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The Influence of Automation on Human Error in Managed Pressure Drilling Well Control

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- uttak av masteroppgave

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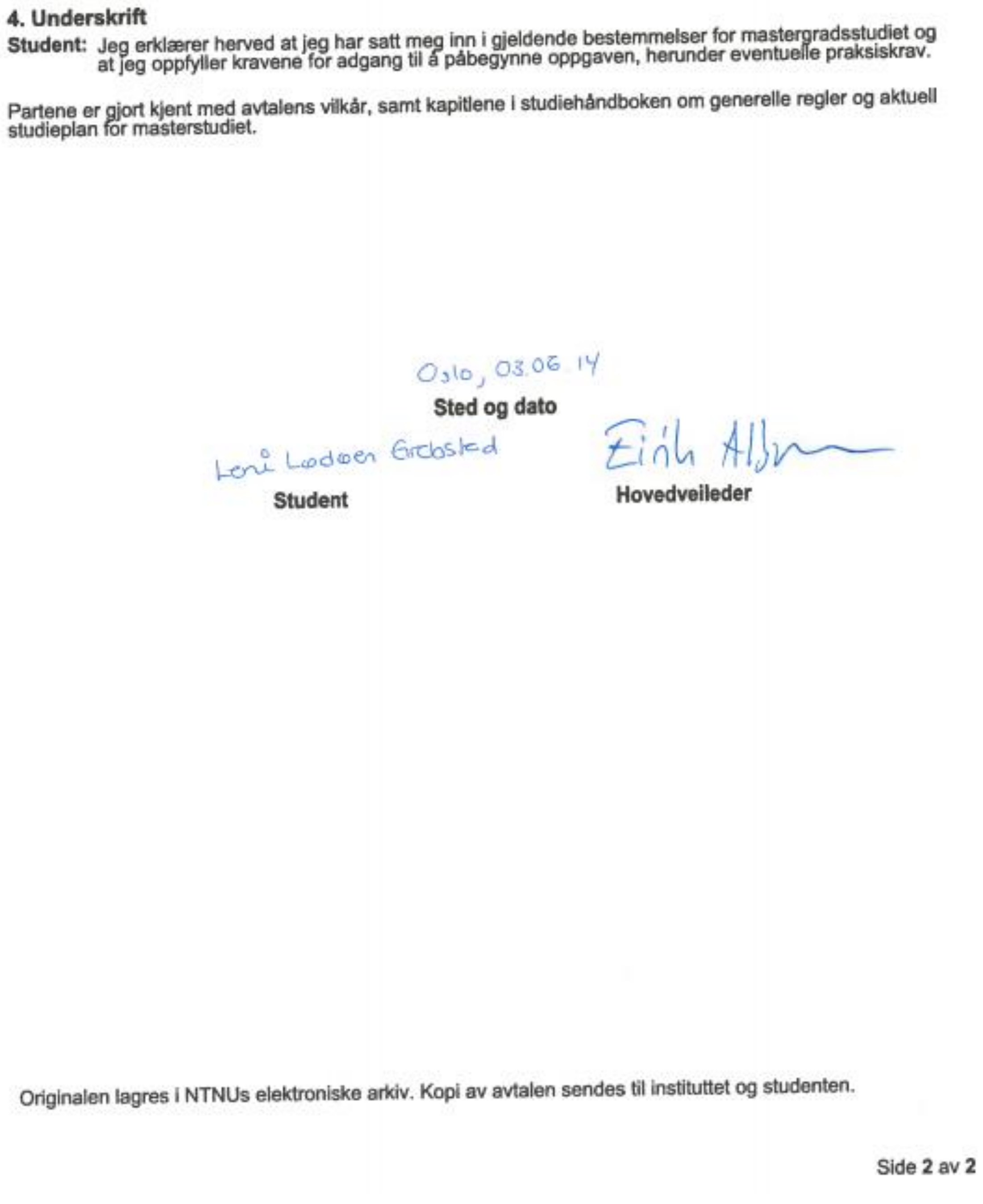

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Preface

This thesis represent the final part of the M.Sc. in Health, Safety, and, Environment at the Norwegian University of Science and Technology, with credits of 30. The work was conducted in collaboration with DNV GL under supervision of Associate Professor Eirik Albrechtsen (NTNU) and Senior Consultant Sondre Øie (DNV GL).

I would like to acknowledge Eirik Albrechtsen for professional advice and structural feedback throughout this semester. Gratitude is extended to Sondre Øie for inspiration, motivation, and knowledgeable guidance. Likewise, I would like to note my appreciation for the employees at the departments Operational Safety and Drilling and Well at Høvik, DNV GL.

I would like to thank MPD Manager Tim Tønnesen at Halliburton AS for giving me the opportunity to use their organization as a case and for providing information. Also, recognition to crew members at Transocean Spitsbergen for their contribution in form of explanations, illustrations, and demonstrations of relevant theory.

Finally, gratitude to my brother, Daniel, for proof reading, and to my significant other, Lars Martin, for support and encouragement.

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Abstract

This thesis aims to explain and discuss the concept of automation in Managed Pressure Drilling systems and how this may influence the risk of well control incidents by its effect on human performance, focusing on human errors. The scope also includes examining the change of mode of automation during a well control incident, and recommend for a future mode of automation from a human factor point of view. An MPD system developed by Halliburton AS was used as a case, while the critical well control incident, lost circulation, formed the scenario. Researchers and technical professionals also shared their point of view in possibilities and challenges with MPD.

The petroleum industry in seeking improved technologies to drill wells with a narrow drilling window, such as depleted reservoirs. Automated MPD has addressed this challenge with dedicated pressure control equipment. A higher mode of automation may reduce some risks, such as kicks and losses. However, it may also introduce new types of safety issues that affect the risk of human error. The Norwegian Petroleum Safety Authority requires systems and equipment to be designed such that the possibility of human error is limited. NORSOK S-002 requires the execution of analysis to ensure that the potential for human error in work systems is minimized. Methods utilized in this thesis were the functional analysis, FAST, allocation of functions, task analysis, and a systematic human error reduction and prediction approach, SHERPA.

Functions required to maintain bottomhole pressure within drilling window was identified with FAST. The analysis demonstrated a more complex primary well control than for conventional drilling. Allocation of functions to human and machine illustrated that the backpressure pump and the MPD choke are automatically controlled during drilling (Mode 3 Management by Delegation), while manually handled during lost circulation (Mode 1 Assisted Manual Control). Allocation of functions and the task analysis clarified a frequent change in task responsibilities between the driller and the MPD operator. SHERPA found that errors made by the driller or the MPD operator could lead to failure of filling the well adequately with mud during losses, which initiates a kick. If the blowout-preventer is not closed, it could result in the kick developing into a blowout. A clear instruction on when to close the BOP was not found, with limitations of time and information available to confirm this finding.

A future mode of automation in MPD systems is recommended to be similar to today's situation. The operation is then enhanced during drilling, while allowing the operator to intervene to varying degrees in case of abnormal operation. This could provide benefits such as improved situation awareness, workload, and overall human-machine performance. However, the increase in complexity, coupled with team-work previously not found in traditional drilling methods, may suggest that communication, interaction between different operators, and mistaken judgments are vulnerable aspects. These findings combined with changed task demands propose that automated MPD introduces new types of human errors that could influence risks prior to and during a well control incidents. Still, the MPD equipment offers a more precise adjustment of the bottomhole pressure proposing that some well control incidents are more simplified to handle. Incorporating the human element in major accident risk analyses has been suggested to be a promising path to improve safety and reliability in safety-critical system.

Sammendrag

Denne oppgaven tar sikte på å forklare og diskutere begrepet automatisering i trykkbalanserte (MPD) boresystemer og hvordan dette kan påvirke risikoen for brønnkontrollhendelser ved automatiseringens effekt på menneskelig ytelse. Fokuset til rettes mot menneskelige feil. Arbeidet inkluderer også det å undersøke endring av automasjonsmodus under en brønnkontrollhendelse, og å anbefale en fremtidig modus for automasjon av MPD-systemer fra en menneskelig faktors ståsted. Et trykkbalansert system utviklet av Halliburton AS vil bli brukt som et eksempel, hvor tap av borevæske til formasjonen vil representere en uønsket brønnkontrollhendelse.

Petroleumsindustrien søker forbedret teknologi for å bore brønner med et smalt borevindu, for eksempel depleterte reservoarer. Automatisert MPD har adressert denne utfordringen med dedikert trykkontrollutstyr. Et høyere modus av automasjon kan redusere noe risiko, for eksempel brønnspark og tap av borevæske. Likevel kan det også introdusere nye typer sikkerhetsproblemer som påvirker risikoen for menneskelige feil. Petroleumstilsynet krever at systemer og utstyr skal være utformet slik at muligheten for menneskelige feil er begrenset. NORSOK S-002 krever utførelse av ulike analyser for å sikre at muligheten for menneskelige feil i arbeidssystemer er redusert. Metoder benyttet i denne avhandlingen var funksjonsanalysen "FAST", fordeling av funksjoner, oppgaveanalyse, og en menneskelig feilanalyse, SHERPA.

Funksjoner som kreves for å opprettholde bunnhullstrykk innenfor borevinduet ble identifisert med FAST. Analysen viste en mer kompleks primærbrønnkontroll enn for konvensjonell boring. Tildeling av disse funksjonene til menneske og maskin illustrerte at mottrykkspumpen og MPD choke manifold blir automatisk kontrollert under boring (Modus 3 Ledelse ved delegasjon), mens de blir manuelt håndtert under tap av borevæske (Modus 1 Manuell kontroll). Tildeling av funksjoner og oppgaveanalyse avklarte en hyppig endring i oppgave/funksjonsansvar mellom boreren og MPD-operatøren. SHERPA eksponerte at menneskelige feil utført av boreren eller MPD-operatøren kan føre til svikt i å fylle brønnen tilstrekkelig med borevæske under tap. En unnlatelse av å ikke lukke utblåsningssikringen kan resultere i at et brønnspark utvikles til en utblåsning. En klar instruks om når boreren bør lukke BOP ble ikke funnet, med begrensninger i tid og informasjon tilgjengelig for å bekrefte dette resultatet.

En fremtidig modus av automasjon i MPD-systemer anbefales å være lik dagens situasjon. Operasjonen blir da forbedret under boringen, samtidig som den tillater at operatøren kan gripe inn i varierende grad i tilfelle en brønnkontrollsituasjon oppstår. Dette kan gi fordeler som bedrer situasjonsbevissthet og generelt bedrer menneske-maskin-ytelse. Økningen i kompleksitet, kombinert med samarbeidet som tidligere ikke var i tradisjonelle boremetoder, kan dog tyde på at kommunikasjon, samhandling mellom ulike aktører, og feilaktige avgjørelser er sårbare sider. Disse funnene, kombinert med endrede type oppgaver, antyder at automatisert MPD introduserer nye typer menneskelige feil som kan påvirke risikoen før og under brønnkontrollhendelser. Likevel gir MPD-utstyret en mer presis regulering av bunnhullstrykk, noe som foreslås å gjøre brønnkontrollhendelser enklere å håndtere. Å innlemme det menneskelige element i storulykkesrisiko-analyser er foreslått å være en lovende vei for å bedre sikkerhet og pålitelighet i sikkerhetskritisk system.

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1 Introduction

Managed Pressure Drilling (MPD) has received considerable attention during the last years. One of the reasons is an apparent demand for new drilling technologies to drill narrow mud window formations, *e.g.* fractured formations, depleted reservoirs, and deep water formations. Summarized, these challenges give a drive for improving well control compared with conventional practice.

For conventional drilling, the annular hydraulic bottomhole pressure (BHP) can vary with hundreds of psi when changing from static to dynamic condition. Hence, drilling narrow pressure formations can be considered impractical or even unsafe using conventional drilling technology. To prevent large BHP variations, such as when rig pumps are being switched from on to off (and vice versa), MPD systems may introduce dedicated MPD pressure control equipment for this purpose.

1.1 Problem Definition

Management of risks during drilling operations is ensured by the use of a primary and a secondary well barrier. The main purpose of the primary barrier is to prevent uncontrolled influx, whereas the secondary barrier is used to mitigate loss of control in case the primary barrier fails. While conventional drilling operations use the mud column weight as the primary well barrier, MPD systems typically apply non-conventional equipment for active control of BHP. As part of an integrated operation (IO), MPD gives a more precise control of BHP which may reduce risks for kicks and losses compared with conventional methods, particular when drilling in narrow mud windows.

At the same time, however, lack of experience with the technology and new ways of managing drilling operations may introduce new hazards and potential hazardous events. The introduction and development of new technology allows for automation of operated well control functions that were previously manually handled (Saeed *et al.* 2012). While introducing a higher mode of automation may lead to optimal performance, it also introduces new safety issues that need to be addressed to ensure safe operational conditions. Hard learned lessons from other industries, such as aviation, have in some cases revealed opposite effect by implementation of automatic functions planned to reduce risk and increase effectiveness (Thorogood *et al.* 2010).

Recent studies also suggest that the use of drilling support systems and levels/types of automation may influence the driller's performance and risk of potential human error.

For instance, increased level of automation may lead to mode confusion, *i.e.*, a situation where the technical system behaves differently than the operators expect (Iversen *et al.* 2012). Because the work distribution between the automation system and the driller changes for each increased mode of automation, a clear understanding of human-machine interaction is needed (Breyholtz & Nikolaou 2012).

The Norwegian Petroleum Safety Authorities entails installations, systems, and equipment to be designed such that the possibility of human error is limited (PSA 2008). The Norwegian petroleum standards (NORSOK) also states that during project development, analyses shall be performed to minimize the potential for human error in work systems that control safety critical activities on the installation. Further, NORSOK defines that during concept definition of systems, the activity shall include a functional analysis and allocation describing functions to be performed, defining system performance requirements, and allocating manual and/or automatic functions. In addition, a task analysis defining tasks based on allocated functions shall be performed (NORSOK 2008).

1.2 Objectives

This thesis aims to explain and discuss the concept of automation in Managed Pressure Drilling (MPD) systems and how this may influence the risk of well control incidents by its effect on human performance, focusing on human errors. Tasks to be performed:

1. Establish an MPD system description with case establishment.

2. Make a brief review of methods for Human Factor and risk methods suitable for addressing this thesis' objectives. Perform a selection of these methods on an MPD system, with focus on achieving system goals, such as primary well control. Discuss the quality of these methods to be used in this context. Further, look at which changes (modes of automation) occur in the human-machine interface during a well incident.

