosis’ reach values in magnitude of 1E-2 and 1E-1, respectively, which influences significantly the final value of the outcome event. It would be important to revisit these values proposed by HOLLNAGEL (1998) and possibly calibrate them. Some kind of Verification & Validation assessment is in development by researchers in Liverpool University (MORAIS, 2018b) and a proper database with human error probabilities for rig operational is suggested for future works.

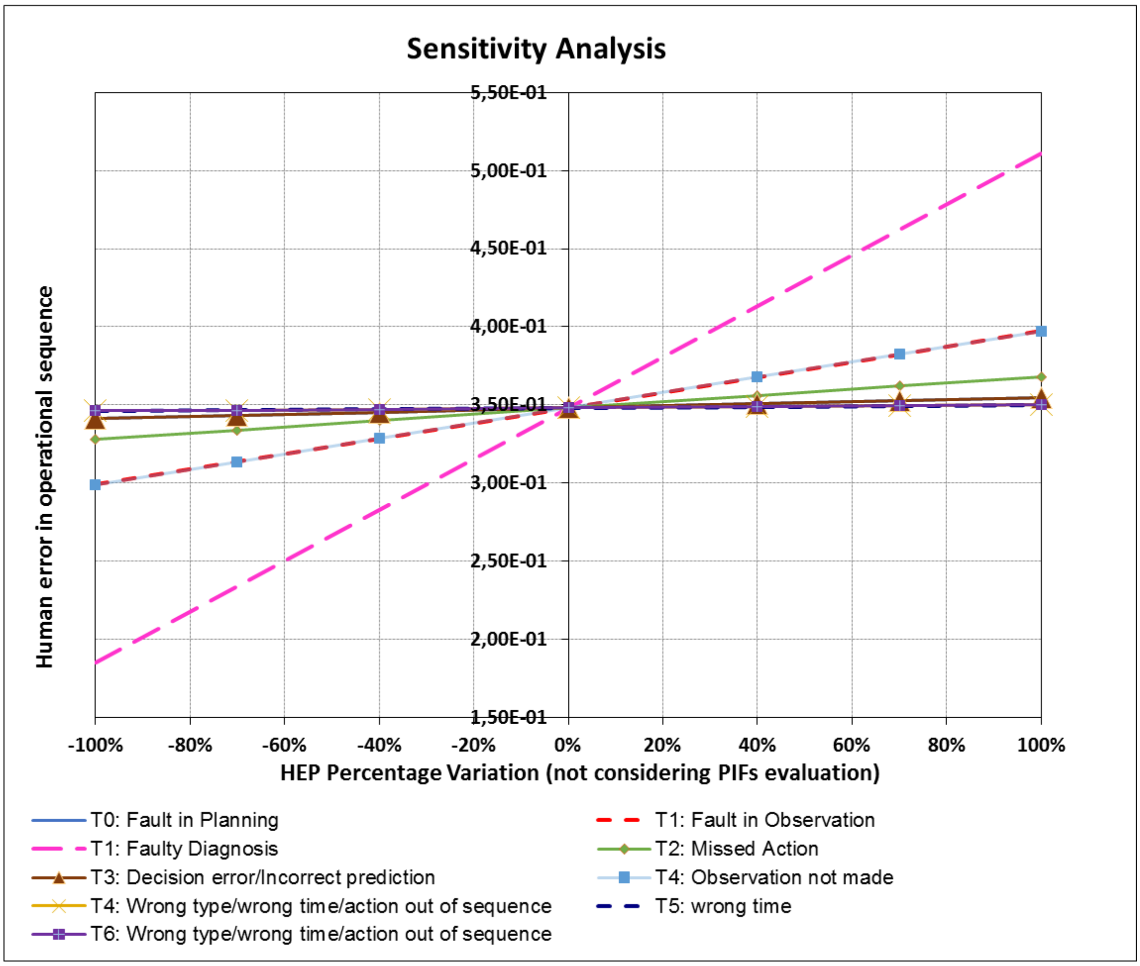


Fig. 43. Sensitivity analysis in relation to variations in HEP basic value not considering PIFs

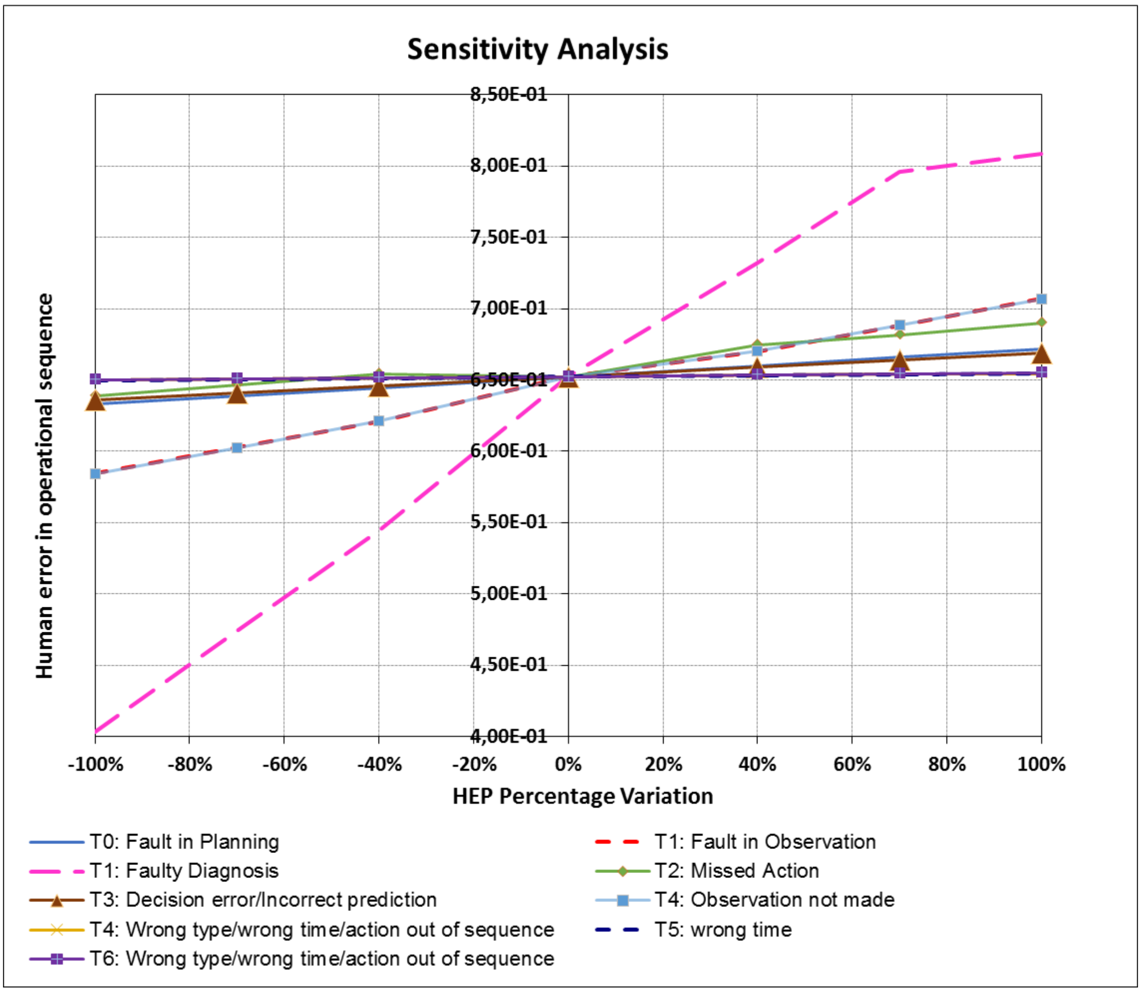


Fig. 44. Sensitivity analysis in relation to variations in HEP bounds with PIFs scored for the base case of Macondo

Chapter 8. Conclusions

This chapter presents the originality and main contributions of the proposed methodology. Concluding remarks emphasizes the main results and benefits observed. Finally, future developments are listed considering improvements and complementation of what was presented in terms of results, scope and modeling capacity.

8.1. Originality and Additional Contributions

The originality of this work is founded upon the methodology proposed that combines a cognitive framework, a mathematical model for human factors consideration and a final model in Bayesian network. In fact, the three techniques already exist, but the combination of them, adaptions, additional intermediate steps and the way of implementation constitute a different approach. The following characteristics may be considered as distinctive aspects:

- Causal diagrams developed for each cognitive function failure considering the links from CREAM classification scheme;
- The analogies between the causal events from CREAM classification scheme and Performance Influencing Factors for failure probability quantification purposes;
- The evaluation of PIFs influence on failure probability according to the associated cognitive function combining HOLLNAGEL's (1998), KARIUKI's (2007) and RIBEIRO's et al. (2016) approaches;
- The use of database from major accidents that use the CREAM classification scheme to evaluate one of the weights that characterizes the influence of PIFs considering accident history;
- The adaption of the PIF score based on the sum of the rating of attributes, rather than on direct assignment of level of maturity of factors;

- Extension of the evaluation of the degree of compliance for PIFs, conceived firstly to be employed in an audit process and, in this case, applied for the use in accident investigation;
- Define applicable PIFs for each cognitive function failure from the causal diagrams.

Furthermore, it is important to mention as additional contributions of this work:

- Selection and definition of set of Performance Influencing Factors from extensive literature survey and based on peculiarities of the application scenario analyzed;
- Selection and adaption of list of attributes associated to each PIF based in literature survey;
- Mathematical model that uses Human Error Probability (HEP) database (basic value and bounds) from CREAM (HOLLNAGEL, 1998) combined with KARIUKI's (2007) approach that avoids extrapolate the admissible values of probability;
- Graphical representation of PIFs contribution for each cognitive function;
- Extension of CREAM classification scheme incorporating links not mapped in the original version;
- Build Bayesian networks model as multilevel components that allows incorporating findings on attributes/PIFs (evidences) in order to update the network results;
- Use of equations of mathematical model as filling-up algorithm to complete automatically Conditional Probability Tables of Bayesian networks in a straightforward way.

8.2. Concluding Remarks

Regarding the objectives mentioned in Section 1.2, the proposed methodology met all the established directions. The framework was based on the cognition model. The set of human factors has been selected from literature review and their weighting factors and score is quantified considering the influence model adapted from KARIUKI

(2007) and RIBEIRO et al. (2016). The updates in probabilities are possible through inferences in Bayesian network.

The exploration of the CREAM classification scheme has proved to be helpful for this kind of analysis given that it provides a starting point and mapping of important connections between events. Moreover, it is also flexible in view of the possibility to extend the scheme to keep coherence and adapt to the domain of analysis. Furthermore, it is possible to systematize the search for antecedents or effects by means of programming tools. For example, the whole classification scheme (with extended categories) was inserted in a worksheet with predetermined links that help moving towards the searching direction.

