Safety Analysis of the Deepwater Horizon Blowout Based on the Functional Resonance Analysis Model (FRAM)

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ABSTRACT

The Functional Resonance Analysis Model (FRAM) defines a framework for accident analysis based on the systems theory and resilience engineering, making it more suitable for complex systems. The purpose of this article is the usage of FRAM to understand the variability in the process of offshore drilling in the Deepwater Horizon accident, and the variability that possibly might exist under other offshore drilling operations. The Deepwater Horizon accident in the Gulf of Mexico occurred when the Horizon ultra-deepwater semisubmersible oil drilling rig exploded and sank in the northern Gulf of Mexico on April 20, 2010, killing 11 crew members, injuring 17 others and initiating a huge marine oil spill. The Deepwater Horizon is one of the greatest environmental accidents in the history of oil. Recent demands for new discoveries and exploitation has led companies to challenge even deeper waters, as in the cases of companies in Brazil and South Africa indicating a need to better understand the overall drilling process to avoid accidents. Results of FRAM analysis of Deepwater Horizon accident show that functions "drilling" "cement placement" and "temporary abandonment" are main functions and they were not prepared to cope with process variability to ensure that processes involving diverse and complex enterprises were resilient enough to kept working when dealing with disturbances.

Keywords: resilience engineering, deepwater oil drilling, functional resonance.

INTRODUCTION

One of the biggest challenges of the oil industry is currently maintaining plant safety and prevent the occurrences of accidents, especially when exploration and production activities occur in deep waters (Muehlenbachs , Cohen , & Gerarden, 2013). This happens due the challenges of deepwater offshore drilling systems whose functions are often poorly described and possibly surprises about the soil formations, weather and production pressures that need to be overcome. One of the ways oil industry use to address the difficulty of dealing with safety in petrochemical processes was developing specific management models for process safety (CCPS , 2007) (OECD, 2008) (HSE , 2006) . According to (Khan, Abunada & John , 2010) process safety is different from occupational safety , because while one is concerned in preventing injuries and illnesses to workers, the other is focused on maintaining the

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integrity equipment and facilities , thus avoiding accidents with major consequences and greater number of victims.

The approach to process safety as a complementary discipline to improving the safety culture can be an interesting approach to cover the gap left by the safety analyzes focused only on the worker. However, the focus on a specific part of safety (equipment, processes), other functions or activities do not appear, and they may contribute to occupational accidents as well as process accidents at the same time. Lest occur oversimplifications, resilience engineering seeks to understand the process as a whole, without focusing on specific faults, because complex systems usually fail in complex ways. The safety processes contribute to safety as a whole when it is not treated as a separate and specific vision of the other objectives of the company, including operational efficiency.

From de point of view of resilience engineering (Hollnagel, 2009; Hollnagel, Woods, & Wreathall, 2010; Shirali, et. al., 2012) safety is not only the absence of accidents and incidents. Safety is the organization's ability to keep processes running, even when variations in performance occur. This approach is particularly important when it is related to activities such as exploration and production of oil, because the frequency that major accidents occur fortunately is small, but a single accident may unfortunately mean a catastrophe. In case of Deepwater Horizon, the report of the National Commission on the BP Deepwater Horizon Oil Spill and Offshore Drilling (Graham et al., 2011) indicated that the company had not had a single " lost -time incident " in seven years of drilling, yet the disaster occurred, showing that the absence of accidents and incidents, as suggested by resilience engineering, not exactly mean safety.

As the Deepwater Horizon Blowout was one of the greatest environmental accidents of history, this study aimed conduct an analysis of resilience aspects of exploration activity and production of oil in deep waters, as this still a current challenge, especially for exploitation of reserves of oil recently discovered in Brazil and South Africa. The Functional Resonance Analysis Model - FRAM is based on resiliency theory and systems engineering and it was used as a methodology to identify resilient aspects to be observed and enable the development of measures for improvement in future similar activities. FRAM has already been used for analysis of accidents in activities such as aviation (Carvalho, 2011), transport systems (Belmonte et al., 2011), and many others.

MODELS OF ACCIDENTS AND RISKS

The correct choice of an accident analysis and risk assessment model can be the key factor to a successful strategy of accident prevention and response to disasters. The application of this risks tools help to explain why accidents occur as well as determine the approaches we take to prevent them (Lundberg, Rollenhagen, & Hollnagel, 2009).