3. Perform an empirical study to map challenges and possibilities with MPD. Discuss advantages and disadvantage of automation in relation to a major accident scenario and human errors.

4. Give recommendations on level/mode of automation of future MPD systems from a Human Factor point of view.

1.3 Delimitations

The scope of this thesis was to examine automated Managed Pressure Drilling and the influence on risk of human errors in a well control incident. MPD is a general term for methods used to more precisely control pressure in the wellbore. This thesis was restricted to study the method Constant Bottom Hole Pressure, as this is the method applied by Halliburton AS, the company utilized as a case throughout the thesis. Further, the framework was set to be on the Norwegian Continental Shelf, which implies that the MPD operation was performed on platforms and not on floating rigs where waves and bad weather may have an impact. In addition, system components of the MPD system were chosen to be those that are currently in operation in Norway (*i.e.* backpressure pump, and not rotating control device).

The empirical study, described in Section 1.2, is delimited to include a pre-study, which means that researchers and technical professional were contacted on email and phone. They were not met in person due to the geographical positions of each participant. Their answers were used to reflect the relevance of the scope, and not directly to support the work performed in the thesis.

As the objectives of the thesis are more focused towards a system's vulnerabilities to human errors, and not to quantify such errors, the thesis was delimited to include qualitative research. The review of Human Factor methods contains those that were actually applied in the thesis. The well control incident chosen to be examined was lost circulation, as this is a critical situation with possibilities to escalate. System failures were not looked upon as a cause of human error when performing the different analyses. To delimit the qualitative research, performance shaping factors that could influence human errors were also excluded.

During drilling operations offshore, a number of different people hold tasks that could have an influence on the scenario and the results of the analyses performed. These include, but are not limited to, the driller superintendent, toolpusher, driller, assistant driller, derrickman, directional driller, data operator, mud engineer, and two or three MPD operators. This thesis was mainly focused on the driller and the MPD operator's roles in influencing the well control incident.

1.4 Report Outline

The remainder of the report is organized as follows

Chapter 2	Contains an introduction to drilling technology where conventional drilling, managed pressure drilling, and Halliburton's Geobalance system are described. Further, a section on safety explains well control, loss of well control with more information on lost circulation. The last part of chapter 2 holds human performance, with the subtopics automation, human-machine interactions and human error.
Chapter 3	Describes the methods utilized to accomplish the objectives, which includes data collection, creating a scenario, and human factors methods; functional analysis, allocation of functions, task analysis, and human error identification.

Chapter 4	Presents the findings from the pre-study which includes possibilities and challenges with MPD, and the different analyses performed throughout the thesis. These are Functional Analysis System Technique, (FAST), allocation of functions with reference to Fitts list, a hierarchical task analysis on lost circulation, and Systematic Human Error Reduction and Prediction Approach (SHERPA). The section ends with a table that combines the different analyses.
Chapter 5	Begins with a discussion on the results obtained from chapter 4 together with relevant theory from chapter 2. A recommendation is given for future mode of automation. The section continues with an evaluation of the methods used in the thesis. Strengths and limitations with the methodologies are given at the end.
Chapter 6	Provide conclusions for the objectives and suggestions for further work.
Chapter 7	Lists the references used in the thesis.
Chapter 8	Gives the Appendix with abbreviations.

2 Theory

This chapter will start with a simplified and short description of conventional drilling, the drilling fluid or drilling mud, and pressure terms. Knowledge about these topics is essential to understand why new drilling technologies are desired. Further, an introduction to the concept of managed pressure drilling (MPD) and Halliburton's Geobalance system will be given. A section about safety will highlight well control, loss of well control, and a lost circulation event. The last part is about human performance and outlines the concept of automation, human-machine interaction, and human error. Finally, a review of human factor methods is provided.

2.1 Drilling

2.1.1 Conventional Drilling

Drilling of wells is performed by drilling rigs such as the rig illustrated in Figure 1. The drillbit is attached to the drillstring, which again is attached to the motor, or topdrive, that rotates the drillstring. The topdrive sits within the derrick, and can be lowered and raised. During drilling, the drillstring is lowered towards the drill floor. After about 27 meters, the drilling pauses while a new stand of drillpipe is connected to the top, called pipe connection, and then well drilling continues (Devereux 2012).

Figure 1: The drilling rig Transocean Spitsbergen currently operated by Statoil. Obtained from Statoil.com.

Mud Circulation System

During the drilling process, a mud, or drilling fluid circulation system is used. Mud is pumped from the storage tanks, or pits, through the suction line to the mud pumps. From the pumps, mud flows via the standpipe through the rotary hose and swivel, and into the topdrive before going through the drill string and out of nozzles in the drillbit. After entering the wellbore from the drillbit, the mud carries downhole cuttings up to the surface through the annulus between the drillstring and the formation being drilled. The cuttings are separated from the mud over the shakers and the cleaned mud flows back to the pits before the process is repeated (Figure 2). In conventional drilling, this circulation is an open system in which mud returns to atmospheric pressure from an open annulus. During connections of new drillpipes, the mud pumps are stopped and circulation is held while a new stand of pipe is connected (Thorbjørnsen 2009).

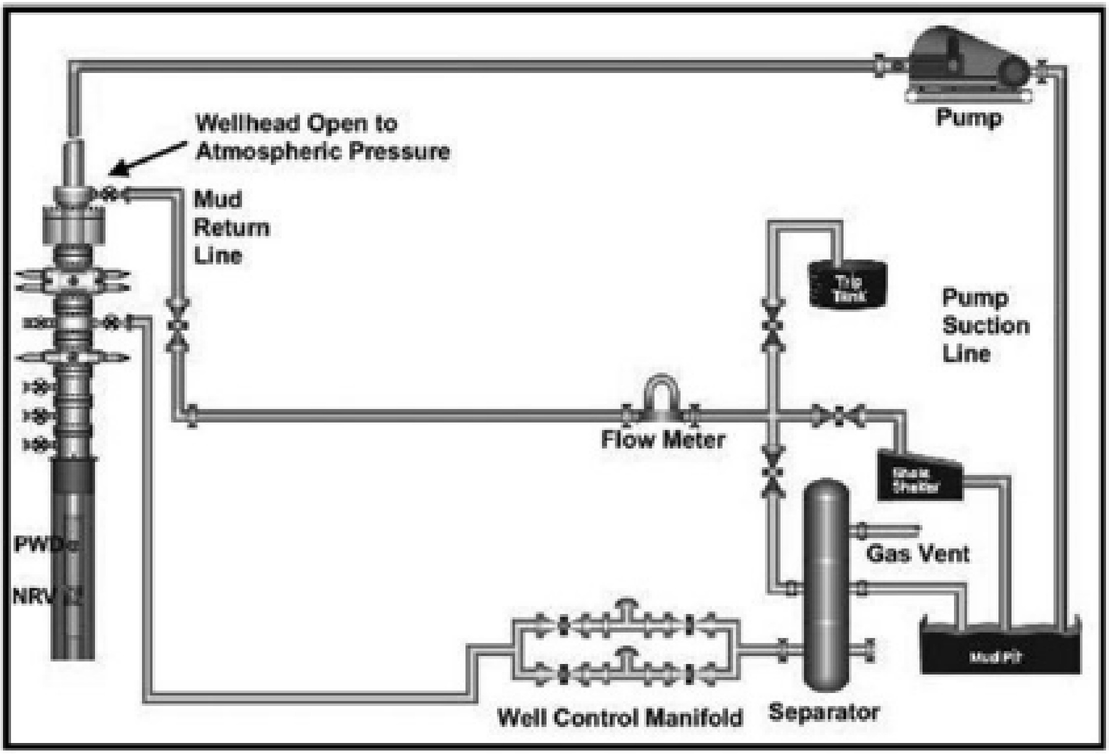


Figure 2: Open circulation system. Mud returns to the surface and flows out of the well through piping open to atmospheric pressure. There is no back pressure (Rehm 2008).

Functions of Mud

The main function of mud is to control pressure in the well by offsetting the pressure of the formation, also called primary well control. Weighting agents are added to the mud to increase its density, and hence, its pressure on the walls of the well. During drilling, mud carries cuttings up to surface where it is separated on the shakers. When drilling stops, the mud functions as a suspension tool to keep the cuttings from falling to the bottom of the hole again. The viscosity of the fluid increases when movement decreases allowing the fluid to have a liquid consistency when drilling is occurring and then it turns into a more solid substance when drilling stops. This gel-like substance transforms again into liquid when drilling continues. A third important function of mud is to provide rock stabilization (Caenn & Chillingar 1996).

Pressure Terms

As mentioned, one of the primary functions of mud is to control the downhole pressure in the wellbore (Skjeggestad 1989). In order to understand how and what is being controlled, different pressure terms need to be addressed (Bourgoyne *et al.* 1991).

In drilling, hydrostatic pressure is the force exerted by drilling fluid in the wellbore, and is maintained by the mud density and the height of the fluid column (1). This term is therefore valid when the mud pumps are shut off and hence no circulation. Formation pressure is the force exerted by fluids in the formation, and is also called reservoir pore pressure. Both fluid in the formation and fluid in the wellbore are under hydrostatic pressure, but in most well-control discussions, hydrostatic pressure refers to the pressure of the drilling fluid in the wellbore. This hydrostatic pressure can be calculated as such:

$$HP = C \times MW \times TVD \tag{1}$$

Where:
HP = hydrostatic pressure, psi
C = constant (value dependent on unit used to express mud weight)
MW = mud weight, ppg, Specific Gravity or other units
TVD = true vertical depth, feet or meters

Differential pressure refers to a difference in pressure between two areas. For example, if hydrostatic pressure in the borehole is higher than the pressure in the formation, a pressure differential exists between the two. When drilling a well, a higher pressure in the wellbore is needed to prevent the wellbore from collapsing and to avoid formation fluids to enter. If formation fluid comes into the wellbore, a kick has occurred. If this fluid is gas, it will expand on its way upwards the annulus because the hydrostatic pressure decreases. If the kick is not detected, it can result in a blow-out (see section 2.2).

The fracture pressure is the amount of pressure that would cause a formation to break down, or fracture. In a well control context, the fracture pressure of the weakest formation exposed to the wellbore must be known as the pressures developed during well-control procedures may exceed the fracture pressure of the formation. Should fracture pressure be exceeded, the formation fractures and lost circulation can occur. Lost circulation will be described in section 2.2.3. The pressure between pore- and fracture pressure is known as the drilling window (Figure 3).

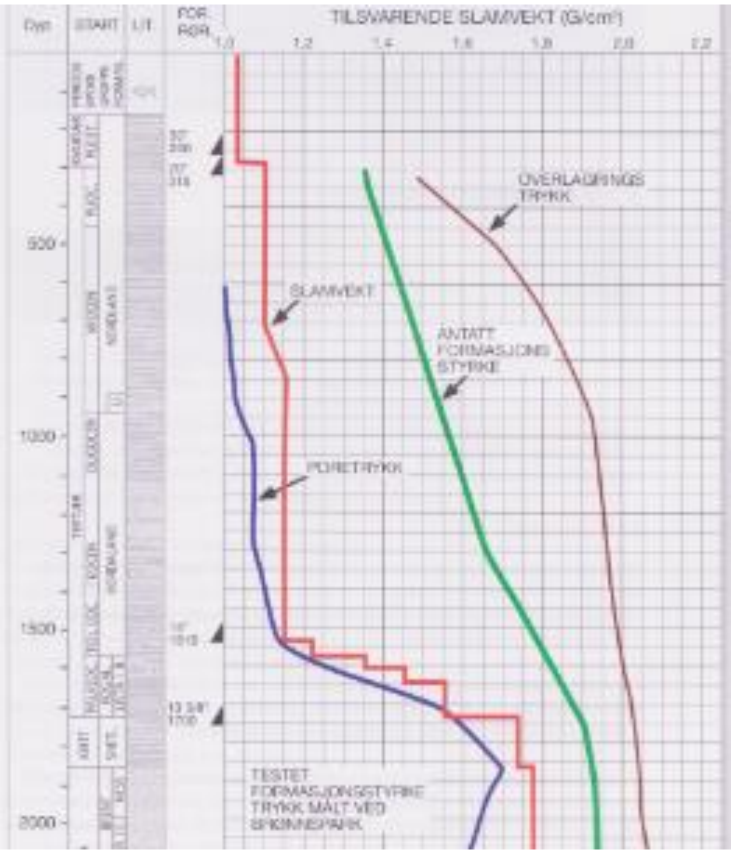


Figure 3: Pressure plot. With increasing downhole depth, both the pore pressure and fracture pressure increases. In order to drill safely, the pressure within the wellbore must be between pore pressure and fracture pressure, also known as the drilling window (Halle 2010).

Another pressure concept is pressure losses through the circulation system. Drilling fluid exits the mud pumps under high pressure and through the elements illustrated in Figure 2. When mud returns to surface from the annulus the original pressure has been spent. Each element in the circulation system absorbs energy as the mud rubs against the walls and the pipe and equipment causing friction, named friction pressure. In general, pressure losses increase when pump speed increases and when mud weight increases. In addition, pressure losses are generally higher with thick, viscous mud than with thin mud. Friction loss is relevant for the term equivalent circulating pressure (ECD), which will be described in the next subsection.

Fluid set in motion is named hydraulic pressure. When mud is being circulated, the bottomhole pressure (BHP) equals the hydrostatic pressure plus the pressure required to move mud up the annulus. Annular pressure exists only when mud is being circulated, and it is caused by the friction that resists the flow of fluid up the annulus. Another way to look at the BHP increase caused by friction losses in the annulus is in terms of ECD. ECD is a combination of the original mud weight plus the equivalent mud weight increase due to pressure loss, or friction. The ECD is an important parameter during drilling as an undesired increase or decrease in ECD could lead to loss of well control. An increase in ECD could mean poor hole cleaning with cuttings buildup in the well due to unsatisfied mud properties, whereas a decrease could be caused by flow from the wellbore into the formation. In order to maintain well control, it is important that the ECD of the mud is within this window at all times.

