Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

S. Iliya Pezeshki

# Functional Resonance Analysis Method (FRAM) Approach for Barrier Management in Offshore Drilling

Master's thesis in Reliability, Availability, Maintainability, and Safety (TK-4950)
Supervisor: Prof. Nicola Paltrinieri, Co-supervisor: Behnaz Hosseinnia Davatgar
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# Abstrakt

Som en del av risikostyringen viser barrierehåndtering seg å være en av de kritiske faktorene for å opprettholde en sikker tilstand for drift i olje- og gassindustrien. Med introduksjonen av ikke-tradisjonell tankegang (Safety-I vs. Safety-II) om hva sikkerhet er og hvordan man oppnår det, er metoder som Functional Resonance Analysis Method (FRAM) utviklet for å kartlegge sosiotekniske systemer fra en annen perspektiv. FRAMs potensiale for å bli brukt eksplisitt i barrierehåndtering har ennå ikke blitt demonstrert. Dermed har denne studien som mål å finne ut hvordan FRAM, som en Safety-II-tilnærming, kan tilføre verdi til sperrehåndteringen i offshore-boring.

For å finne egnetheten til FRAM i barrierehåndtering og dens potensial, ble for det første konseptene risikostyring, barrierehåndtering og FRAM gjennomgått. Deretter har FRAM-tilnærmingen blitt brukt til en offshore-brønnproduksjon basert på dens utformede barrieresystem angående kick and blowout-risikoer som en av de vanlige risikoene i offshoreindustrien. FRAM-modellen ble deretter sammenlignet med en tradisjonell (Safety-I) representasjon av systemet, bowtie-tilnærming, og fordelene og ulempene ved begge metodene ble diskutert.

Konklusjonen av denne studien er anvendelsen av FRAM i barrierehåndtering kan være fordelaktig. Ikke bare det indikerer gjensidig avhengighet av systemet, men gir også analytikeren ytterligere informasjon for beslutninger. FRAM i denne studien erstatter ikke en vilt brukt bowtie-metode for barrierehåndtering. Samtidig som den erkjenner fordelene med Safety-I, bringer den begrensningene og gir analytikeren et mer omfattende beslutningsstøtteverktøy.

# Abstract

As a part of risk management, barrier management proves to be one of the critical factors in maintaining a safe state for operation in the oil and gas industry. With the introduction of non-traditional school of thought (Safety-I vs. Safety-II) on what safety is and how to achieve it, methods such as Functional Resonance Analysis Method (FRAM) have been developed to map sociotechnical systems from a different perspective. FRAM's potential to be used explicitly in barrier management has yet to be demonstrated. Thus, this study aims to find out how FRAM, as a Safety-II approach, can add value to the barrier management in offshore drilling.

To find the suitability of FRAM in barrier management and its potential, firstly, the concepts of risk management, barrier management and FRAM were reviewed. Then, the FRAM approach has been applied to an offshore well production based on its designed barrier system regarding the kick and blowout risks as one of the common risks in offshore industry. The FRAM model was then compared to a traditional (Safety-I) representation of the system, bowtie approach, and the advantages and disadvantages of both methods were discussed.

The conclusion of this study is the application of FRAM in barrier management can be beneficial. Not only it indicates the interdependencies of the system, but also provides the analyst with additional information for decision making. FRAM in this study is not replacing a wildly used bowtie method for barrier management. Still, while acknowledging Safety-I's advantages, it brings out its limitations and provides the analyst with a more comprehensive decision-making support tool.

# Acknowledgements

"*As we express our gratitude, we must never forget that the highest appreciation is not to utter words, but to live by them.*" —JFK

The longer and harder the struggle, the higher the achievement. As one achieves what he desires, there shall not be room for anything but honor, humbleness, and gratitude towards who helped and supported him reach higher. May what I have learned in this path shine my way in my future struggles.

Hereby, I start by surrendering my highest form of gratitude to my parents, to whom I will be forever in debt.

My infinite gratitude shall be towards my professor, Dr. Nicola Paltrinieri, who has been ever-present and accessible with lots of care and knowledge to share; I could not have wished for any better situation.

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A special thanks to Mr. M. Mohseni for being a reliable source of pure positivity in my life

**REFERENCES**

**APPENDIX A: FRAM'S STEPWISE DEVELOPMENT**

# 1 Introduction

The oil & gas industry is responsible for the highest share in global energy production (IEA, 2019). Oil and natural gas are accounted for the highest share in global energy consumption as well (Rodrigue et al., 2020); a high demand that requires a high supply.

The industry has always been associated with profit, risk, and accidents. Oil and gas are highly flammable hydrocarbons that are found in high pressure and temperature reservoirs (Ahmed, 2016) and can be extracted by wells that can reach a depth of 10km (ENI, 2005). While this gives praise to advances in equipment and technologies, it also indicates to the challenges the oil & gas industry must overcome to be able to meet the high demands. Difficult working environment, presence of highly flammable substances, high pressure and temperature lines and equipment, vehicle collisions and other work-related hazards make the oil and gas production prone to accidents (OSHA, 2013).

Whether onshore or offshore, dealing with the associated risks of harsh environments and hazardous substances has been an inevitable concern of the industry. The offshore sector, particularly, has been challenged by even more extreme conditions to maintain the workers' safety and protect the environment and the assets (LiveScience, 2010). Unfortunately, the offshore sector has had its share of disasters that included several fatalities and immeasurable environmental consequences. Ekofisk's Aledxander L Kielland semi-submersible platform in the North Sea capsized in March 1980, killing 123 people. Piper Alpha disaster in the North Sea in 1988, killing 167 people, which to this day, remains to be the deadliest offshore major accident in history. The Seacrest drillship in the gulf of Thailand that reported missing in 1989, had capsized and killed 91 on board crew members. Although the industry managed to reduce the number of major accidents in the '90s, regrettably, the offshore disasters found their way into the 2010's with BP Deepwater Horizon in Gulf of Mexico in 2010 leading to 11 fatalities and more than 65 Billion USD in compensation expenses by British Petroleum (Offshore Tech., 2019). The statistics demonstrate the constant need for safety measures and improvement in regulations and risk management (IOGP, 2020). Alas, fatal accidents continue to happen in the industry, such as Maersk Interceptor in 2017 (PSAN, 2019), even though there are observing and regulating organizations that govern the industry, and the industry itself has given more attention to the safety education and requirements.

The need for safety, not only emphasizes the importance of managing the risks that are inherent to the oil & gas industry, but also implicates the necessity for improvements in the way we manage those risks. Kaplan & Garrick (1981) associate risk with the likelihood and severity of events. In simpler words, the risk is what can go wrong, its associated likelihood, and the severity of its consequences (Rausand, 2011). Reducing the likelihood of hazardous events and the severity of their consequences has become an essential task for all the sectors of the industry; specifically, the oil & gas.

## 1.1 Safety-I and Safety-II

Throughout the history different methods have been developed to minimize the risk in systems. More specifically, in the chemical engineering world, techniques such as FMECA[1], HAZOP[2], and SWIFT[3] have been employed for this purpose (Rausand, 2011). All these methods have one thing in common and that is they are based on identifying the hazards; that is what Safety-I mentality is.

The concept ‘Safety-I’ was introduced to highlight the perspective from which a system’s safe state has been defined. This philosophy includes practices that are designed to identify what went wrong (Anderson, 2012). In this philosophy things that can go wrong are identified as a basis for risk analysis and implementing safety measures (Hollnagel, 2013; Hollnagel, Wears, & Braithwaite, 2015).

The traditional way of thinking regarding risk analysis has been successfully used to identify where things can go wrong, whether for event investigation or risk assessment. Throughout the history, the classical view on safety has been developed from considering humans as prone to errors, as in obliged to make errors, to considering what may affect human performance, recognizing

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[1] Failure Mode, Effects and Criticality Analysis

[2] Hazard and operability study

[3] Structured what if technique

Performance Shaping Factors (PIFs). This recognition temporarily helped people to understand more complex accidents, yet it failed to describe many other situations (Hollnagel, 2007).

The idea behind another perspective for safety arose when the nontrivial complex sociotechnical systems' safety became a concern for safety experts. They believed the established approaches to safety were, if not harmful, ineffective (Hollnagel, 2017). This concern was supported in the early 2000s, and the concept of resilience engineering was introduced and further developed in the early 2010s as an alternative to the conventional view on safety with an emphasis on tackling the philosophy of cause and effect between phenomena (Hollnagel, 2016; 2017).

What makes the approach traditional or non-traditional simply lies in the philosophy of it and how the approach looks at the risk (Hollnagel, 2013). While the conventional safety point of view (Safety-I) focuses on identifying a hazardous state or the state in which there is a lack of safety, the non-traditional point of view (Safety-II) tries to focus on the disturbance and the system's ability to adjust itself. The difference lies in searching for things that go wrong (Safety-I) and how things go right (Safety-II) (Hollnagel, 2017).

The more complex the system, the harder it is to estimate and manage its behavior. The need for more modern approaches for controlling and reducing the risk rises as technology advances. The magnitude of accidents such as the Deepwater Horizon (US GOV., 2011) demonstrates the need for wholesome approaches in socio-technical systems (Franca et al., 2019).

### 1.1.1 Complex systems

Complexity in a system prevents it from being decomposed into smaller elements; that is, the system cannot be constructed by a summation of all the small elements. Binary models fail, and assuming linear relationships between the system's functions fail to estimate the system's characteristics. These systems are characterized by emergence rather than cause-effect relationships. Complexity itself can be of interactive, dynamic, de-compositional, and non-linearity nature (Frost & Mo, 2014).

### 1.1.2 Socio-technical systems

The socio-technical concept dates back to Britain's post world war II and it is entangled with the concept of resilience (Foster, 2018). A socio-technical system is well-named and almost completely self-explanatory; that is a system that has both social and technical features. To put it in better terms, while several technical aspects could be present as constituents of such systems, the role of humans, its relation to these technical elements and itself, and the organization that acts hierarchically characterize a socio-technical system (Frost & Mo, 2014).

### 1.1.3 Modeling complex socio-technical systems

The traditional approaches, such as bowtie analysis, have tried and modelled socio-technical systems with a degree of success and accuracy. More recent systemic approaches such as STAMP[4], a causality model based on systems theory (Leveson, 2017) and AcciMap, that maps multiple contributing factors to an accident and their inter-relationships (STL, 2020) have been implemented to model sociotechnical systems for the purpose of accident investigation (Underwood & Waterson, 2012; Igene, Johnson, Long, & Liu, 2017; Wienen, Allah Bukhsh, Vriezekolk, & Wieringa, 2017).

However, these methods follow the Safety-I mentality and as explained in section 1.1, there is a rising need to consider the Safety-II mentality in modeling sociotechnical systems (Hollnagel, 2012; 2017). Safety-II point of view requires the analyzer to look at the system in its wholesomeness (Pariès, Wreathall, & Hollnagel, 2011). This holistic point of view in addition to changing the focus from hazard to stability is the reason this approach can be introduced as a non-traditional approach to deal with risk in socio-technical systems. The application of the methods, and in particular FRAM, that share the Safety-II perspective has shown a promising potential for facing the complexities of the sociotechnical systems (Hollnagel, 2013; Åhman, 2013; Patriarca, et al., 2020).

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[4] System-Theoretic Accident Model and Processes

## 1.2 Objectives

This study aims to respond to the main question ‘‘How can Safety-II mentality add value to the barrier management in offshore drilling operation?’ To narrow down this question a set of sub-questions has been defined:

1- How to model the safety barriers in this approach?
2- How does the model handle the disturbances?
3- What can be interpreted from the model’s response?

Therefore, the main objectives of this study are:

1. Study and review the concepts of risk management and barrier management and demonstrate how the latter is related to the former.

2. Describe a Safety-II approach and model a sociotechnical system with Safety-II mentality for barrier management.

3. Compare the model’s response with a model that shares Safety-I mentality.

4. Discuss how the findings can answer the main question presented at the beginning of this section.

## 1.3 Limitations

The first limitation to accomplish the set objectives in this study is a lack of access to real industrial environments and experts which leads to difficulties when describing the system; for this reason, some assumptions were made in the study. The second limitation is that the data collected in this study are limited to the public and academic access data, which underlines the first limitation as well.

## 1.4 Approach

This study starts with a brief review on risk and risk management to provide understanding and supporting theoretical background. FRAM is chosen as a Safety-II approach to model an offshore drilling rig using available Safety-I data. A normal state of the FRAM model is then presented and exposed to two disturbance scenarios. The model's response is then compared to a traditional risk analysis approach, and the results of the comparison are discussed.

## 1.5 Structure of the study

While the introductory chapter provides the basic understandings required for performing the research, it also indicates and introduces the goals to be achieved and the objectives to be accomplished. The remainder of the report is organized as follows:

**Chapter 2** introduces the concepts of risk and barrier management and their importance in the oil and gas industry. As it serves the purpose of providing background information, it explains the traditional approaches to safety. It also briefly summarizes the concept of barriers as well as the methods to identify them.

**Chapter 3** introduces the Functional Resonance Analysis Method. Although FRAM is briefly mentioned in the first chapter, chapter 3 provides a more comprehensive understanding of FRAM, and serves as the background necessary to understand and perform the research.

Chapters 1 and 2 serve the purpose of accomplishing the 1st objective of this study, while chapter 3 partially accomplishes its 2nd objective.

**Chapter 4** describes the methodology undertaken to apply FRAM on a case study. This chapter facilitates the accomplishment of the study's 2nd and 3rd objective.

**Chapter 5** introduces the case study and the application of the FRAM in a thorough manner that accomplishes the 2nd objective of the study.

**Chapter 6** discusses the results of the analysis and serves the purpose of answering the research's main question by defining two "what-if" scenarios and compares the FRAM with the Event Tree. This chapter serves the purpose of accomplishing the 3rd and the last objective of the study.

**Chapter 7** concludes the work by summarizing the most important details of each chapter.

# 2 Risk and Barrier Management in the Oil & Gas Industry

For better understanding the importance of what is proposed in this research, a brief review of the theories and concepts of risk and barrier management has been presented.

## 2.1 Risk management in the oil & gas industry

Although the original concept of risk management dates to after World War II (Dionne, 2013), the risk management application in the oil & gas industry in a modern sense is relatively new (Rasmussen, 2017). Risk management as a continuous process to identify potential hazards regarding an activity has become of great importance and a field of interest as it serves the purpose of diminishing and controlling the risk (Rausand, 2011). Figure 2.1 shows Rausand's idea of how risk management is done (Rausand, 2011).

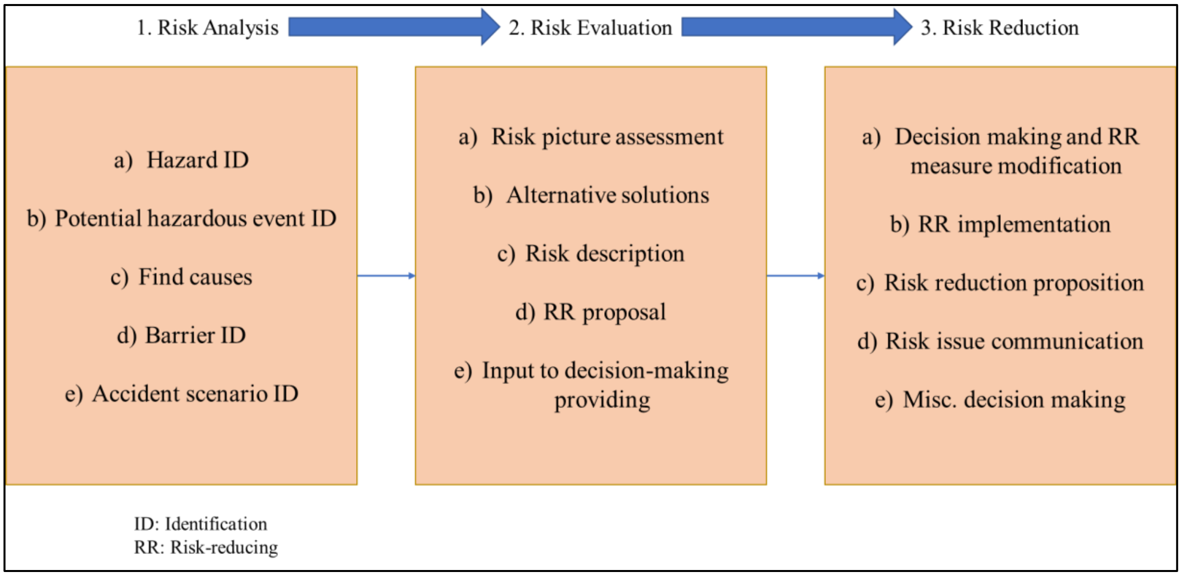

**Figure 2.1 Risk management's main elements (Rausand, 2011)**

The core part of risk management is analyzing the risk. Risk management consists of different stages of which hazard identification and hazardous event identification are amongst the very first. When the hazards are identified, the risk related to such hazards must be controlled and reduced. This is done by the application of the safety barriers that should be identified. (Rausand, 2011).

Barrier management serves as a means of regulation and management for the safety barriers (PSAN, 2013).

The stages of risk management are hereby explained with more detail, followed by a summary of barriers and barrier management.

### 2.1.1 Traditional risk analysis approaches – Safety-I

Following Safety-I mentality, the risk is defined and associated with quantification[5]. The process of quantification of risk in terms of likelihood and severity are taken care of by using methods such as Fault Tree Analysis based on Boolean logic and Event Tree Analysis (Rausand, 2011). Other concepts, such as the Swiss Cheese Model (Reason, 1990) are integrated into the design of the system to create a more conservative safety design. Furthermore, modifications have been made on simple models to increase their precision. Some of these modifications are mentioned in the next section.