To be able to understand an accident and seek ways to prevent recurrence, we try to represent the accident evolution as closely as possible to the reality of operation. However, the traditional models of accidents and risks used in the oil and gas industry, such as HAZOP and Fault Tree are based on chains of events and usually do not consider the combination of possible variations in human actions, equipment behavior, as well as the relations embedded in sociotechnical systems. Traditional models considers the chain of events in a static way from postulated design basis accident resulting in accident evolution represented as a sequence of well-defined events, in which one or more triggering events (main cause) combine in a static way lead to well-defined effects (Leveson, 2011).

According to (Perrow, 1981), accidents are emergent phenomena in complex systems, making difficult its understanding and adoption of measures for prevention. Perrow came to use the term normal accidents to show that disasters happen even in rare situations where processes appear to be reliable, since accidents emerge from typical variations and combinations of complex socio-technical systems.

The studies of (Rickles, Hawe, & Shiell, 2007) show that complex systems are different from chaotic systems, since chaotic systems are totally unpredictable and provide random answers that suggest the idea of "Normal Accidents". However, sociotechnical complex systems are a bit different, because despite a large number of variables difficult to understand and represent, there is some predictability and measures can be taken to avoid totally unexpected results (turning points). To assist in the modeling of sociotechnical complex systems, models like FRAM (Hollnagel, 2012) and STAMP (Leveson, 2004) was developed. In this study, we apply the FRAM, because the same job using

STAMP has already been studied by Syvertsen (2012).

THE FUNCTIONAL RESONANCE ANALYSIS MODEL (FRAM)

The Functional Resonance Analysis Model (FRAM) (Hollnagel, 2012) defines a model for accident analysis based on the systems theory and resilience engineering, making it more suitable for complex systems. FRAM promotes a vision of system's functions as the basis for the analysis of the accident. The strength of FRAM is not in representation through models to assess functions feedbacks and interconnections, but in uncover new possibilities for the evaluation of some aspects in each function and the interrelations of aspects across functions. To model the process according to FRAM (Herrera & Woltjer, 2010; Hollnagel, 2012) we should follow the following steps:

1. Identification essential system functions, and characterization of each function by six parameters (Input, Output, Time, Control, Precondition, and Resource, as shown in figure 1):

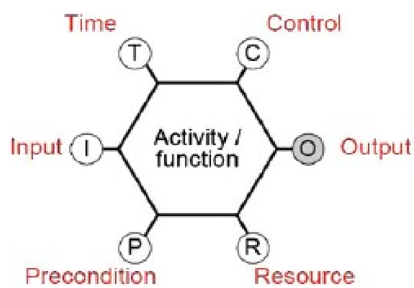

Figura 1 - FRAM Model.

2. Assessment and evaluation of the potential variability. Consider worst case and normal
3. Identification of functional resonance. The combinations of variability may result in undesirable outputs.
4. Identification of Effective Countermeasures, identifying barriers for variability.

THE DEEPWATER HORIZON BLOWOUT

On April 20, 2010, at around 21h, at the Gulf of Mexico, an explosion on the drilling rig Deepwater Horizon, owned by Transocean and operated by BP Company - British Petroleum, began what is recorded as one of more serious accidents Exploration and Production of Oil. The accident caused the death of 11 workers, injured 17 and left a huge oil spill which lasted for 87 days, causing the greatest environmental catastrophe of the oil industry in the United States. The cause of the disaster was a lack of control of the well, called Blowout Petroleum industry (Graham et al., 2011). To better understand how the accident happened, it is necessary to know a little about the process of oil and therefore, this paper aims to briefly explain this activity so complex.

Before starting drilling activities, many seismic studies are conducted to know the rock formation and the potential exploitation of oil reserves likely. Using these studies, the oil well is then constructed in stages with the support of a rotating drill that pierces the seabed. The drill is conducted to the drill site through huge rigs where there is all the necessary drilling equipment.