2.1.2 Managed Pressure Drilling

MPD is a general description of methods for managing wellbore pressure in challenging wells that cannot be drilled by conventional methods. In addition to the traditional mud weight and friction pressure, MPD introduces another variable for primary well control; applied pressure from surface (2) and (3). The mud weight can then apply a pressure similar to the pore pressure while an overbalance is kept by the additional backpressure. In formation zones where pore and fracture pressure can constantly change, or the drilling window is narrow, the wellbore pressure can be altered accordingly. The formula for BHP while circulating and at static conditions are, respectively (Saeed *et al.* 2012):

$$\text{BHP} = \text{Hydrostatic pressure (MW)} + \text{frictional pressure (ECD)} + \text{backpressure} \qquad (2)$$

$$\text{BHP} = \text{Hydrostatic pressure (MW)} + \text{backpressure} \qquad (3)$$

The International Association of Drilling Contractors defines MPD as (IADC 2012):

"An adaptive drilling process used to precisely control the annular pressure profile throughout the wellbore. The objectives are to ascertain the downhole pressure environment limits and to manage the annular hydraulic pressure profile accordingly. It is the intention of MPD to avoid continuous influx of formation fluids to the surface. Any influx incidental to the operation will be safely contained using an appropriate process.

- *MPD process employs a collection of tools and techniques which may mitigate the risks and costs associated with drilling wells that have narrow downhole environmental limits, by proactively managing the annular hydraulic pressure profile.*

- *MPD may include control of backpressure, fluid density, fluid rheology, annular fluid level, circulating friction, and hole geometry.*

- *MPD may enable faster corrective action to deal with observed pressure variations. The ability to dynamically control annular pressures facilitates drilling of what might otherwise be economically unattainable prospects."*

This definition is general for methods that manipulate the wellbore pressure. Further, IADC has agreed upon four variations of MPD, which is Constant Bottom Hole Pressure (CBHP), Mud Cap Drilling, Dual Gradient, and Return Flow Control. Often, a combination of these methods is used (Hannegan 2011; Rohani 2012). In this thesis, Halliburton's MPD system is used as a case. This is a CBHP system, and will therefore have a further focus.

Constant Bottom Hole Pressure

CBHP refers to a process where the annular pressure in the well is held constant or near constant at a specific depth. In this context constant means maintaining BHP within a window bounded by an upper fracture and lower pore pressure limit. This is accomplished by placing a rotary control device (RCD) above the BOP which seals off the annulus. Instead of mud flow going to open atmosphere as in conventional drilling, mud is led to an automatic choke manifold. The opening of the choke can be adjusted to regulate the backpressure to ensure desired BHP (Rehm & Paknejad 2008). When the mud pumps are shut off, an additional pump is used to circulate mud through the choke to create a backpressure. The purpose of using the backpressure pump while circulation is to prevent pressure spikes due to change in ECD when stopping and starting the mud pumps. As pressure is applied to the annulus, a float-valve is installed inside the bottomhole assembly (BHA) to prevent backflow through the drillstring (Florence *et al.* 2013). Iversen *et al.* (2006) has demonstrated the feasibility of MPD with automatic choke control in a depleted reservoir field.

In other words, MPD replaces the pressure exerted by static mud weight with dynamic friction pressure to maintain control of the well. A challenge with this method is to coordinate the gradually up and down ramping of the mud pumps and backpressure pump while simultaneously closing the surface choke (Figure 4). A carefully designed pump and choke operating schedule and good cooperation between the pump and choke operators is needed (Rehm & Paknejad 2008). Operations that may result in fluctuations of BHP are connections, sending downlink, and movement of pipe up and downwards causing swabbing and surging (Breyholtz *et al.* 2009).

Advantages by using MPD

The primary advantages of MPD is to reduce drilling costs due to nonproductive time (NPT) while increasing safety with specialized techniques and surface equipment (Rehm & Paknejad 2008). From a risk perspective, the main advantage of using MPD is to improve control of the BHP with intuitively enhanced well control (Handal *et al.* 2013). With real-time measurements of well parameters and the possibility to continuously adjust the pressure downhole, the method facilitates “walking the line” with the pore pressure. Also, the fluid mud flow is more accurately measured compared with conventional methods (Hannegan 2009). This gives an enhanced primary well control. Other advantages are found in the table below (Table 1):

Table 1: Advantages found by utilizing Managed Pressure Drilling (Rehm & Paknejad 2008).

Description	Advantages
Extending casing points	Casing point can be extended beyond the normal pore pressure of fracture pressure gradient limit to reduce the number of casing strings required. This allows the target to be reached with a larger hole diameter for production.
Lost circulation	Maintaining the mud density below the fracture pressure and using a variable annular back pressure at the surface enable the operator to maintain the wellbore pressure within drilling window.

Well kicks	MPD seeks to avoid the problem of well kicks by carefully monitoring the ECD in the hole and controlling inflow and outflow or pressure changes in the wellbore with impressed surface pressure.
Differential stuck drill pipe	Often a well kick initiates or is the result of pipe sticking. Differential sticking is caused by the difference in pressure between the wellbore and a permeable zone, causing the pipe to be stuck against the wall. Keeping a lower differential pressure between the wellbore and the formation reduces sticking tendencies.
Deepwater drilling	In deep waters, upper layers of the subsurface often have the fracture strength close to the hydrostatic pressure of seawater. The small margin between the pore pressure and the formation strength dictates that multiple casing strings often have to be set. The long column of drilling fluid in the riser can be given the density to control this challenge.

Pressure Control Equipment

Every supplier of MPD systems offers a unique version to the costumer; however, the principles are the same. To facilitate a way to evaluate the systems role in ensuring primary well control, Handal *et al.* (2013) have suggested a generic description of an MPD pressure control system. The system is decomposed into subsystems and components, in addition to functions and sub functions (Table 2). A simplified version will be given here, while a generic MPD system is demonstrated in Figure 4:

Table 2: Generic description of MPD pressure control equipment (Handal *et al.* 2013).

1. MPD control system used to maintain BHP within operational pressure window.
    - Logic unit used to perform arithmetic and logical operations.
        - Controller used to control dynamic MPD pressure control equipment like choke and pumps.
        - Mechanistic models used to simulate other operational parameters.
    - Well monitoring system used to monitor operational parameters and gives input to MPD control system. Different measuring devices used to monitor well, and dynamic and static MPD pressure control equipment, *e.g.*:
        - Flowmeters measuring mud return flow through mud return lines, and MPD choke manifold.
        - Pressure transmitters positioned close to dynamic or passive MPD pressure control equipment.
        - Temperature transmitters.
        - Other relevant measurements.
2. Dynamic MPD pressure control equipment used to dynamically adapt the annular hydraulic pressure profile could be, but are not limited to:
    - Automated MPD choke manifold used to regulate annular hydraulic backpressure and mud return flow. Adjustable chokes.
    - Conventional pumps used to circulate fluid or cement.
        - Rig pumps
        - Cement unit
    - Additional circulating systems connected to the well.
        - Backpressure pump used to maintain flow through MPD choke manifold.
    - Dedicated valves or tools used to restrict flow in drillstring or in well.
3. Static MPD pressure control equipment used to isolate back pressure:

Rotating Control Device (RCD) used to close well system and maintain backpressure.

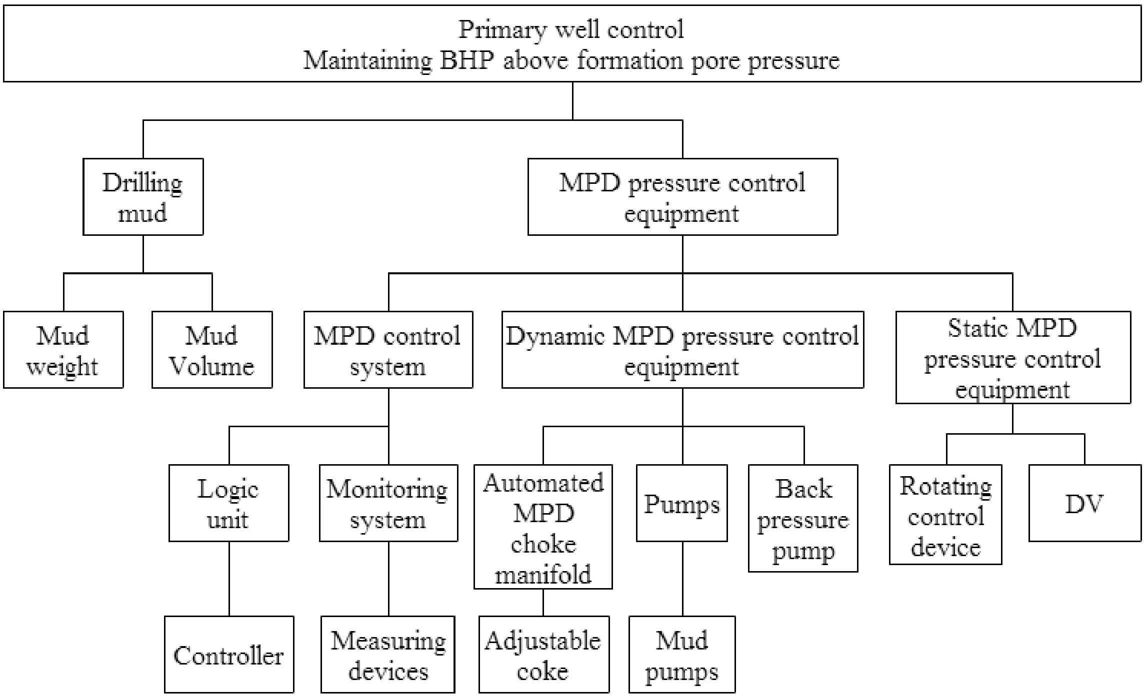


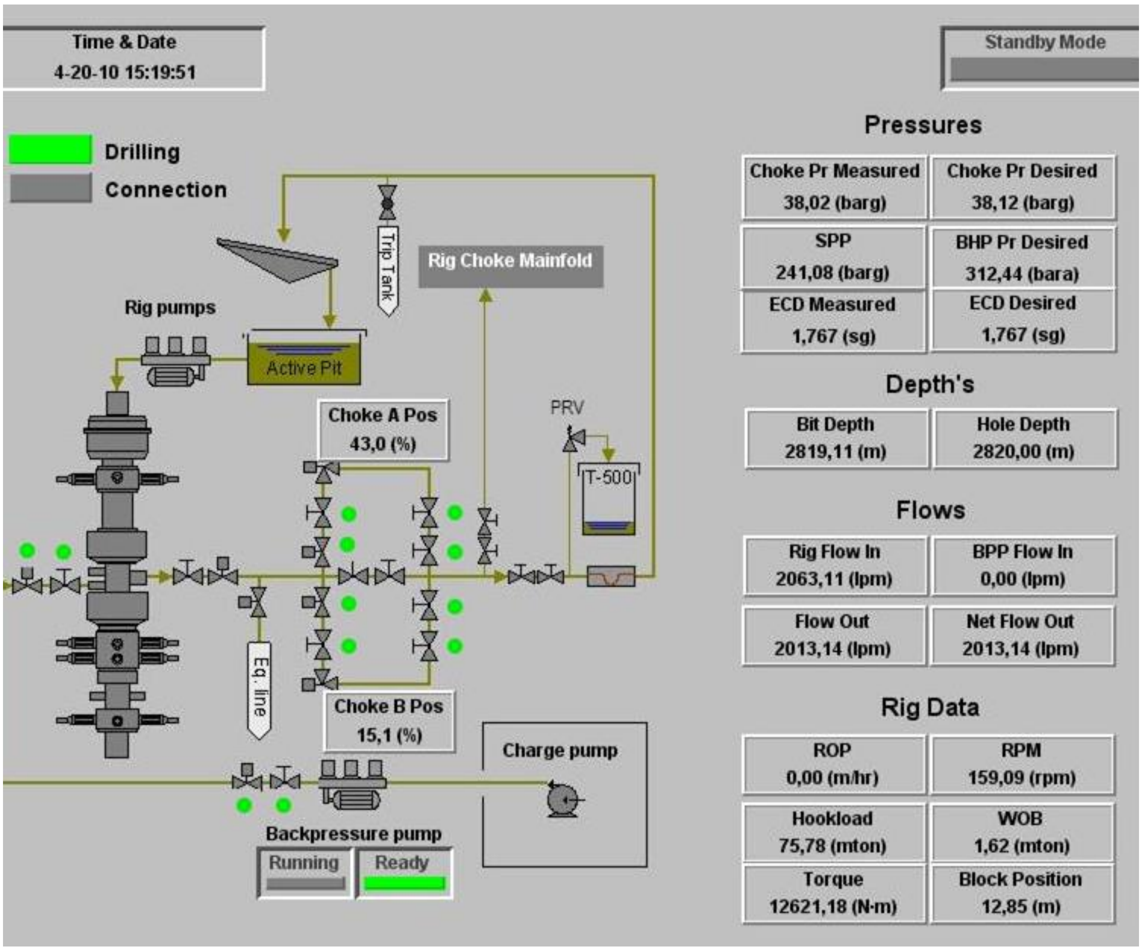
Figure 4: Decomposition of a generic MPD system, presenting the hierarchy of equipment for managing flow and pressure. MPD pressure control equipment can be broken down into: the MPD controller unit with its monitoring system, the dynamic MPD pressure control equipment, and the static MPD pressure control system. Adapted from (Handal *et al.* 2013).

2.1.3 Halliburton Geobalance MPD

Halliburton is one of the leading suppliers of MPD system solutions on today's market. Their CBHP system has been used to drill successfully on the Kvitebjørn field on the Norwegian Continental Shelf (Tonnessen *et al.* 2006). Kvitebjørn is located in the Northern North Sea, and is classified as a High Temperature High Pressure (HTHP) gas field. Nine wells had been drilled into the reservoir prior to introducing the MPD technique. On the last conventionally drilled well, massive losses were experienced. Drilling was therefore suspended before reaching TD due to the well control situation created by these mud losses. No further drilling on Kvitebjørn was possible until MPD was introduced to operate within the reduced drilling window of the reservoir (Mosti & Flatebo 2008). Other technologies were selected to support MPD, however, these will not be presented in this thesis. The following is an introduction to Halliburton's MPD system, CBHP, which is called GeoBalance (Halliburton).