#### 2.1.1.1 FTA, ETA, and Bowtie analysis

Fault Tree Analysis (FTA) has been widely used in the oil and gas industry to explain the causes of the hazardous event (i.e., top event). FTA uses a top-down approach and Boolean logic gates that provides a simple and efficient way to represent the causes of the top event graphically, and describes the risk in a quantitative way (Lundteigen & Rausand, 2009; Ferdous, Khan, Sadiq, Amyotte, & Veitch, 2010; Alkhaledi, Alrusaid, Almansouri, & Alrashed, 2015; Choi & Chang, 2016; Taleb-Berrouane & Lounis, 2016). This method has been combined with different mathematical approaches to increase the quantification's efficiency, presenting an even more meticulous model. Dawotola, Van Gelder, & Vrijling (2009) combine FTA with AHP to enhance the accuracy in risk assessment and estimate the most crucial failure mode of the oil pipeline. One of the more popular combinations of FTA is with the fuzzy approach for when there is a shortage of data (Aqlan & Mustafa Ali, 2014) or uncertainty or imprecision (Olawoyin & Alavi, 2017). Other combinations exist such as SOM (Self-Organizing Maps) (Liang, Hu, Zhang, Guo, & Lin, 2012), Fragility (Peng, Yao, Liang, Yu, & He, 2016) and Realtime Continuous Fuzzy approach

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[5] Kaplan & Garrick (1981)

(Senol & Sahin, 2016). Although Bayesian Network can be used as a separate method for a qualitative and/or quantitative risk assessment (Rausand, 2011), it can also be combined with FTA and ETA (Mirzaie Aliabadi, Mohammadfam, & Ahmadi gahar, 2018) for a dynamic approach (Paltrinieri & Khan, 2016; De Ruijter & Guldenmund, 2016).

While it is flexible, quantifiable, relatively simple and a quick way to analyze the causes of the top event by taking into account technical errors as well as human errors, FTA has its limitations such as not being applicable when the system does not have a binary fail-success working state (Rausand, 2011). It is also limited to the analyzer's imagination, meaning it only considers what is foreseen by the analyzer. When the system is large, FTA can be very time consuming to perform and the result is not as easily understandable as when it is applied on smaller systems. Furthermore, because the method provides a static risk picture of the system, it cannot be used for dynamic descriptions; unless, it is combined with other methods (Rausand, 2011; Fussell (Supervisor), 2017). In case of modeling the safety barriers as failure mechanisms, there is a possibility of redundancy in representing the system using this method (De Ruijter & Guldenmund, 2016). It should be noted, FTA is only used for identifying the causes and not the consequences of the event. To deal with the consequences the Event Tree Analysis (ETA) is used which follows the same binary logic of fail-success state (Rausand, 2011).

A bowtie diagram is commonly used to combine and present the FTA and ETA simultaneously (De Ruijter & Guldenmund, 2016). The bowtie analysis shows the identified hazardous event, or main event, in the center with the causes to its left (FT), and the consequences or the subsequent events to its right (ET). The resulting diagram resembles a bowtie; hence, the name of the method (Rausand, 2011). Safety barriers can be seen on a bowtie diagram. Figure 2.2 represents a generic bowtie diagram (CGEA, 2019).

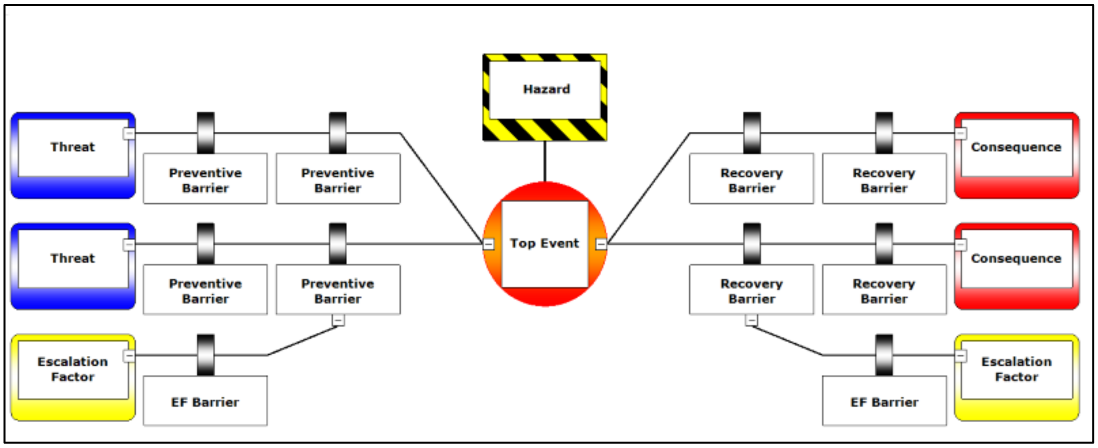

**Figure 2.2 Generic bowtie representation (CGEA, 2019)**

### 2.1.2 Risk evaluation

When the risk analysis is completed, the risk picture is compared with safety guidelines and the risk acceptance criteria. If the risk needs to be reduced, in both senses of frequency and severity, then risk management proceeds to its final step (Rausand, 2011).

### 2.1.3 Risk control and reduction

With the higher emphasis put on frequency reducing measures, the last step of the risk management is to propose risk reduction measures in terms of preventive and mitigating (NO GOV., 2018). The inherent safety design of the system will realize the minimization of the risk, which makes it a preventive measure (Rausand, 2011). Considerations such as, eliminating the use of a substance, or substituting it with a less hazardous one, or optimizing the used amount of it, can be taken. More considerations to realize a lower risk in the system can be the introduction of more barriers, whether proactive or reactive, and detecting and warning by transmitting information regarding a hazardous event. In this step, competence requirements are defined to prevent or mitigate human errors, in addition to quality requirements and other specifications (NO GOV., 2018).

## 2.2 Barrier management

As stated before, risk management means to identify, assess, and evaluate the risk, and then control and reduce it. One of the most used means of reducing the risk, no matter which method is used for hazard identification, is the introduction of barriers. As it is clear to understand, barriers play an important role in risk management (Rausand, 2011). To ensure barriers are maintaining their functionality over time in the system, barrier management seems a must (Johansen & Rasuand, 2015). The purpose of barrier management is to make sure barriers will handle the risks at any time (PSAN, 2017). Barrier management itself is defined as a systematic and continuous process that ensures barriers' functionality is intact (PSAN, 2017).

Since barrier management is a continuous procedure, as shown in Figures 2.3 and 2.4, the method can be classified based on the different phases of the process itself, as in early design, detailed design, and operation phase (Hauge & Øien, 2016). Indeed, barrier management heavily relies on the hazard identification and barrier analysis techniques. Barriers are used for the purpose of reducing risk in most well-designed systems (Rausand, 2011), and as seen in Figure 2.3, methods to identify them play an important role in barrier management.

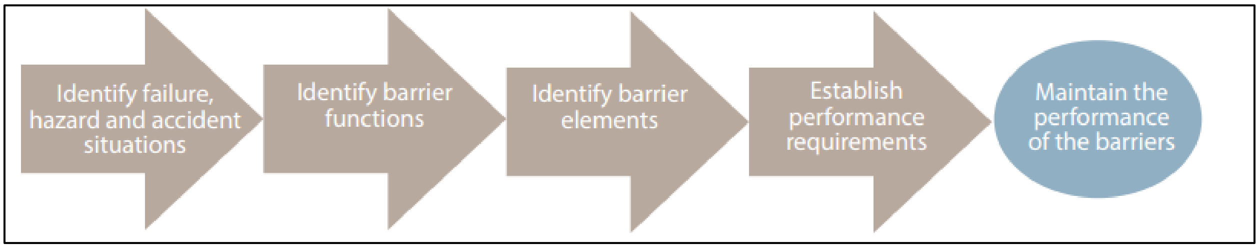

**Figure 2.3 Key points in barrier management, adopted from (PSAN, 2017)**

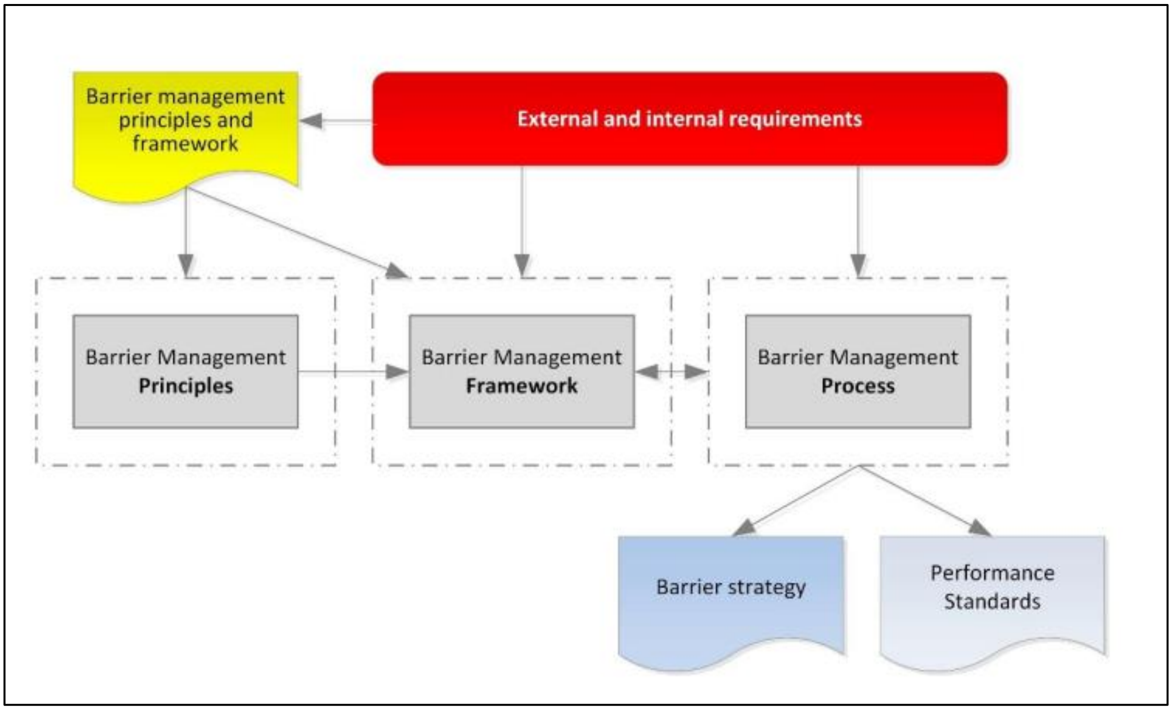

**Figure 2.4 Barrier management overview, adopted from (Hauge & Øien, 2016)**

### 2.2.1 Safety barriers

There are various definitions of what a safety barrier is and various ideas on how to define and classify them. (Sklet, 2006) defines safety barriers as "*a physical and/or nonphysical means planned to prevent, control, or mitigate undesired events or accidents".* No matter how we define the safety barriers or which definition we use, they can ultimately be considered as measures that reduce 'the risk' of hazardous events; either by lowering the likelihood of its happening, or by decreasing the severity of such event's consequence. Thus, a barrier's function is the task it should be performing properly. All barrier functions need to be realized with what is called a barrier element (Rausand, 2011). Barrier functions may be realized with only one barrier element or may have sub-functions and sub-sub functions and be realized with several barrier elements. The decomposition from functions to elements is shown in Figure 2.5 (Hauge & Øien, 2016).

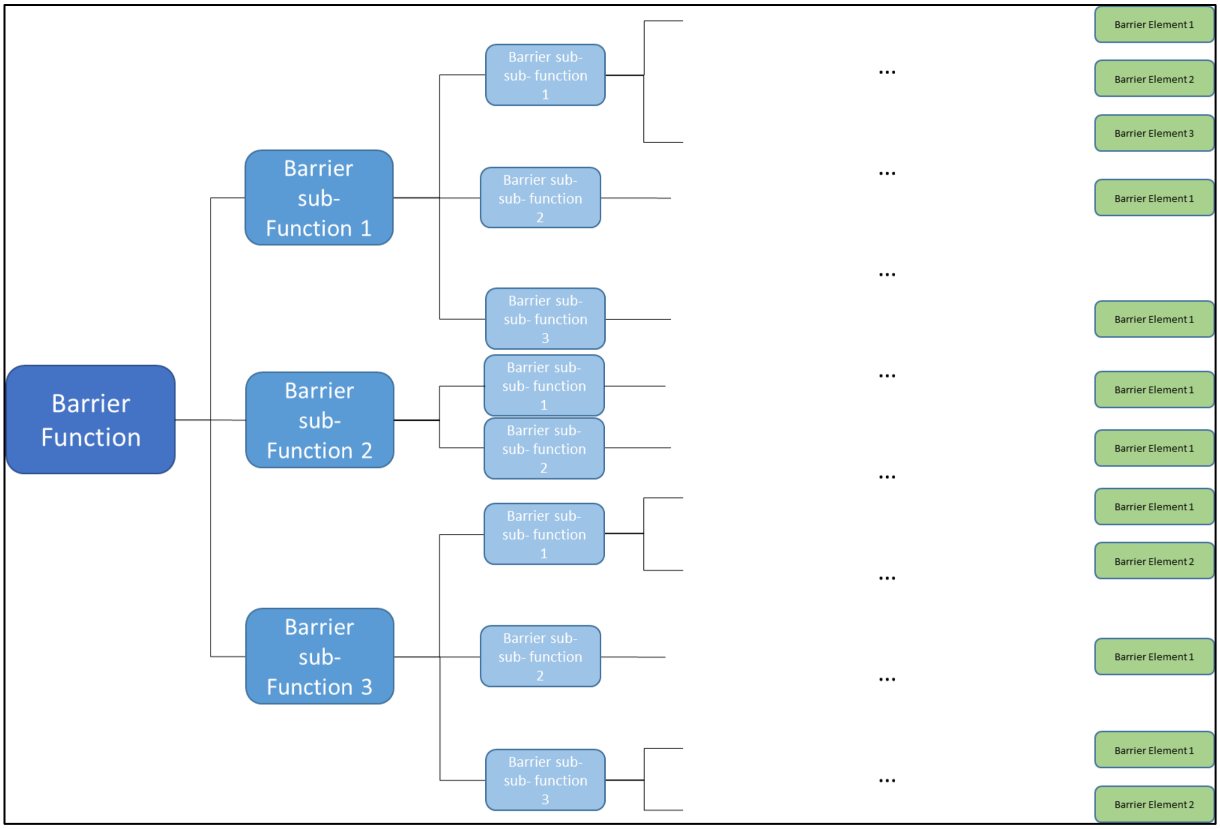

**Figure 2.5 Barrier classification in terms of functions through elements (Hauge & Øien, 2016)**

Barriers have played a crucial role in maintaining safety of systems and are required by legislations; however, the terminology was not unified (Sklet, 2006). To prevent confusion and create a unified terminology system, different classifications were introduced by experts. These classifications help us distinguish between types of barriers in place and address them when necessary. A summary of these classification is provided in Table 2.1.[6]

Barriers should have specific characteristics that make them reliable and provide us with criteria to evaluate them. Rausand uses the terms *specificity*, *adequacy*, *independence*, *dependability*,

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[6] Next page

*robustness*, and *auditability* (Rausand, 2011). PSAN[7] uses the terms *Functionality, integrity, and robustness* (PSAN, 2017).

**Table 2.1 Barrier classification summary (Hourtolou & Salvi, 2003; Sklet, 2006; Rausand, 2011)**

| | | | |
|---|---|---|---|
| **Rausand** | Proactive: Reduces the probability of the hazardous event | | |
| | Reactive: Reduces the consequences of the hazardous event | | |
| **Sklet** | **Passive** | *Physical* | |
| | **Active** | *Technical* | |
| | | *Human and/or operational* | SIS[8] |
| | | | Other technology safety-related system |
| | | | External risk reduction facilities |
| **Reason** | Create *understanding* and *awareness* of local hazards | | |
| | Give clear *guidance* on how to operate safely | | |
| | Provide *alarms* and *warnings* when danger is imminent | | |
| | *Restore* the system to a safety state in and off-normal situation | | |
| | *Interpose* safety barriers between the hazards and the potential losses | | |
| | *Contain* and *Eliminate* the hazards should they escape this barrier | | |
| | Provide the means of *Escape* and *Rescue* should hazard containment fail | | |
| **Hollnagel** | Material barriers: fences, guardrails, containers, clothing, and fire walls | | |
| | Functional barriers: locks, interlocking, passwords, entry codes, etc. | | |
| | Symbolic barriers: road signaling systems, signs, markers, instructions, and work permits | | |
| | Immaterial barriers: operators' competence, laws, guidelines, safety principles, monitoring, and supervision | | |
| **ARAMIS[9]** | Avoidance: Changing the design to avoid what causes the accidents | | |
| | Prevention: Reducing the probability or consequences of a hazardous event | | |
| | Control: To limit the deviations, and delimit the emergency situations | | |
| | Protection: Protective measures in case of an accident | | |

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[7] Petroleum safety authority Norway

[8] Safety Instrumented Systems

[9] Accidental Risk Assessment Methodology for Industries in the framework of the Seveso II directive

### 2.2.2 Barrier analysis (Identification and evaluation)

Several methods have been developed to fulfill the purpose of identifying and evaluating barriers. A summary of each technique is as follows:

*Hazard-Barrier Matrices*

When the hazards are identified, one useful tool to identify and evaluate the barriers can be the hazard-barrier matrices method. The protective barriers are identified, as well as barriers that can be protective against more than one hazard. Moreover, adequacy and inadequacy of barriers are evaluated. A simple matrix is then prepared, and the result is reported (Rausand, 2011).