In order for the platform does not stay on the move while drilling and impede the work, a sophisticated satellite positioning and powerful engines that can maintain the position of the platform in various work situations are used. To make it possible, the drilling fluid is also used as a way for drilling drill lubrication, cleaning the well and

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containment of hydrocarbons. The containment of hydrocarbons is necessary because while drilling, reserves in rocks can invade the wellbore and make the drilling difficult or cause accidents. This containment is achieved by controlling of the density of drilling fluid which exerts pressure on the hydrocarbon formation, keeping them controlled within the well. Due to the important function of the drilling fluid, it is developed through a series of compounds to have adequate density. Cannot be little dense and unable to contain the hydrocarbons to prevent their return by the well, or very dense, fracturing formations and causing leakage of hydrocarbons through the formation. After a few steps of drilling, a steel tube is positioned in well and cementing is performed to prevent the invasion of hydrocarbons through the formation. At the entrance of the well is positioned protective device called BOP (Blowout Prevent). This equipment has a complex set of valves, which lets you close the well in the event of abnormal pressure of oil or emergency situations, and can seal the well at the seabed and disconnect the platform as a last resource. The lock can be manually or automatically in case of accidents and disconnection of the platform. We say that there is a "kick" when an invasion of hydrocarbons into the well through the formation occurs. If this "kick" is not controlled by the aforementioned mechanisms, the well will be out of control, and this is called Blowout (Skalle, 2012).

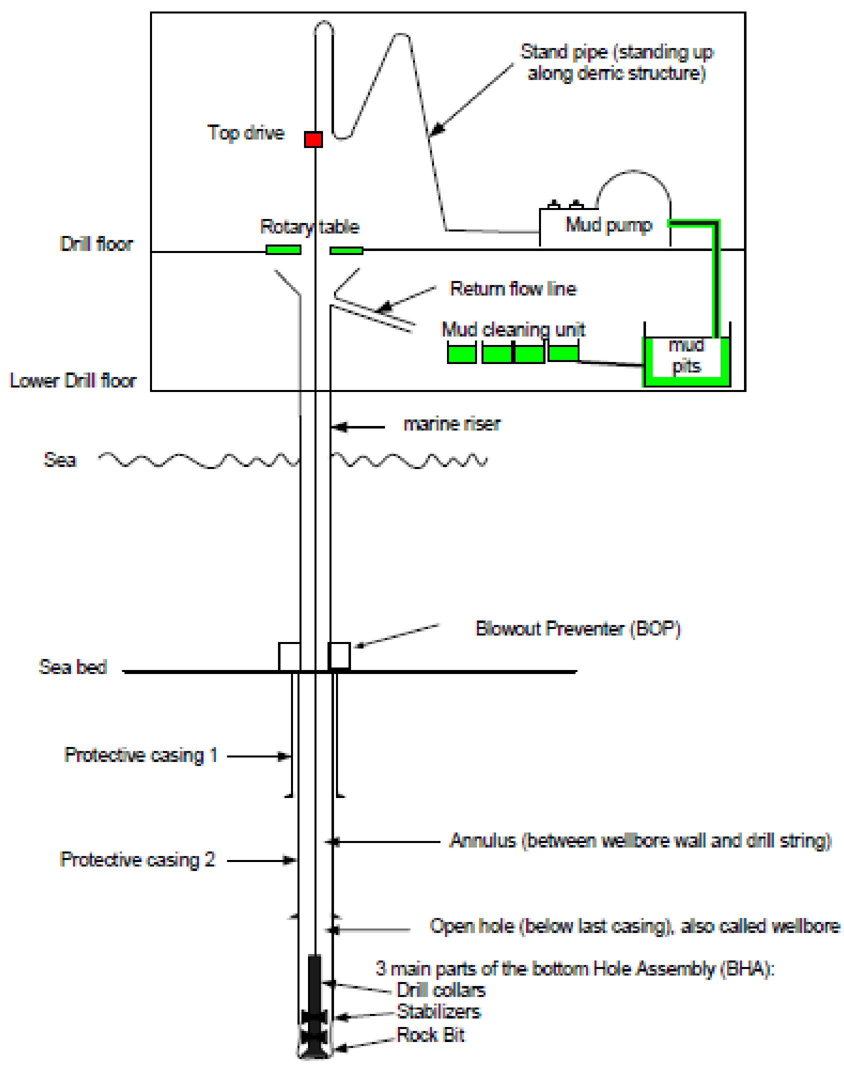

Figure 2 - The Drilling Process (Skalle, 2012).

Geographic Location of Deepwater Horizon - Macondo

The Macondo well is located approximately 48 miles from the nearest shoreline; 114 miles from the shipping supply point of Port Fourchon, Louisiana; and 154 miles from the Houma, Louisiana - United States, as shown in figure 3. The area where the well is located is quite sensitive, it focused intense fishing and tourist activity.