One of the main advantages of the mathematical model adopted is to keep the modified HEP within the lower and upper bounds defined in the database, which avoids the recognized issue with CREAM formulation of probabilities higher than 100% and truncated values. The data obtained were inserted into the BN model. It is important to mention that the equations from the mathematical model play a role of filling-up algorithm. Such equations help filling the CPTs in a straightforward way encompassing all the domain of possible states of PIFs.

The incorporation of the concept of level of maturity adapted from KARIUKI (2007) evaluated per attribute and scale of degree of compliance for each PIF was also helpful for better defining context state. In CREAM (HOLLNAGEL, 1998), the CPC levels is described in terms of linguistic variables whose conceptual differences may be difficult to differentiate, becoming dependent on the analyst. The description of maturity levels may reduce the subjectivity taking more elements/evidences for comparison and definition of PIFs states.

It is important to emphasize that the high values of failure probability found may be partially related to the first assumption of conservative hypotheses. This suggested that modelling of failure events was characterized by deterministic relationships represented by OR-gates between task steps and cognitive function failures. Hence, the outcome event represents the failure at any task step. No recovery actions were considered and the task analysis was based in a high-level description of the operational sequence. Therefore, aiming to perform complete quantitative analysis, it is necessary consider a breakdown of task steps, for example, using hierarchical task analysis and include equipment failure, as well as, incorporate the probability of triggering events:

loss of minimum DP system redundancy and rig reaches red condition.

Sensitivity analyses were also carried out with modifications in the input data of human error probability for every cognitive function failure. The events related to failures in observation and faulty diagnosis presented the major influence, what can be explained to some extent by the high values of HEP from the database. CREAM provides a generic database. If specific data was gathered to the type of activity studied, the number found could be reduced. It depends on the nature of the activity and expected variability.

Finally, it is important to highlight the observed advantages of using Bayesian networks for human reliability analysis. Among the benefits, one may point out the capacity to model explicitly uncertainties, multistate nodes and conditional relationships between failure events and Performance Influencing Factors. Additionally, BN allows to perform inferences about state of any node of the network through evidences on the states of other nodes, what can be used for retrospective, prediction and other types of inference (e.g. intercausal). Although the well-known shortcomings in BN modelling regarding the amount of data necessary to fill up Conditional Probability Tables, the use of equations to automatically compute the influence of PIFs and fill the CPTs overcome this potential issue.

To sum up, in this case study, it is possible to observe how beneficial it is to take into account the characteristics of the installation to capture the background that can contribute to reduce or increase the failure probability. Furthermore, the methodology allowed differentiating the effects of PIFs according to the cognitive function involved.

8.3. Future Works

For future work, it is recommended estimating the weights of each attribute associated to PIFs in order to adopt a weighting score for the degree of compliance. These weights can be defined by means of expert elicitation or repeating the same methodology applied to the PIFs of three degrees of influence, in case of enough information available for this. Moreover, the development of a questionnaire can be formulated to help judging the level of maturity of attributes.

It is recognized that there could be sensible differences in PIFs quantification according to the rig team and its workplace. Generally, the work conditions can significantly modify and influence in different degrees the cognitive function failures.

For example, the evaluation of PIFs for DP bridge crew and drill floor crew can be considerably different. In this work, this differentiation was not possible because the available information on reports about Macondo well blowout was not sufficient to that. However, this can be accomplished in future work associated to an auditing process, generating more calibrated results.

An extension of PIFs to cover regulatory & statutory influences such as presented by THEOPHILUS et al. (2017) could be valuable, especially when dealing with the evaluation of maintenance and inspection programs and other internal policies. Furthermore, new application scenarios could be studied. For example, well control event, operations in drill floor, Managed Pressure Drilling and other critical operations/systems, as well as a more advanced version of the task description of operational sequence presented herein considering recovery actions and a hierarchical task analysis method.

Additionally, it would be important to obtain HEP basic values for the application scenario. This can be accomplished through the development of proper database for the kind of installation and operation analyzed or by means of further advances in Verification and Validation of comprehensive database, such as MATA-D presented by MOURA (2015, 2016).

Finally, this approach can be integrated to system reliability for a complete risk assessment. The BN model is flexible and robust enough to incorporate data from different sources and allows including uncertainty in a straightforward way and update estimations. Then, the network can be built in order to include human and technical aspects.

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Appendix A. Literature Survey of Human Factors – Purpose of Performance Influencing Factors

Table A-1. Purpose of Performance Influencing Factors based on literature review

<table>
<tr><th rowspan="5">Factors</th><th colspan="10">Source</th></tr>
<tr><th>CREAM (HOLLNAGEL, 1998)</th><th>PIHFAT KARIUKI, 2007</th><th>FRAM HOLLNAGEL, 2012</th><th>LADAN and TURAN, 2012</th><th>RISK OMT VINNEM et. al, 2012,
GRAN et al. 2012</th><th>ALVARENGA et al., 2014</th><th>PALTRINIERI et al., 2016</th><th>RIBEIRO et al, 2016</th><th>RISK OMT STRAND and LUNDTEIGEN (2016, 2017)</th><th>Proposal</th></tr>
<tr><td>Adequacy of organization</td><td>Organization</td><td>Quality and support of the organization</td><td>Welfare/ logistics</td><td>Management_general (level 2)</td><td>Available Staffing and resources

Quality of training

Quality of procedures and administrative controls

Accident sequence diversions/deviations</td><td>Work processes</td><td>Safety Culture / Behavior Based Safety

Management of Change / Emergency Preparedness and Response / Qualitative Hazard Analysis / Quantitative Risk Assessment / Safety Systems</td><td>Management_ general (level 2)</td><td>Organizational Support</td></tr>
<tr><td rowspan="2">Working Conditions</td><td>Workplace design</td><td rowspan="2">Conditions of work</td><td rowspan="2">Environment</td><td rowspan="2">Design</td><td>Accessibility and operability of the equipment to be manipulated

Special fitness needs

Ergonomic quality of human-system interface

Need for special tools</td><td></td><td>Control Center Design/Process Equipment Design/Process Control Systems/Project Planning, Design
and Execution</td><td rowspan="2">Design</td><td>Workplace Design</td></tr>
<tr><td>Task Environment</td><td>Environmental factors</td><td></td><td>Environmental factors</td><td>Task Environment</td></tr>
</table>

(continued)

	Source									
	CREAM (HOLLNAGEL, 1998)	**PIHFAT KARIUKI, 2007**	**FRAM HOLLNAGEL, 2012**	**LADAN and TURAN, 2012**	**RISK OMT VINNEM et. al, 2012, GRAN et al. 2012**	**ALVARENGA et al., 2014**	**PALTRINIERI et al., 2016**	**RIBEIRO et al, 2016**	**RISK OMT STRAND and LUNDTEIGEN (2016, 2017)**	**Proposal**
Factors	Adequacy of HMI and operational support	Human System Interface	HMI and operational support	Logistics/supervision	HMI	Availability and clarity of instrumentation	Ergonomics/human-machine interface	Human Computer Interface/Safe Havens/Labelling	HMI	HMI
	Availability of procedures/plans	Information (attribute: Procedures and procedure development, Documentation)	Availability of procedures and plans	Procedure	Disposable work descriptions Governing Documents Technical Documentation	Quality of procedures and administrative controls	Procedures	Procedures	Disposable work descriptions Governing Documents	Procedures and Documentatio n
	Number of simultaneous goals	Job design (attributes: Work schedules, Staffing, Shifts and overtime, Manual handling)	Number of goals and conflict resolution	Stress Logistics (scheduling) Circadian rhythms	Workload Time pressure	Workload, time pressure and stress	Complexity/Stress	Workloads and Staffing Levels/Shift work issues/Manual Materials Handling	NA	Job Design
	Available time		Available time and time pressure				Available time			
	Time of day (circadian rhythm)		Circadian rhythm and stress		NA				NA	
	Adequacy of training and experience	Information (attribute: Training) Operator characteristics (attribute skills and knowledge)	Training and experience (competence)	Training/crew quality audit (skills)	Competence	Quality of training	Experience/Training	Training	Competence	Competence

(continued)

Factors	Source									
	CREAM (HOLLNAGEL, 1998)	**PIHFAT KARIUKI, 2007**	**FRAM HOLLNAGEL, 2012**	**LADAN and TURAN, 2012**	**RISK OMT VINNEM et. al, 2012, GRAN et al. 2012**	**ALVARENGA et al., 2014**	**PALTRINIERI et al., 2016**	**RIBEIRO et al, 2016**	**RISK OMT STRAND and LUNDTEIGEN (2016, 2017)**	**Proposal**
	Crew collaboration quality	NA	Team collaboration quality	Crew quality audit/supervision	NA	NA	NA	NA	NA	Operator & Team Characteristics
	NA	Operator characteristics (attributes: Fitness for duty, Attention/Motivation)	NA	NA	NA	Team available and time required to complete the act including the impact of concurrent activities Crew dynamics and characteristics Complexity of the required diagnosis and response	Fitness for duty	NA	NA	
	NA	NA	Availability of resources	NA	NA	Available Staffing and resources	NA	NA	NA	Organizational Support
	NA	Information (attribute: Communication)	Quality of communication	Communication	Communication	Communication (strategy and coordination) and whether one can be easily heard	NA	Communication/ Documentation Design and Use	Communication	Communication
	NA	NA	NA	NA	NA	NA	NA	Remote Operations	NA	NA

(continued)

Factors	CREAM (HOLLNAGEL, 1998)	PIHFAT KARIUKI, 2007	FRAM HOLLNAGEL, 2012	LADAN and TURAN, 2012	RISK OMT VINNEM et. al, 2012, GRAN et al. 2012	ALVARENGA et al., 2014	PALTRINIERI et al., 2016	RIBEIRO et al, 2016	RISK OMT STRAND and LUNDTEIGEN (2016, 2017)	Proposal
	NA	NA	NA	NA	NA	NA	NA	Maintenance / Safe Work Practices and Permit to Work	NA	Organizational Support
	NA	NA	NA	NA	NA	NA	NA	Incident Investigation	NA	Organizational Support
	NA	NA	NA	NA	Supervision	NA	NA	NA	Supervision	Organizational Support
	NA	Operator characteristics (attribute: Attention/motivation)	NA	NA	Work motivation	NA	NA	NA	NA	Operator & Team Characteristics
	NA	NA	NA	NA	Management_ competence (level 2)	NA	NA	NA	Management_ competence (level 2)	Organizational Support Competence
	NA	NA	NA	NA	Management_ technical (level 2)	NA	NA	NA	Management_ technical (level 2)	Organizational Support Workplace Design
	NA	NA	NA	NA	Management_ task (level 2)	NA	NA	NA	Management_ task (level 2)	Organizational Support Job Design
	NA	NA	NA	NA	Management_ information (level 2)	NA	NA	NA	Management_ information (level 2)	Organizational Support Procedures and Documentation

Appendix B. Level of Maturity of Attributes (original version from KARIUKI, 2007 and revised/complemented with API, 2001, IOGP, 2012, LADAN and TURAN, 2012, HSE, 2017)

Table B-1. Level of Maturity for Attributes associated to PIF Organizational Support, attribute Organizational learning (audit and reviews)

PIF ORGANIZATIONAL SUPPORT – Attribute Organizational learning (audit and reviews)				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
The company does not have a policy for organizational learning. Minimal regulatory requirements are met, data are collected aiming to comply with statutory regulations, but not used for safety performance enhancement.	There is a general understanding of organizational learning, but audits and reviews exist only to comply with legal and other subscribed requirements. Operations are usually audited after serious or fatal accidents. May be audited by regulators or audit contractors, but do not usually audit themselves, and if they do, omit less risky areas. Audits and reviews are seen as a punishment.	Organizational learning policy exists in a written form with clear targets and objectives but there is no evidence of the objectivity and independence of the auditors. There is a regular, scheduled audit program, but it is superficial. It concentrates on high hazard areas.	Organizational learning policy exists in a written form with clear targets and objectives with evidence of the objectivity and independence of the auditors. There is extensive audit program including cross auditing within the organization. Audits results are important for the management reviews. Enough information and documentation are available for management at the review period.	In addition to level 4, organizational learning policy and procedures are periodically reviewed and revised in order to look for continuous improvement. Reviews are very complete and they include all decisions and actions leading to changes in policy, targets, objectives or management system. There is good follow-up of audits and search for non-obvious problems with self and cross audits. There are fewer audits of hardware and systems, more at the level of behaviors.