*Safety Barrier Diagrams*

This method is a graphical representation that shows the events in sequential order from causes to the consequences with a 'main event' in the center. Binary and Boolean logic are used to complete the depiction (Rausand, 2011). Figure 2.6 depicts a generic Safety Barrier Diagram. It is clear from the presentation that B1 is installed to prevent event 1 from happening, same goes for B2 and event 2. If either event 1 or 2 happens, event 3 will be happening and there for barriers B3 and B4 are installed to prevent consequences 1 and 2.

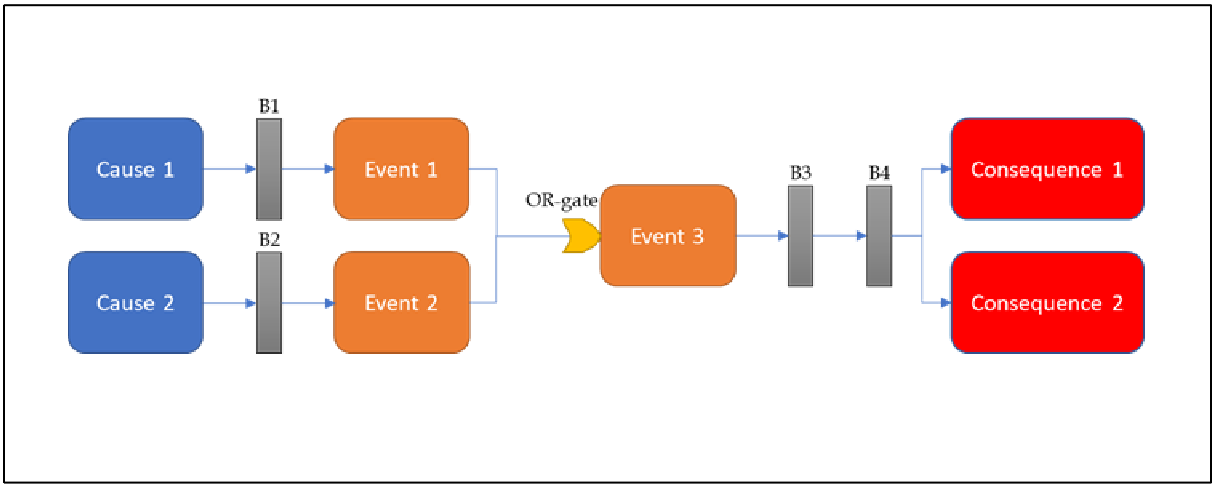

**Figure 2.6 Safety Barrier Diagram method, (Rausand, 2011)**

### *Energy Flow/Barrier Analysis (EFBA)*

Another qualitative method that focuses on the energy pathways from its sources to the assets in the system that are potentially harmed by the adverse effects of the energy. This method is used for accident investigation as well as risk assessment by identifying energy sources, the assets, energy pathways, and barriers. Lastly, it proposes improvements on the system and the results are reported in a table called the EFBA worksheet. It is a simple method to understand, systematic, suitable to be combined with other methods such as PHA[10], and its recommendations are easily translated to actions and instructions. Yet, it cannot identify every hazard in the system, but only the ones related to the energy, and it may not be reproducible for larger systems (Rausand, 2011).

### *Layer of Protection Analysis (LOPA)*

A semiquantitative method for process risk analysis, for determining if the existing barriers in the system are adequate, or they need betterment (CCPS, 2001). Barriers in this method are called protection layers. Typically, this method is combined with other techniques to assess the risks, for example, after completing a HAZOP[11] study, the identified initiating events are used to set a starting point for the LOPA (Rausand, 2011). Another example of these combinations is LOPA's integration into a bowtie diagram[12] for a clear representation of the identified events and accident scenarios with the associated protection layers or use of an Event Tree Analysis (ETA)[13] to estimate the order of magnitude of the accident scenario's probability (Willey, 2014). The results are then reported in the LOPA worksheet. This method helps to highlight those barriers that are critically more important. It may indicate hazards that had not yet been identified with other qualitative methods, and while less time-consuming than most quantitative methods, its thoroughness surpasses methods like HAZOP. However, it may not be suitable for low-risk decisions and very complex systems (Rausand, 2011; Dekra, 2019).

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[10] Preliminary hazard analysis

[11] Hazard and operability

[12] See Chapter 1

[13] See Chapter 1

*Barrier and Operational Risk Analysis (BORA)*

This method is developed to deal with the oil and gas installations phase and its operational reactive and proactive barriers (Rausand, 2011). This method gives a better understanding of the safety barriers and is strongly active in recognizing Risk Influencing Factors (RIFs) and categorizing them into technical, human, and organizational and ranking them in the system based on their importance to the system (Teng, Vatn, & Mostue, 2010); the numbers given in this ranking system are not justified (Rausand, 2011). It mostly focuses on Hydrocarbon releases, in addition to its capability to indicate installation-specific risk. A barrier block diagram is used to represent the results graphically, and these diagrams are translatable into Event Trees and Fault Trees [14] (Rausand, 2011).

### 2.2.3 Barrier monitoring

To ensure barrier status at a given time, monitoring barriers is necessary to the barrier management overall procedure when the system is operational. Many petroleum companies have implemented techniques and methods to monitor the barriers, tag them, and reveal the failed or degraded status by alarms. Some examples of these methods which try to maintain a real-time picture of the barriers are:

Conoco Philips' iSee system, Petrotechnics' Procient, Shell's Total Risk, British Gas' Cumulative Risk Assessment, IFE's IOMap, and SINTEF's Risk Barometer. The latter is used for barrier condition monitoring (Edwin, 2015).

### 2.2.4 Barrier management improvement

Understanding the goal of barrier management and its objective leads us to think about ways to improve the efficiency of barrier management in terms of thoroughness and dynamicity. The hazard identification process can become more thorough, but it will be more time-consuming. Maybe a combination of methods is used, or a modified version of a technique is implemented.

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[14] See chapter 1

Furthermore, the barrier analysis process can be improved in the same way as the hazard identification process.

As mentioned in the introduction section, in recent years, a change in the perspective of what safety means (Hollnagel, 2013) has led to the development of methods, such as Functional Resonance Analysis Method (FRAM), and the need to use such methods has increased as well. This method and its applications are introduced in the next chapter.

# 3 Functional Resonance Analysis Method (FRAM)

The word ‘resilience’ is defined as ‘*the ability to recover from or adjust easily to misfortune and change’* (Merriam-Webster, n.d.). In a more practical sense, a system is resilient if it is able to maintain its stable state. It is understandable that in resilience engineering the focus for describing the system is stability which in itself is not a binary point of view, even though a ‘stable/not stable’ argument seems emerging. System resilience is not having resilience as a property or a quality, but its sustainability in expected and unexpected situations to perform required operations (Pariès, Wreathall, & Hollnagel, 2011).

Resilience engineering championed the idea that what is perceived as success or failure has in fact but one origin, meaning the success and failure have the same nature, similar to two sides of a single coin. This later became the very first principle on which the Functional Resonance Analysis Method, FRAM, was built on (Hollnagel, 2007).

FRAM is a method for analyzing and assessing a system that focuses on work-as-done, providing a way to understand how diversion from the defined parameters (work-as-imagined) can lead to different outcomes (Hollnagel, 2012). As Hollnagel (2012) describes the FRAM approach is developed based on four resilience principles.

## 3.1 Principles of FRAM

FRAM is based on four principles (Hollnagel, 2007; 2012):

- *Equivalence of Success and failure:* To put simply, the source of what we perceive as success and failure is the same. What makes things go right have the same nature as what makes them go wrong. Just because the outcome has a different nature does not mean what causes them is different.

- *Approximate adjustment and performance variability:* The complexity of the socio-technical systems makes them in most cases intractable; therefore, the work as done is never equal to work as imagined. This makes individuals, groups, and organizations to always adjust their performance when facing variations, meaning there is always a performance variability. This adjustment is always approximate and not exact, since the resources for meeting the existing conditions are finite. The performance variability arose from the approximate adjustment is what makes things go right or wrong.

- *Emergence:* Events are emergent, as in what causes an event might not exist anymore; thus, making the cause of a phenomenon, although leaving trace and effects that could be permanent, elusive. Instead of searching for what causes an outcome FRAM reconstructs it. In FRAM's view, causality does not have a place in describing how things go right or wrong. For example, an explosion cannot be explained solely based on a failed valve, neither a successful valve should be seen as the sole reason for a no-explosion state. FRAM uses variability to describe outcomes, which is always present when a phenomenon happens.

- *Functional resonance:* The interconnections of the system, when there is variability, make each part affect other ones when resonating. If these resonances are of reinforcing nature, it may lead to a certain function's variability to be extraordinarily high. In order to explain how causal links can be replaced by this, the functional resonance is described as '*the detectable signal that emerges from the unintended interaction of normal variabilities of many signals.'*

## 3.2 How the FRAM is developed

According to Hollnagel (Hollnagel, 2012; 2013) FRAM consists of 5 main steps.

*Step 0- Define the purpose of FRAM*

To perform a FRAM analysis, Whether the FRAM is used for event investigation or risk assessment should be defined from the beginning. Understandably, an event investigation is done when the observable outcome demands the reconstruction of what lead to it, while the risk assessment is done when the observable cause may lead to the outcome.

*Step 1- Identify and describe the functions*

The analyzer needs to understand the scope of the analysis, and what is analyzed. After the 0th step, the goal of the FRAM analysis for a specific case has been understood. This specific case must be described, meaning how something is done in detail. For every Function of the FRAM, which is an activity or a set of activities to be carried out, 6 aspects must be considered. The 6 aspects of each function are the Input, Output, Precondition, Resource, Time, and Control. These may not be introduced all together, and, as a matter of fact, there might not be a need for their description, depending on the resolution and extent of the analysis. The only obligation of the analysis is that each aspect must come from a function and must go to another function; meaning, aspects cannot emerge out of nowhere and disappear into a void. In graphical representations of the FRAM model (see Figure 3.1), the function is depicted using a hexagon. Functions can be upstream, downstream or both, showing the respective position of each function in the system. Functions that are studied are the Foreground Functions, as opposed to the ones that affect Foreground Functions and the focus of the study is not towards them, the Background Functions.

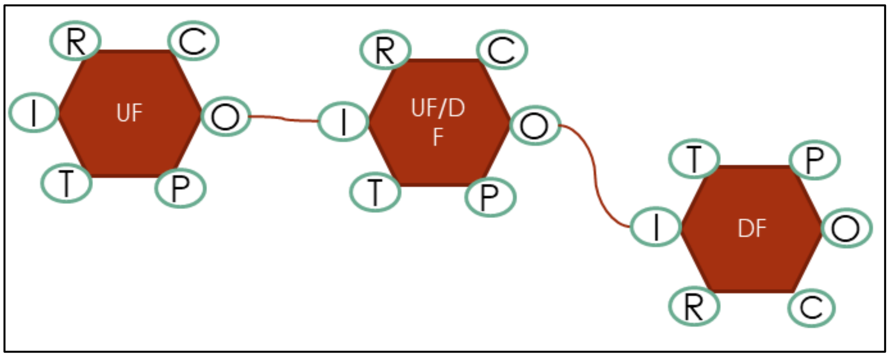

**Figure 3.1 A hexagonal depiction of upstream (U), up/downstream(U/D), and downstream (D) FRAM Function (Hollnagel, 2012)**

*Step 2- Identify the variability*

The variability can be the actual variability from the design or the potential variability which has not happened in the system, but it is our assumption about the Function. Given all the circumstances the potential variability may never become an actual variability. The focus is firstly on the variability of the Output of the Function because it determines if the variability of the Function itself should be studied or not. Sources of variability in each of the human, technical and organizational Functions (carried out by humans, machinery, and organizations respectively) can be endogenous (internal), exogenous (external), and coupled. When defining the coupled sources of variability, the analyzer will automatically shift to the next FRAM step. After recognizing the internal and the external sources of variabilities, the focus shall be on the manifestation of these variabilities. For characterizing these variabilities, FRAM offers two solutions: simple and elaborate. The simple solution searches for the Output variability in terms of its timing and precision, whereas the elaborate solution searches for the Output variability in terms of its timing, duration, force, distance, direction, wrong object, and sequence. The simple solution is often done and may indicate the need for an elaborate solution; of course, this depends on the scope of the analysis.

*Step 3- Aggregation of the variabilities*

In this step these questions should be answered: Can these functions be coupled? Can they lead to unexpected events? For example, how an Output signal that is late, on time, or early can affect the variability in its Downstream Function; would it increase the variability in such Function, or decrease it, or none. This procedure helps to determine if the couplings can lead to extreme and excessive variability that needs to be dampened.

*Step 4- Consequences of the analysis*

The last step of a FRAM analysis will be to manage the performance variability. FRAM, regardless of the ‘fail-success’ way of thinking considers variabilities, and since it is not bound to limiting the negatives, it may offer to augment the positives. FRAM, in addition to elimination, prevention, protection, which are usually done by introducing safety barriers or defenses like traditional methods, offers facilitation for when the variabilities have the desired effect. Furthermore, FRAM offers monitoring and dampening since it can propose ways to control the couplings that lead to increased performance variability and shows how the upstream Functions’ Output may vary and, understandably, by reducing the variability from their Output, the overall variability can be dampened.

Although FRAM is a textual based approach and can be done on a piece of paper, there are software to facilitate the representation (Hollnagel, 2012; Patriarca, Di Gravio, & Costantino, 2017). No matter how the final representation of the system i.e. instantiation is represented, a set of time-consuming tasks defining the scope and describing the Functions and their Aspects must be carried out.

## 3.3 FRAM applications

FRAM is becoming more popular in recent years; especially, in academia. Since 1995, FRAM has been used to investigate aviation safety (Patriarca, Falegnami, Costantino, & Bilotta, 2018) and later on in modeling various systems in different fields, including the chemical industry. Indeed, earlier works have been done by Eric Hollnagel himself and his associates (Macchi, Hollnagel, & Leonhard, 2009; Herrera, Hollnagel, & Håbrekke, 2010; Hollnagel, 2013). Underwood and Waterson (2012) have done a critical review of FRAM as a systemic accident analysis model and concluded with the reasons for the industry to be reluctant to use the FRAM and other systemic modeling approaches at that time. Halseth (2012), in her master's thesis, concluded that FRAM has the potential to capture the larger systems' model while it lacks quantification.

Jens Åhman in his thesis concluded that FRAM needs to undergo more development, yet it is a promising method (Åhman, 2013). Melanson & Nadeau have successfully shown the FRAM's usability for managing Occupational Health and Safety (OHS) in complex manufacturing systems (Melanson & Nadeau, 2016). Anvarifar et al. employed FRAM for an enhanced qualitative risk analysis of a multifunctional flood defense (Anvarifar, Voorendt, Zevenbergen, & Thissen, 2017). The FRAM has been simultaneously applied with Fault Tree and Bayesian Network to provide a completer picture of the system (Smith, Veitch, Khan, & Taylor, 2017). FRAM has also been adopted in Maritime safety (Abaei, Arzaghi, Abbassi, & Garaniya, 2017). In a chemical industry-related work, Hosseinnia et al. have modeled the maintenance operations' socio-technical nature by using FRAM as a facilitator, successfully assessing the dynamic interactions and their associated risks (Hosseinnia, Khakzad, Patriarca, & Paltrinieri, 2019).

FRAM's flexibility has been shown in the work of Rosa et al. by proposing the application of the Analytic Hierarchy Process (AHP) to enhance FRAM (Villarinho Rosa, Naked Haddad, & Rodrigues de Carvalho , 2015). FRAM-AHP approach has been employed to analyze offshore well drilling (França, Hollnagel, Luquetti dos Santos, & Haddad, 2019). In 2016, Patriarca et al. introduced a semi-quantitative approach that uses FRAM and Monte Carlo evolution to enhance Environmental Auditing (Patriarca, Di Gravio, Costantino, & Tronci, 2017; Patriarca, Di Gravio,

& Costantino, 2017). Patriarca et al. successfully used the FRAM to be used in a neurosurgery case study while recognizing more modeling effort is needed, so that FRAM could be considered as a decision support tool (Patriarca, Falegnami, Costantino, & Bilotta, 2018). FRAM application in automated driving safety analysis indicates the strong potential of FRAM as a systematic approach (Grabbe, Kellnberger, Aydin, & Bengler, 2020). Slim & Nadeau used a mixed rough sets and fuzzy logic approach for modeling systemic performance variabilities in FRAM, simulating aircraft deicing operations with ideal data (Slim & Nadeau, 2020).

Understandably, as a relatively new method FRAM is not wildly used for risk assessment. However, it is becoming more popular especially since 2016. Table 3.1 is based on a search on Scopus for the keywords ‘FRAM’, ‘risk’, and ‘assessment’ in the chemical engineering field.

**Table 3.1 Number of FRAM-risk assessment publications in Scopus, in chemical engineering**

| Year | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Number of Publications | 0 | 1 | 1 | 2 | 1 | 6 | 12 | 6 | 6 | 4 | 39 |

# 4 Methodology

## 4.1 Method overview

To understand FRAM’s suitability for barrier management, the proposed methodology illustrates integration of conventional barrier analysis into FRAM. The approach consists of 4 phases, each having a series of steps. The first phase, similar to the barrier management’s hazard identification phase, provides a basis for the integration of the Safety-I approach into the FRAM. The second phase is the conversion phase in which based on the system itself, firstly, FRAM Functions are defined as well as using the barrier functions to develop the FRAM model. In the third phase, the analysis of the FRAM model is done based on the FRAM’s stepwise descriptions. In the last phase, a normal state of the system is analyzed in FRAM model, and later the FRAM model is compared with a Safety-1 approach. Figure 4.1 shows the method overview and its link to barrier management framework and the FRAM’s steps.