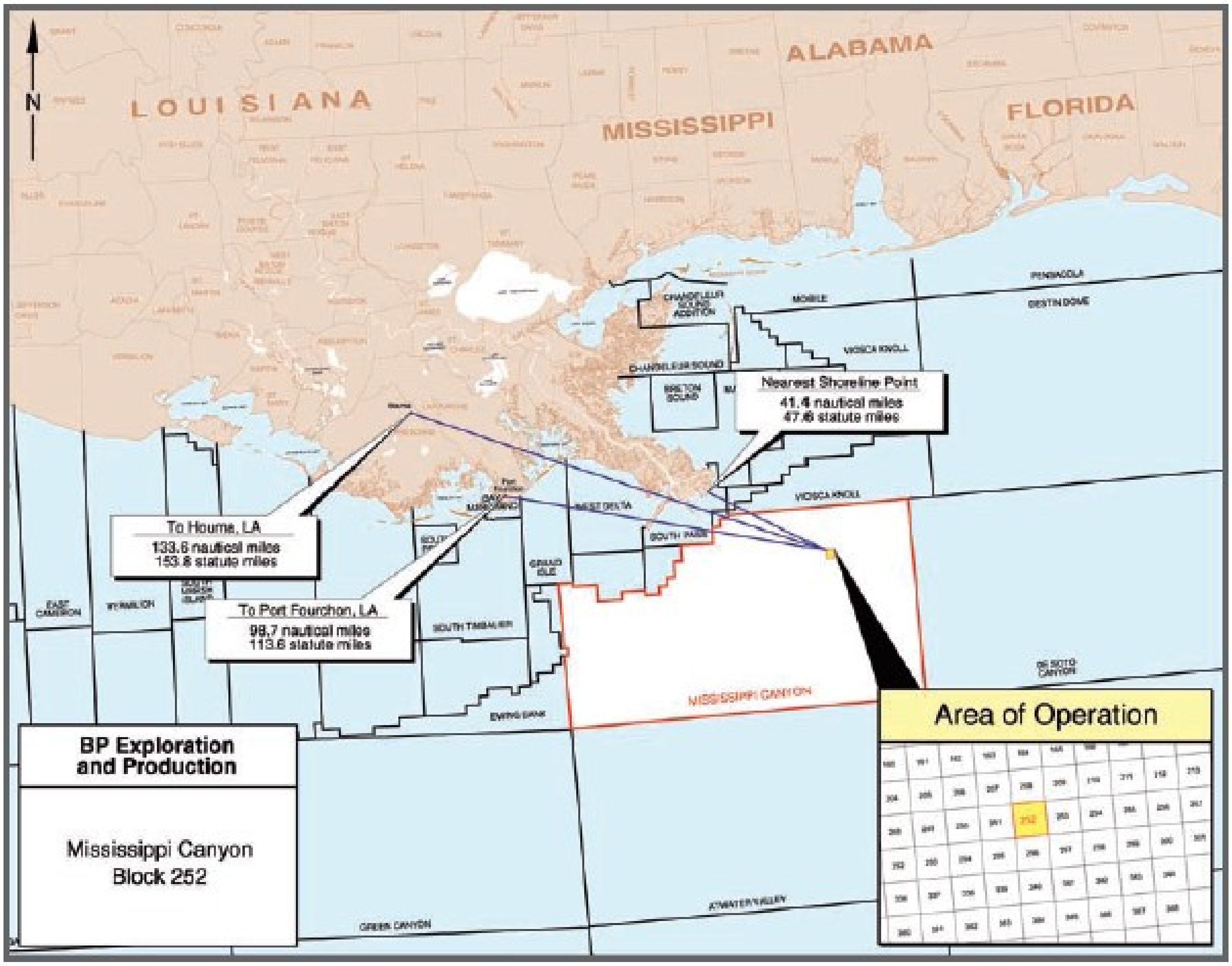

Figure 3 - Geographic Location of Deepwater Horizon (BP, 2010).

The chronology of the accident

According to According to (BP, 2010) table 1 presents the chronology of the accident.

Table 1 – Accident sequence (BP, 2010).