Table B-2. Level of Maturity for Attributes associated to PIF Organizational Support, attribute Line management and supervision/Resources management

PIF ORGANIZATIONAL SUPPORT – Attribute Line management and supervision/Resources management				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
The company does not have a specific plan or policy for supervision or providing with sufficient amount of equipment, protections, material, procedures, and personnel. Spares and tools are not available for servicing equipment. Crew struggle to manage. Operational resources (allocation) are denied or sub-standard items provided.	There is a general understanding of supervision and line management, but there are not any clear definitions of either line management or supervisory roles and responsibilities. Resources are partially made available and without reserve for emergency.	There is a clear definition of line management and supervisory roles and responsibilities, but still resources are not always available or sufficient when required. The suitability of people for supervisory roles is not checked and they do not receive a specific training on the matter.	There is a clear definition of line management and supervisory roles and responsibilities. Resources are available and accessible when required. Suitability of people for supervisory roles is checked and they are specifically trained for it. Responsible for line management and supervision roles are provided with enough time, support and understanding for developing their tasks. Supervision and line management is important for the company in order to warrant safety. Supervision arrangements for contractors are partially defined.	In addition to level 4, supervision and line management are frequently evaluated and formally reported in order to improve the way supervision is delivered. Supervision arrangements for contractors are defined and supervisory problems with contractors are identified, evaluated and solved. Complete inventory of necessary spares and essential tools are borne onboard e.g. servicing calibration, repair of essential defects and damage control/firefighting.

Table B-3. Level of Maturity for Attributes associated to PIF Organizational Support, attribute Contractor Management

PIF ORGANIZATIONAL SUPPORT – Attribute Contractor Management				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Contractor management is focused entirely on price, and does not consider safety, reliability and quality issues. The company regards the contractor as wholly responsible for their own workers' safety.	The company pays attention to HSE, reliability and quality issues in contracting companies only after an accident. The primary selection criterion is still price, but poor safety or operational performance has negative consequences for a contractor.	Contractors are expected to jump through many HSE, reliability and quality hoops, some of which may not be necessary. Pre-qualification is based on previous safety and operational records. Standards are lowered if no contractor meets requirements. No effort is made to help contractors get up to speed.	HSE, reliability and quality issues are seen as a partnership. Pre-qualification is based on safety and operational records and having systems in place. The company helps with contractor training. Joint efforts begin to be seen.	Contractor and company staff are not seen as separate, but an integrated workforce. Shared information leads to integration of policies, procedures (bridging document) and practices. Work is postponed if no contractor meets the HSE, reliability and quality requirements. Joint training and competency programs are standard.

Table B-4. Level of Maturity for Attributes associated to PIF Organizational Support, attribute Incident investigation and analysis

PIF ORGANIZATIONAL SUPPORT – Attribute Incident investigation and analysis				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Cover up of incidents is common. Investigation only takes place after a serious accident. Do not consider Human Factors; do not do more than is legally required; do not look beyond protecting the company and its profit.	Define zero accidents as the desired state. Lay down a paper trail to show an investigation has taken place. Has some informal reporting system. There is no reporting system that can get root causes. There is no systematic follow through, and previous similar events are not considered.	Lots of information is collected and filed. The company has detailed investigative procedures, and may suffer information overload. The company pays attention to root causes. There is no systematic follow through on the findings and recommendations. The investigation and its results do not go beyond the local workforce.	Reports are sent companywide in order to share information and lessons learned. There are trained investigators, and a systematic follow-up to check that change has occurred and been maintained, but this is not always done. There is no focus on incident potential, or looking at the total reports, near misses, incidents and accidents.	Data are aggregated across business functions to look for trends and issues that need to be addressed. There is a systematic follow-up to check that change has occurred and been maintained and it is always used.

Table B-5. Level of Maturity for Attributes associated to PIF Competence, attribute Training & Drills

PIF COMPETENCE – Attribute Training & Drills				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
The company does not have a written training program. Neither supervisors nor employees receive enough training specific to their work. Training is a response to statutory requirements only. It is seen as unavoidable by management and supervisors.	There is a general training understanding in the company, but not a well-established written training program. Workers and supervisors receive some training but on general terms and do not prepare them for the dynamic abilities expected for the kind of activity, There is a massive training/retraining effort following an accident, but the training effort diminishes over time.	There is a written training program, but it is not outlined how the training is to be designed, developed or evaluated. There is no assessment for competency, as going through the training is seen as an end in itself. Employees and supervisors receive adequate training assisted with a written hand out. Special times for training are set.	There is a training program in a written form with clear targets and objectives. It outlines how to assess the trainees' needs and training requirements, as well as how to design, develop and evaluate training. Training needs start to be also identified by the workforce. The workforce involved in specialized operations also receives periodical training to review correct procedures. In addition, training is reinforced with periodic onsite drills so workers can practice and perfect their skills.	In addition to level 4, the training and onsite drills program is periodically reviewed and revised in order to be improved. There is also a periodical assessment of training needs and performance statistics in order to better plan and implement refreshing training. Training is seen as a process rather than an event. Needs are identified and methods of training are suggested by the workforce, who are seen as an integral part of the process rather than just passive receivers.

Table B-6. Level of Maturity for Attributes associated to PIF Communication, attribute Organizational Communication Flow and Technological aspects

PIF COMMUNICATION – Attribute Organizational Communication Flow and Technological aspects				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Organizational communication in the company is bad. Management is unaware of what occurs in the operation. As far as technical communication is concerned, the communication equipment is not very reliable and messages are often distorted or lost in or during retrieval due to the channel or technical aspects.	There is a general understanding of organizational communication. People in the team have a general idea to whom they should address, but they are sometimes unable to deliver or receive messages on time. Management has a general idea of what happens in the operation. Communication equipment reliability has been improved and messages are not distorted or lost due to channel or technical problems.	The company has developed a communication system in which team components know who is to be addressed in each occasion. Information is generally available on time, but now the problem is that too much information is given and it takes time to discern the important from the irrelevant. Management wants to know what happens in the operation, but it still is not aware of the best moment or means to approach workers to acquire this information.	Communication is a very important issue in the company. There is an effort to transmit only relevant information and team members know exactly to whom they must address and from whom they must receive information. Management knows what happens in the operation and has an understanding of when and how best to approach workers for information. Workers' opinion is longed for, but it is still hard for workers to express their problems to their seniors. Technical communication equipment is very reliable.	In addition to level 4, communication structure is regularly revised in order to look for optimizing potential. Communication with management is very fluid. The amount and relevance of information is at the optimal level.

Table B-7. Level of Maturity for Attributes associated to PIF Communication, attribute Communication within the team, between teams and shifts (hand-overs)

PIF COMMUNICATION – Attribute Communication within the team, between teams and shifts (hand-overs)				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Communication between teams and shifts is inexistent or very poor. Crew handing over happen while the in-coming personnel are not on ground or by informal means without any record.	There is some communication between shifts and teams, but still not at an adequate level. There is no due diligence and formal procedure for handing over.	Communication between shifts and teams is given required importance, but still the means to develop it in an adequate way have not been provided yet. Handing over is carried out verbally, but sometimes crew cannot express himself with clarity.	Communication between shifts and teams is well structured and it occurs in a way of verbal or written reports. Handing over is done verbally and associated notes with highlights are available.	Communication within the team, between teams and shifts is very fluid. The organization develops staff's communication skills (assertiveness) and provides procedures for shift handover. Handing over is done verbally with the presence of observer and notes are taken and kept in formal means which allows to recover the information asap. The shared information is based on analysis of incoming staff needs.

Table B-8. Level of Maturity for Attributes associated to PIF HMI, attribute Design of controls and instrumentation

PIF HMI – Attribute Design of controls and instrumentation				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
The design of controls is in general very poor. There is no consistency of controls with the same function across the unit and operator expectations are not fulfilled. Controls' dimensions are not adequate and inadvertent activating of controls is common. There is a lack of suitable sensors for equipment/systems integrity and key operational parameters monitoring.	The design of controls and instrumentation is at an acceptable level in the sense that it allows operators send signals accurately and quick enough and to gather some information about equipment/systems integrity and operational parameters. Inadvertent activation of controls could occur in some cases, but is quickly detected. Within the working area there are controls with same function that are not designed in a consistent way. Controls still do not have the adequate dimensions and they do not completely fulfil operators' expectations.	The design of controls and instrumentation is at an acceptable level, because it allows transmission of accurate signals on time and monitoring of key operational parameters and critical equipment/systems integrity. Inadvertent activation of controls hardly occurs. The controls with the same function are consistent across the unit. However, operators' expectations on how to operate controls are not always fulfilled.	The design of controls and instrumentation could be termed as very good, because it allows transmission of accurate signals on time and monitoring of all key operational parameters and critical equipment/systems integrity based on a comprehensive analysis of relevant data for situation awareness. The surface available for controls' installation is big enough and the controls' dimensions are adequate. Inadvertent activation of controls does not occur any more. The controls with the same function are consistent across the unit. Operators' expectations on how to operate controls are always fulfilled.	In addition to level 4, controls and instrumentation are periodically revised to check that their design is still at an optimal level and if not implement the necessary corrective measures.