Choke Manifold

GeoBalance MPD Choke is the main tool for controlling the surface pressure and thereby accurately controlling the BHP on MPD operations. The hydraulic chokes are automatically controlled to keep a desired surface pressure from an advanced hydraulic model, based on the measurement readings. The unit's choke manifold with dual chokes is configured such that each of the chokes act as redundancy for the other in case the it is plugged or washed out. A bypass line is incorporated, which also has dual block valves. Data is recoded in the INSITE Data Acquisition System (DAS) system (figure 5), for use in the GeoBalance control system. The control system software utilizes Data Validation Software, which verifies the integrity of transducers, flow meter, MPD system data, and third party acquisition system interfaces.



Time & Date
4-20-10 15:19:51

Choke A Pos
43,0 (%)

Choke B Pos
15,1 (%)

Pressures

Choke Pr Measured 38,02 (barg)	Choke Pr Desired 38,12 (barg)
SPP 241,08 (barg)	BHP Pr Desired 312,44 (bara)
ECD Measured 1,767 (sg)	ECD Desired 1,767 (sg)

Depth's

Bit Depth 2819,11 (m)	Hole Depth 2820,00 (m)

Flows

Rig Flow In 2063,11 (lpm)	BPP Flow In 0,00 (lpm)
Flow Out 2013,14 (lpm)	Net Flow Out 2013,14 (lpm)

Rig Data

ROP 0,00 (m/hr)	RPM 159,09 (rpm)
Hookload 75,78 (mton)	WOB 1,62 (mton)
Torque 12621,18 (N·m)	Block Position 12,85 (m)

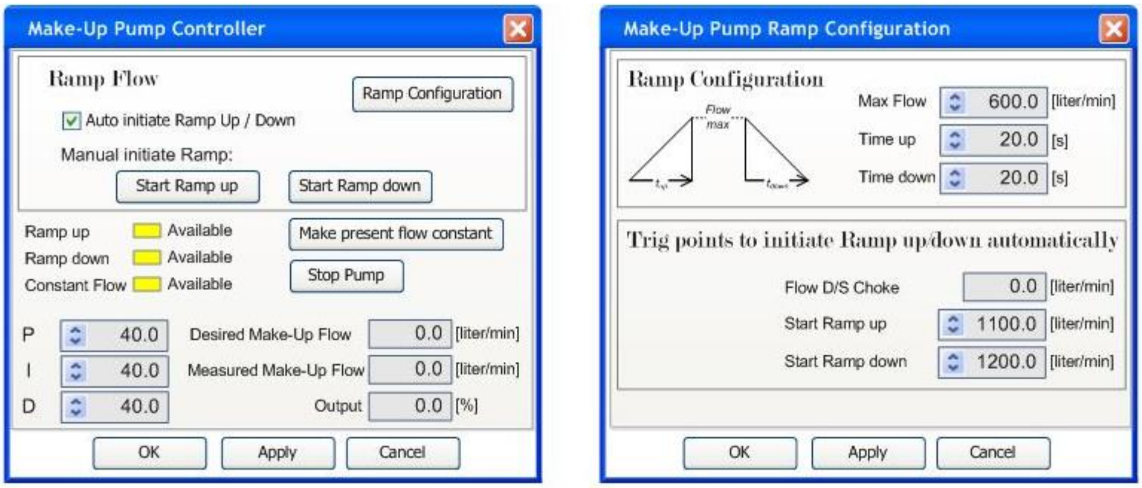
Figure 5: Display of the Geobalance MPD Control System (Halliburton). The system is set to drilling, and the display is illustrating different pressures, depths, flows, and rig data.

Rotating Control Device

The rotating control device (RCD) is a key piece of well control equipment by diverting flow from the annulus to the MPD choke manifold.

Backpressure Pump

Backpressure Pump (BPP) is situated upstream to the return line of the choke manifold**.** The pump maintains pressure in the well by pumping fluid into the annulus when needed, for instance during connection of new drillpipes. The advantage of using a BPP with variable speed drive is that the ramping of flow can be configured such that the total flow rate change through the choke is kept as smooth as possible. The rate of change can follow a predefined ramp, both for starting and stopping the pump. Starting/stopping the flow from the BBP is possible on command from an operator in the human-machine interface, or triggered by lowering/rising flow from rig pumps. The pre-scheduled ramp up or down can be interrupted and stopped at any time by the MPD system. The pump can be controlled either remotely or locally in the field with the control display on the pump skid (Figure 6).



Make-Up Pump Controller

Ramp Flow

☑ Auto initiate Ramp Up / Down

Manual initiate Ramp:

Ramp up 🟨 Available
Ramp down 🟨 Available
Constant Flow 🟨 Available

P 40.0
I 40.0
D 40.0

Desired Make-Up Flow 0.0 [liter/min]
Measured Make-Up Flow 0.0 [liter/min]
Output 0.0 [%]

Make-Up Pump Ramp Configuration

Ramp Configuration

Max Flow 600.0 [liter/min]
Time up 20.0 [s]
Time down 20.0 [s]

Trig points to initiate Ramp up/down automatically

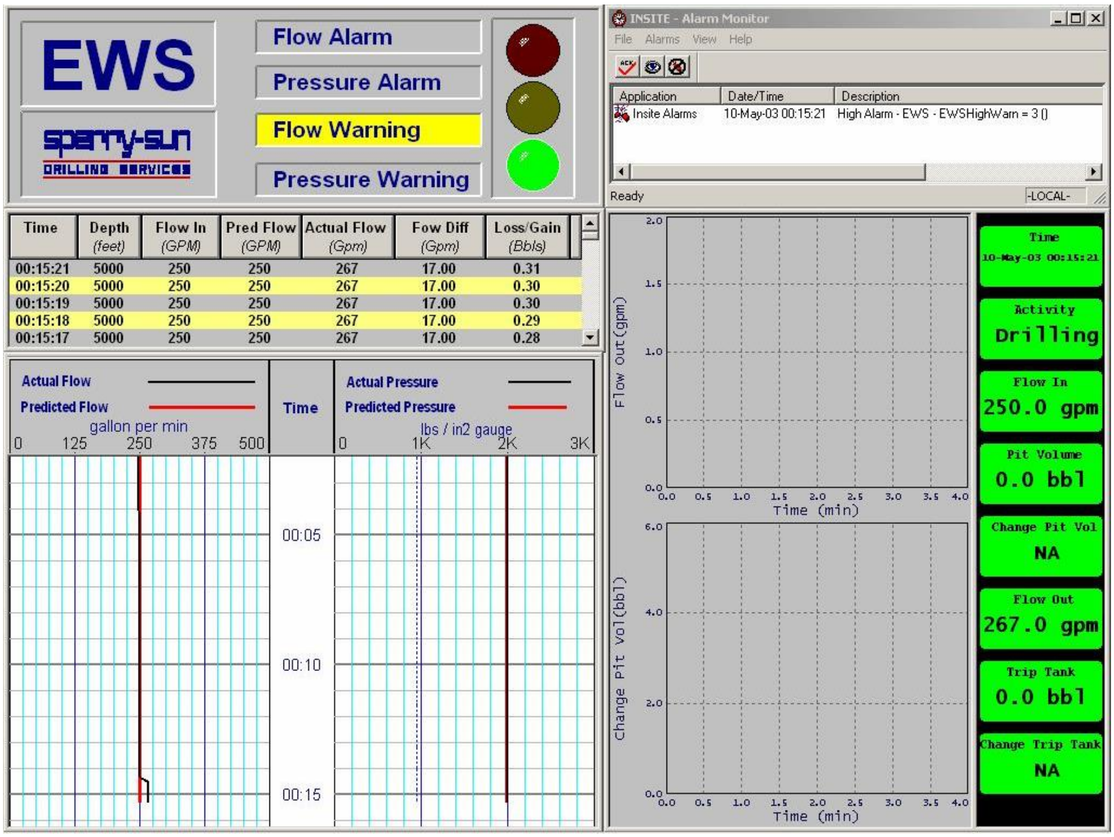
Flow D/S Choke 0.0 [liter/min]
Start Ramp up 1100.0 [liter/min]
Start Ramp down 1200.0 [liter/min]

Figure 6: Inputs of automatic ramping schedule for the backpressure pump (with permission from Halliburton AS).

An alternative to use a backpressure pump, is to use a Rig Pump Diverter (RPD). Instead of turning mud pumps off and starting a backpressure pump, RPD diverts flow from existing rig pumps away from stand pipe into the MPD flowline and across the automated choke. This will provide continuous non-interrupted flow during multiple operations. This automated approach is key to precise BHP during these operations.

Flowmeter

The Flow Metering Unit downstream of the choke unit measures the total returned fluid flow rate, temperature and density of the well. It is a standalone unit and uses a single phase Coriolis flowmeter which sits upstream of the BPP. The Coriolis meter has a flowrate measurement range of 0 to 1500 liters per minute (lpm). The flow rate, density, and temperature data is recorded by the DAS system, and forms an integral part of the control automation of the MPD system (Figure 7). Fluid flow rate out data is correlated to injected drilling mud rate from the rig mud pumps and the BPP.



Time	Depth (feet)	Flow In (GPM)	Pred Flow (GPM)	Actual Flow (Gpm)	Fow Diff (Gpm)	Loss/Gain (Bbls)
00:15:21	5000	250	250	267	17.00	0.31
00:15:20	5000	250	250	267	17.00	0.30
00:15:19	5000	250	250	267	17.00	0.30
00:15:18	5000	250	250	267	17.00	0.29
00:15:17	5000	250	250	267	17.00	0.28

Application	Date/Time	Description
Insite Alarms	10-May-03 00:15:21	High Alarm - EWS - EWSHighWarn = 3 ()

Time 10-May-03 00:15:21
Activity Drilling
Flow In 250.0 gpm
Pit Volume 0.0 bbl
Change Pit Vol NA
Flow Out 267.0 gpm
Trip Tank 0.0 bbl
Change Trip Tank NA

Figure 7: Demonstration of an increase in flow which could be an indication of a kick (with permission from Halliburton AS).

Control Cabin

The control cabin functions as an MPD operations Command Center, and houses the Autochoke Control Systems and Insite Data Acquisition System (DAS) (Figure 8). The aim of the MPD Control System and Insite DAS system is to provide the dynamic hydraulic model which is required for automated control of the BHP. Third party rig data, mud loggers, and Measurements While Drilling (MWD) systems data can be tied into the MPD Insite DAS system, so all relevant circulating system data is available real time to the driller, client and MPD crew. Also, an Insite DAS display is installed in the rig floor dog house. This allows the driller to monitor the MPD system data while drilling (Figure 8).

The inner control loop of the Command center consists of the controller and the choke. The controller system is composed of a number of functional blocks which are usually implemented in a dedicated computer known as a PLC. A PLC is an industrial computer used for automation of many industrial processes. This is an example of a real-time system because output results must be produced in response to input conditions. The PLC's primary functions are to monitor, control, and communicate. It monitors data from sensors. It controls chokes and valves using a chosen control algorithm. Moreover, it acts as a conduit or translator to transfer (or communicate) information between equipment and software.

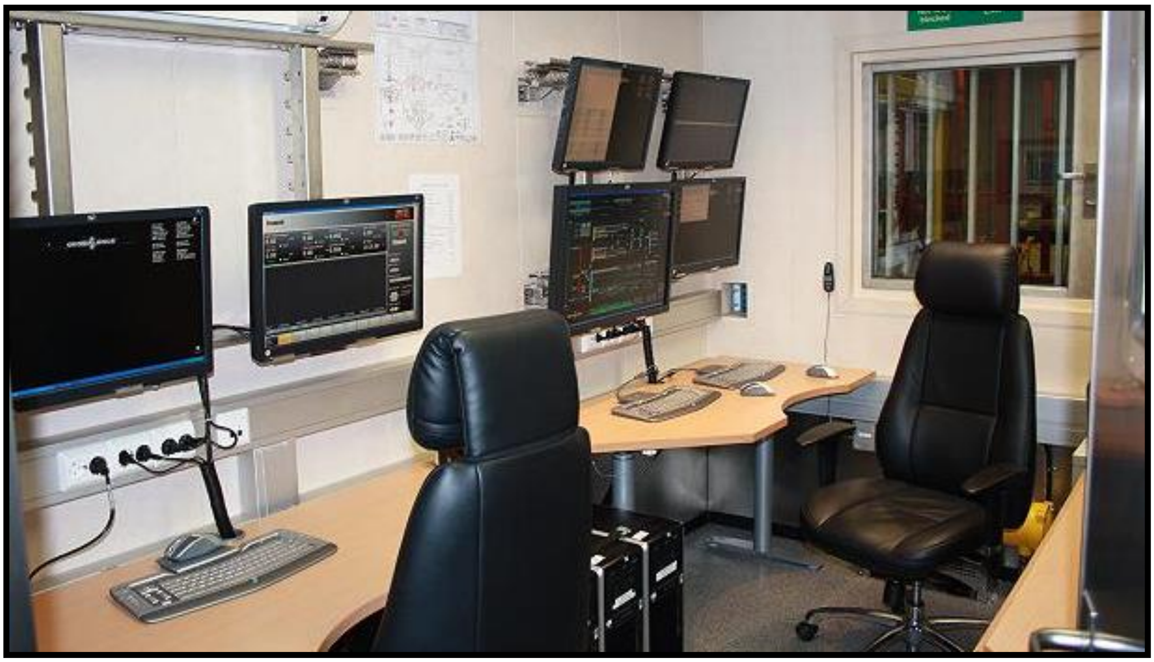


Figure 8: An example of a control cabin for MPD operation (with permission from Halliburton AS).

Training for the personnel that are part of the MPD operation offshore is not looked upon in this thesis. However, this has been the focus on a previous master thesis (Lorentsen 2012) which uses Halliburton's MPD setup in a implemented, full scale drilling simulator developed by Statoil and cooperating partners; SINTEF, eDrilling, and Oiltec Solutions. The simulator has an MPD module which simulation of well control challenges (Statoilasa 2012).

2.2 Safety

2.2.1 Well Control

Well control is to maintaining the fluid column hydrostatic pressure to prevent influx of formation fluids into the wellbore. This is achieved through safety barriers. In general, barriers are measures that reduce the probability of releasing a hazard with potential for harm and reduce its consequences (Figure 9) (Rausand 2013). PSA defines barriers as "Technical, operational and organizational elements which are intended individually or collectively to reduce possibility/ for a specific error, hazard or accident to occur, or which limit its harm/disadvantages". An explanation on the definition can be found in PSA (2013b).