Date	Time	Description	Source
2009 **October 6**		Spudded Macondo well with Transocean's Marianas.	OpenWells®
November 8–27		Pulled riser and evacuated Marianas for Hurricane Ida. Marianas subsequently damaged and moved to safe harbor for repairs.	OpenWells®
2010 **January 31–February 6**		Pilot valve leak of 1 gpm noticed on yellow pod of BOP; leak reduced after switching to blue pod.	OpenWells®
February 23–		Well control event at 13,305 ft. Pipe stuck; severed	OpenWells®

March 13		pipe at 12,146 ft.	
April 9–14		Halliburton OptiCem™ cement model review concluded zonal isolation objectives could be met using 9 7/8 in. x 7 in. long string as production casing.	OpenWells®
April 14		OptiCem™ model updated with open hole caliper and survey data. Input included 21 centralizers and 70% standoff above the top centralizer.	Halliburton 9 7/8 in. x 7 in. Production Casing Design Report
April 15		Decision made to order 15 additional centralizers. Order placed.	Company emails
April 18	20:58	Partial lab test results, a new OptiCem™ model report (using seven inline centralizers) and Halliburton’s cementing recommended procedure for the Macondo well cement job were provided to BP and Halliburton staff. [Complete lab test results on planned slurry design not provided to BP before job was pumped.]	Email from Halliburton inhouse cementing engineer to BP and Halliburton staff
April 19–20	19:30–00:36	Cement job pumped as planned with full fluid returns observed. Bottom plug burst disk ruptured at higher-than-planned pressure, 2,900 psi. Cement job completed; bumped top wiper plug at 00:36 hours.	OpenWells® Real-time data
April 20	00:40–07:00	Dril-Quip seal assembly installed in subsea wellhead. Two pressure tests successfully completed. Drill pipe pulled out of riser.	Real-time data OpenWells® Interviews
April 20	~07:30	BP and service providers discussed running cement bond log (CBL) during morning operations call. Decision made, in accordance with pre-established BP Macondo well team decision tree, not to run CBL.	Interviews
April 20	10:55–12:00	Successful positive-pressure test of the production casing.	Real-time data Interviews
April 20	18:35–19:55	Discussion ensued about pressure anomalies and negative-pressure test procedure. Seawater pumped into the kill line to confirm it was full. Opened kill line and bled 0.2 bbl to mini trip tank; flow stopped. Kill line opened and monitored for 30 minutes with no flow. At 19:55 hours, the negative-pressure test was concluded and considered a good test.	Real-time data Interviews
April 20	21:31–21:34	Drill pipe pressure increased from 1,210 psi to 1,766 psi. ~21:33 hours, chief mate observed toolpusher and driller discussing “differential pressure.” Toolpusher told chief mate that cement job may be delayed.	Real-time data MBI testimony

April 20	21:38	[Calculated that at approximately 21:38, hydrocarbons passed from well into riser.]	OLGA® model
April 20	21:40–21:48	~21:40 hours—Mud overflowed the flow-line andonto rig floor.~21:41 hours—Mud shot up through derrick.~21:41 hours—Diverter closed and flow routed tomud gas separator (MGS); BOP activated (believedto be lower annular preventer).[Drill pipe pressure started increasing in responseto BOP activation.]~21:42 hours—M/V Damon Bankston was advisedby Deepwater Horizon bridge to stand off 500 mbecause of a problem with the well. The ship beganto move away.~21:42 hours—Drill pipe pressure increased steadilyfrom 338 psi to 1,200 psi over 5-minute period.~21:44 hours—Mud and water exited MGS vents;mud rained down on rig and M/V Damon Bankstonas it pulled away from rig.~21:44 hours—Toolpusher called well site leaderand stated they were “getting mud back” andthat they had “diverted to the mud gas separator”and had either closed or were closing the annularpreventer.~21:45 hours—Assistant driller called the seniortoolpusher to report that “The well is blowingout . . . [the toolpusher] is shutting it in now.”~21:46 hours—Gas hissing noise heard andhigh-pressure gas discharged from MGS ventstowards deck.~21:47 hours—First gas alarm sounded. Gas rapidlydispersed, setting off other gas alarms.~21:47 hours—Roaring noise heard and vibration felt.~21:47 hours—Drill pipe pressure started rapidlyincreasing from 1,200 psi to 5,730 psi.[This is thought to have been the BOP sealingaround pipe. Possible activation of variable borerams [VBRs] at 21:46 hours.]~21:48 hours—Main power generationengines started going into overspeed (#3 and #6were online).	Real-time dataInterviews MBI testimony
April 20	21:49	Rig power lost. Sperry-Sun real-time data transmission lost. First explosion occurred an estimated 5 seconds after power loss. Second explosion occurred an estimated 10 seconds after first explosion.	Real-time data Interviews MBI testimony
April 20	21:52:57	Mayday call made by Deepwater Horizon.	M/V Damon Bankston log
April 20	~ 21:52–21:57	Subsea supervisor attempted to activate emergency disconnect sequence (EDS) for the BOP at the panel on the bridge. Lights changed on panel, but no flow was observed on the flow meter. Lower marine riser package did not unlatch. Deepwater Horizon master announced the activation of the EDS at 21:56.	MBI testimony Interviews
April 20	~ 22:00–23:22	Transfer of 115 personnel, including 17 injured, to M/V Damon Bankston. 11 people were determined to be missing, and search and rescue activities ensued. U.S. Coast Guard arrived on-site at 23:22 hours.	MBI testimony
April 22	10:22	Deepwater Horizon sank.	Unified Command
April 23	17:00	The search for the 11 missing people was suspended.	Unified Command
April 21–22	18:00–01:15	Remotely operated vehicle (ROV) operations were initiated.	IMT reports