Table B-9. Level of Maturity for Attributes associated to PIF HMI, attribute Equipment and valves

PIF HMI – Attribute Equipment and valves				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Design and layout of equipment and valves in the company is generally inadequate because they are not easily accessible. Equipment and valves are poorly labelled and it is very difficult to know what happens when a local equipment control is activated or a valve is actuated. Valves are located in places hard to reach and to operate. The layout of the piping is very confusing, because there are many unnecessary crossings. There is no systematic program of maintaining and inspecting equipment and valves.	Most frequently used equipment can be easily accessed. Equipment and valves are labelled, but it is still not obvious to realize what happens when a local equipment control is activated or a valve is opened or closed. Valve location is acceptable according to the force and position to operate it, but it is still possible to find valves located badly. The layout of the piping is sometimes confusing, because there are some unnecessary crossings. Equipment maintenance and inspection is based on an internal program, but it is still inadequate and ineffective.	All equipment is generally easily accessible. Equipment and valves are adequately labelled, and it is still only in rare exceptions that it is not obvious to realize what happens when a local equipment control is activated or a valve is opened or closed. Valve location is acceptable according to the force and position to operate it, and badly located valves are very rare. The layout of the piping is acceptable and the number of unnecessary crossings is minimal. Equipment maintenance and inspection is based on a specific maintenance and inspection program following international standards and industry best practices.	Equipment and valves are adequately labelled, and it is always obvious to realize what happens when a local equipment control is activated or a valve is opened or closed. Valve location is very good according to the force and position to operate it. The layout of the piping is acceptable and the number of unnecessary crossings is minimal. There is a specific maintenance and inspection program that combines information from international standards and industry best practices with specific reliability analysis considering unit conditions.	In addition to level 4, a revision and evaluation of equipment and valves is done periodically to check if they are still at an optimal level, despite possible changes in the equipment/systems and operational activities.

Table B-10. Level of Maturity for Attributes associated to PIF Procedures & Documentation, attribute Documentation - Availability and System

PIF PROCEDURES & DOCUMENTATION – Attribute Documentation - Availability and System				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
The company does not have any documentation system, and then documentation is not readily available or is not accessible for personnel at the sharp end.	There is a general understanding of documentation, but more in the sense that it is done only to comply with regulatory requirements. Documentation is neither easy to trace nor complete.	The company understands documentation as a way of improving and not just achieving compliance with requirements. Documentation management system is still undeveloped and it is sometimes difficult to trace important documents. Some documents might still be incomplete in some areas.	The company has a good working documentation management system. Documentation is well archived, easy to find and available for all the personnel involved in operations. It is up to date, readable, and it is easy to see the documents' version. It is also easy to find how often they are approved, reviewed and revised. Documentation is complete and covers all required areas.	In addition to level 4, review, evaluation, maintenance and dissemination of documentation and documentation management is done on a regular basis with the participation by all parties involved in the operation. This process includes an analysis of the relevance of the documentation being stored in order to find potential for improvement.

Table B-11. Level of Maturity for Attributes associated to PIF Procedures & Documentation, attribute Procedures/Internal standards

PIF PROCEDURES & DOCUMENTATION – Attribute Procedures/Internal standards				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Procedures and procedure management do not exist in this company or they are very rare and arise out of necessity. Minimum regulatory requirements are the most there are. There are no internal standards.	There is a general understanding of procedures, but procedures only exist to comply with regulation and other obligatory requirements. Procedures exist but no much attention is given to their quality or location. Procedures are ambiguous and confusing. They are written by staff less experienced or far from operational area. There are compliance-based industry standards.	The company understands procedures as a way of better and safer operation. , but it still has not matured to a procedure management system as such. A lot of time and effort is devoted to the development of procedures, but they may not be good and/or appropriate, and may exist excessive number of procedures. There is an interest and effort to have procedures cast in a usable form and easy to locate, but this has not materialized in a procedure management system yet. Usually, procedures are written by staff far from operational area. There are regulatory and internal standards often based on incidents. The company is willing to spend money on improvement.	The company has a procedure management system, because it wants to have procedures cast in a usable form and easy to locate at the workplace. Procedures are easy to understand, written in the right language with short and simple commands ordered in the logical steps to complete a task successfully. Procedures are updated and have been revised to reflect the current state of the unit. The issue of ambiguity has been addressed. The company takes a leadership role, striving to exceed minimum standards for the industry. Standards are set by the workforce, and approved by management	In addition to level 4, review, evaluation and maintenance of procedures is done on a regular basis, including an exhaustive analysis of why procedures have not been followed and what can be done to improve them. Procedures are developed and can be tailored to fit the job at the suggestion of the local workforce. Some procedures are scrapped, as they are no longer necessary. The company tries to influence the regulator in the setting higher standards. Is it not worried about spending money to attain higher standards. The workforce defines standards.

Table B-12. Level of Maturity for Attributes associated to PIF Job Design, attribute Work schedules, shifts and overtime

PIF JOB DESIGN – Attribute Work schedules, shifts and overtime				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Shifts are too long and work and breaks are not well scheduled. Overtime is normal practice in the company and employees are often under time pressure to complete activities. There are not any dining rooms or food facilities.	There is a general understanding of work schedules and shifts, but workers do not participate in the selection of the shifts. Overtime is a common practice in the company; the employees have excessive task demands or insufficient time to carry out them. Breaks exist, but they are not long enough.	The company understands that a good work schedule and shift planning is a way for better operation and decreasing the accident rate, but a system for evaluating the effects of the shifts and work schedules on the workforce has not been developed yet and the number of task demands and available time is still not correctly balanced. Workers can participate in the selection of shifts. There are dining rooms or warm food facilities.	The company understands that a good work schedule and shift planning is a way for better operation and decreasing the accident rate. A system has been developed for evaluating the effects of the shifts and work schedules on the workforce, including circadian rhythm effects. Moreover, number of parallel task demands and available time are adequately synchronized to the process dynamics. Medical surveillance and incident reports are very much considered when planning shifts and work schedules. There are dining rooms or warm food facilities.	In addition to level 4, revision and evaluation of work schedules, shifts and breaks are done periodically to check if everything is going as planned and if not implement the necessary corrective measures.

Table B-13. Level of Maturity for Attributes associated to PIF Operator & Team Characteristics, attribute Crew Collaboration Quality

PIF OPERATOR & TEAM CHARACTERISTICS – Attribute Crew Collaboration Quality				
Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
There is no cohesiveness in the team mainly reinforced by internal competitive environment or lack of clear team objectives. There is no mutual trust. Individuals look after themselves.	"Look out for yourself" is still the rule. There is a voiced commitment after accidents by management and workforce, but this is short-lived and the level of care for team-mates is limited. There is little cohesiveness in the team, hence little collaboration.	The organization establishes superior guidelines on expected performance but is not so clear on detailed roles and responsibilities within the team. There is some commitment and collaboration specially motivated by established collective goals.	The roles and responsibilities within the team are well defined and well understood and the organization contributes to a collaborative environment. There is a clear job description, then type and nature of job is commensurate to crew qualification. Team-mates work well together and share information and resources in a flexible manner.	In addition to level 4, the distribution of work/ responsibilities within the team is mutually agreed and the organization develops staff's skills such as assertiveness, shared situation awareness and conflict resolution. Level of commitment and care are very high and are driven by employees. Contractors are included in care from day one.