Different regulations mention requirements for well barriers in the petroleum industry, such as The Facilities Regulations, The Management Regulations, and the Activities Regulations (Lovdata) in addition to NORSOK Standard D-010. In summary, they state that two barriers are required when drilling in hydrocarbon bearing formations or abnormal pressure formation. In addition, there shall be sufficient independence between the barriers. This relationship of two independent barriers can be illustrated in a

Bow Tie diagram (Figure 9). When adapting the figure to drilling; the hazard is the formation pore pressure and hydrocarbons, while preventive barriers are primary well control/well barrier. The hazardous event is a well kick, and mitigating barrier is the secondary well barrier/well control. The consequence is a blowout. For conventional drilling, the primary well barrier is ensured by the mud column in the well, or the hydrostatic pressure in the annulus. If the primary barrier fails, the blowout-preventer system with additional barrier equipment *e.g.* wellhead, casing strings, casing cement, and casing packers is the secondary barrier**.**

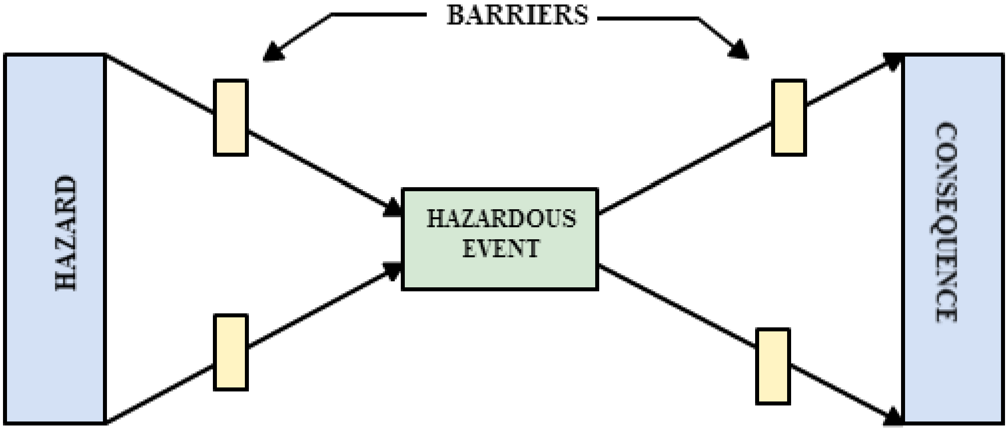


Figure 9: The Bow Tie Model. Safety barriers are introduced to prevent major accidents from happening, and to mitigate the consequences when they do occur Hazard could be pressure from the formation, hazardous event could be well kick influx and consequences could be a blowout. Primary barrier is the mud while secondary barrier is the blowout preventer with other components. Adapted from (Rausand 2013).

In 2013, The NORSOK Standards D-010 was revised (Rev 4) (D-010 2013) with a chapter including MPD. The purpose of this chapter is to describe the establishment of well barriers by the use of well barrier elements, and additional requirements and guidelines to execute MPD operations in a safe manner. Here, the primary well barrier in MPD operations is described to be maintained by a statically underbalanced fluid column with applied surface pressure. The BHP is controlled by means of a closed loop surface system and equipment providing backpressure. The secondary well barrier for MPD is the same as for conventional drilling. However, sufficient independence between barriers is struggling to be fulfilled (pers.com. Sondre Øie, DNV GL). More on well barriers in MPD operations can be found in Grebstad (2013).

2.2.2Loss of Well Control

Mainly two types of situations can cause loss of well control, either a kick can occur or a lost circulation (LC) can occur. LC will be described later in this section. As a repetition, a kick is an influx of formation fluid such as oil, gas, or water into the wellbore from the formation. It occurs when the pressure exerted by the column of drilling fluid in the wellbore is lower than the pore pressure. Once a kick happens, the intruded fluid further reduces the hydrostatic pressure of the mud column since formation fluid usually is less dense than drilling mud. If a kick is not detected a blowout is underway. A blowout is an uncontrolled release of fluid from the wellbore after pressure control systems have failed (Baker & Fitzpatrick 1998). In the table 3, the general reasons for loss of well control are listed:

Table 3: Causes that could lead to loss of well control during drilling (Baker & Fitzpatrick 1998).

Reason for loss of well control	Description
Insufficient mud weight	During conventional drilling, the weight of the mud is the primary means of controlling a well. If the mud weight develops less pressure than formation pore pressure, the well is underbalanced and fluid from a permeable formation can enter the wellbore. On the other hand, an overbalanced condition, in which mud weight develops more pressure than formation pressure can create problems such as fracture of weak formations. Mud weight can unintentionally be decreased by adding water to the system, or weight materials can settle out of the mud. Temperature affects the mud’s density, in which a higher temperature makes mud less dense.
Swabbing	Swabbing is caused by drillstring dragging along mud as the string is pulled out of the hole. The likelihood of swabbing is increased by pulling the pipe too fast, using mud with high viscosity and gel-strength, having a thick plugged drillstring, and having small clearance between the string and the hole. Most swabbing occurs when the bit is first moved off bottom.
Surging	Surging is the increase in borehole pressure caused by downward movement of the drill string. The tendency of mud to adhere to drill pipe and to the wall of the hole creates friction as the pipe is moved downwards. Pressure on the wellbore caused by surging can lead to lost circulation. To minimize surging, pipe must be run into hole slowly, keep the mud in the system in good condition, and break circulation periodically while tripping.
Failure to keep the hole full of fluid	When the drillstring is pulled from the hole, the fluid level drops because of the volume of steel being removed and the drop of mud level reduces hydrostatic pressure. To prevent hydrostatic pressure from dropping as pipe is pulled, the volume of steel and mud removed need to be replaced with fluid. If the hole takes less fluid than calculated, an influx from the formation to the wellbore has occurred. Another cause failure to keep the hole full of fluid is during a lost circulation situation. The drop in fluid level due to lost circulation can cause the BHP to decrease below the level required to balance the pore pressure, resulting in a kick.

Detection of Kicks

The signs for detecting a kick are fairly simple and should be known by all personnel in the field. Usually, a combination of many signals is present at the same time when a kick has occurred (table 4) (Baker & Fitzpatrick 1998).

Table 4: Some of the signs that may indicate that the well has made a kick (Halle 2010).

Kick signals	**Description**
Well flow with pumps shut down	Mud returns to surface even though the pumps are shut off. This can be observed in the flowline.
Sudden increase in mud returning to the surface	If the well kicks, the flow rate of the mud returning from the hole increases as the kick fluid pushes the mud upwards. This can be detected from flow-measurement devices.
Change in flow into the well versus flow out of the well	Monitoring the volume of flow going into the well and volume flow going out of the well can reveal a possible kick. This volume should at all-time be the same, however, if the volume changes a kick may have occurred.
Sudden increase in drilling rate	Usually, when the bit enters an overpressured formation, the rate of penetration increases. The ROP is also dependent on how well the mud cleans the hole, bit weight, mud fluid's properties and drilling through new type formation, so the increase may not be a sign for a kick.
Standpipe pressure drop	A kick will help mud flow to the surface, hence, the standpipe pressure drops.
Increased torque	Torque increases with depth in normal pressured zones but shows a greater increase in a transition zone where formation pressures are becoming abnormal. In transition zones, large amounts of shale cuttings can enter the wellbore and impede drillstring rotation.
Increased drag	If formation pressure is greater than hydrostatic pressure during the time circulation is stopped for connection or trip, the formation may close in around the drill pipe. This closing in causes the pipe to drag as it is moved. If the pipe is off bottom, the formation may slough or cave into the hole, preventing the bit from returning to its previous depth because of hole fill-up.
Gas-cut mud	Gas-cut mud can occur when gas-bearing formation is drilled or gas gets into the mud from the rock that is destroyed by the bit. During tripping or connections, the friction pressure is lost and gas in the mud could cause a large difference in the BHP causing a kick.
Mud pit volume change	A pit gain is a sure sign that fluid in the hole is being displaced by formation fluid entering the well. A pit loss could mean a lost circulation situation. Many factor can increase or decrease pit volume measured by sensors, like rig movement, leakage of water or losing mud over the shakers.
Other signs	Change in cuttings size and volume, increase in salinity or chlorides in the drilling fluid due to salinity of the formation water, or indications from well logging data.

Kick develops into a blowout for one or more of the following reasons (Baker & Fitzpatrick 1998):

- Lack of early detection
- Failure to take proper initial action
- Lack of adequate control equipment
- Malfunction of control equipment
- Incorrect kill procedure

Regain Well Control after Kick Detection

In conventional well control procedures, the first response after detecting a kick is to do a flowcheck. The pumps are stopped and the well is monitored to see if it flows. If necessary, the well is isolated by closing a valve on the BOP. By shutting down the mud pumps the frictional pressure is removed which decreases the BHP. This will most probably increase the influx of formation fluid if a kick has happened. However, because the BOP is closed, the pressure will start to increase again as more fluids enter the well until the downhole pressure balances the formation pressure. When the well is in balance, the subsequent action process is to kill the well. The most common procedure is referred to as the driller's method. The short explanation is that the formation fluid is carefully circulated out of the wellbore, and then the original light mud is replaced by a heavier mud (Devereux 2012).

The MPD system can be configured to detect kicks by monitoring flow-in and flow-out. In a more responsive kick detection method, the system continuously monitors average annulus fluid density by comparing the real-time hydraulic model to actual BHP measurements. If a kick occurs, the model will detect the reduction in the average density, and produce an alarm. Because the system is designed to maintain the BHP constant, it will close the choke in, an effort to offset the previously recorded density. This limits influx by maintaining what is a constant drawdown on the reservoir and prevents hole unloading as would be the case if a kick was not detected. Once a kick is detected, the standard procedure is to shut the well in and allow the pressure to build up to prevent further influx and determine reservoir pressure. The operator can then choose to let the system automatically circulate out the kick of the well (Fredericks *et al.* 2006), or use the conventional driller's method described earlier (pers.com. Tim Tønnesen, MPD Manager, Halliburton AS).

2.2.3 Lost Circulation

Loss of circulation (LC) is the uncontrolled flow of whole mud into a formation due to pressure in the well being above the fracture pressure. The losses can be total which means that no fluid is returning to surface. Partial lost circulation means that mud continues to flow to surface with some losses to the formation. LC may occur due to formations that are inherently fractured, cavernous, or with high permeability. Other reasons may be improper drilling conditions, or induced fractures caused by excessive downhole pressure. (Halle 2010).

The complete prevention of lost circulation is impossible, because some formations, such as fractured, cavernous, or high-permeability zones, are not avoidable if the target zone is to be reached. However, limiting circulation loss is possible if certain precautions are taken, especially those related to induced fractures. These precautions are to maintain proper mud weight, minimizing annular-friction pressure losses during drilling and tripping, and have adequate hole cleaning. Setting casing to protect upper weaker formations and updating formation pore pressure and fracture gradient for better accuracy with log data may also be precautions.

Indications of losses are decreasing drillpipe pressures casing pressures, or decreasing pit volume. If lost circulation zones are anticipated, preventive measures should be taken by treating the mud with lost circulation materials (LCMs) which are course materials aiming in sealing off downhole fractures. In addition, preventive tests such as the Leakoff test and formation integrity test should be performed to limit the possibility of loss of circulation. Description of these methods can be found in Baker & Fitzpatrick (1998). One of the major concerns during LC is if a failure of keeping the hole filled with mud results in a kick. The next subsection will explain a situation with losses to the formation.

The Incident at Gullfaks C

On May 19th 2010, an incident on Gullfaks C, Well 34/10-C-06 AT5 occurred. The well was drilled with MPD to a total depth of 4800 meters. During the final circulation and hole cleaning of the reservoir section, a hole appeared in the 13 3/8” casing with subsequent loss of mud to the formation. The casing was a common well barrier element, and thus the hole in the casing implied loss of both well barriers. Loss of backpressure lead to influx from the exposed reservoir into the well until solids or cuttings packed off the well by the 9 5/8” liner shoe. The pack-off limited further influx of hydrocarbons into the well. Both the crew on the platform and the onshore organization struggled to understand and handle the complex situation during the first twenty-four hours. The well control operation continued for almost two months before the well barriers were reinstated. The incident did not involve any damage on humans, any spillage or fire/explosion.

Statoil’s investigation report found that the hole in the 13 3/8” casing was caused by insufficient technical integrity of the casing. Another cause was lack of monitoring and follow- up of the pressure in the annulus behind the casing. A cause contributing to the difficulties related to handling the well control situation was that the MPD operation was started and carried out with insufficient margin between the pore and fracture pressure. They also found an insufficient risk assessment related to application of the 13 3/8” casing as a common well barrier. Moreover, the risk evaluation during the execution of the MPD operation and transfer of experience related to pressure control from another MPD operation was insufficient. Other causes were related to insufficient planning of the operations, knowledge to and compliance with requirements, MPD knowledge, and involvement of the company’s technical expertise. While MPD has the potential of providing increased well control, the introduction of new technology also adds complexity and unknown risks. This implication was one of the findings in an investigation (Statoil 2010).

2.3 Human Performance

The nature of the work in industrialized societies has changed since the 1950s, from being manual to mostly cognitive – or work with the mind. Thus, human functions are partly being replaced by machines in an automatic process, a development which is also seen in the oil and gas industry in Norway (Larsen *et al.* 2010). To assess and improve interactions between man and machine, Human Factor (HF) methods with various scientific disciplines from sociology, psychology, physiology, health, working environment and engineering, may be used. One of the objectives for human factor methods is to review human performance which is the accomplishment of tasks in accordance with agreed upon standards of accuracy, completeness, and efficiency (Stranks 2007). Within the field of automation, many aspects of human performance exist. In this report, the focus will be on human error in relationship to safety and well control. Human Factors in the design phase are both mentioned in the ISO-standard, ISO 11064, part 1 and in the Petroleum Safety Authorities Norway (Heber & Åsland 2005).

2.3.1 Automation

In broad sense, automation is to introduce control system and information technology to reduce the physical and/or mental workload of human operators that are in charge of running the process. In general, process automation is motivated by a desire to increase economic and/or operational performance while making the process as safe as possible. In the current drilling industry, humans are usually not replaced by automated systems; instead they are acting in a joint human-machine system. The systems are thereby used to improve the performance during normal operations while allowing the operator to intervene to varying degrees in case of abnormal operation (Breyholtz & Nikolaou 2012). This can lead to new or changed types of tasks to the operator (Lee & Seppelt 2009).