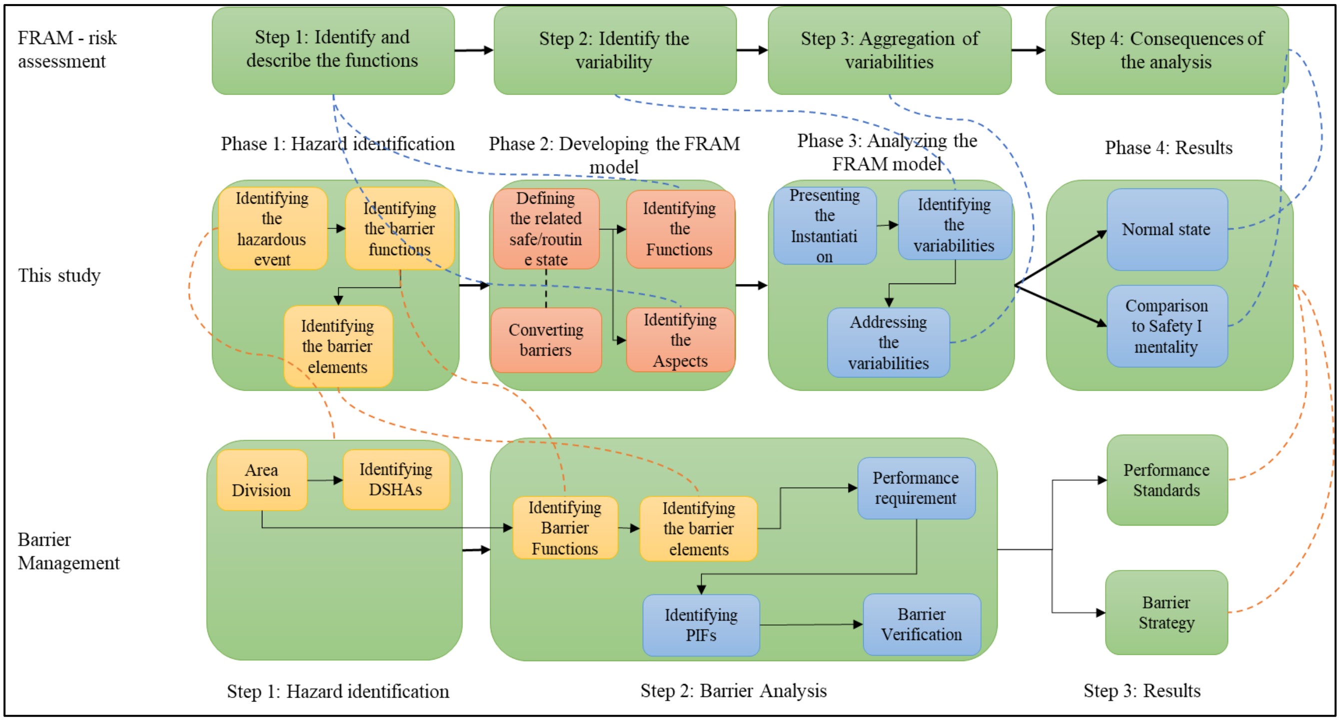

Figure 4.1 Graphical representation of the link between barrier management phases and the study's approach and the FRAM

## 4.2 Phase 1: Hazard identification

### 4.2.1 Identifying the hazardous event

The procedure starts from a Safety-I mentality that requires a hazardous event to be identified. Risk, threat, and hazard have been defined many times by different organizations such as PSA (Britton, 2020). Here, a hazardous event can be defined in the same way set when constructing an event tree (Rausand, 2011). Traditionally speaking, every method for risk assessment starts from identifying a hazard or a main hazardous event that in chemical industry is usually the moment the control over a hazardous substance is lost (Rausand, 2011).

### 4.2.2 Identifying the barrier functions and barrier elements

Barrier function is the task a safety barrier is expected to do successfully and completely (PSAN, 2013) and failure to do so may lead to undesirable consequences (PSAN, 2010). Identifying barrier functions can be a simple logical response to a particular hazard or hazardous event. As mentioned in section 2.1.1.1, ET diagrams can be constructed based on an identified hazard and its progression to an accident. Event trees are developed based on the failure of specific barriers in place, and studying them can reveal information about the barrier functions and their elements; depending on how detailed the bow-tie diagram is (Rausand, 2011). This research employs the predefined event trees as a starting point and a primary source to identify the related barrier functions and its elements to be integrated into the FRAM model.

## 4.3 Phase 2: Developing the FRAM model

This phase is an intermediary with the purpose of constructing our FRAM modeling, and more importantly, to define the FRAM Functions[15] based on each barrier function identified in the previous step. Although the FRAM can be used to define the barriers from scratch based on the process to be modeled (Hollnagel, 2012), this assignment uses predefined barriers for a certain

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[15] To prevent ambiguity, all terminology in the FRAM that have certain meaning in context while other meanings elsewhere are written with a first capital letter, such as Function, Aspect, Input, … instead of function, aspect, input, …

hazardous event[16]. Depending on these barriers' functionality, they can be employed directly or indirectly within the model.

### 4.3.1 Defining the related safe/routine state

The FRAM does not share the traditional way of thinking about safety and does not focus on a failure or an incident. A safe state of the model is defined, for example, a normal working day on a platform where oil is produced without a problem or abnormality. At the same time, identified barrier functions are redefined into FRAM Functions. However, this conversion must be done in a way that does not contradict the original FRAM's principle of equivalence of the success and failure causes. This way, the barrier functions and their elements can be included, without directly including the barrier's functionality in an emergency state.

It should be noted while FRAM allows us to model an accident and provide an 'event investigation' analysis based on how things were done, in this research, the main objective is to evaluate FRAM's ability for 'risk assessment'. Therefore, it will be based on how things should be. This, understandably, demands more creativity and imagination. Analyzing things that can go wrong is more accessible than figuring out what makes the system succeed (Hollnagel, 2012).

### 4.3.2 Identifying the Functions and Aspects

In this step, the functions of a FRAM model are defined. As mentioned by Hollnagel (2012), a FRAM analysis can be similar to task analysis and be initiated from any defined functions. FRAM requires us to provide each Function with a title, description, and its related Aspects. These Aspects are Input, Output, Precondition, Time, Resource, and Control[17]. As the Aspects are defined for each Function, other Functions will be revealed in the process because of the interconnectivity of the functional aspects; one Function's Output can be a Precondition for another Function. Furthermore, the boundaries for the analysis needs to be defined with the progression of the model, depending on how detailed the modelling is.

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[16] This was performed to have an idea of work-as-imagined since work-as-done required more information that were not available.

[17] See chapter 3, section 2

## 4.4 Phase 3: Analyzing the FRAM model

When the FRAM model is completed, the instantiation of the system can be presented graphically. The variabilities and their sources for all the identified Functions can be identified using the solutions[18] described in the FRAM's instructions.

### 4.4.1 Presenting the instantiation

After having defined every relevant FRAM Function and its Aspects, the FRAM instantiation of the system can be shown by using FMV software (Hollnagel, "FMV." FRAM Model Visualiser, 2012). FMV provides a graphical representation of the interconnectivity of the system and its elements. In this instantiation, all the Functions can be seen as well as their functional relation.

### 4.4.2 Identifying the variabilities

For each of the FRAM Functions, there can be different sources of variability that can be identified by following the FRAM's instructions and understanding how each Function can show diversion from the normal state, regarding timing and precision. A more elaborate approach can be done by introducing more phenotypes such as speed and direction. For this assignment, the simple solution was chosen[19].

### 4.4.3 Addressing the variabilities

Variabilities are in fact performance variabilities in the system which need to be managed. FRAM can introduce different ways to manage the variabilities to the system's benefit; limiting diversions that lead to adverse effects and even augment the ones leading to stability and higher efficiency of the system. The person/team that has done the analysis should think about how to detect, monitor, control and specifically dampen the effects of a potentially disruptive performance variability (Hollnagel, 2012).

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[18] See section 3.2

[19] See section 3.2

## 4.5 Phase 4: Results

When the variabilities and their aggregations are identified, a set of default assumptions (Hollnagel, 2012) is considered to define a normal state for the described system. Two ‘what-if’ scenarios in which there is an increase in variability of a Function are introduced to analyze the FRAM model’s response. These scenarios are used to define simplified event trees in order to compare the results of Safety-I (Event tree) and Safety-II (FRAM) mentality.

The applicability of the method is addressed in a case study in the next chapter.

# 5 Case Study and Analysis

## 5.1 Case study definition

Oil & gas production is done through drilling wells (API, 2020). The process in which a hole is bored using a drill bit to extract oil and gas is called drilling. (Pearson, 2020). These wells require a great deal of care and precision as working with hydrocarbons, especially under high pressures and temperatures (Ahmed, 2016), demands advanced technologies and proper safety measures (NORSOK, 2019; Baggermans, 2019; API, 2020).

Oil and gas extraction can be performed by onshore or offshore drilling rigs that are generally similar but different in operational aspects. A generic offshore drilling rig, as seen in Figure 5.1 (Akers, 2015), must exist on an offshore platform that needs to be built with specific details regarding the location and the depth of the well. These well locations are marked with a subsea drilling template that is a large metal box with holes (J.M.K.C. Donev et al, 2016) as seen in Figure 5.2 (Aquaterra, 2020). The drilling process is started after the locations of the wells are known.

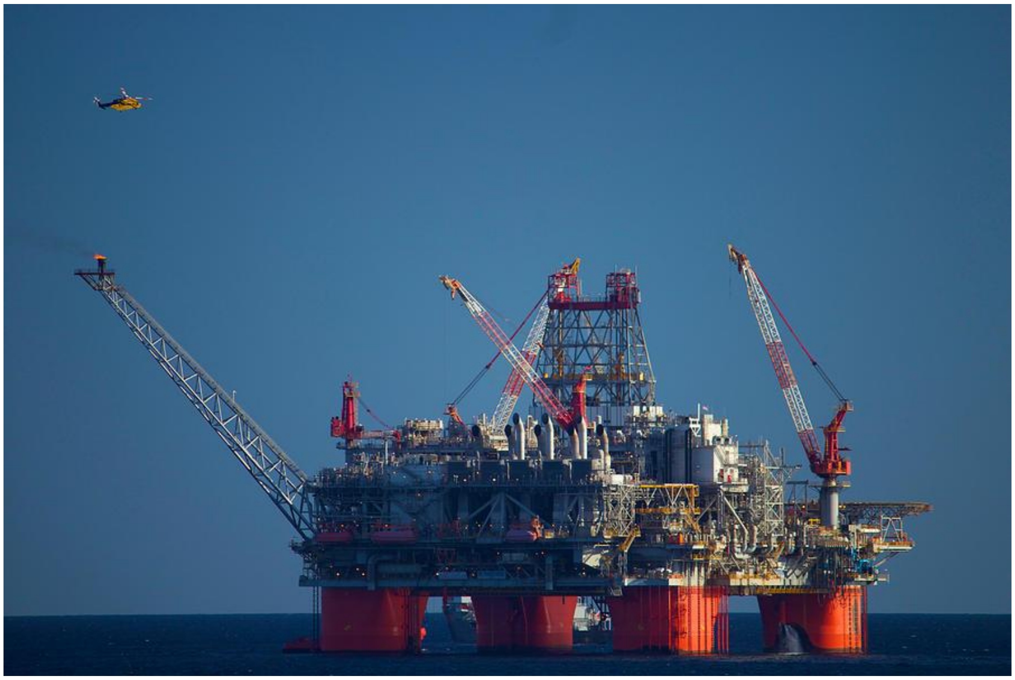

**Figure 5.1 An offshore drilling rig in the Gulf of Mexico (Akers, 2015)**

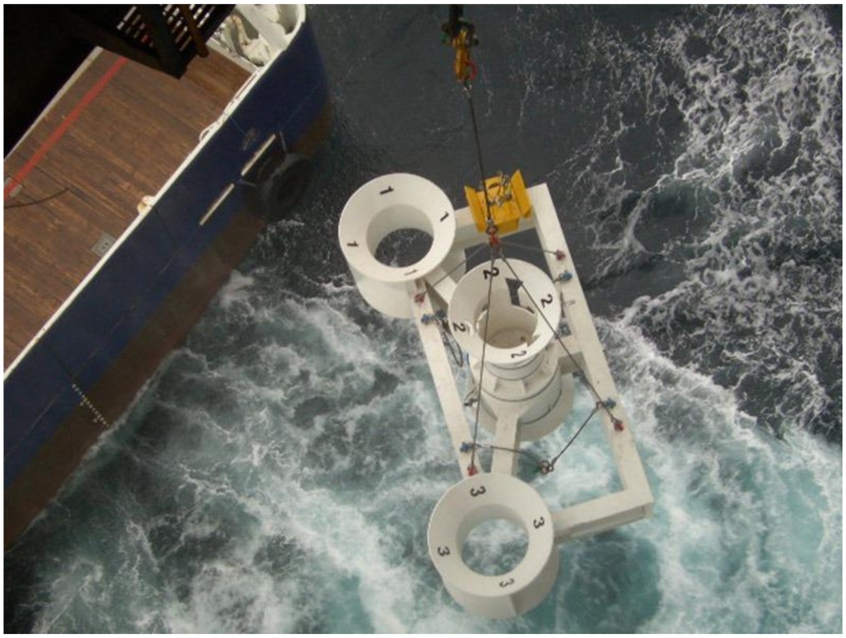

**Figure 5.2 A subsea drilling template adopted from (Aquaterra, 2020)**

To be able to reach deep into the sea and Earth's crust, a large drilling string with a drill bit at its bottom is utilized by connecting several 9-meter drill pipes. The top section of this string is connected to what is called a rotary table (Lamb, 2016). This spinning facilitates the process of grinding down into the Earth (J.M.K.C. Donev et al, 2016).

To ensure the safety of the wells at any given stage, different techniques and regulations are in place (NORSOK, 2019). As the bore reaches deeper, a constant flow of drilling mud is sent down to the drilling bit that lubricates it and serves as an essential safety barrier (Lamb, 2016). The drilling mud cools the bit down, returns stone particles to the surface, and exerts pressure on the fluid formation to prevent kick and blowout (ENI, 2005). Figure 5.3 shows a blowout in a natural gas well in the Gulf of Mexico (Snow, 2015).

Another safety measure that is essential to the drilling procedure is the blowout preventer (BOP) that in an emergency state seals the well hydraulically. (Lamb, 2016). When the well is completely sealed, a final casing called 'production casing' is installed that will be fracked with explosives to allow oil and gas to be extracted. This is done in the ‘completion’ phase of the oil and gas extraction. (J.M.K.C. Donev et al, 2016).


From US Bureau of Safety and Environmental Enforcement

**Figure 5.3 A natural gas well blowout in the Gulf of Mexico (Snow, 2015)**

A simplified workflow of the drilling activity from planning to operation in the offshore oil and gas industry is shown in Figure 5.4.

Considering the advances of the technologies used in the oil & gas industry for production, it is understandable to assume a large and complex model is needed to represent a realistic picture of it. However, breaking down this complex picture and focusing on its smaller sections helps to understand each section in more detail. By breaking it down to what are the most probable accidents in different stages for an offshore platform, it will be possible to narrow down the complexity by a great deal. Thus, a subsea well operation in an offshore platform with focus on ‘kick’ is considered as the case study. Kick is further explained in section 5.2.1.1.

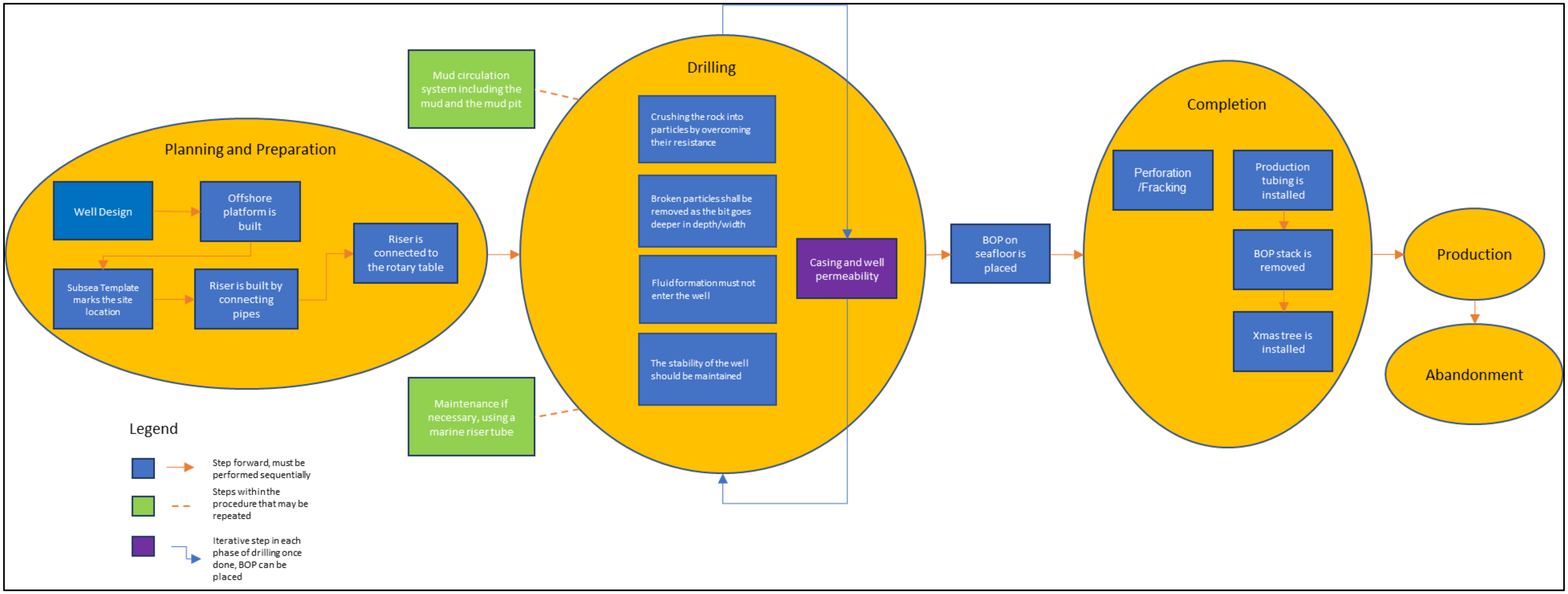

**Figure 5.4 Simplified diagram for well operation (ENI, 2005; J.M.K.C. Donev et al, 2016; Singh, 2019; Times Square Chronicles, 2019)**

## 5.2 Application of the methodology

### 5.2.1 Phase 1: Hazard identification

The most dangerous threat in any given stage of the production stage is a blowout (Hauge, et al., 2011; Hauge & Øien, 2012; Hauge & Øien, 2016; Hamilton, Gevondyan, Braun, & Fraser, 2017; Wyatt Law Firm, 2019) . Blowouts are the uncontrolled kicks (ENI, 2005), whereas kicks are the unwanted flux of the formation fluid into the wellbore (ENI, 2005). This means if there is no kick in the system there will be no blowout; moreover, stopping the kick is the best way to prevent a blowout.