Appendix C. Causal Diagrams for the Tasks of Emergency Disconnection Scenario

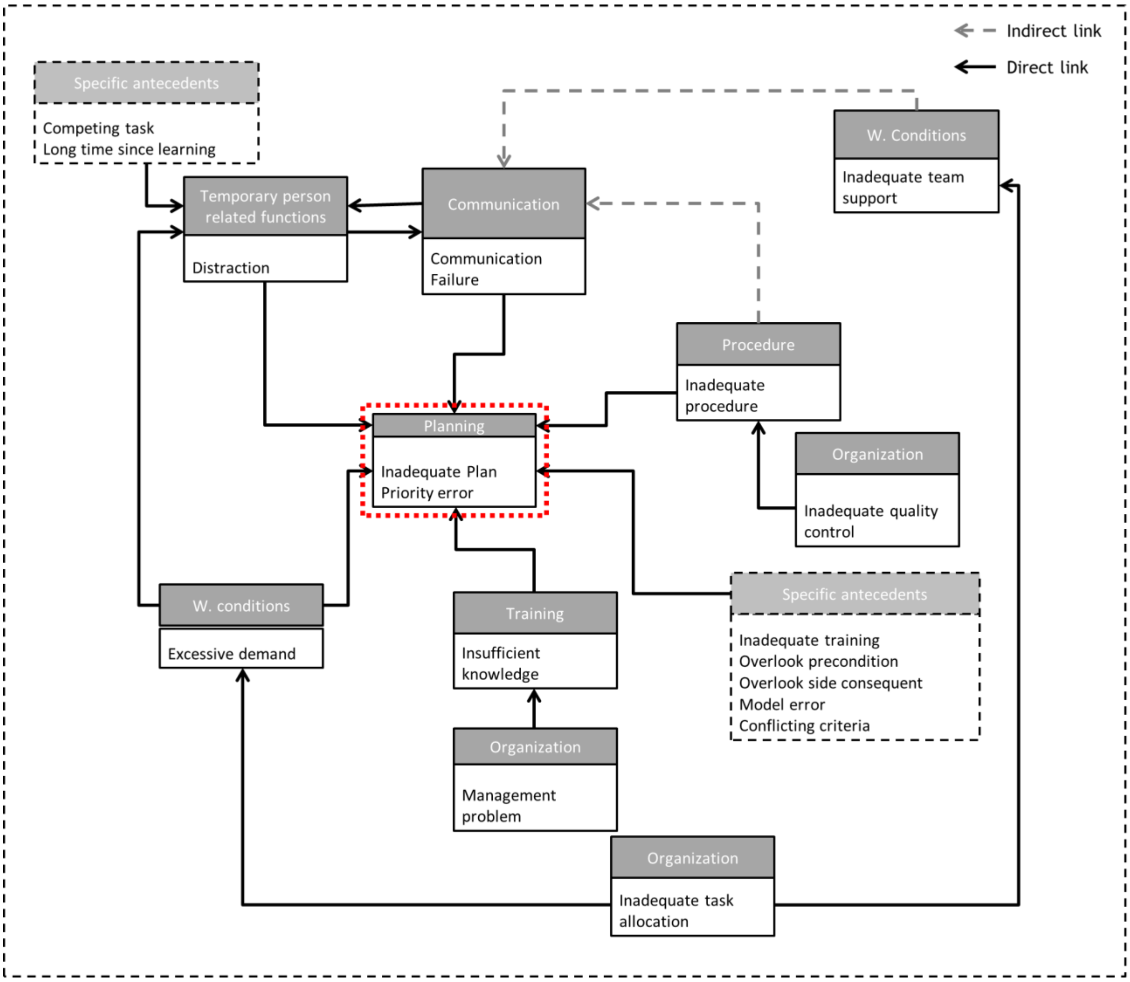

Fig. C-1. Causal diagram for task 0: Planning Actions to Emergency Disconnection

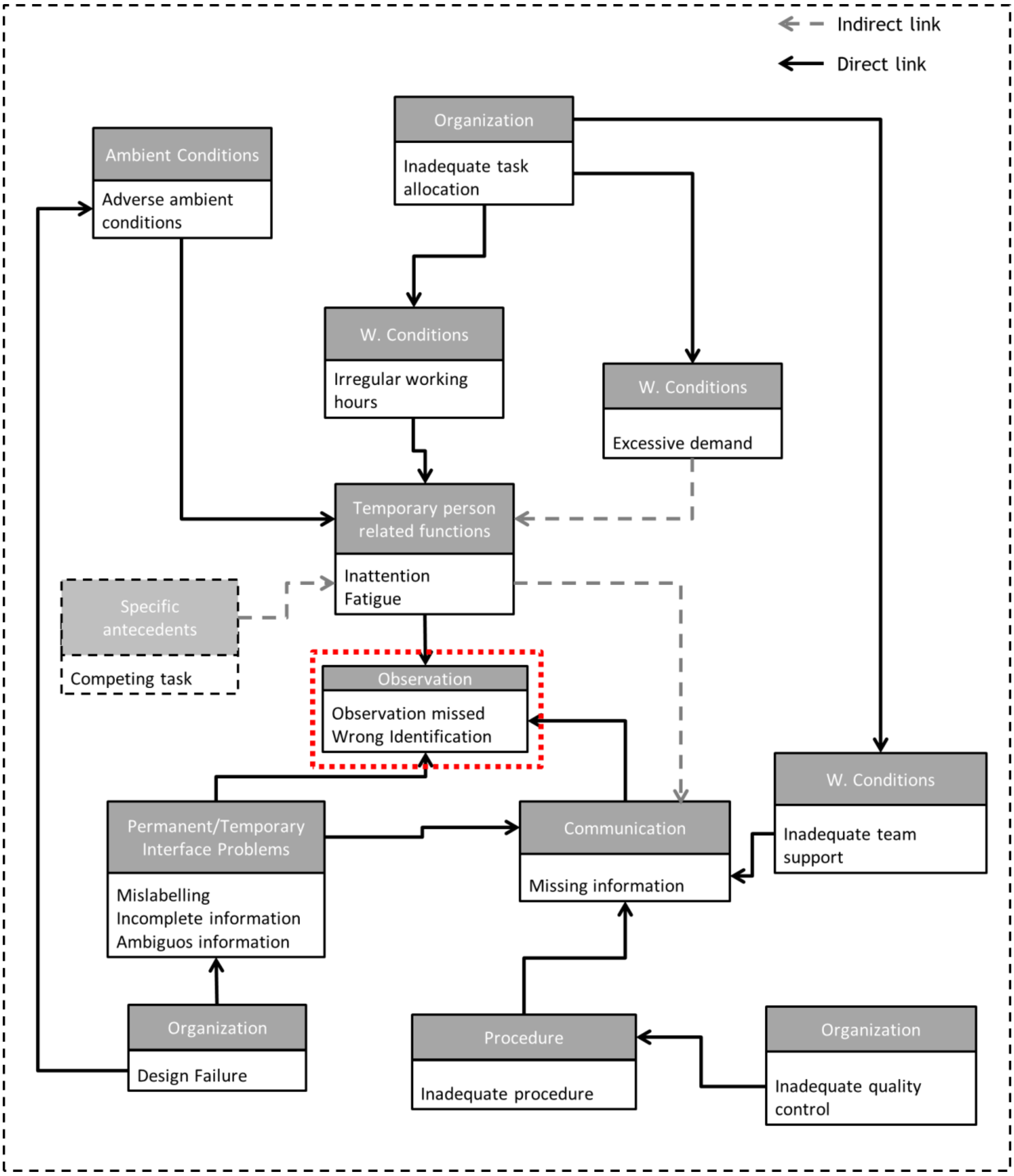

Fig. C-2. Causal diagram for task 1: Monitor Rig and Metocean parameters – Fault in observation

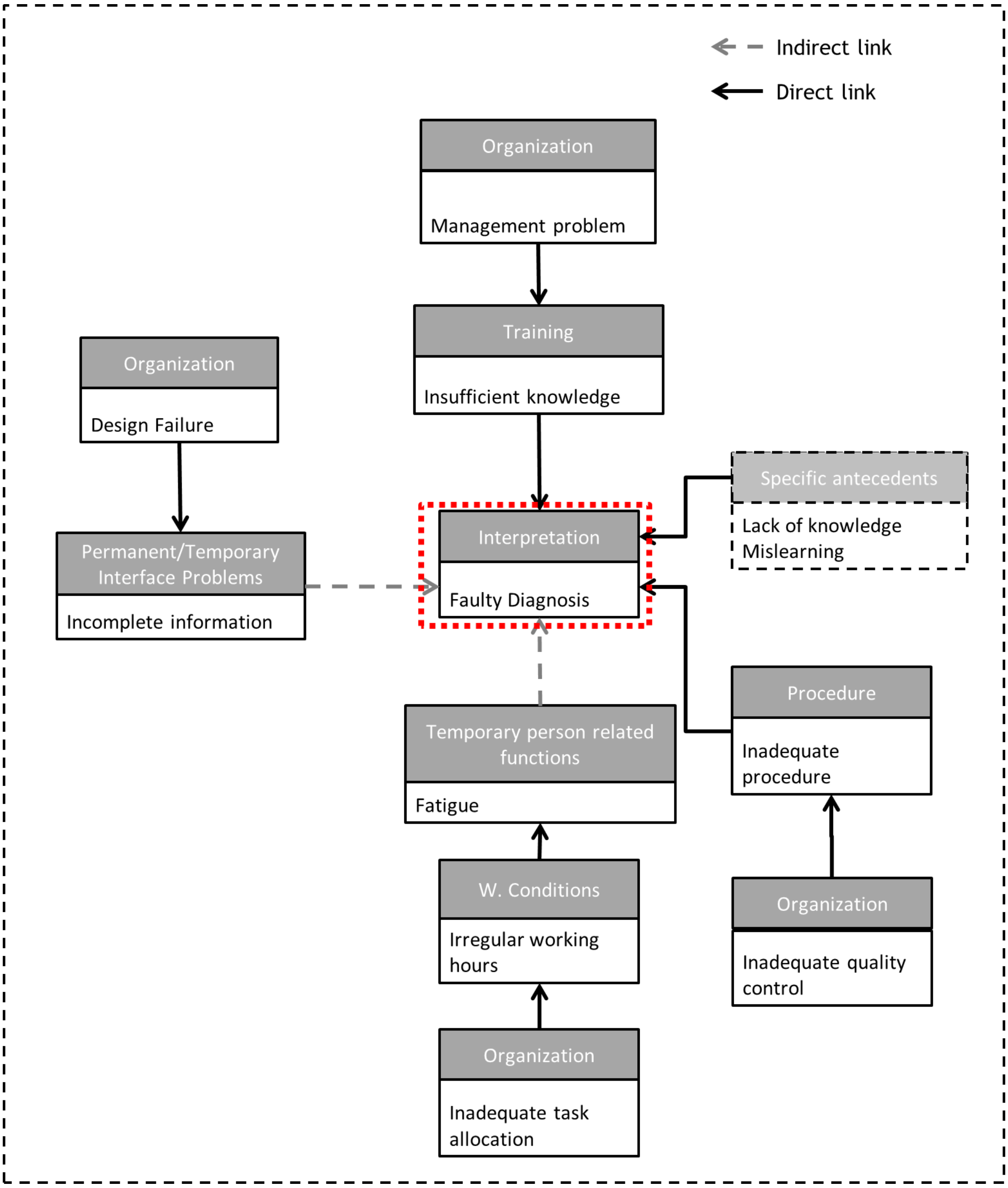

Fig. C-3. Causal diagram for task 1: Monitor Rig and Metocean parameters – Faulty Diagnosis

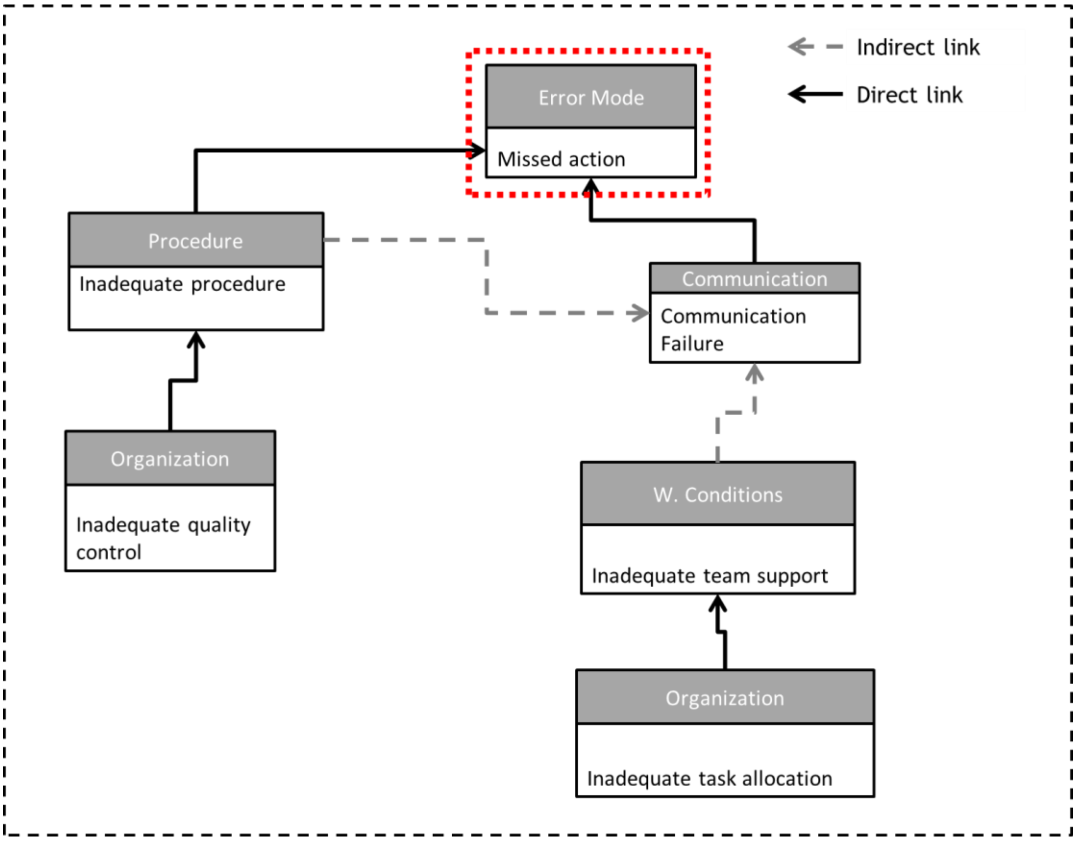

Fig. C-4. Causal diagram for task 2: Communicate Rig Conditions from DP bridge to Drill floor