	ROV attempted hot stab interventions to close VBRs and blind shear rams (BSRs); ROV attempts were ineffective.	

SAFETY ANALYSIS OF THE DEEPWATER HORIZON BLOWOUT BASED ON FRAM

1 - Identification essential system functions, and characterization of each function by six parameters (Input, Output, Time, Control, Precondition, and Resource):

The process of exploration and production of oil involves a large number of companies working on the platforms according to their specialties. In the case studied, the activity is conducted primarily by business Transocean (owner of the platform), Halliburton (supplier of cementing services), and British Petroleum - BP (operator). To better focus on the analysis of the accident, we studied the functions directly involved at the time of the accident. However, for a deeper analysis there will be a need to consider that the activity of exploration and production involves much more functions. The functions to be used in this research are Drilling, Cement Placement and Temporary Abandonment. Drilling is the function of drilling well as previously developed project and supported by geological and geophysical studies. During this activity, the drilling mud is used to cool the well. Monitor the volume and density of the mud is necessary to avoid problems in the formation and remove drilling waste. During this activity, the invasion of hydrocarbons in the well can occur and controls should be done by controlling the mud pressure or to use safety valves to contain the invasion of hydrocarbons and prevent the blowout. After drilling a step, the activity of Cement Placement occurs. Cement Placement is the activity of removing column used to drill the well and insertion of a steel tube insulation. The space between the steel tube and the formation is completed with special cement, which is injected through the system of injection of mud in the well (Swivel) device. To ensure uniform and no weak cementation points, centralizers, which are devices that keep the steel tube centralized inside the well, are used.

Temporary abandonment is the activity of testing the well, including sealing and safety devices and disconnection of the platform so that the well can be resumed in the future and put into production. In the case of the Deepwater Horizon disaster occurred before this activity was completed, however this was the goal of the activities.

With the support of software FramModelBuilder and FramModelVisualizer we model the main functions involved according to the documents issued by the research team of the Chair (Graham et al., 2011) and British Petroleum (BP, 2010) and technical aspects of the activity (Skalle 2012; Skogdalen & Vinnem 2012). Figure 4 presents the initial model.