Automation has most extensively been studied in the aviation industry. The reason is the last century's great development within the field, which has simplified some tasks like horizontal aviation, but has also led to some fatal accidents. Due to these accidents, "out of the loop" performance has received considerable attention, including concern of loss of skill, and loss/impairment of situation awareness (Endsley & Kiris 1995). Lessons learned from this and other industries should be considered when introducing more automation in drilling operations (Thorogood *et al.* 2010).

Mode of Automation

As a general term, automation is referring to a variety of automation strategies with different modes of human-machine interactions. The role of both the human operator and the automation system will be affected by the chosen automation strategy. Today's mode of automation in the drilling industry is low, but increasing. Based on the aviation industry, six different strategies have been described, (Breyholtz & Nikolaou 2012) in which mode 0 has the lowest degree of automation, and mode 6 has the highest mode of automation (Billings 1997; Parasuraman *et al.* 2000). From Table 5, MPD has a mode 3 Management by Delegation, where some tasks are delegated to the automated system by a closed loop controller while other tasks are performed manually. Alternative modes of automation can be found in Thorogood *et al.* (2010).

Table 5 Different modes of automation adapted from the aviation industry (Billings 1997).

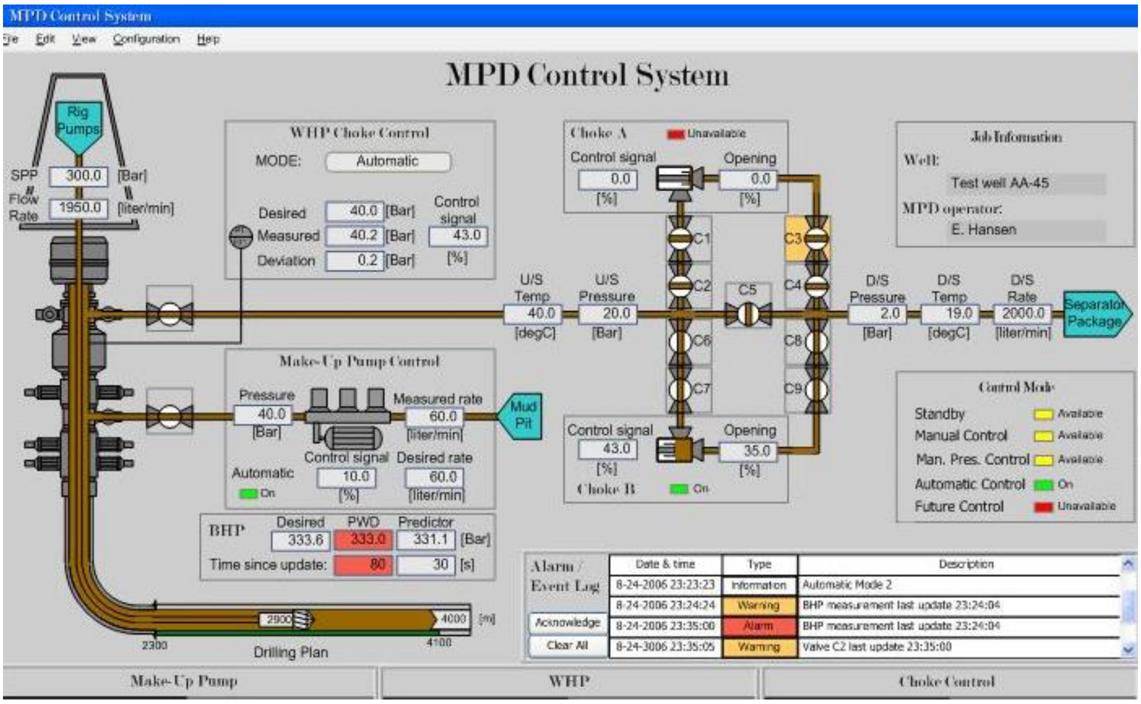
Mode	Management Mode	Automation Functions	Drillers Functions
6	Autonomous Operation	Fully autonomous operation	No particular function. Monitoring is limited to fault detection.
5	Management by Exception	The automation system chooses operation and defines operational goals. Informs the driller on critical decision.	The driller is informed of the system's intent. Must consent to critical decisions. May intervene by reverting to lower mode of management.
4	Management by Consent	The automation provides coordinated control of multiple control loops.	The driller feeds the automation system with a chosen operation and operation goals.
3	Management by Delegation	The automation system provides closed loop control of individual tasks. (*E.g.* Choke pressure control in an MPD system; automated tripping module).	The driller decides setpoints for the individual control loop (*E.g.* pressure in MPD operations) Some tasks still performed manually (envelope protection active).
2	Shared control	The automation system could interfere to prevent the driller from exceeding specified boundaries.	Envelope protection systems are enabled. Decision support/advisory systems are available.
1	Assisted Manual Control	Provides downhole information trends and detects abnormal conditions. Does not intervene.	The driller has direct authority over all systems. Decision-making is computer-aided.
0	Direct Manual Control	Normal warnings and alarms. System does not have any direct authority.	The driller has direct authority over all systems.

A manual takeover during drilling is likely to be motivated by an abnormal situation, and usually requires both skills and experience to recognize the reason and how to bring the well/system back to normal operational condition. The time available to do both tasks is most likely limited, and an important task is to know when to take appropriate measures. Drillers with experience from manual operations would have a more intuitive understanding of when this is needed than those without experience. (Breyholtz & Nikolaou 2012). From the aviation industry, Metzger & Parasuraman (2001) found that high traffic density and a passive controller degrades conflict detection performance. They recommend keeping the controller in authority.

It is worth pointing out that mode has two meaning in this thesis. Mode could refer to automatic or manual mode, or mode could refer to level of mode as described in Table 5.

How is Automation achieved?

MPD comes in a number of different varieties of automation influence. The segment that primarily has been developed for automation is to control BHP by applied backpressure and a choke device, which can both be fully or partly automated (Figure 10). This workflow lends naturally well to automated philosophy (Saeed *et al.* 2012). The rotating control device is not directly involved in the automations, but is essential in forming a closed loop system by dynamically sealing off the annulus and diverting all return flow to a designated choke. Most suppliers prefer to use a feedback loop in which sensors are installed to monitor controlled variables. Values from signals received are transmitted to a feedback control system, where a specialized controller makes automatic determinations of deviation between desired values and actual values. The controller then calculates appropriate signals that reflect the BHP, and these are automatically transmitted to the control devices (choke). The choke will adjust to whether a higher or lower pressure in the well is needed.



SPP 300.0 [Bar]
Flow Rate 1950.0 [liter/min]

WHP Choke Control
MODE: Automatic
Desired 40.0 [Bar]
Measured 40.2 [Bar]
Deviation 0.2 [Bar]
Control signal 43.0 [%]

Make-Up Pump Control
Pressure 40.0 [Bar]
Measured rate 60.0 [liter/min]
Control signal 10.0 [%]
Desired rate 60.0 [liter/min]
Automatic 🟩 On

BHP	Desired	PWD	Predictor	
	333.6	333.0	331.1	[Bar]
Time since update:		80	30	[s]

Choke A 🟥 Unavailable
Control signal 0.0 [%]
Opening 0.0 [%]

U/S Temp 40.0 [degC]
U/S Pressure 20.0 [Bar]
D/S Pressure 2.0 [Bar]
D/S Temp 19.0 [degC]
D/S Rate 2000.0 [liter/min]

Choke B 🟩 On
Control signal 43.0 [%]
Opening 35.0 [%]

Job Information
Well: Test well AA-45
MPD operator: E. Hansen

Control Mode
Standby 🟨 Available
Manual Control 🟨 Available
Man. Pres. Control 🟨 Available
Automatic Control 🟩 On
Future Control 🟥 Unavailable

Alarm / Event Log

Date & time	Type	Description
8-24-2006 23:23:23	Information	Automatic Mode 2
8-24-2006 23:24:24	Warning	BHP measurement last update 23:24:04
8-24-2006 23:35:00	Alarm	BHP measurement last update 23:24:04
8-24-3006 23:35:05	Warning	Valve C2 last update 23:35:00

Figure 10: The HMI is displaying as much information as possible to keep high focus on the critical information needed in the present situation. The figure suggests the main window when the system is in Automatic mode (with permission from Halliburton AS).

To enable easy user interaction and supervision, a mechanism is required for accepting and processing user instructions and commands. This requirement is fulfilled by a human-machine interface (HMI). The interface is implemented to provide a convenient centralized control panel (or dashboard) to the entire system. This has to be done in an effective and efficient, but also simple, intuitive, and user friendly way. The interface provides both display of acquired and calculated information, and also interactive control elements in one unified location. This is vital, as it enables operators to control all aspects of the operation, from selecting computation algorithms that performs advanced hydraulic computation, controlling valves and chokes, to setting levels of automation (Saeed *et al.* 2012).

In the HMI described, the driller or MPD operator should be able to move between different modes of automation during a single drilling operation, and he should be in absolute authority of the operation even though a high mode of automation is used. This means that the operator must be given the means to override the automation if necessary (Breyholtz & Nikolaou 2012). The mode of automation for today's situation might not always be the case for future systems, and since the work distribution between the automation system and the driller changes for each increased mode of automation, a clear understanding of human-machine interaction is needed (Breyholtz & Nikolaou 2012).

Drillers' Role

During a drilling operation, the driller must maintain control of the well, lead and communicate the work on the drill floor, and deal with technically advanced, screen-based solutions in the drilling cabin (Figure 11). It may thus be challenging to understand, operate and maintain an overview of all the incoming data - and simultaneously maintain control and overview of what is physically taking place on the drill floor (PSA 2013a).

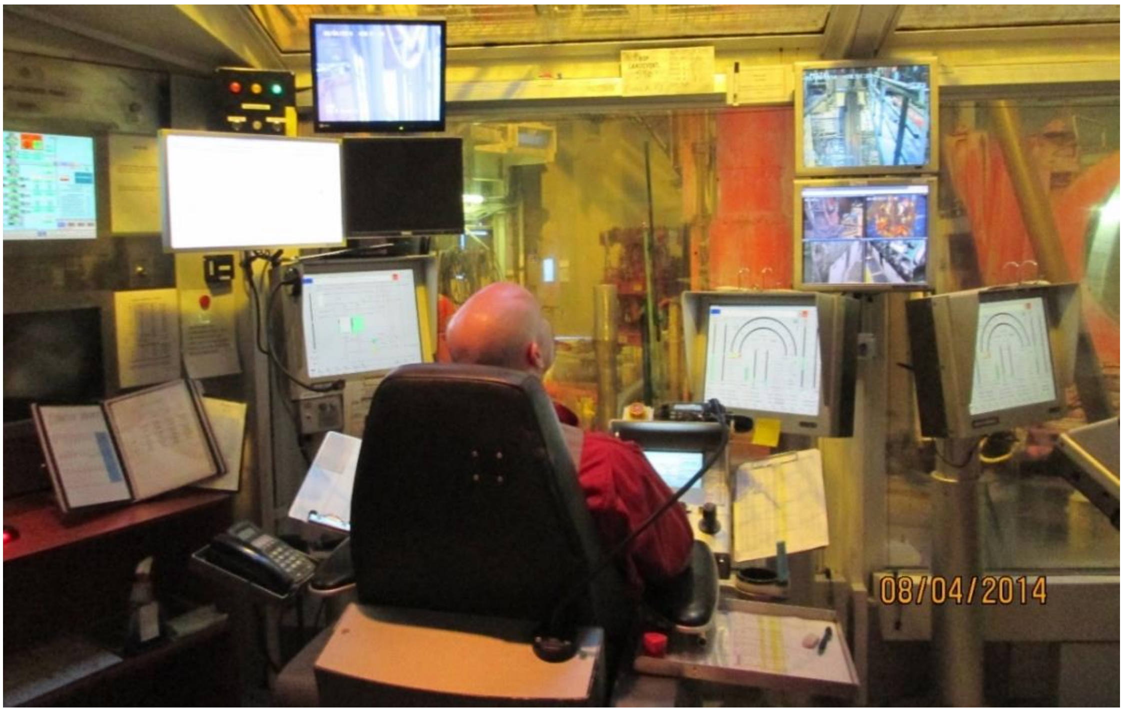


Figure 11: Driller's cabin during conventional drilling operation. Private picture.

MPD has an inherent closed loop setup, coupled with conventional methodology. This translates to the driller performing the drilling operation while monitoring an extra MPD screen. The driller is not responsible for control of the MPD system, which is a task performed by MPD operators (Figure 10). However, the driller still has the overall responsibility of the operation and the secondary well control if the primary barrier fails. One of the reasons why a fully automated MPD system does not exist on the market today is the unpredictable nature of drilling operations, in which it is difficult to foresee all scenarios (Saeed *et al.* 2012). The communication strategy during drilling is illustrated in Figure 12.