As dangerous the consequences of a high-pressure hydrocarbon release can be, it is noteworthy to know it is preventable and manageable (Lancaster, 2005). There are different barrier elements in place to eliminate, prevent, control, and mitigate (Rausand, 2011) the kicks and/or their consequences.

#### 5.2.1.1 Kick

A kick occurs when the pressure in the wellbore falls below the formation pressure. Meaning that either the mud weight has dropped, or the estimated formation pressure is too low. This is called and underbalanced kick (Schlumberger, 2020), which understandably is the result of an insufficient hydrostatic pressure applied to the formation fluid (Grace, 2017). The induced kick, however, happens in a dynamic way and it’s the result of the pressure change due to string or casing motion (Schlumberger, 2020), also known as the swabbing in which the bottom hole pressure drops due to string being pulled allowing the fluid formation to enter into the wellbore (DrillingCourse, 2016).

Robert D. Grace (2017) summarizes the causes of the kick as follows:

1. Mud weight less than the formation pore pressure

2. Failure to keep the hole full while tripping

3. Swabbing while tripping[20]

4. Lost circulation[21]

5. Mud cut by gas, water, or oil.[22]

Understanding this helps us realize what barrier functions should be applied to prevent each of these. No matter what has specifically caused it, kick always happens when the pressure exerted on the fluid formation is insufficient, allowing it to enter the wellbore (DrillingCourse, 2016) (Grace, 2017). Understandably, barrier functions should be defined in a way that prevent this from happening. Hauge et al. (2011) introduced and categorized a complete list of the barrier functions related to kick in a generic subsea well. The case study uses these defined barriers as the starting point for analysis.

For subsea drilling, the barrier functions for the kick are summarized in Table 5.1 (Hauge, et al., 2011):

**Table 5.1 Barrier functions for the kick**

| **Barrier Function** | **Type (with respect to kick)** | **Function Code Name** | **Barrier Elements** | **Type of element** | | | **Element Code Name** |
|---|---|---|---|---|---|---|---|
| | | | | H | O | T | |
| **Kick Detection before HC reaches BOP** | Reactive | SF1 | Pit Gain | | | X | SF1T1 |
| | | | Flow-out/in | | | X | SF1T2 |
| | | | Drill pipe pressure | | | X | SF1T3 |

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[20] Tripping is when the pipe is removed or replaced for maintenance.

[21] Loss of circulation is when the mud enters the formation and does not return.

[22] The density of the mud is changed because of the presence of gas, water, or oil.

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  |  | Gas content |  |  | X | SF1T4 |
|  |  |  | Human detection and action | X |  |  | SF1H1 |
|  |  |  | Operational procedure |  | X |  | SF1O1 |
|  |  |  | Reservoir/pore pressure predictions |  | X |  | SF1O2 |
| **BOP seals and HC is restricted below BOP** | Reactive | SF2 | Topside activation and signal transfer system |  |  | X | SF2T1 |
|  |  |  | Hydraulic actuation system |  |  | X | SF2T2 |
|  |  |  | Annular/ ram preventers |  |  | X | SF2T3 |
|  |  |  | Human detection and activation | X |  |  | SF2H1 |
|  |  |  | Operational procedures |  | X |  | SF2O1 |
|  |  |  | Emergency procedures |  | X |  | SF2O2 |
| **Circulation of heavier mud** | Reactive | SF3 | System interface and control |  |  | X | SF3T1 |
|  |  |  | System utilities |  |  | X | SF3T2 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
|  |  |  | Choke and kill valve |  |  | X | SF3T3 |
|  |  |  | Mud circulation valve |  |  | X | SF3T4 |
|  |  |  | Mud circulation and cementing system (pumping) |  |  | X | SF3T5 |
|  |  |  | Mud mixing and bulk systems |  |  | X | SF3T6 |
|  |  |  | Cementing system |  |  | X | SF3T7 |
|  |  |  | Sensors and positioners |  |  | X | SF3T8 |
|  |  |  | Human behavior | X |  |  | SF3H1 |
|  |  |  | Operational procedure |  | X |  | SF3O1 |
|  |  |  | Reservoir/pore pressure predictions |  | X |  | SF3O2 |
| **Drill string safety valve seals drill string** | Reactive | SF4 | Activation systems and control system |  |  | X | SF4T1 |
|  |  |  | Stabbing valve |  |  | X | SF4T2 |
|  |  |  | Human action | X |  |  | SF4H1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Operational procedures | | X | | SF4O1 |
| | | | Emergency procedures | | X | | SF4O2 |
| **Blind Shear ram cuts drill string and seals well** | Reactive | SF5 | Topside activation and signal transfer systems | | | X | SF5T1 |
| | | | Hydraulic actuation systems | | | X | SF5T2 |
| | | | Shear ram | | | X | SF5T3 |
| | | | Human intervention | X | | | SF5H1 |
| | | | Operational procedures | | X | | SF5O1 |
| | | | Emergency procedures | | X | | SF5O2 |
| **Diverter system vents HC overboard** | Reactive | SF6 | Activation and control systems | | | X | SF6T1 |
| | | | Diverter packer and valve | | | X | SF6T2 |
| | | | Human activation and operation | X | | | SF6H1 |
| | | | Operational procedures | | X | | SF6O1 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | Emergency procedures | | X | | SF6O2 |

In the presented event tree (ET) for the sequential events of a kick as shown in Figure 5.5, barriers for controlling and mitigating the kick effects can be recognized (Hauge & Øien, 2016).

#### 5.2.1.2 Assumptions in the case study

The assumptions made in this study are as follows:

1- The well is in the design phase.

2- There is no gas injection, the well is assumed to be producing oil in a normal state.

3- No coil-tubing or side well drilling is performed, only standard bottom hole drilling.

4- The human-machine interface systems are considered as an intermediate between technical systems and human action, not barriers themselves.

5- The proactive barrier functions regarding kick are considered to be out of the scope of the analysis. This is because the mud circulation is what guarantees the exerted pressure on the formation fluid and is identified as a reactive barrier. Thus, it is assumed a fault tree representation is irrelevant.

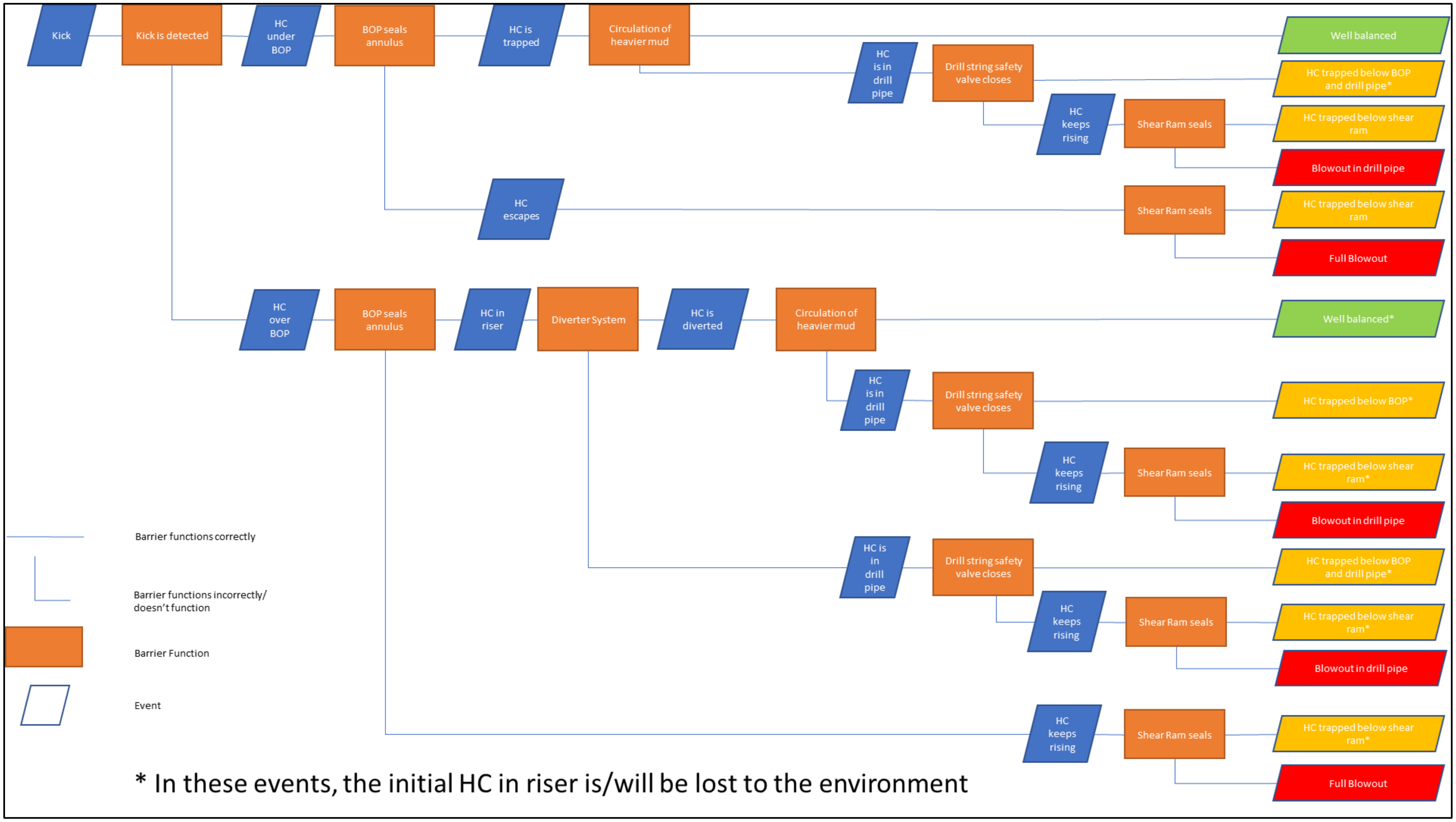

**Figure 5.5 Event tree for the kick adapted from SINTEF (Hauge & Øien, 2016)**

### 5.2.2 Phase 2: Developing the FRAM model

For developing the FRAM model, several activities are defined. The step by step development of the normal daily activity functions is explained in Appendix A.

Table 5.2 shows a summary of the identified Functions and categorizes them. When all Functions are identified, at this step, the analyzer considers if all the Aspects of each Function should be described or not. As Hollnagel mentions, it may not be a necessity to define and describe each Aspect (Hollnagel, 2012). In this case, the decision to continue the descriptions is made after the completion of the FRAM analysis itself; the result will determine whether these Aspects were enough regarding the scope of the analysis or not.

**Table 5.2 Summary of the identified Functions**

| | | Total | | | |
|---|---|---|---|---|---|
| **Foreground Functions** | <Well is producing normally>, <Operator opens the Xmas tree valve>, <Control room confirms the well's stability>, <Achieve well stability>, <Detect kick>, <Complete well>, <Pit gain is controlled>, <Flow-out/in is monitored>, <Human behavior>, <BOP monitoring, maintenance and activation>, <Emergency>, <Mud circulation system>, <Mud pumps and cementing system>, <System interface and control>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, <Diverter system in place and functioning> | 5 | 6 | 5 | 1 |
| **Background Functions** | <General safety requirements are defined>, <Install Xmas tree>, <Install production tubing>, <Remove the BOP stack>, <Operators are on site>, <Drill pipe pressure is controlled>, <Gas sensors in place>, <Predictions and well design>, <Organizational emergency prediction>, <Organizational prediction>, <Hydraulic actuators in place and functioning>, <Signals are transferred and understood>, <Annular/ram preventers are functioning>, <Sensors and positioners in place>, <Mud circulation valve>, <System utilities>, <Choke and kill valve>, <Cement systems>, <Mud mixing and bulk systems>, <To the process phase>, <Operational procedures>, <To the drilling step>, <Activation systems and control system>, <Stabbing valve is in place and checked>, | 4 | 0 | 23 | 2 |

| | | | | | |
|---|---|---|---|---|---|
| | <Shear ram in place>, <Topside activation and signal transfer systems>, <Hydraulic actuators>, <Activation and control systems>, <Diverter packer and valve> | | | | |
| **Legend** | <Main Functions><br><Barrier functions translated as Functions><br><Barrier elements translated as Functions><br><Emergency state as a Function><br><Out of scope Functions> | 46 | | | |

### 5.2.3 Phase 3: Analyzing the FRAM model

As seen indicated in Table 5.2, 46 Functions are identified, of which 17 are foreground Functions. The first instantiation of the system is shown Figure 5.6.[23]

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[23] The Figure 5.6 legend is presented as follows:

White hexagon: Foreground Function
Grey hexagon: Background Function
Red border: Integrated barrier function
Blue border: Integrated barrier elements
Gold border: Specific time Function
Green border: Foreground Functions that are not integrated from the Safety-I approach
Purple Border: Functions out of the study's scope

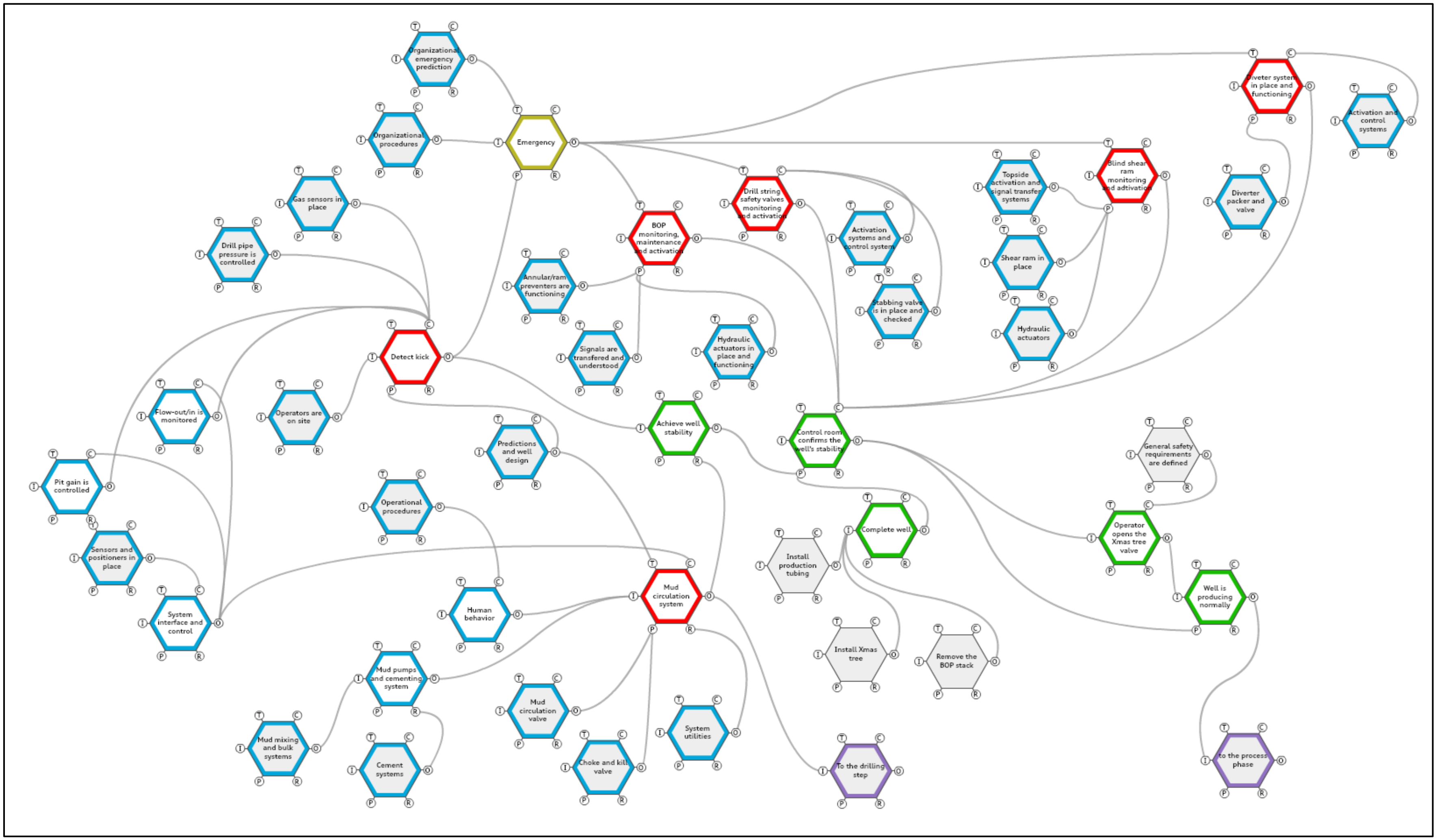

Figure 5.6 The instantiation of the system depicted by FMV

The sources of variability for each technical, operational, and organizational Functions could be endogenous or exogenous[24]. Table 5.3 shows these 17 Functions in proper the defined categories.