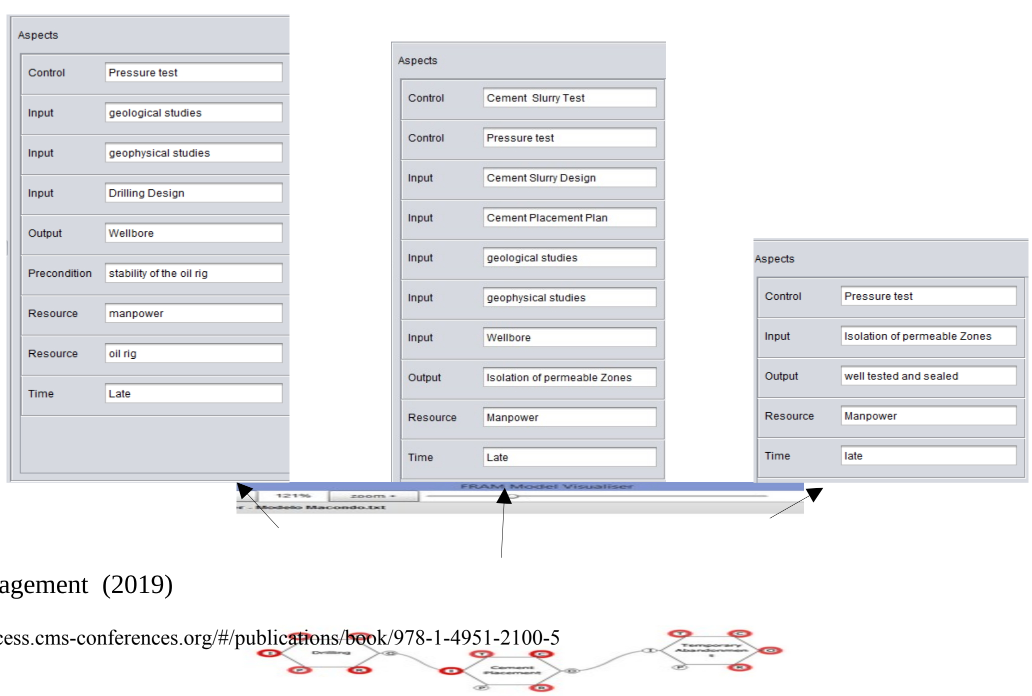

Figure 4 – FRAM describing the functions Drilling Cement Placement, and Temporary Abandonment.

2- Assessment and evaluation of the potential variability. Consider worst case and normal situation.

The Deepwater Horizon has as inputs for the function Drilling the geological and geophysical studies. These studies may have as variation the incompleteness and inaccuracy about the formation. However, the set of mechanisms of the oil rig and continuous analysis of drilling wastes that return with mud may help to make the process resilient and to perform corrections during drilling. Additionally wells with specific objective to know better the formation are drilled. Another source of variation that apparently occurred in the case study is the restriction of time because delays in the oil industry generate huge financial losses forcing workers to compromise the performance of other issues, including those related to safety, to reduce the times of the activities. The control consists of punching signals of an array of sensors of temperature, pressure and position. Here we highlight the pressure tests because variations in performance of these sensors can seriously compromise the work on the platform. Significant variations are also reading and misinterpretation of information or interpretation of data.If variations in the performance of dynamic positioning of the oil rig occur, the equipment that connect to the bottom of the well can be broken or controls may be compromised.

The activity Cement Placement aims to isolate the well of the invasion of hydrocarbons and ensure future operating safely. At this stage special steel pipe is introduced into the well and cement is pumped through of drill equipment to fill the space between the pipe and the formation. As the tube placed in the well can move during this activity, compromising the cement placement, centering devices between the pipe and training are used to ensure a uniform distribution of cement, as Figure 5. Performance variations related to cement slurry design can make the weaker cement and cause the invasion of hydrocarbons in the well or cause fractures in the formation. Additionally, variations in the amount of centralizers may affect the ability of insulation cement, because centralizers ensure uniform distribution of cement. The controls on the activity of cement placement are mainly pressure test and cement slurry testing, allowing actions may be taken before a leak occurs. Pressure tests are performed by applying positive and negative pressure in the well, however performance variations can occur in reading and misinterpretation of information. There are no work standards able to prescribe how to analyze all variables checked by operators, then the process becomes resilient according to the ability to train on the job the crew. A way used to make the process more resilient is the use of operators / experts onshore, through communication systems to support the offshore decisions.

Additional tests are performed to assess the formulation of cement (cement slurry test). These tests are performed in laboratory outside of the platform, using standard procedures, and the results are stored in a database. As the activity of cementation is very specialized, the team that performs the tests usually have no contact with the platform teams and usually are member of a different company. Tests can help to make the process more resilient, if a procedure for communicating the results to stakeholders is established and are defined corrective or preventative measures with the participation of teams involved. Cementing correction is one of the actions that can be taken in case of variation in performance detected. In the aforementioned tests, other methods can be applied to evaluate the cement placement.

The temporary abandonment activity consists in assessing the integrity of the well and seal for future exploration. The main objective is to isolate the well for safe abandonment. Performance variations can be detected during testing for abandonment of the well, making the process resilient when corrective / preventive actions are established according to the teams involved. For this activity, checklists are used and there are procedures to review that there are no variations in performance due to forgetfulness of requirements by operators, but operator training makes the process more resilient as it is not possible to anticipate all situations in a platform in the checklist. Possible variations in performance need to be noticed by the crew, even when the checklist does not prescribe.