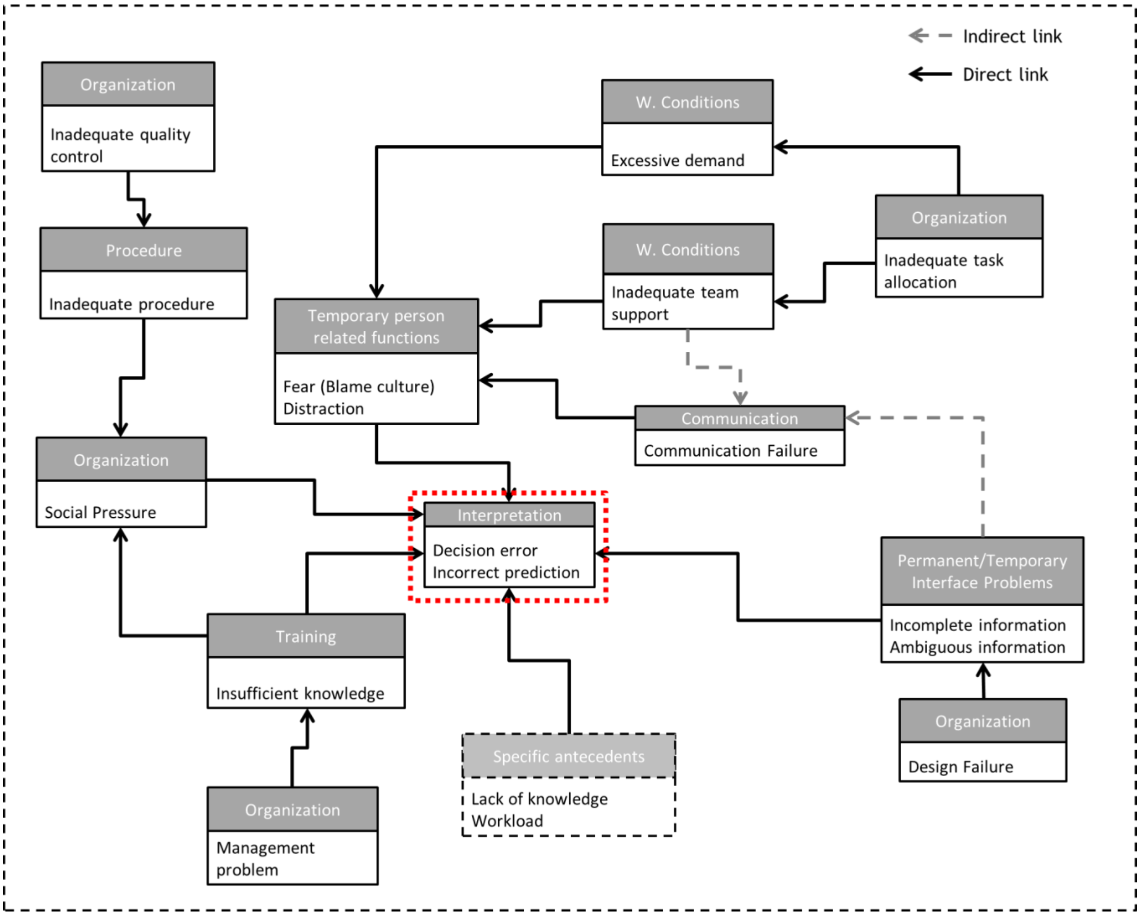

Fig. C-5. Causal diagram for task 3: Evaluate current conditions and decide on action line

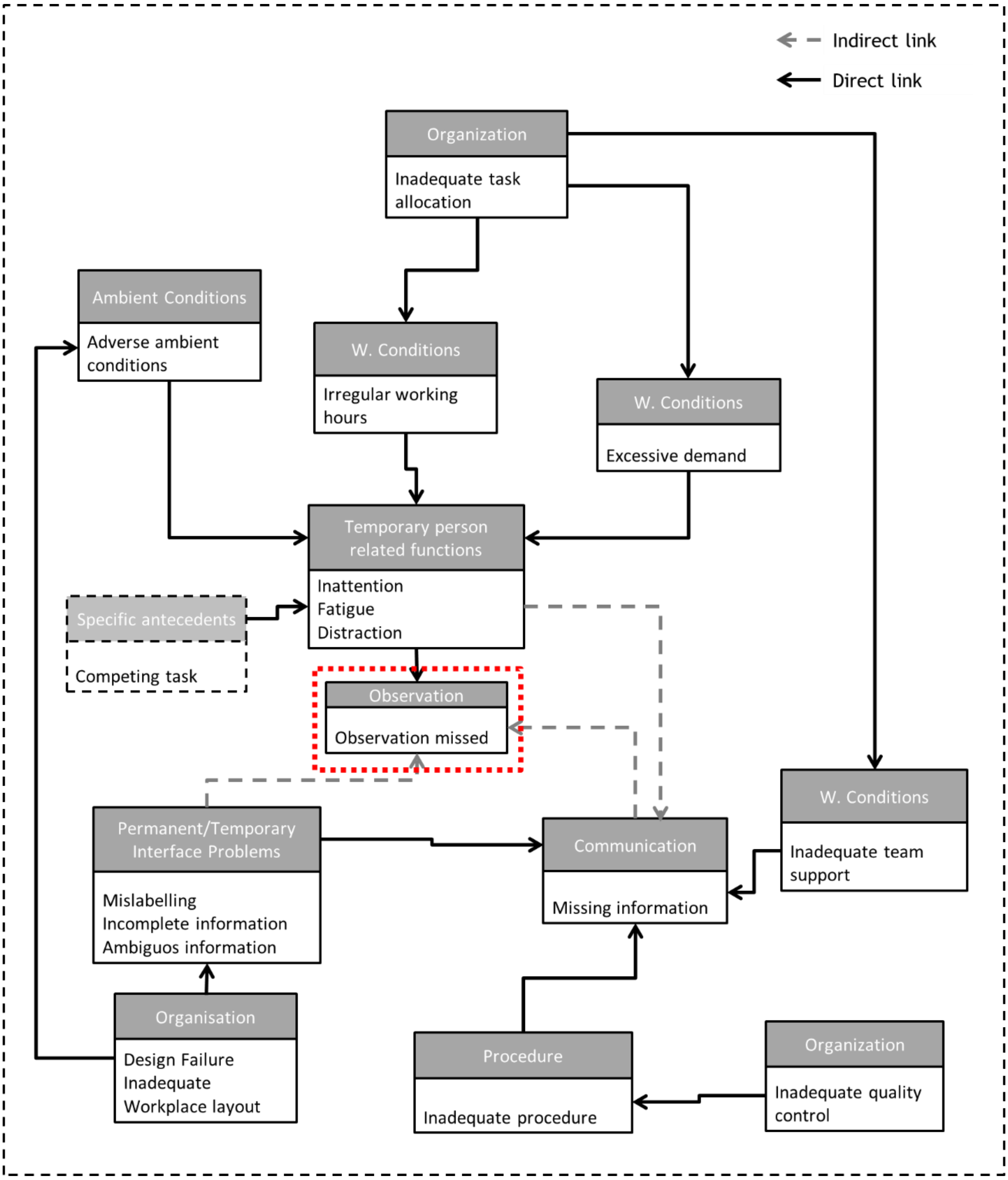

Fig. C-6. Causal diagram for task 4: Conduct Preparatory Actions – Observation Missed

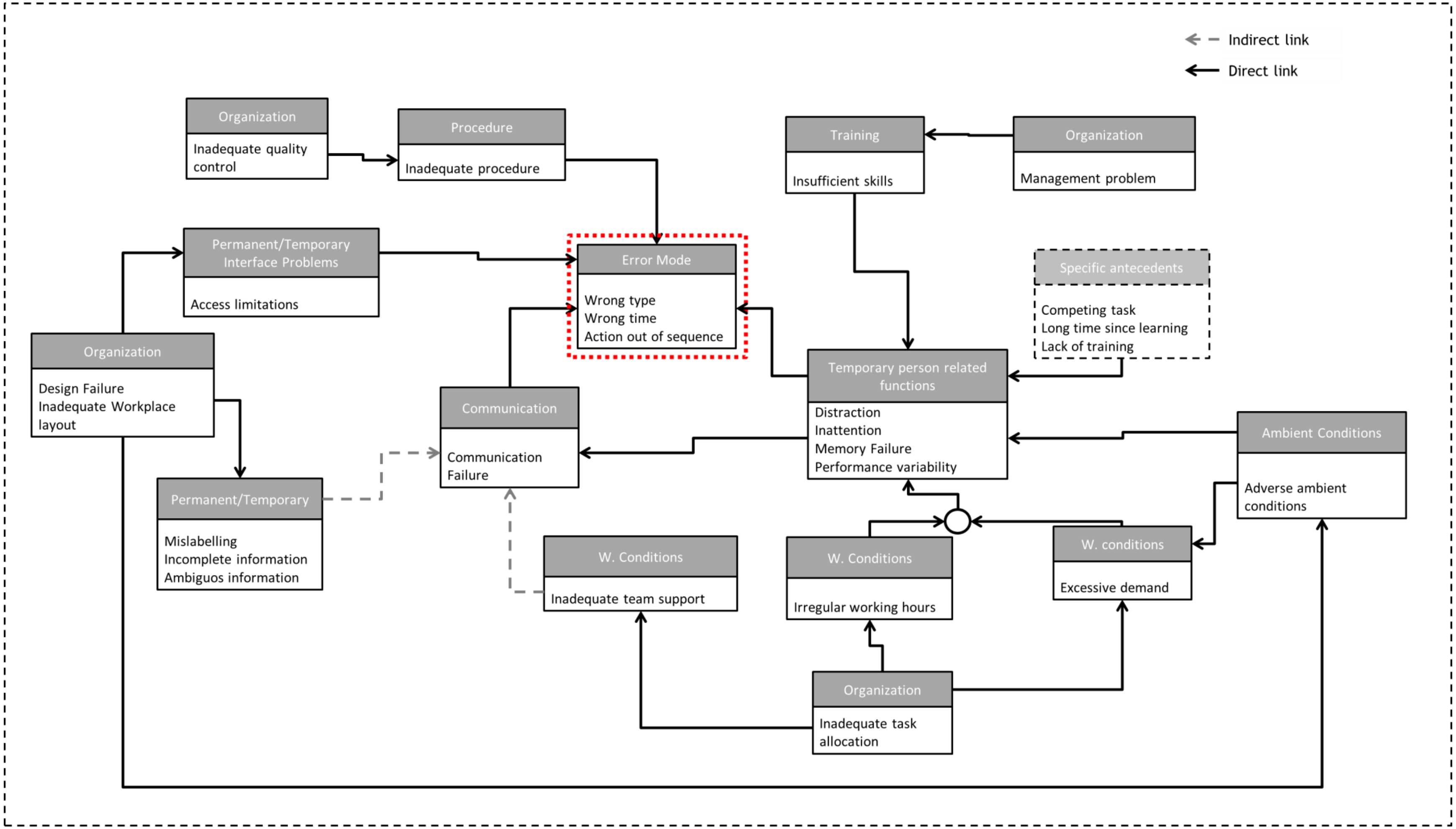

Fig. C-7. Causal diagram for task 4: Conduct Preparatory Actions – Fault in Execution