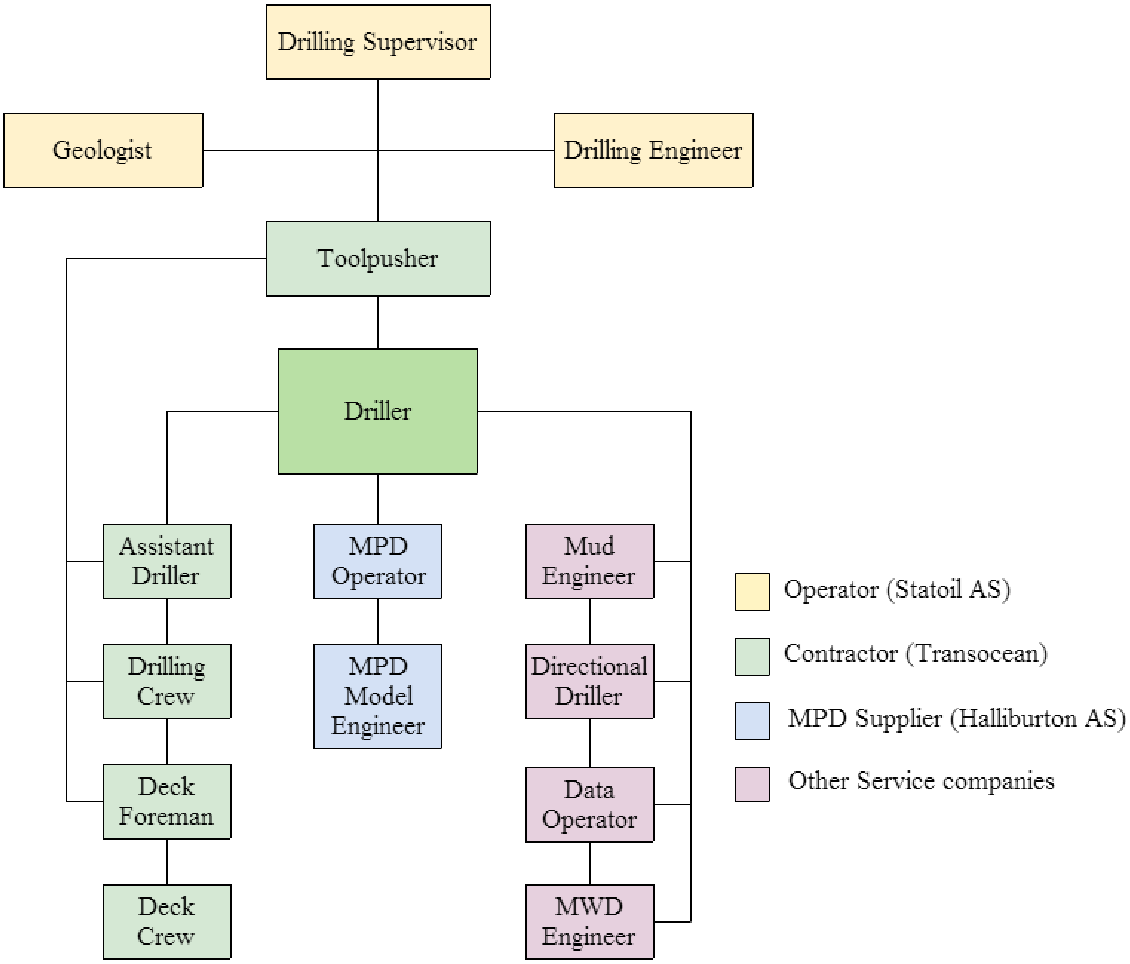


Figure 12: Communication structure during drilling operation.

Team Performance in Complex Systems

Advances in information technology have allowed development of increasingly sophisticated systems for command and control. With this sophistication has come increased complexity for operators. Decision making in such complex systems are often characterizes by: 1) typically incomplete, uncertain, and ambiguous information, 2) typically multiperson teams; thus, overall performance depends on more than just individual performance, and 3) members of teams have differing roles and responsibilities; consequently communication and coordination are central issues. Accidents in complex systems, such as The Three Mile Island (Le Bot 2004), are viewed as illustrations of what Perrow terms” normal accidents, with complex, tightly coupled, with catastrophically potential (Perrow 1984).

Team-related phenomena often appear to be common across accidents such as the Three Mile Island. Problems associated with teams identified are lack of clearly, and appropriately, delineated roles, lack of explicit coordination, and communication difficulties. Difficulties of roles, coordination, and communication can be caused by a variety of contributing factors. It is quite possible for advanced technology, especially automation, to move against team performance, by for example isolating team members from each other. While there are numerous concepts of available group decision support (Fracker 1988), the notion “team-centered” design of such technologies has not equally emerged. Rouse *et al.* (1992) present a view that team performance should be enhanced to extent that team members hold shared or common mental models of the tasks and team. Further, the article argues that the effectiveness of most complex systems depends to a great extent, on the ability of the team of individuals to coordinate action, integrate information and resources and adapt to changing task demands.

2.3.2 Human-Machine Interactions

Human-machine interaction is the study of interaction between people and computers (Preece *et al.* 1994). This interaction can be input provided from the operator to the machine. The machine acts on the input and displays information back to the operator regarding its status and the consequences of input. The operator evaluates the information and decides which controlling actions are needed, and further provides new inputs to the machine (Figure 13). A need of research on human-machine interactions in a risk management perspective has been documented by Rasmussen (1997). Different factors have been suggested to affect this interaction between the human and machine. Some of these will be commented in the following paragraphs.

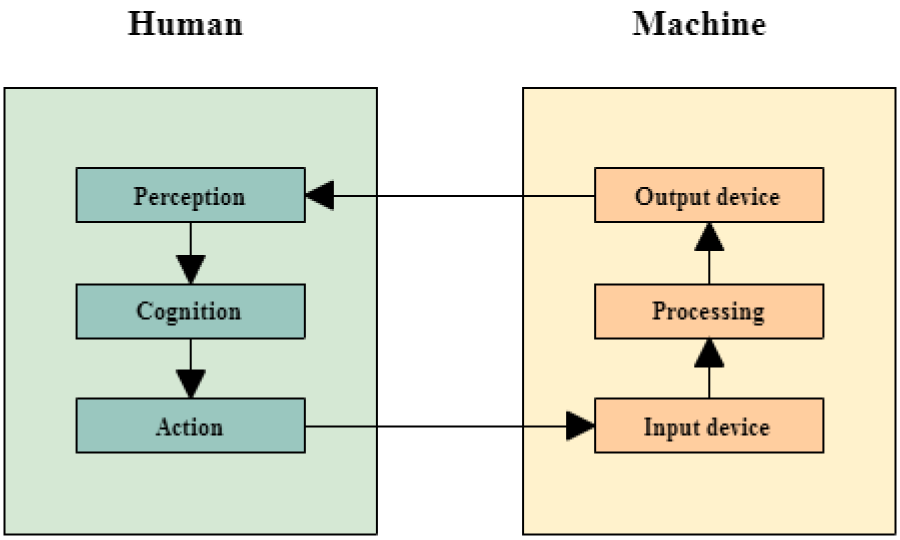


Figure 13: Human-machine interaction (Salvendy 2012).

Situation Awareness

Situation awareness (SA) is the perception of elements in the environment, the comprehension of their meaning, and the projection of their status in the near future (Parasuraman *et al.* 2008). In dynamic environments, many decisions are required across a short time frame, and tasks are dependent upon an ongoing, up-to-date analysis of the environment. Since the state of the environment is constantly changing, often in a complex way, a major portion of the operator’s task becomes to obtain and maintain upright SA. A lack of SA has been hypothesized to underlie the out of the loop decrement that can accompany automation. Operators who have lost SA may be slower to detect problems and will also require extra time to reorient themselves in order to proceed with problem diagnosis and assumptions of performance when automation fails. This might occur for a number of reasons: (a) a loss of vigilance and increase in complacency associated with the assumptions of a monitoring role under automation, (b) the difference between being an active processor of information in manual processing and a passive recipient of information under automation, (c) a loss or change in the type of feedback provided to operators concerning the state of the system under operation (Endsley 1995).

It has been hypothesized that keeping humans involved in system operations, may provide better performance and SA than that found with highly automated systems, thus minimizing the out of the loop performance problem (Endsley & Kiris 1995). Further, Endsley (1999) discuss that irrespective of the capabilities of the human and computer components, when a human operator must take control in the event of an automation failure, he is affected by the level of automation that was operated under prior to failure. A higher degree of automation makes it more demanding to manually take control. Another finding in the same article is an improved performance under normal operation conditions due to automation, while it may be compromised following an automation failure due to lack of SA of the automated system.

Trust, Reliance, Communication, and Workload

Today, trust is seen as a key concern in relation to automation (Lee & See 2004; Parasuraman & Riley 1997). Instead of monitoring the automated system, attention may be allocated to other manual tasks (Parasuraman *et al.* 2008). This is also the case when it comes to reliability. If the automated system rarely makes mistakes, a possibility exists that when it fails, the operator will not detect the failure due to overreliance (Sheridan & Parasuraman 2005). Metzger & Parasuraman (2005) demonstrates that a conflict is better detected under manual conditions than under automated conditions when the automation is imperfect. Understandable communication between the system and the operator is important in order to detect a critical situation (Breyholtz & Nikolaou 2012). It has been suggested that misunderstandings occur because of a mismatch between the mental model of the pilot and behaviors of the automated system. Several examples of incidents and accidents resulting from these misunderstandings have been reported (Billings 1997; Sarter & Woods 1995). Workload is also a central aspect when considering the efficiency and safety of automated systems. The effects of workload are related to the limitations of humans to be attentive to several tasks simultaneously , and come into play when operators have to relocate mental resources away from automation to others tasks that need to be attended to (Gressgård *et al.* 2013).

An example of how important it is to understand changes made by the system is provided in the following paragraph. A feedback control system (closed loop) will at all times try to compensate for undesirable situations. The operator will not necessarily detect such a situation. If influx into the well occurs, the pressure in the well will increase during an initial phase until there is equilibrium between pressure in the reservoir and in the well. The response of a low-level automation will be to detect this as a deviation from the given set point and the measured value. The closed loop algorithm will try to reduce the pressure in the well to compensate for this deviation by slightly opening the topside choke to reduce the pressure. This will result in the system unintentionally trying to achieve a state of underbalance. If the driller or MPD operator is not observant and relies on the automated system, it may take several minutes before the condition in the well is detected. The pressure control system has probably made the situation worse than it would have been without such a system (Saeed *et al.* 2012).

2.3.3 Human Error

While the machines today become more reliable, human errors contribute more to major accidents such as Three Mile Island (Le Bot 2004) and Exxon Valdez oil spill accident (Harrald *et al.* 1990). According to literature, humans are error-prone in their decisions, especially in complex systems where decisions are made under pressure (Reason 2008). Hollnagel (1993) estimates that human errors are involved in 60-90 percentages of the incidents in nuclear and oil and gas industries. Errors can be defined as a failure of planned actions to achieve a desired goal – without the intervention of some unforeseeable event (Reason 1990). In the human error approach, the plan may be adequate but the associated action does not go as intended (slips and laps), or the plan is inadequate to achieve its intended outcome (mistake).

Reason (1995) discusses many aspects of human error, and one of his statements is that increased automation does not cure the human factor problem; it simply changes its nature. Systems become more opaque to their operators. Instead of causing harm by slips, lapses, trips and fumbles, people are now more prone to make mistaken judgments about the state of the system. In addition to removing localized slips and lapses, automation can increase the probability of higher-level mistakes with the capacity to cause larger destructions (Reason 2008).

Literature in the field of supervisory control provides evidence that poor system design is responsible for many of the errors, which are incorrectly seen as irresponsible human actions (Woods & Cook 1999). Reason (2000), using his Swiss Cheese Model, argues that even multiple levels of defences of barriers may be penetrated by an accident trajectory. He claims that the holes in the defences arise for two reasons: *Active failures*, which are errors that are committed by people who are directly in contact with the system (*e.g.* slips, lapses, mistakes) and Latent Errors which arise from decisions made by designers, builders, and high-level decision makers (Figure 14). Another definition of a latent human error could be an error which is likely to be made due to systems or routines that are formed in such a way that humans are disposed to making these errors.

It is important to understand how changes in technology shape human cognition and action in order to see how designers can create latent failures. For example, a particular technology change may increase the coupling in a system (Perrow 1984), which may increase the cognitive demands on the operator. If the system gives weak feedback about its state, this can function as a latent failure waiting for the right circumstances and triggering events to lead the system close to an accident (Woods 2010). The supervisory control literature provides several prescriptions to remedy errors arisen from both active and latent errors. These include minimizing the likelihood of errors by carefully designing systems with safeguards and barriers, awareness interfaces, and training as well as prescribed ways to tolerate errors (Cummings *et al.* 2010). However, a well-designed system might not always be enough for avoiding errors. The operator using the system also needs to understand how it works.

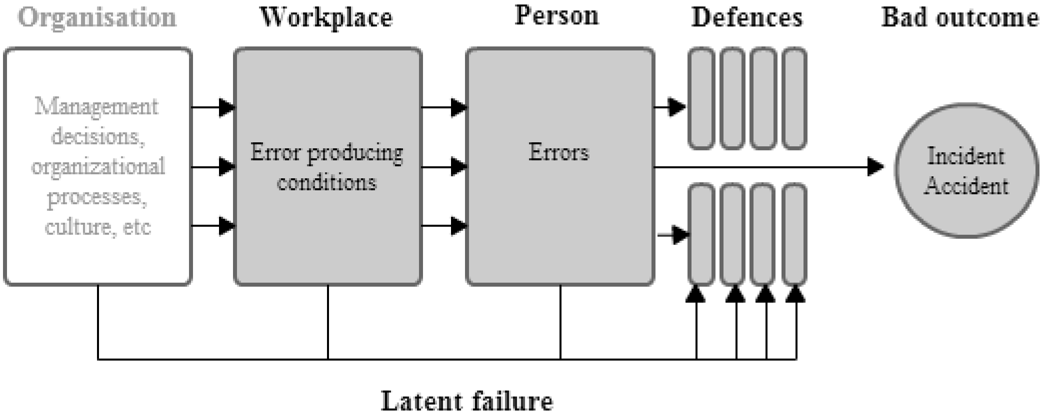


Figure 14: Stages in the development of an organizational accident. Organisational factors are not so relevant in this context. Adapted from (Reason 1997).

Mode Confusion

One important source of errors are mode confusion. Mode confusion occurs when an automated system behaves differently than expected, and the operator not being aware of, or not properly understanding what the system is doing. As a consequence, mistaken judgments may cause human errors. This phenomenon is well recognized in the aviation industry and has been specified in a number of high profile aviation accidents. The potential for the same type of problems, and associated safety hazards, arise in drilling operations as a result of an increasing trend of automation (Iversen *et al.* 2013). Another error may be that the operator takes an action that is appropriate for one mode of the device when it is, in fact, in a different mode. Here, the operator could make a wrong assessment of the active mode at a particular time or the operator fails to notice transitions in mode status. In both cases, the causes can be traced to “clumsy” automation. Woods (2010) demonstrates that the complexity of modes, interactions across modes and indirect mode changes create new paths for errors and failures. A problem may form when two operators are handling the system as it may be difficult to maintain awareness about the history of interactions.

There are several sources of mode confusion which may impact the risk of human error. One factor is the operator’s knowledge about the system and how to remember and use it when needed (Woods 2010). Another important factor is that an increase in autonomy of automation systems is accompanied by an increased delay between the user input and feedback about the system behavior. The operator is kept out of the loop from the process and activities of the system. This effect may further be strengthened by the fact that modes may change based on sensors information concerning the environment and system variables. In systems with high levels of autonomy and complexity, there may also be a large number of indicators of the status and behavior of the systems, distributed over several displays in different locations. All of these factors increase the complexity. As a consequence, it becomes challenging to maintain mode awareness, which again increases the potential for failing to detect and recover from errors (Iversen, 2012).