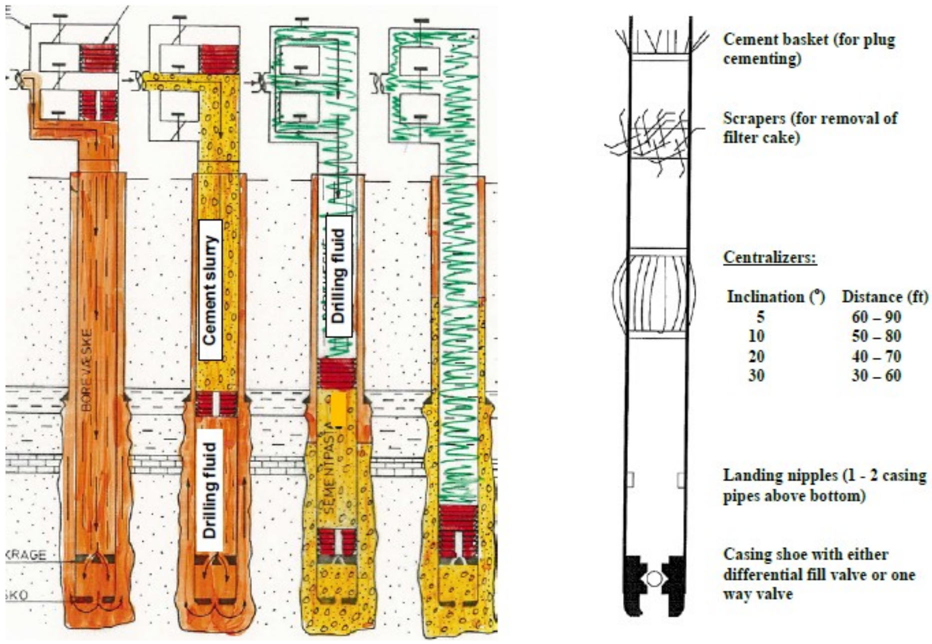

Figure 5 - Cementing technique (Skalle, 2012)

3- Identification of functional resonance. The combinations of variability may result in undesirable outputs

The combination of the variability of the performance aspects of cement slurry design and cement placement plan (including the number of centralizers) can seriously compromise the activity of cement placement. A most fragile cement caused by a variation of the cement slurry design associated with an inadequate distribution of the cement due to cement performance variation in performance placement plan may cause the invasion of hydrocarbons in the well and possibly a situation of uncontrolled.

To become the plataforms resilient to face any performance variations that can lead to oil spills, safety devices known as blowout Preventure, which allow you to control abnormal pressures from wells or the complete closing are used. Thus it is clear that performance variations on the BOP make the process less resilient.

CONCLUSIONS

As the work on oil rigs are performed by more than one company, the responsibility for the operation of some aspects is usually performed by a team with members from various companies, so the combination of aspects that can generate disproportionate impact is further accentuated, because decisions can be taken separately for each aspect, not considering relationships with other features / aspects. In the case studied, the Drilling and Cement Placement functions present beyond individual variation, combinations that can generate disproportionate results.

A proposal to deal with this type of variation would be the definition of "safety gates". Safety Gates would be milestones in the process, with work standards that would not have the function of prescribing in detail what to do for each type of risk, but indicate the group decision and the minimum information necessary when certain performance variations or combinations of variations occur. Indications of green, yellow and red could be used as guidance for the combination of risks and actions to be taken. Risk situations or unexpected combinations that indicate high risk would be like a red traffic light, in which the process should be paralyzed and an instruction indicate the group needed to make the decision and the minimum information for it. Decisions also would generate lessons learned to guide the development of standards and support future decisions. Similarly would be indicated situations to yellow or green light, which should also generate lessons learned to share with the team and improving standards. In the case of the Deepwater Horizon, unilateral decisions on certain aspects, without recognizing the risks assumed may have become less resilient process.

One of the weaknesses of the oil and gas industry is no database of safety best practices among companies of the sector Accidents are usually reported to the authorities, but the information about and actions to prevent are restricted to databases of the authorities or are published only the statistical numbers, since information on accidents are seen as confidencial making it difficult for companies learn from errors. You must continually learn in order to to make the process resilient , however only the information of where accidents occur frequently are not enough. It is important to understand the aspects, how they can be combined and how to act in unexpected situations.

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