**Table 5.3 Categorization of the foreground Functions**

| Technical | Human | Organizational |
|---|---|---|
| <Well is producing normally>, <Achieve well stability>, <Detect kick>, <Complete well>, <Pit gain is controlled>, <Flow-out/in is monitored>, <BOP monitoring, maintenance and activation>, <Mud circulation system>, <Mud pumps and cementing system>, <System interface and control>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, <Diverter system in place and functioning> | <Operator opens the Xmas tree valve>, <Control room confirms the well's stability>, <Human behavior>, <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation> | <Emergency>, <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation> |

When considering the internal sources of variability, the technical Functions show a few, well-known reasons with a low likelihood of their influence on such Functions' performance variability such as internal wear and tear. Regarding the human Functions, the time needed to perform such tasks has to be considered because it has an influence on the physiological and psychological state of workers that ultimately affects their actions and reactions. Regarding the organizational Functions, usually the performance variability is "culture" related, which can be a company's internal way of communication or similar; therefore, it is specific to the Function.

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[24] The coupling variabilities are mentioned later in section 5.2.3.1

In the case of external variability sources, the technological Functions are influenced by the way they are maintained and used. Human Functions are very much influenced by other Functions types, in addition to social pressures such as norms and policies. For organizational Functions, the business environment the organization is functioning in can be an influential factor (Hollnagel, 2012).

The likelihood of the performance variability when considering the organizational Functions, in both internal and external cases, is relatively low, yet has a significant influence. Additionally, human Function variability can happen with a high frequency and large amplitudes. The default FRAM assumption is that technological Functions are relatively stable (Hollnagel, 2012).

In this research, the "simple solution" is taken into consideration to characterize the performance variability to signal timing and precision. Each signal in a temporal term, can be too early, on time, too late, and not at all. Signals in precision terms can be delivered precisely, acceptable, and imprecise. For each Function type, FRAM assumes a default set for the variability of response (Hollnagel, 2012). These assumptions are applied to the 17 foreground Functions in Table 5.3.

As shown in Table 5.3, noticeably, a few Functions are repeated meaning they have aspects and characteristics that relate to either category. For this analysis, these Functions are considered for internal and external variability sources depending on their categorization.

Furthermore, there are many aspects to be considered when describing internal and external sources of performance variability, which can be too heavy of a task for only one person, this study merely considers the six barrier functions identified in Table 5.1. The FRAM equivalent Functions of these six barrier functions are:

<Detect kick>, <BOP monitoring, maintenance and activation>, <Mud circulation system>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, <Diverter system in place and functioning>.

For each of these Functions, the temporal and precision variability in signals are provided in tables 5.4 and 5.5.

**Table 5.4 Possible Output variability with regard to timing**

| | | **The temporal range of variability of response** | | | |
|---|---|---|---|---|---|
| | | Too early | On time | Too late | Not at all |
| **Technical** | <Detect kick>, <BOP monitoring, maintenance and activation>, <Mud circulation system>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, <Diverter system in place and functioning> | Unlikely | Normal, expected | Unlikely, but possible if software is involved | Very unlikely, only in case of a complete breakdown |
| **Human** | <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation> | Possible (snap answer) | Possible, should be typical | Possible, more likely than too early | Possible, to a lesser degree |
| **Organizational** | <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, | Unlikely | Likely | Possible | Possible |

**Table 5.5 Possible Output variability concerning precision**

| | | **Precision range of variability of Output** | | |
|---|---|---|---|---|
| | | Precise | Acceptable | Imprecise |
| **Technical** | <Detect kick>, <BOP monitoring, maintenance and activation>, <Mud circulation system>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, <Diverter system in place and functioning> | Normal, expected | Unlikely | Unlikely |
| **Human** | <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation> | Possible, but unlikely | Typical | Possible, likely |
| **Organizational** | <BOP monitoring, maintenance and activation>, <Drill string safety valves monitoring and activation>, <Blind shear ram monitoring and activation>, | Unlikely | Possible | Likely |

#### 5.2.3.1 Aggregation of the variabilities

Upstream-downstream couplings should be considered for each Function's Output regarding its destination which can be another Functions' Input, Resource, Control, Time, and Precondition. If a technical Output is on time, it dampens the variability of its downstream Function; similarly, if it is precise, it dampens the performance variability. If a human Function's Output, as previously made assumption, is on time, it dampens the variability in the downstream Function; likewise, if the Output is acceptable, it has no effect on its downstream Function. If an organizational

Function’s Output is on time, it possibly dampens the performance variability of the downstream Function; however, if the signal is imprecise, there will possibly be a loss of time and misunderstanding so the performance variability of the downstream Function is increased.

This procedure has been applied for all the six barrier functions, and the increased performance variability is reported in Table 5.6. The possible variabilities are defined based on the assumption that signals received from either type of Function, in term of precision, are either precise or acceptable, which ultimately, have no/reducing effect on the performance variability of the downstream Functions, and hereby the aggregation is only considering the timing variabilities.

**Table 5.6 Possible variability of Output coupling regarding timing for barrier functions**

| Function | Output | Possible variability of Output |
|---|---|---|
| <Detect kick> | Kick does not exist | Too early, premature start<br>Too late, delay in the process, loss of time<br>Omission, loss of time |
| | Kick exists | Too early, false emergency, possible loss of time and resources<br>Too late, kick propagation<br>Omission, blowout |
| <BOP monitoring, maintenance and activation> | BOP is functioning | Too early, control room may confirm an unstable situation as safe<br>Too late, kick propagation, possible loss of time to perform further actions<br>Omitted, blowout |
| <Mud circulation system> | Mud column | Too late, possible kick propagation<br>Omission, drilling is not possible without the mud column, so if the mud column stopped being provided after the drilling procedure, kick and blowout are a possibility |

| | | |
|---|---|---|
| <Drill string safety valves monitoring and activation> | Drill string safety valve functions correctly | Too early, control room may confirm an unstable situation as safe<br>Too late, kick propagation, possible loss of time to perform further actions<br>Omitted, blowout |
| <Blind shear ram monitoring and activation> | Blind shear ram functions correctly | Too early, control room may confirm an unstable situation as safe<br>Too late, kick propagation, possible loss of time to perform further actions<br>Omitted, blowout |
| <Diverter system in place and functioning> | Diverter system functions correctly | Too early, control room may confirm an unstable situation as safe<br>Too late, kick propagation, possible loss of time to perform further actions such as evacuation<br>Omitted, blowout, possible loss of life |

### 5.2.4 Results

The represented tables (Table 5.4-5.6) demonstrate a normal state for the system based on a set of default assumptions that provide a FRAM model for the barrier system in a generic manner and successfully integrates the Safety-I approach into the Safety-II model. To better establishing the FRAM's potential for dealing with variabilities, the model must be exposed to more specific assumptions[25]. Therefore, the FRAM model of the case study is applied in two different situations in which the variability has increased.

The first scenario considers an increased performance variability in a technical function, while the second scenario assumes the increase to be in a human function. These scenarios are fully explained and analyzed in the next chapter.

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[25] Analysis of the FRAM model is case specific (Hollnagel, 2012).

# 6 Results and Discussion

## 6.1 Exposing the FRAM model to two increased variability scenarios

- 1st scenario: increased variability in the Function <Pit gain is controlled>. This can happen due to a broken gauge that shows a wrong number which leads to an imprecise signal as its Output. This will effectively influence the Output of <Pit gain is controlled> that leads to a coupled increased variability in its downstream Function <Detect kick>. This increased variability in terms of precision, in the latter Function if not dampened leads to increased variability in its downstream Function <Achieve well stability>. It should be noted that <Detect kick> has other Control Aspect contributors in place to be able to control the detected variability. This means, in order to dampen the increased variability in one of the barrier elements, all the other barrier elements' performance should be adjusted. This can lead to a loss of time which is critical for handling a possible kick.

- 2nd scenario: increased variability in the Function <Human behavior>. This can be due to the influence of an internal or external source of variability, such as fatigue (endogenous) or a storm (exogenous). It can safely be assumed that the <Human behavior>'s Function will be changed in both precision and timing terms for the worse. A transition from 'acceptable' and 'typically on time' to 'imprecise' and 'too late' is expected for the Output signal. The downstream Function <Mud circulation system> shows variability due to this transition. If there is no controlling measure for this variability, this will affect the <Achieve well stability> as the next downstream Function. Indeed, <System interface and control> Function, as the Control measure should try to handle the increased variability in <Mud circulation system>. This means the <System interface and control>'s variability increases as well to adjust itself to the <Mud circulation system>'s variability.

For the 1st first scenario, as explained in scenario's explanation, an imprecise Output signal will lead to a delay in downstream functionality of kick detection that propagates into an undetected kick. After the kick has been detected, it is important to know how fast the response teams can follow the proper controlling procedures. The FRAM representation clearly emphasizes on the interconnectivity of the Functions in the system. A broken gauge engages other parts of the system to adjust their performance which leads to a delay in the system. The instantiation represented in Figure 6.1 shows all the possible variabilities regarding a broken gauge[26].

In order to avoid such incidents, it will be necessary to check the other barrier elements[27] to identify the source of the error. A series of communications can be set in order to provide directions regarding the matter at hand. Understandably, a delay is a variability that needs to be dealt with. In the instantiation of this scenario[28], it is seen how the broken gauge can affect the control room's operator decision making. When studying human Functions, or Functions that have human Aspects, it is logical to assume a way of communication between humans carrying out these tasks. This, although not explicitly discussed in this analysis, has proven to be one of the most important contributing factors in terms of offshore safety (França, Hollnagel, Luquetti dos Santos, & Haddad, 2019). Table 6.1 summarizes the possible coupling Output variabilities for the first scenario. Although, it does not consider the possibility of a kick and does not show <Flow-out/in is monitored>, <Drill pipe pressure is controlled>, and <Gas sensors in place>'s variability for they are not coupled variabilities.

**Table 6.1 Possible variability of Output coupling – 1st scenario**

| **Function** | **Output** | **Possible variability of Output** |
|---|---|---|
| <Pit gain is controlled> | Pit gain | Imprecise, wrong number is reported |

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[26] The Figure 6.1 legend is presented as follows:
White hexagon: Foreground Function
Grey hexagon: Background Function
Red border: Integrated barrier function
Blue border: Integrated barrier elements
Gold border: Specific time Function
Green border: Foreground Functions that are not integrated from the Safety-I approach
Purple Border: Functions out of the study's scope
Curved orange line: Increased variability

[27] The other constituents of the <Detect kick>

[28] Figure 6.1

| | | |
|---|---|---|
| <Detect kick> | Kick does not exist | Too late, delay in the process, loss of time |
| <Achieve well stability> | Well is stable | Too late, loss of time |
| <Control room confirms the well's stability> | The command to open the Xmas tree valve | Too late, delay in sending the order |
| | Well is controlled | Too late, this will result in economic loss because the Function <Well is producing normally> is yet to function |

For the 2nd scenario, a Control Aspect represents a supervisory role or a regulator of how a Function operates, and it is not in the sense of 'control' in process control. This means the variability is increased in human's functionality and not the technical elements of the system, such as a PLC[29]. The increased variability in <Human Behavior> which has <Operational procedures> as its regulator can easily be changed due to any sort of internal or external stress which may or may not has been predicted by the procedures. When <Mud circulation system> receives an imprecise and too late Input signal, its performance variability increases which needs to be handled. Figure 6.2 represents the instantiation of the second scenario.[30]

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[29] Programmable Logic Controller

[30] The Figure 6.2 legend is presented as follows:
White hexagon: Foreground Function
Grey hexagon: Background Function
Red border: Integrated barrier function
Blue border: Integrated barrier elements
Gold border: Specific time Function
Green border: Foreground Functions that are not integrated from the Safety-I approach
Purple Border: Functions out of the study's scope
Curved orange line: Increased variability

The human aspect of the <System interface and control> needs adjustment to dampen the increased variability. This might be done by a series of communications and orders which are not present in this instantiation[31] of the FRAM model, yet they can be assumed to be existent. No matter how these communications are done, they will take a certain amount of time. This is a loss of time regarding the mud circulation system that is one of the two main barrier functions in place to prevent a kick from happening. The loss of time can be due to several reasons such as ignoring the control room's order under stress, or the operators reporting a measurement, or opening/closing a certain valve too late.

Providing a complete list of what may or may not cause the variability in performance may take days and seems quite unnecessary. What FRAM highlights is how increased variability can lead to a loss of valuable time. Since the mud production is not stopped, there will not be a noticeable variability in terms of <Mud circulation system>'s Output that could influence its downstream Function. Table 6.2 shows the coupled variability in the second scenario. <System interface and control> is not mentioned in the table because its increased variability is not a coupled one.

**Table 6.2 Possible variability of Output coupling – 2nd scenario**

| **Function** | **Output** | **Possible variability of Output** |
|---|---|---|
| <Human behavior> | Human interaction | Imprecise, a variety of possibilities, including but not limited to reporting a wrong measurement or ignoring a check due to biased experience<br>Too late, the signal can be received later than usual due to the circumstances |

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[31] Another way of saying how work as done is different than work as imagined. This will be discussed further in next chapter, under limitations.

|  |  |  |
|---|---|---|
| <Mud circulation system> | Mud column | Imprecise, this imprecision should be detected by the control measures |

Table 6.3 summarizes the analysis of the scenarios and possible suggestions of how to address the variabilities. These are non-expert suggestions. It is, however, valuable in terms of providing a solution to a minor issue that could be developed into a more investigated result by an expert.

**Table 6.3 Summary of the scenario analysis**

| # | **Initiating variability** | **Predicted damage** | **Possible suggestions** |
|---|---|---|---|
| **Scenario #1** | Technical Function variability | Economic loss | Barrier online status report, could be a software, that reports the status of the barriers consistently. Hands free wireless headsets in addition to/instead of walkie-talkies to increase communication speed |
| **Scenario #2** | Human Function variability | Time loss | Clear communication framework. For some operators it may be useful to be in in direct contact with the control room consistently.[32] |

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[32] An example of this way of connection can be found in the gaming community where team members are in contact for long hours.