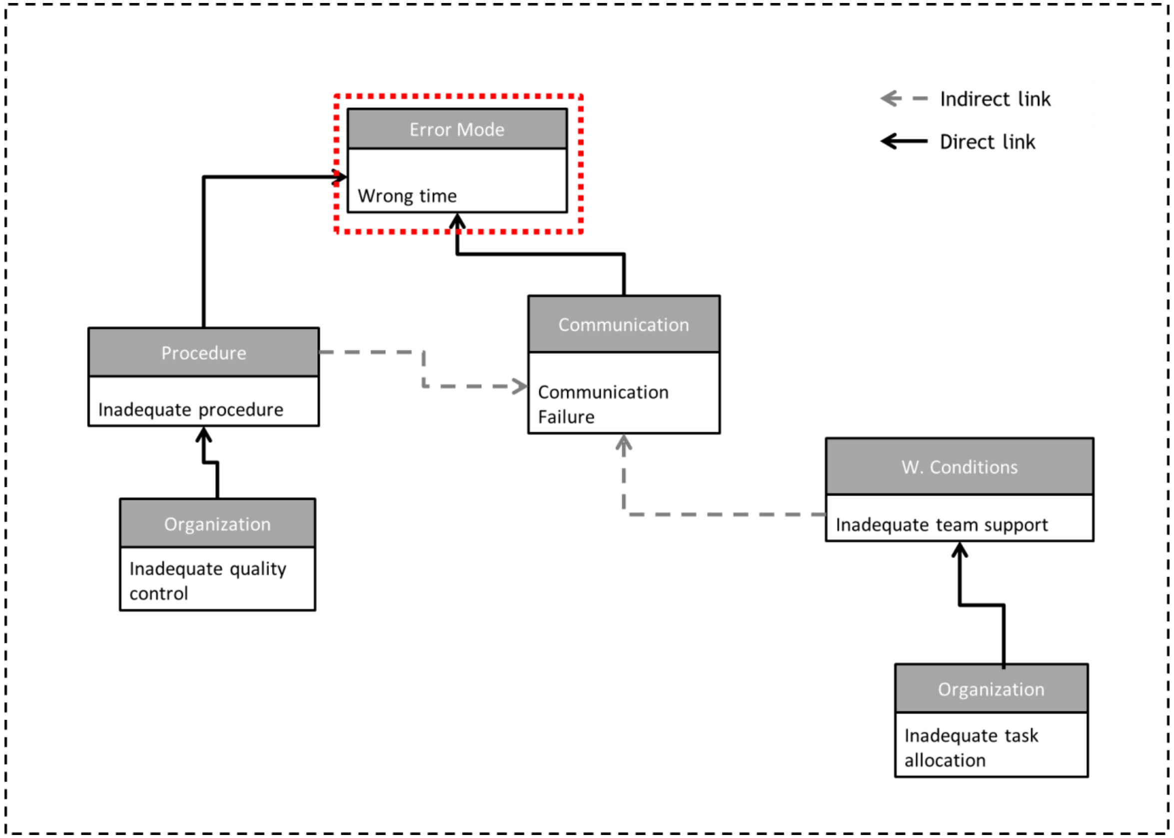

Fig. C-8. Causal diagram for task 5: Sound Red Alarm

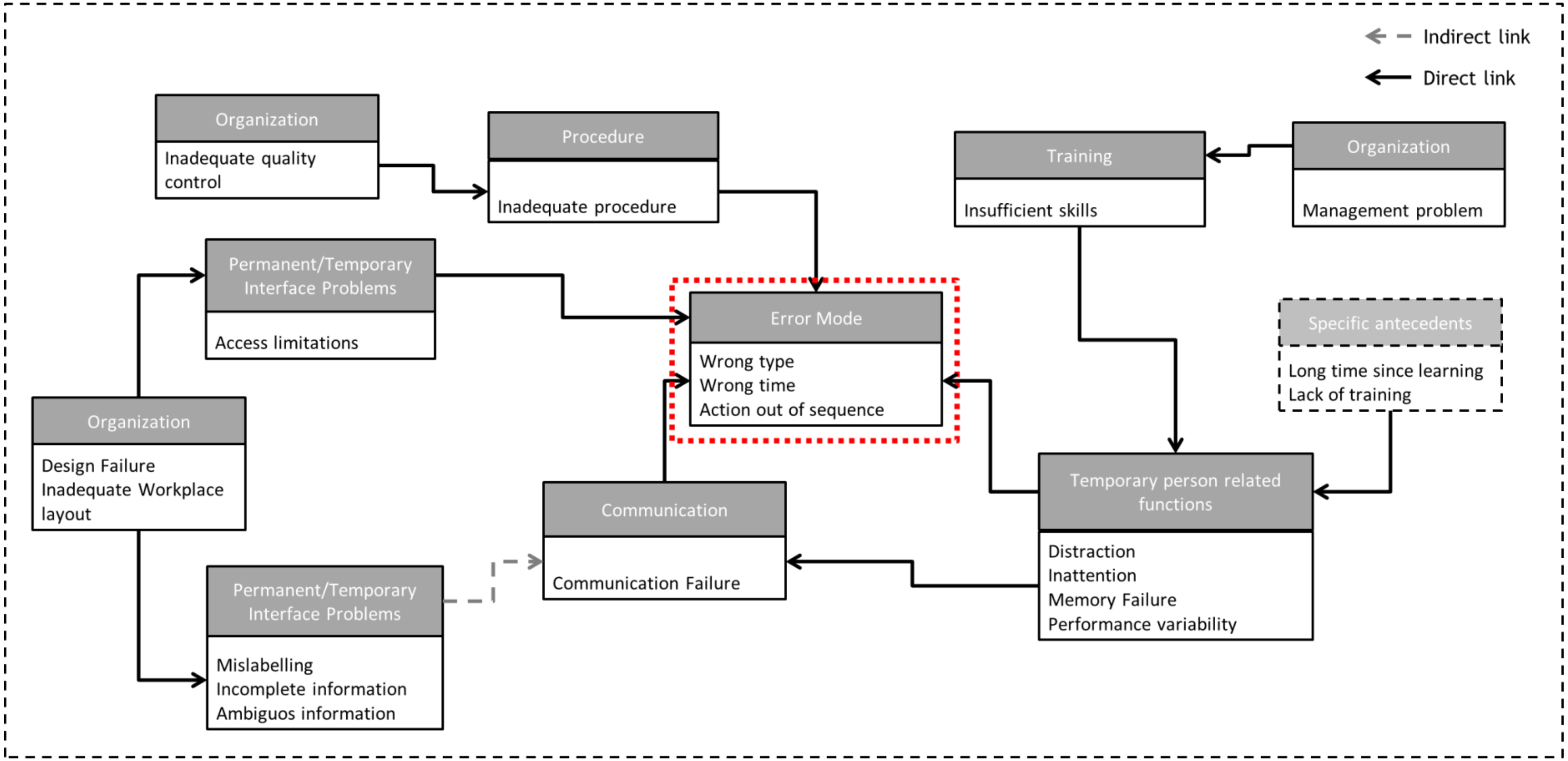

Fig. C-9. Causal diagram for task 6: Activate EDS

Appendix D. Bayesian Network Model

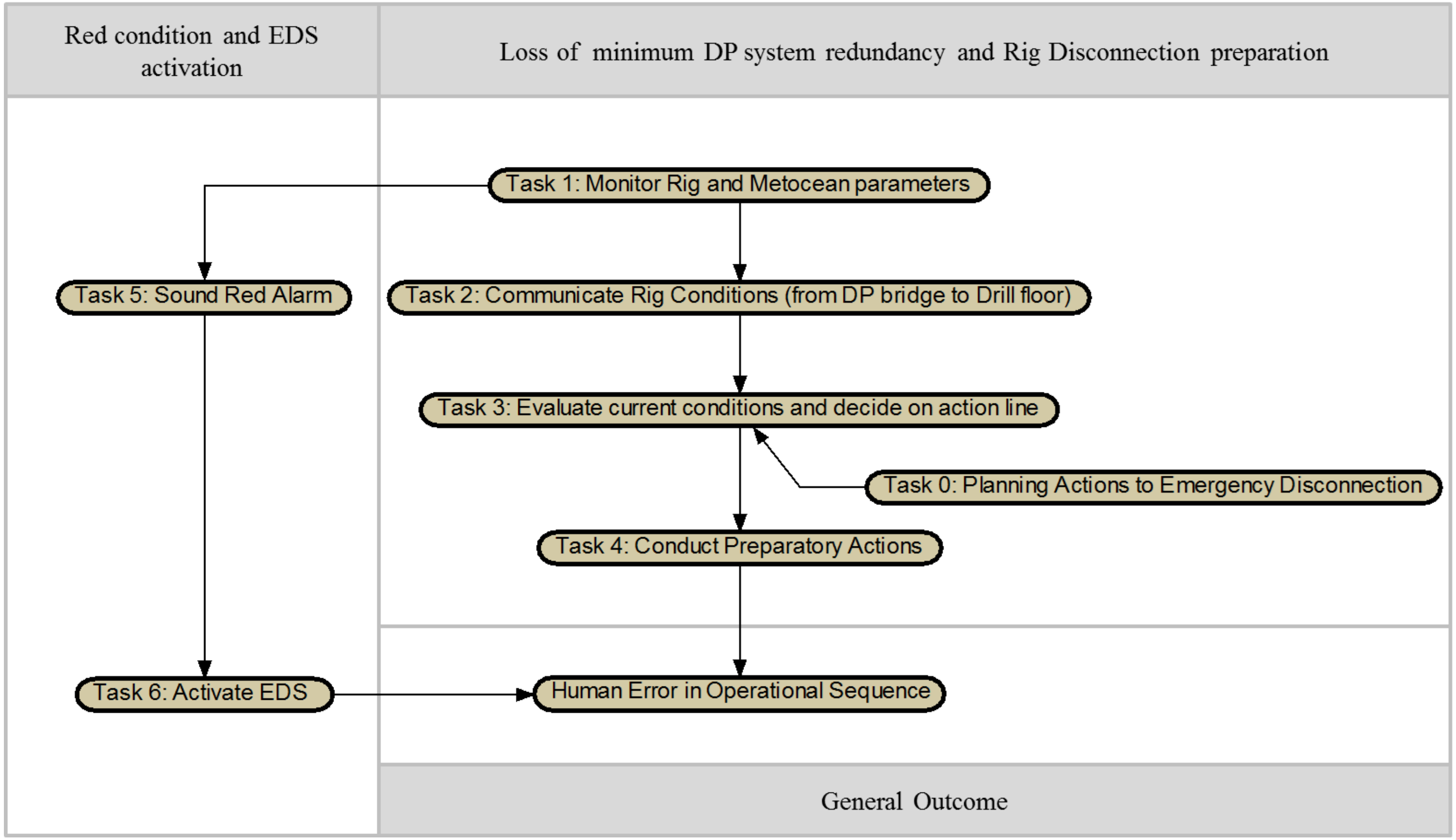

Fig. D-1. BN framework with the generic operational sequence of emergency disconnection