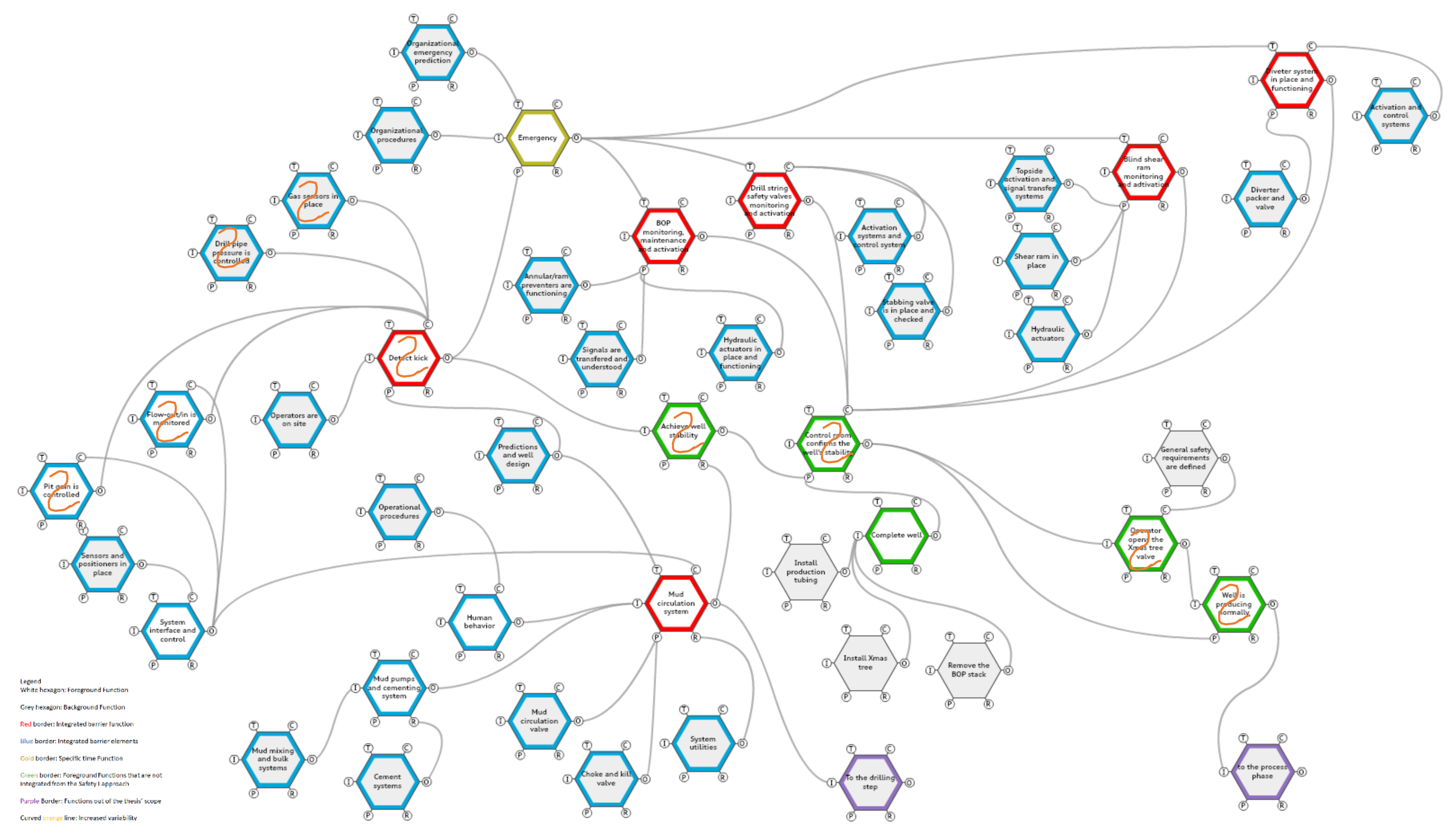

**Figure 6.1 The instantiation of the 1st scenario**

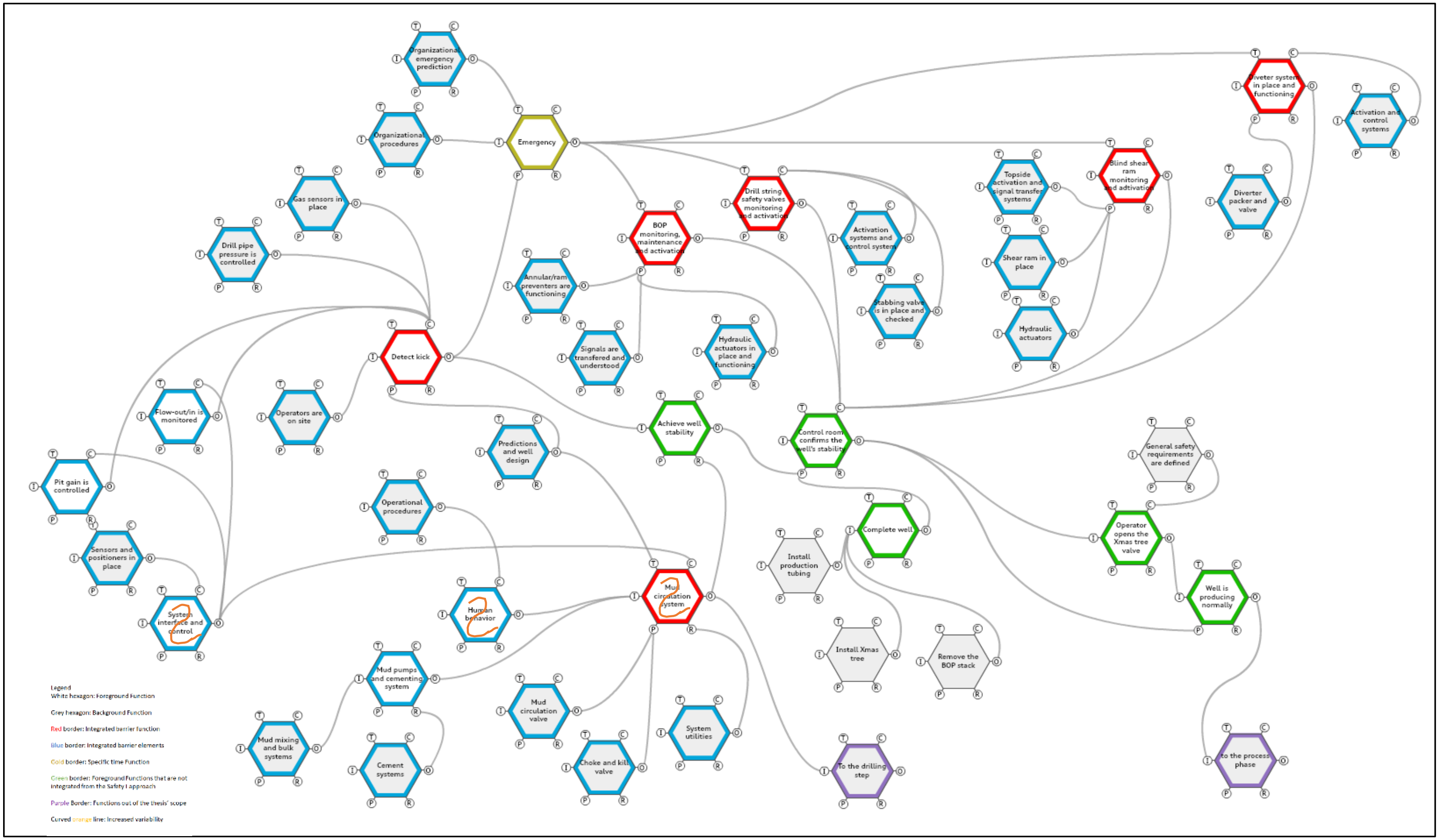

**Figure 6.2 The instantiation of the 2nd scenario**

## 6.2 FRAM and barrier management: risk treatment

Since this study was performed on a ‘safe’ system described by a team of experts, this analysis may not be able to introduce additional barrier functions or methods to reduce the risk in its traditional sense. Yet, it can emphasize the importance of barrier monitoring and communication methods. Specifically, regarding the communication methods, the analysis shows the necessity for a clear and reassuring way of communication between operators and the control room; possibly a hands-free system.

To address the internal sources of variability, organizations need to hire and select competent people and provide proper training for them. Regarding the external sources of variability, for example the weather, the possible solutions may not be practical as the working environment cannot be changed, or it will take a lot of time and resources to change. As far as the coupling variability is considered, it can be concluded that the only way to reduce the variability in downstream Functions is to minimize the Output variability of the upstream ones.

FRAM, as an easily understandable representation of the system, can be employed simultaneously with the traditional safety methods, to create a completer risk picture, provide indicators for barriers, and depict how human roles interact with barrier functions. This is specifically highlighted in FRAM because it can represent variability in human and organizational factors with a clear precision. Performance shaping factors can be introduced to the model as human performance variability and how this change in human actions and reactions can affect the barrier functions’ performance. Barrier strategy and their performance standards as a risk treatment measure in barrier management can benefit from this.

This analysis also shows FRAM’s flexibility in terms of including numerous Functions and describing the system in a holistic way. A suggestion would be to divide the system into smaller parts and do the FRAM analysis for each section; for example, a foreground Function and its Aspects can be analyzed entirely and comprehensively by one person, and another team member can do the same with another foreground Function. This ultimately leads to a set of FRAM models that will be connected to each other to create a comprehensive representation of the system, although it makes it more difficult to do the third step of the FRAM (Aggregation of the performance variability).

## 6.3 FRAM Vs. Bowtie (ETA) for barrier management

For each scenario, an event tree has been developed to understand how ETA or bowtie analysis would deal with the same defined scenarios. The represented 'kick' event trees in Figure 5.2 only represents the ET big picture by considering all the available barriers. However, for each defined scenario, the detail of ET is presented separately.

For the first defined scenario, the initiating event can be assumed to be a broken gauge in the pit tank. The broken gauge event tree is shown in Figure 6.3. Since in this scenario, the identified errors are human errors an HRA[33] seems necessary that indicates a limitation of ETA on how to handle human functions. Nonetheless, the ETA's simplicity in the application is observed; additionally, it provides an easy representation of consequential events.

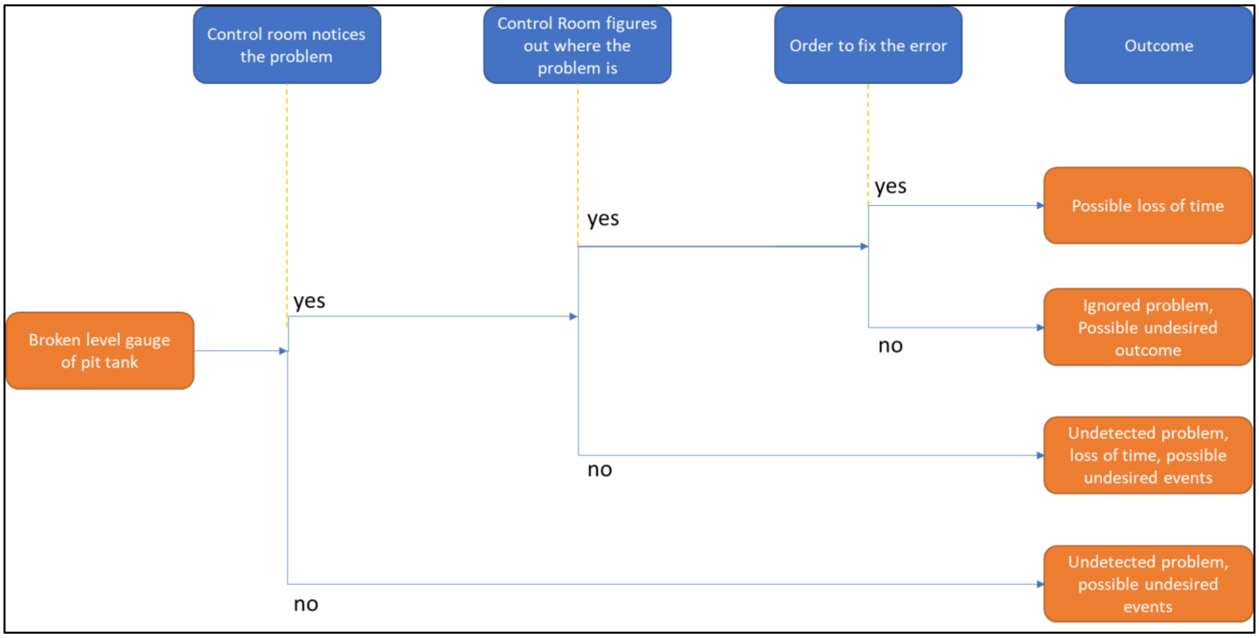

**Figure 6.3 ET for a broken level gauge of a pit tank**

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[33] Human Reliability Analysis

However, it may be argued that the event tree is simplified more than necessary because of the author’s possible bias, and a more comprehensive ETA representation may lead to more comprehensive results. It is noteworthy to mention that the goal of this simplified model is to show ETA’s essential need for an event tree in addition to the previously existing ones. A comprehensive ETA representation; makes the simplicity and the possible bias irrelevant to the matter at hand.

For the second scenario, another event tree is required since, as mentioned before, the ‘kick’ and ‘blowout’ even trees fail to address the problem. A specific initiating event should be defined that captures the essence of <Human behavior>’s increased variability. The initiating event can be a storm that may result in failure to follow an order by an operator to close a particular valve. Figure 6.4 illustrates the abstract ETA suggested for the second scenario.

Understandably, all the known accident scenarios have been studied with regard to a gas leak, Figure 6.4 does not try to illustrate how the system will deal with a leak, but rather how the human behavior changes as a result of a stormy day. It is arguable that external stress, such as a stormy weather, can be a risk influencing factor (RIF) and not an initiating event, and in this case the initiating event should be defined as a ‘loosen valve’. This is open to the argument since there are fields in which even natural disasters are considered as an initiating event (Lee & Jones, 2014). This may change the representation and other aspects of the simple event tree. Nonetheless, much like the first what-if scenario, this is not a question of an actual event tree representation but rather the necessity for an additional event tree.

While quantification seems possible and the probability of a loosened valve can be calculated or found in the literature, the rest of the events are human functions that need HRA to better estimate the risk factors. Similar to the first scenario, ETA proves to be very simple, and while not evaluating the human error on its own, it can integrate the human errors into the modelling.

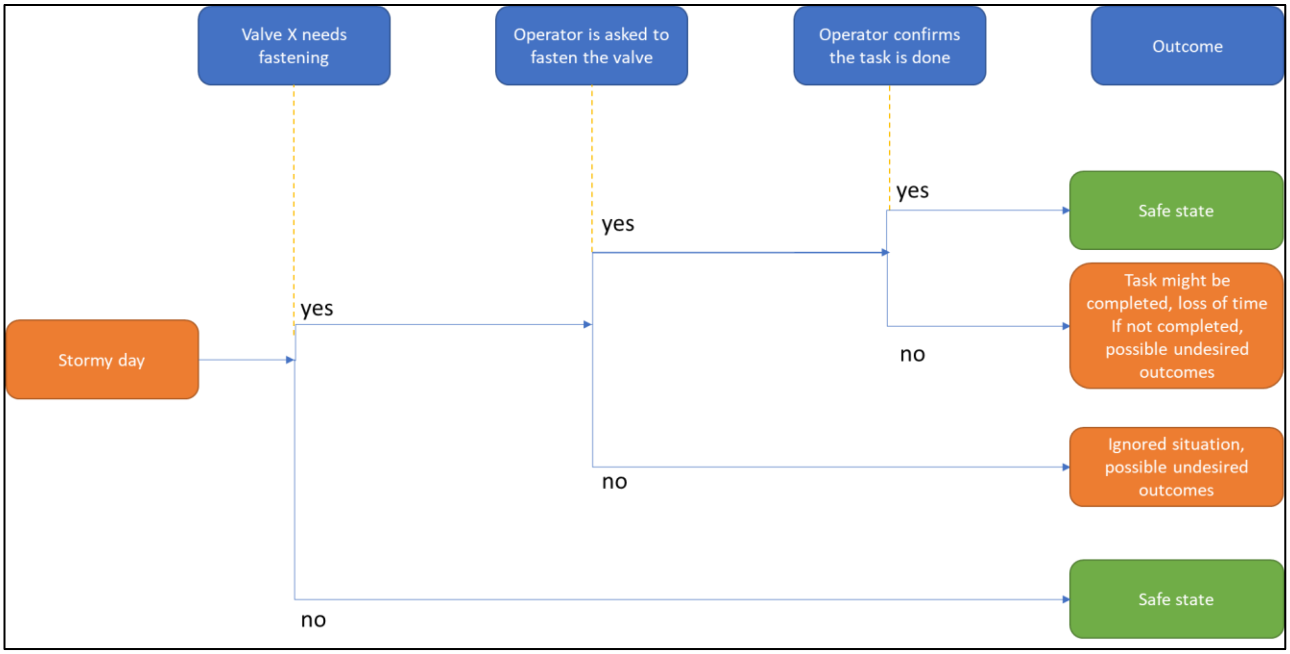

**Figure 6.4 ET for a stormy day**

The strengths and limitations of the FRAM model for risk assessment are explained through a comparison to a traditional and widely used bowie analysis (ETA) method. The main idea of this research was to show how the FRAM approach can contribute to barrier management during operation in the oil and gas industry. Therefore, the strengths and limitations of the FRAM model for barrier management in comparison to traditional and widely used bowtie method have been provided.

In this research, in order to compare Safety-I and Safety-II approach for barrier management, the result of a hazard identification technique was used as a basis for developing the FRAM model. The primary FRAM model was built based on the ETA model for the studied system in the case study. While ETA shows the sequence of events with a Boolean logic, FRAM emphasizes the dynamicity of the system as a whole and captures the human aspects of the sociotechnical systems. Furthermore, as Hollnagel (2012) emphasizes the goal of FRAM is not dealing with hazards, but with variabilities. This in principle shows that FRAM has the flexibility to integrate known hazards as well as real working conditions.

Table 6.4 shows a summary of the differences and similarities between the two methods underlining the advantages and disadvantages of the modeling aspect of each method for barrier management.

**Table 6.4 Advantages and disadvantages of FRAM vs. Bowtie (ETA) for barrier management**

| | **ETA (Bowtie)** | **FRAM** |
|---|---|---|
| **Advantages** | Quantifiable<br>Easy to apply<br>Fully developed and used<br>Easily understandable<br>Based on failure-success (in terms of being easy to follow) | Flexible<br>Captures the human and organizational aspects as their own entity<br>Can indicate unpredicted situations by introducing coupling variabilities<br>Can be used for barrier management<br>Based on variabilities and not failure-success (in terms of being holistic) |
| **Disadvantages** | Static<br>Deals with the human and organizational aspects as technical elements<br>Limited to predicted scenarios and identified hazards<br>Limited to the assumptions made to develop the model<br>Needs modification to be used for barrier management | Non-quantifiable<br>Time-consuming<br>Needs to be developed further<br>May be too complicated to understand<br>Limited to the assumptions made to develop the model |

## 6.4 Limitations in analysis

It should be noted, the options for choosing a case study were limited to the public access documents. Additionally, FRAM can be the model that describes the system from scratch and provides barrier functions while in this study benefits from the kick's established safety barriers.

Moreover, a lack of access to the industry experts was the main reason for several assumptions. This is particularly important for what is described in this analysis, especially regarding the two scenarios that could not have been verified by an expert opinion in terms of similarity to real-world possibilities. Although the assumptions are made using public access data, meaning that supporting material exist for the assumptions, a sociotechnical system is surely better described with access to the real-world system and the people who operate in it. FRAM has shown a great potential for describing the work as done. While this analysis provides an acceptable work-as-imagined picture, the extent of similarity to the real world must be confirmed by subjective expert opinion.

The heavy workload for such a large system has also contributed to the simplification of the analysis in its final steps. Admittedly, this analysis was done on a large system with numerous identified Functions. It is safe to assume including other foreground Functions can lead to other aggregation possibilities and provide a more comprehensive result. It is also noteworthy to mention the fact that most of the previous FRAM applications are in small scale or sponsored by the industry in larger scales, mostly for event investigation. A sponsored risk assessment would result in a more comprehensive and detailed work. Not to omit the fact that this study while showing FRAM's potential for indicating some of the unforeseen events, it is applied in a mostly technical system. This reduces FRAM's efficiency while proving its flexibility.

Regarding quantification, there are no known methods to completely quantify the analysis since the FRAM analysis does not focus on failure and its probability (Patriarca, et al., 2020). Additionally, in words of Hollnagel himself that argues the necessity of quantification for the FRAM result:

> There will inevitably be a question of whether the outcomes of a FRAM analysis can be expressed as probabilities, at least partly. In other words, can quantification become part of the FRAM? Before trying to give an answer to that, it is reasonable to consider whether the question is meaningful, which is another way of asking whether quantification is necessary?
>
> Erik Hollangel, 2012, p. 93

## 6.5 Suggestion for future work

Based on the limitations faced to perform this research, the very first suggestion for future work will be for the FRAM to be applied to a work-as-done state and not work-as-imagined one. A set of questions to be answered for future works can be as follows:

1- Can the performance variability indicator exist as a measurable quantity? If yes, how would it be possible?