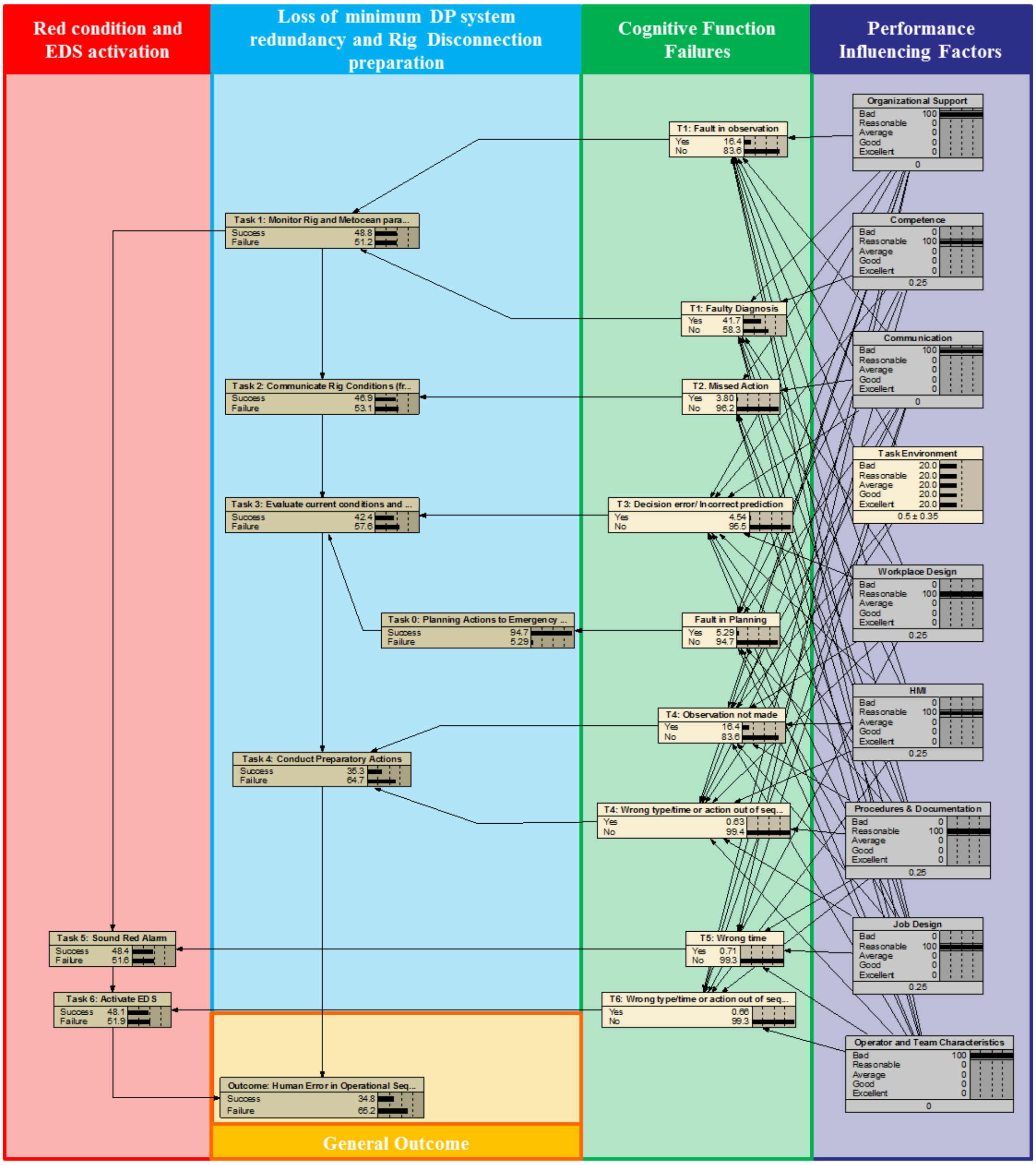

Fig. D-2. Overview of BN model

Appendix E. Macondo Well Blowout Evaluation – Association to PIFs

Table. E-1. Macondo Well Blowout Evaluation (table adapted from SMITH et al. (2013) and information from BP, 2010, TRANSOCEAN, 2011, SMITH et al., 2013, SUTTON, 2013, ROBERTS et al. 2015, ST JOHN, 2015a, 2015b, STRAND and LUNDTEIGEN, 2017, PRANESH et al., 2017)

		PIFs								
	Events	OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Before Accident	Poor treatment of previous well control events. Lessons learned of previous event in March 2010 did not result in practical actions to improve the time response of crew.	●		●				●		
Before Accident	Issues with BOP tests previous to the operation. The tests had positive results, but problems have been found during BOP activation.	●						●		
Well integrity was not established or Failed	Possibility of channeling due to the decision to run smaller number of centralizers than defined in simulation.	●	●	●				●		
Well integrity was not established or Failed	Problems with conversion of float collar were not appropriately checked and addressed what could represent an indication of failure in one of the shoe track barriers.	●	●	●				●		
Well integrity was not established or Failed	Problems with cement slurry design (foamed) without complete program tests to verify them (especially the concentration of Nitrogen) and with questionable parameters of displacement (low volume and flow rate) may have contributed to failure in well annular isolation.	●	●	●				●		

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(continued)

	Events	PIFs								
		OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Well integrity was not established or Failed	Crew inexperience with the cementing design and variables of displacement proposed.	●	●	●				●		●
	Poor communication between well owner crew and service company for cementing operations and either with rig crew about the risks associated with cement design and its displacement.	●		●				●		●
	Poor communication with experts in zonal isolation who could give support in cementing design guidelines and internal procedures.	●		●				●		●
	Quality of cementing operations service was not assured by the well owner.	●	●	●						
	Violation of internal standard that determines conducting proven cement evaluation technique given that the parameters of TOC (Top of cement) and centralization were not fulfilled.	●	●	●				●		
	Violation of API RP 75 (API, 2004) which establishes parameters of fluid circulation that were not met.	●	●					●		
	Inadequate Management of change not accompanied with risk assessment in relation to abandonment procedures and its apparently violation for the approval process of regulatory agency.	●	●	●				●		

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(continued)

	Events	PIFs								
		OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Hydrocarbons entered the well undetected and well control was lost	Negative pressure test interpreted erroneously as a positive well integrity. Some reports emphasize the overconfidence in cementing operations and isolation due to poor risk communication, incomplete instrumentation in work string, inexperience in this kind of test and incomplete procedures.	●	●	●			●	●		
	Conflicts between rig crew and well owner about the monitoring of pressures through kill line or drill pipe.	●		●				●		●
	Divergences in pressures monitoring in kill line and drill pipe were not considered as underbalanced pressures and influx, mainly because no flow was observed in kill line. Kill line could be plugged by debris or incorrect alignment during test preparation.	●	●	●				●		●
	Attention shift due to simultaneous activities, mainly related to final procedures for abandonment activities, could have caused the response delay in detection.	●							●	●
	With the simultaneous activity of fluid offloading, the capacity to monitor volume of tanks was compromised.	●		●			●		●	●
	Deficient communication between shift can have contributed to the overconfidence of operators and to reduce the level of alertness,	●	●	●				●		●
	Drillers did not share information about anomalies observed and tried to respond without alert stakeholders.	●	●	●				●		●

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(continued)

	Events	PIFs								
		OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Hydrocarbons entered the well undetected and well control was lost	Inadequate communication to mudlogger’s team not informing when the offloading ended. So, they cannot return pit levels monitoring.	●	●	●				●		●
	Well control handbook incomplete not covering the method of monitoring for all possible scenarios (influx test, conditioning and well final activities) and to deal with cases of escalation of well control event.	●						●		
	No evidences demonstrated the capacity to monitor the mud pits during sea water displacement.						●			
	No evidences of periodic flow checks during the event sequence.	●	●					●		●
	Inappropriate display design both in relation to the presentation of the information (e.g. display clutter) and data resolution. Some available information was difficult to capture trends.					●	●			
	Delayed detection of well control event even with successive indications of influx, especially anomalies in drill pipe pressure. The first well control action was observed only after mud overflowed onto rig floor.	●	●	●				●		●

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(continued)

		PIFs								
	Events	OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Hydrocarbons ignited on Deepwater Horizon	Decision to direct the well flow to mud gas separator (MGS) system instead of diverting fluids overboard.		●					●		
	Design of outlet vents and other flow-lines can have contributed to direct gas onto the rig and maybe into spaces under the deck.	●				●			●	●
	HVAC (Heating, Ventilation and Air Conditioning) system had not automatic shut down upon gas detection. There was migration of gas to not electrically classified rooms.	●				●				●
	The areas classified could be excessively limited.	●				●		●		
Blowout Preventer did not seal the well	Delayed response to the well control event. Annular BOP and pipe rams were activated when the influx was above the BOP and had already entered into the riser. EDS was initiated 7 minutes after the first explosion.		●	●						●
	AMF (Automatic Mode Function) system did not work as expected after loss of communication, hydraulic and electrical power. Problems with control PODs could have induced failure in activating Blind Shear Ram by means of AMF.	●	●				●	●		

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(continued)

	Events	PIFs								
		OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Blowout Preventer did not seal the well	Possible weaknesses in maintenance management were reported, including lack of records of maintenance tasks, and also problems with test implementation, particularly for AMF and ROV intervention system.	●					●	●		
	Failure in the implementation of Management of change process for some modifications in Subsea BOP that cannot be supported by a complete assessment nor correctly documented. Furthermore, not all impacted areas were adequately modified, such as the ROV intervention panels. Moreover the alterations would not have correctly communicated to the well owner.	●	●	●		●	●	●		
Other Factors	In the date of the accident, a team shift (disembark) was to be done, so the crew could be more affected by fatigue. Furthermore, there was a commercial pressure to complete well abandonment activities due to financial issues (late end of activities, budget exceeded).	●								●
	Expectations on promotion of some key personnel for supervision functions could have affected them in relation to situational awareness and decision making.	●								●

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(continued)

	Events	PIFs								
		OS	Comp.	Comm.	TE	WD	HMI	Proc. & Doc.	JD	Op. & Team Char.
Other Factors	Shift of attention on well monitoring in view of visitors from BP and Transocean in the afternoon of the accident associated to shift rotation.	●							●	●
	Reports pointed out conflicts between managers (proven by emails), decisions made without communication with onshore base, low risk consciousness, deficient Management of Change and risk assessment process as main contributors to the accident.	●	●	●						●
	Organizational changes would be accomplished in a fast way that there would be not time enough to the necessary adaptations and not every personnel be conscious about the new roles and responsibilities.	●	●						●	●

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