2- Can automatization reduce the performance variability for the better? This question can be rephrased as if sociotechnical systems become more technical, can it necessarily reduce accidents?

# 7 Conclusions

This study aimed to determine the possibility of adding value to barrier management in the offshore oil and gas production by adopting Safety-II mentality. For this purpose, FRAM was chosen to perform a risk assessment analysis on a generic offshore subsea drilling operation in its design phase. The reason for this selection, as mentioned in section 1.1.3, was FRAM's promising potential to tackle the complexities of socio-technical systems. FRAM representation of the case study demonstrated the FRAM's potential as an indicator to be employed in barrier strategy development phase of barrier management.

Chapters 1 and 2 have provided the necessary background information explaining what risk management is, and how barrier management is related to the concept of risk management. Additionally, this information was provided in certain detail to introduce and reflect the prominent mentality of Safety-I.

FRAM was introduced in the 3rd chapter as the chosen Safety-II approach to provide the essential information needed for carrying this study out. Because of the natural difference between Safety-I and Safety-II in their philosophy, a short chapter was dedicated to FRAM and separated from the 2nd chapter as a means of indicating this very difference.

While the reason for choosing such methodology is noted in the limitation section[34], the method indicated a flexibility for integration of established Safety-I analysis into FRAM that still proved to be utilizable regarding the main study question. Chapter 4 introduced the developed methodology in this study by categorizing it in different phases and briefly explaining each phase's steps.

In the 5th chapter, the case study was defined, and the applicability of the methodology was addressed. The kick as an identified hazard was described and its established reactive barrier functions were introduced and integrated into the FRAM model. Main assumptions for carrying out the study were mentioned, and the methodology's phases were explained in detail by

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describing how each phase is applied on the case study. This phase proved to be time-consuming and the tables presented in Appendix A indicate the time-consuming nature of the methodology in its earlier phases.

The 6th chapter discussed the results of the FRAM modeling. Firstly, two variability scenarios were defined to create specific scenarios to which the FRAM model of the case study is exposed. Secondly, the FRAM's potential for risk treatment was addressed by noting some of the FRAM's strengths without comparison to other methods. Thirdly, a comparison was made to a widely used Safety-I method, bowtie analysis (ETA), to highlight the strengths and limitations of the FRAM for barrier management. Finally, chapter 6 summarized the limitations in this study, and provided a couple of suggestions for future work.

The FRAM representation of the case study clearly emphasized the importance of barrier management, in the sense that it showed how any sort of misconduct regarding the barrier functions can lead to a hazard propagation or a disaster. The FRAM analysis indicated the importance of the barrier function presence with the emphasis on barrier management in terms of making sure these barriers are functioning properly. As mentioned before[35], FRAM can be used as a method to propose indicators; specifically, where there is a higher probability of performance variability. FRAM as a qualitative method demonstrates its potential to be used as a decision support tool. In principle, this study explored the possibility of providing additional information that can be used in barrier management by utilizing the Safety-II mentality.

All the disasters and most smaller accidents have not had a sole reason, but a set of performance variabilities that led to an all-around 'failure' in performance (Hauge & Øien, 2012; Hollnagel, 2012). FRAM can be used to identify variability, indicate them, and provide the safety analyst with the means to propose dampening measures. This can be considered in the iterative barrier strategy procedure in barrier management. This concludes the answer to the study's main question as the added value to the barrier management.

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[35] Chapter 3

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# Appendix A: FRAM's stepwise development

This is the steps to develop the FRAM model that was mentioned in section 5.2.2.

For a well that is producing oil, the following main functions are chosen to give us a starting point.

1- Well is producing normally

2- Well is completed

Understandably, these 2 functions are not all the functions that will be appearing on the final instantiation of the system. And, for example, "Well is completed" refers to the whole completion step in the drilling procedure; therefore, it can be expanded and thoroughly explained.

A table such as table 1 is required for defining each function.

Table 1. <Well is producing normally>

| | |
|---|---|
| Function Label | Well is producing normally |
| Description | This function serves the purpose of the system's final outcome which is producing oil and gas in a normal operation. |
| Aspect | Description of the aspect |
| Input | Xmas tree valve is opened |
| Output | Oil is produced |
| Precondition | Well is controlled |
| Resource | Not initially described |

| | |
|---|---|
| Control | Not initially described |
| Time | Not initially described |

We can understand that each aspect of this function is pointing out to other functions. For example, the Input is pointing out to the function of <Operator opens the Xmas tree valve>.

Table 2. <Operator opens the Xmas tree valve>

| Function Label | Operator opens the Xmas tree valve |
|---|---|
| Description | This function describes the decision applied on the last control valve on the surface of a drilling rig before the process phase. With this decision, the oil will enter the choke and manifold and on its way to the separators for processing. |
| Aspect | Description of the aspect |
| Input | The command to open the Xmas tree valve |
| Output | Xmas tree valve is opened |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | General Safety requirements (such as dress code) |
| Time | Not initially described |

It is once again understandable that this function points out to 2 other functions: <Control room confirms the well's stability and requests the production to be started> and <General safety requirements are defined>

Table 3. <General safety requirements are defined>

| | |
|---|---|
| Function Label | General safety requirements are defined |
| Description | This function describes the organizational procedures such as health and safety codes for all the employers in certain sectors of the plant to follow. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | General safety requirements |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

One can notice that for this function there is no Input to be defined which ultimately makes it a background function.

Table 4. <Control room confirms the well's stability>

| | |
|---|---|
| Function Label | Control room confirms the well's stability |
| Description | This function defines the duty of the control room in monitoring the stability of the well |

| | |
|---|---|
| | and providing the operator with the necessary commands. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | The command to open the Xmas tree valve<br>Well is controlled |
| Precondition | Well is stable<br>Well is completed |
| Resource | Not initially described |
| Control | BOP is functioning<br>Drill string safety valve functions correctly<br>Blind shear ram functions correctly<br>Diverter system functions correctly |
| Time | Not initially described |

Table 5. <Achieve well stability>

| | |
|---|---|
| Function Label | Achieve well stability |
| Description | This function defines the only state in which production is acceptable. |
| Aspect | Description of the aspect |
| Input | Kick does not exist |
| Output | Well is stable |
| Precondition | Not initially described |

| | |
|---|---|
| Resource | Mud column |
| Control | Not initially described |
| Time | Not initially described |

Table 6. <Detect kick>

| | |
|---|---|
| Function Label | Human detection and action |
| Description | This function defines the procedure to identify a possible threat; kick. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Kick does not exist<br>Kick exists |
| Precondition | Reservoir/pore pressure prediction |
| Resource | Not initially described |
| Control | Gas content<br>Pit gain<br>Flow-out/in<br>Drill pipe pressure |
| Time | Not initially described |

Table 7. <Complete well>

| Function Label | Complete well |
|---|---|
| Description | Well completion is achieved using a perforating gun the perforates the well bore allowing the oil and gas to enter it. |
| Aspect | Description of the aspect |
| Input | Production tubing is installed<br>The Xmas tree is installed<br>The BOP stack is removed |
| Output | Well is completed |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 8. <Install Xmas tree>

| Function Label | Install Xmas tree |
|---|---|
| Description | This function defines one of the steps before the well is completed. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | The Xmas tree is installed |

| | |
|---|---|
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 9. <Install production tubing>

| | |
|---|---|
| Function Label | Install production tubing |
| Description | This function defines one of the steps before the well is completed. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Production tubing is installed |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 10. <Remove the BOP stack>

| | |
|---|---|
| Function Label | Remove the BOP stack |
| Description | This function defines one of the steps before the well is completed. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | The BOP stack is removed |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 11. <Mud circulation system>

| | |
|---|---|
| Function Label | Mud circulation system |
| Description | The circulation of mud to provide enough pressure on the formation without fracturing it. |
| Aspect | Description of the aspect |

| | |
|---|---|
| Input | Mud is provided<br>Human interaction |
| Output | Mud column |
| Precondition | Valves are functioning<br>Choke and kill valve |
| Resource | Utility |
| Control | System interface and control |
| Time | Reservoir/pore pressure prediction |

Table 12. < BOP monitoring, maintenance and activation>

| | |
|---|---|
| Function Label | BOP monitoring, maintenance and activation |
| Description | BOP is the blow out preventer and shall be monitored and maintained. It is activated in case of emergency. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | BOP is functioning |
| Precondition | Topside activation and signal transfer system<br>Annular/ram preventers<br>Hydraulic actuation system |
| Resource | Not initially described |
| Control | Not initially described |

| | |
|---|---|
| Time | Human activation (ICE) |

Table 13. < Emergency>

| | |
|---|---|
| Function Label | Emergency |
| Description | This is the case of an emergency if the kick develops into a blowout and is not detected nor controlled previously. |
| Aspect | Description of the aspect |
| Input | Operational procedures |
| Output | Human activation (ICE)<br>Human activation (ICE)2nd<br>Human activation (ICE)3rd<br>Human activation (ICE)4th |
| Precondition | Kick exists |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Emergency procedures |

Table 14. < Organizational emergency prediction>

| | |
|---|---|
| Function Label | Emergency |
| Description | Since we have the risk picture, the emergency procedures shall be defined and clear. |

| Aspect | Description of the aspect |
|---|---|
| Input | Not initially described |
| Output | Emergency procedures |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 15. < Organizational procedures>

| | |
|---|---|
| Function Label | Organizational procedures |
| Description | Operator(s) confirm the state of the barrier or activates it based on the procedures in case of emergency |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Operational procedures |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |

| | |
|---|---|
| Time | Not initially described |

Table 16. < Hydraulic actuators in place and functioning>

| | |
|---|---|
| Function Label | Hydraulic actuators in place and functioning |
| Description | All the hydraulic actuators shall be monitored and functioning. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Hydraulic actuation system |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 17. < Signals are transferred and understood>

| | |
|---|---|
| Function Label | Hydraulic actuators in place and functioning |
| Description | Signals from the BOP shall not be interrupted and misinterpreted. |
| Aspect | Description of the aspect |

| | |
|---|---|
| Input | Not initially described |
| Output | Topside activation and signal transfer system |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 18. < Annular/ram preventers are functioning>

| | |
|---|---|
| Function Label | Annular/ram preventers are functioning |
| Description | To check and maintain the preventers in the BOP. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Annular/ram preventers |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 19. < Mud pumps and cementing system >

| Function Label | Mud pumps and cementing system |
|---|---|
| Description | This function is briefly describing the production of mud |
| Aspect | Description of the aspect |
| Input | Mud is ready |
| Output | Mud is provided |
| Precondition | Not initially described |
| Resource | Cement |
| Control | Not initially described |
| Time | Not initially described |

Table 20. < System interface and control>

| Function Label | System interface and control |
|---|---|
| Description | Mud and cement control systems and monitoring. |
| Aspect | Description of the aspect |
| Input | Not initially described |

| | |
|---|---|
| Output | System interface and control |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Sensors and positioners |
| Time | Not initially described |

Table 21. < Mud mixing and bulk systems>

| Function Label | Mud mixing and bulk systems |
|---|---|
| Description | This step is describing the mix and bulk systems |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Mud is ready |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 22. < Sensors and positioners in place>

| | |
|---|---|
| Function Label | Sensors and positioners in place |
| Description | The necessity for the sensors and positioners |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Sensors and positioners |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 23. < Mud circulation valve>

| | |
|---|---|
| Function Label | Mud circulation valve |
| Description | One of the valves that its existence is vital to the mud system |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Valves are functioning |
| Precondition | Not initially described |
| Resource | Not initially described |

| | |
|---|---|
| Control | Not initially described |
| Time | Not initially described |

Table 24. < System utilities>

| Function Label | System utilities |
|---|---|
| Description | The function that shows the utility provision |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Utility |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 25. < Choke and kill valve>

| Function Label | Choke and kill valve |
|---|---|
| Description | Important valves that are vital to the system and should be maintained |
| Aspect | Description of the aspect |

| | |
|---|---|
| Input | Not initially described |
| Output | Choke and kill valve |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 26. <Cement systems>

| | |
|---|---|
| Function Label | Cement systems |
| Description | To produce one of the important ingredients of well stability |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Cement |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 27. < Human behavior>

| | |
|---|---|
| Function Label | Human behavior |
| Description | This function includes all sorts of psychological and other factors that contribute to decision making |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Human interaction |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Operational guides |
| Time | Not initially described |

Table 28. < Operational procedures>

| | |
|---|---|
| Function Label | Operational procedures |
| Description | Specific predetermined procedures for operating |
| Aspect | Description of the aspect |
| Input | Not initially described |

| | |
|---|---|
| Output | Operational guides |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 29. < Drill string safety valves monitoring and activation>

| | |
|---|---|
| Function Label | Drill string safety valves monitoring and activation |
| Description | In case of an emergency, these safety valves should be activated so it is necessary for them to be maintained and monitored |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Drill string safety valve functions correctly |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | System activation is functioning properly<br>Stabbing valve is functioning |
| Time | Human activation (ICE)2nd |

Table 30. < Blind shear ram monitoring and activation>

| | |
|---|---|
| Function Label | Blind shear ram monitoring and activation |
| Description | In case of an emergency, these rams should be activated so it is necessary for them to be maintained and monitored |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Blind shear ram functions correctly |
| Precondition | Shear ram is in place and functioning<br>Hydraulic actuation is available<br>Signals are well transmitted and understood |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Human activation (ICE)3rd |

Table 31. < Diverter system in place and functioning>

| | |
|---|---|
| Function Label | Diverter system in place and functioning |
| Description | In case of an emergency, there should be a diverter system that is activated so it is necessary for them to be maintained and monitored |
| Aspect | Description of the aspect |

| | |
|---|---|
| Input | Not initially described |
| Output | Diverter system functions correctly |
| Precondition | Packer and valve are functioning |
| Resource | Not initially described |
| Control | System activation is functioning properly |
| Time | Human activation (ICE)4th |

Table 32. < Activation systems and control system>

| | |
|---|---|
| Function Label | Activation systems and control system |
| Description | The function describes the necessity for the control system that monitor and activate the drill string valves. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | System activation is functioning properly |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 33. < Stabbing valve is in place and checked>

| | |
|---|---|
| Function Label | Stabbing valve is in place and checked |
| Description | Stabbing valves are necessary in case of an emergency, they should be maintained and monitored. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Stabbing valve is functioning |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 34. < Shear ram in place>

| | |
|---|---|
| Function Label | Shear ram in place |
| Description | Another safety measure in place that should be monitored and checked. |
| Aspect | Description of the aspect |
| Input | Not initially described |

| | |
|---|---|
| Output | Shear ram is in place and functioning |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 35. < Topside activation and signal transfer systems>

| | |
|---|---|
| Function Label | Topside activation and signal transfer systems |
| Description | Signals should be transmitted and understood properly. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Signals are well transmitted and understood |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 36. < Hydraulic actuators>

| | |
|---|---|
| Function Label | Hydraulic actuators |
| Description | These actuators, when necessary, will be activating the valves |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Hydraulic actuation is available |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 37. < Activation and control systems>

| | |
|---|---|
| Function Label | Activation and control systems |
| Description | Signals should be transmitted and understood properly. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | System activation is functioning properly |
| Precondition | Not initially described |

| | |
|---|---|
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 38. < Diverter packer and valve>

| | |
|---|---|
| Function Label | Diverter packer and valve |
| Description | Each diverting systems needs its packer and valve and these should be functioning when necessary |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Packer and valve are functioning |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 39. < To the drilling step>

| | |
|---|---|
| Function Label | To the drilling step |

| | |
|---|---|
| Description | This function is out of the analysis scope |
| Aspect | Description of the aspect |
| Input | Mud is provided |
| Output | Not initially described |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 40. < To the process phase>

| | |
|---|---|
| Function Label | To the process phase |
| Description | This function is out of the analysis scope |
| Aspect | Description of the aspect |
| Input | Oil is produced |
| Output | Not initially described |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |

| | |
|---|---|
| Time | Not initially described |

Table 41. < Pit gain is controlled>

| | |
|---|---|
| Function Label | Pit gain is controlled |
| Description | A necessary control in place to ensure well's stability |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Pit gain |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | System interface and control |
| Time | Not initially described |

Table 42. < Operators are on site>

| | |
|---|---|
| Function Label | Operators are on site |
| Description | Simply the role of humans in detecting the kick, for example with a smell or such |
| Aspect | Description of the aspect |

| | |
|---|---|
| Input | Not initially described |
| Output | Human detection and action |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 43. < Flow-out/in is monitored>

| | |
|---|---|
| Function Label | Flow-out/in is monitored |
| Description | One of the measures with which the mud is controlled. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Flow-out/in is monitored |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | System interface and control |
| Time | Not initially described |

Table 44. < Drill pipe pressure is controlled>

| | |
|---|---|
| Function Label | Drill pipe pressure is controlled |
| Description | Another important pressure to be controlled. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Drill pipe pressure |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 45. < Gas sensors in place>

| | |
|---|---|
| Function Label | Gas sensors in place |
| Description | These sensors are in place to alert the operators if there is gas content in returning mud. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Gas content |

| | |
|---|---|
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

Table 46. < Predictions and well design>

| | |
|---|---|
| Function Label | Predictions and well design |
| Description | The very first step in oil and gas production. |
| Aspect | Description of the aspect |
| Input | Not initially described |
| Output | Reservoir/pore pressure prediction |
| Precondition | Not initially described |
| Resource | Not initially described |
| Control | Not initially described |
| Time | Not initially described |

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FRAM Approach for Barrier Management

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