In many research studies of mode confusion in a variety of automated control systems, Woods (2010) has identified numerous human factor problems that could lead to errors. Automation could give an increased demand on the user’s memory, or cause the operator to be uncertain as to where he should focus his attention. If many operators are working in teams, it could be difficult for them to share the same awareness. Automation could also lead to increased stress and workload during high-demand periods. Even though automation is supposed to help the human operator, it will also demand new knowledge and more difficult judgments. Automation could also limit the operator’s ability to develop effective strategies for coping with task demand.

As humans, we are generally more flexible than technical systems and it is therefore difficult to predict the types of error we may commit. A feature that makes us very different from technological systems is our ability to detect and recover our own errors as well as errors committed by other persons or by technical systems. Bearing that in mind, we may claim that human actions contribute to risk, but also to safety. However, it is recognized that even well-trained and highly motivated people occasionally make errors, and it is necessary to find preventive measures to these. Procedures and training may not always be the crucial factor. Some ironies of automation follows (Bainbridge 1983; Reason 1997):

- By taking away the easy parts of human operator’s task, automation can make the difficult parts of the job even more difficult.

- Many system designers regard human beings as unreliable and inefficient, yet they still leave people to cope with those tasks that the designers could not think to automate.

- In highly automated systems, the task of the human operator is to monitor the system to ensure that the automatics are working as they should. But it is well known that the best motivated people have trouble maintaining vigilance for long periods of time.

- Skills need to be practised continuously in order to preserve them. Yet an automatic system that fails only very occasionally denies the human operator the opportunity to practice the skills that will be called upon in an emergency situation.

- The most successful automated system with rare need for manual intervention may need the greatest investment in operator training.

2.4 Review of Risk Methods

It has become clear that human factors often have not been adequately addressed in the analysis and control of major accident risk in drilling and other offshore operations (McAndrews 2011). One area where other industries, like nuclear, has come further than the petroleum industry, is in the integration of human factors and human reliability analysis (HRA) in particular, into major accident risk analysis (Gould *et al.* 2012). HRA is used to qualitatively and quantitatively assess human performance, and is usually part of a probabilistic risk assessment (PRA) that includes both technical systems and the human operators (s) (Bedford & Cooke 2001). McAndrews (2011) believe that integration of HRA in major accident risk analyses is a promising path to improved safety and reliability of safety- critical systems in the petroleum industry. In this thesis the focus is on qualitative analysis. Qualitative research points to any kind of research that produces findings not arrived at by means of statistical procedures or other means of quantification (Golafshani 2003). It is exploratory and inductive in nature and often use interviews and observations as a base (Patton 2005).

The main steps of a HRA is to identify critical operations where human errors could lead to accidents, analyse relevant tasks and break them down into subtasks, identify potential human error modes and potential error causes, and determine the human error probabilities for each error mode (Rausand 2013). A report, "Human Factors Methods: Functional and Task Analysis according to requirement stipulated in NORSOK S-002. Best Practice" by Øie & Fernander (2009) gives a well introduction to some of the methods that can be used in HRA. This section will further comment on those analysis techniques employed in the thesis. Evaluations and limitations of them are found in section 5.3. According to the Norwegian petroleum standards:

During concept definition and optimization, the activity shall include (NORSOK 2008):

- a functional analysis and allocation describing functions to be performed, defining system performance requirements, and allocating manual and/or automatic functions (4.4.5.0-5)

- a task analysis defining tasks based on allocated functions, and defining requirements (time, cognitive demands, etc.) for operator tasks, including information needed and the interface devices necessary to handle these tasks (4.4.5.0-6).

Further, the Petroleum Safety Authorities states that (PSA 2008):

- Installations, systems, and equipment shall be designed in the most robust and simple manner possible and such that the possibility for human error is limited PSA, The Facility regulation, Section 10.

Functional analysis is the examination of the functional goals of a system with respect to available manpower, technology, and other resources, to provide the basis for determining how the function may be assigned and executed (NEK 2009). A variant of functional analysis is called Functional Analysis System Technique (FAST). FAST focuses on identifying system functions and is often used to allocate functions to human and machine (Creasy, 1980). Allocation of functions (AF) is the process of distributing tasks, system functions, or responsibilities between human and machines based on their capabilities (Stanton 2006). It is performed to optimize performance, make the work done more efficient, which increase safety, quality, and profits (Beevis *et al.* 1996). This process is often based on Fitts list from 1951 (Table 7), with the overall recommendation that those functions that are better performed by machines should be automated, while the other functions should be assigned to a human operator. The list is no longer valid in its original state as machines have long since surpassed humans in many of his categories; though, it is still frequently cited today (de Winter & Dodou 2011). However, Jordan (1963) points out that men and machines are complementary rather than comparable, and Price (1985) claims that there are tasks that neither machines nor humans do well and tasks that machines and humans both do well.

Table 6: The original Fitts list. Adapted from de Winter & Dodou (2011 (de Winter & Dodou 2011).

Humans appear to surpass present-day machines in respect to following:	**Present-day machines appear to surpass humans in respect to the following:**
1. Ability to detect small amount of visual or acoustic energy	a. Ability to respond quickly to control signals
2. Ability to perceive patterns of light and sound	c. Ability to store information briefly and then to erase it completely
3. Ability to improvise and use flexible procedures	d. Ability to reason deductively, including computational ability
4. Ability to store large amounts of information for long periods and to recall relevant facts at the appropriate time	e. Ability to handle highly, complex, operations i.e. to do many different things at once
5 Ability to reason inductively	f. Ability to apply great force smoothly and precisely
6 Ability to exercise judgment	

Task Analysis is the study of what an operator (or a team of operators) is required to do in terms of action and/or cognitive processes to achieve system goals (Kirwan & Ainsworth 2004). The analysis comprises a breakdown of tasks into subtasks with a fundamental approach of assisting in reaching higher safety and productivity standards (Rosness 1994). Task analysis covers a range of varieties, used by ergonomists, designers, operators, and assessors to describe or evaluate the human-machine interactions in a system. In addition, the results can be used to assess and evaluate operability workload, identify and help prevent human error, and identify communication needs (Øie & Fernander 2009). Different varieties of task analysis have been described (Kirwan & Ainsworth 2004), with hierarchical task analysis (HTA) as one of them. HTA was first proposed in the late 1960s. Since then, it has been widely adopted and used in many application areas, such as process control, military applications, aviation, and power generation (Shepherd & Stammers 2005).

Human Error Identification (HEI) techniques are used to predict potential human or operator error in complex, dynamic system. The method was originally developed in response to a number of human operator errors related catastrophes in the domain of nuclear and chemical power domains (Three Mile Island disaster, Chernobyl). Today, HEI is widespread in nuclear power and petro-chemical processing industries, air traffic control (Shorrock & Kirwan 2002), aviation (Stanton *et al.* 2009), and public technology (Baber & Stanton 1996). Different HEI techniques have been described (Stanton & Walker 2013); however, the literature consistently suggests that The Systematic Human Error Reduction and Prediction Approach (SHERPA) is the most promising of the HEI techniques available in terms of performance (Kirwan 1992). In essence, the SHERPA technique works by indicating which error modes are credible for each step in analysis such as HTA (Embrey 1986). Studies reported in SHERPA show how it can be applied to the evaluation in aviation (Stanton *et al.* 2009) and oil extraction (Stanton & Wilson 2000).

3 Methods

This section describes the different methods applied to examine if automated MPD may influence the risk of well control incidents by its effect on human errors. These methods include collecting data, creating a scenario, perform a functional analysis of an MPD system, allocate functions to human and machine, carry out a task analysis on lost circulation scenario, and identifying human error (See figure 15). The flow lends well to requirements from NORSOK S-002 (2008) and The Facility Regulations, PSA (2008).

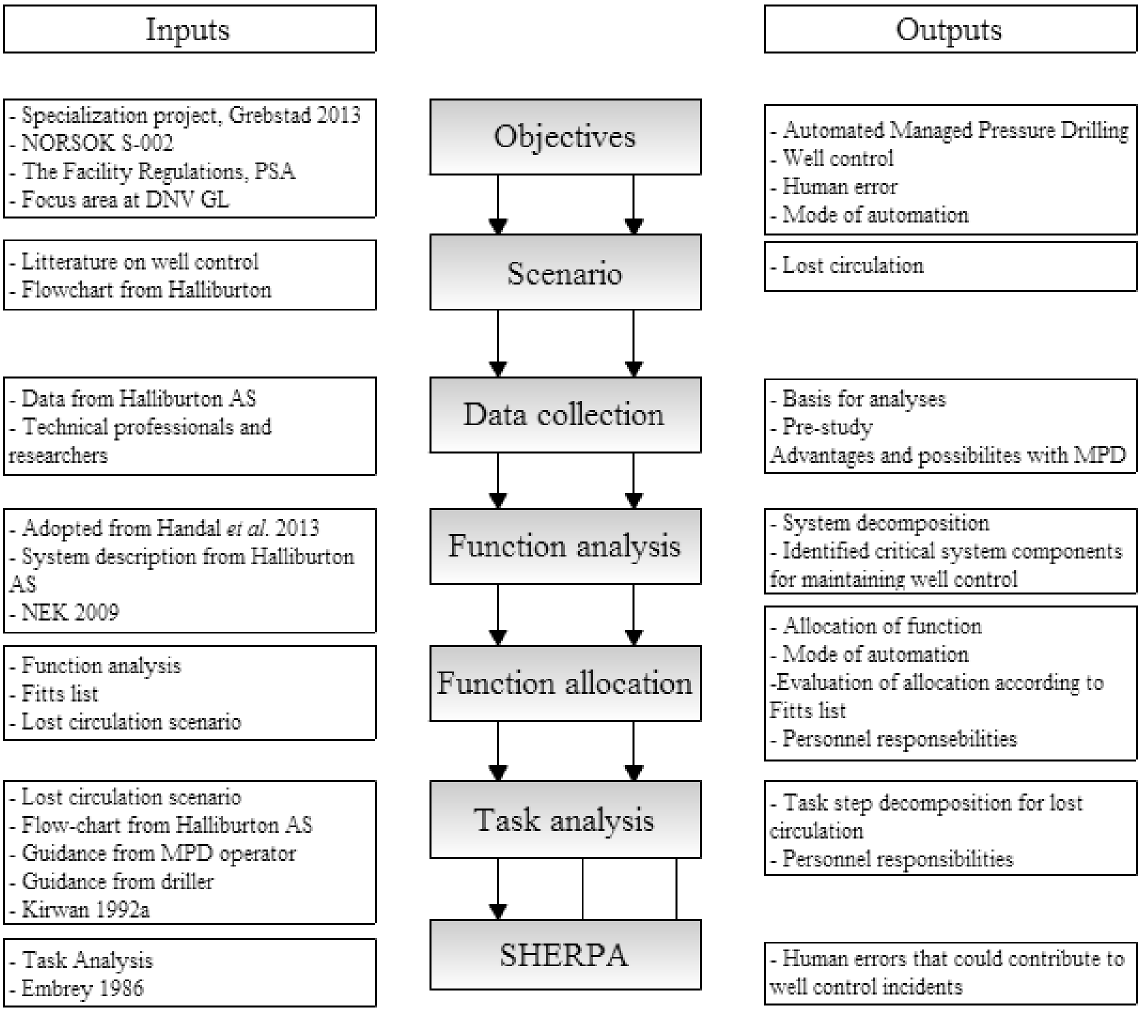


Figure 15: A flowchart of the different methods performed in this thesis. Objectives can be found in section 1.2, while the other methods are described in the current section.

3.1 Creating a Scenario

The purpose of selecting a scenario is to give the analyst a way of capturing how the system functions in a given situation. This means that the description of the scenario also will cover not only the actions that take place, but also the contextual factors that surround the action, allow it to happen, and provide opportunities for errors (Fields *et al.* 1997). The objectives highlight that well control incidents are in focus. As lost circulation is a critical well control event which can escalate from kick to a blowout, this scenario was chosen as a scope to study.

Table 7: Description of the event Lost Circulation during MPD drilling operation.

	Description
Agents	The scenario takes place on a drilling platform where drilling operation is performed by the driller and an MPD operator, with the other crew members present. The primary job of the two is to reach the target, maintaining safety by keeping pressure in the well within drilling window, and comply with the feedback of the system.
Rationale	This scenario highlights a relevant challenge that the industry most probable will have the focus on in the years to come. The reason is the need for technology to drill reservoirs that cannot be drilled conventionally.
Situation and Environment	The scenario involves detecting an abnormal situation during drilling, and regaining control of the well. The scenario begins just before the agents are given indications that mud might be lost to the formation. As MPD is not a widely used method today, the signals from the well may be more difficult for the driller and MPD operator to spot. Also, more personnel than usual are involved in the operation which could affect the level of awareness and stress.
Task Context	In the execution of this scenario, the driller carries out a number of tasks and will need to draw on substantial task knowledge that he possess as a result of experience and training. The tasks include performing the drilling operation, monitor well parameters, communicate the operation, and function as a team leader. The MPD operator need to monitor the system, communicate with different personnel, follow the operation, and adjust parameters to the system when required.
System Context	The operators are supported by modern drilling equipment and software applications. These need to be monitored and adjusted throughout the duration of the scenario.
Action	As the event of losses to formation is not standard, a sequence was chosen which includes that a) losses are observed, b) a flowcheck indicates that severe losses (>6 m3/hour) is present, c) the system is not able to maintain wellbore pressure with mud pumps and backpressure pump, d) losses are cured by filling well using kill line and pumping lost circulation materials, and finally e) the drilling strategy is adjusted and operation can continue. To fulfil the goals, a close collaboration between the driller and MPD operator is essential.
Exceptional circumstances	The scenario can develop in many different directions, all dependent on the severity of losses. Either the lost circulation event can be fixed at an earlier stage, or it can develop into a situation where the well takes a kick.

3.2 Data Collection

Planning of a human reliability analysis (HRA) was conducted with the first issue to address as to whether the analysis should be qualitative or quantitative. As the objectives of the thesis are more focused towards system's vulnerabilities to human errors and not to quantify these, qualitative analysis was suggested to be sufficient (The Energy Institute, 2012). Data was collected through a pre-study and a case study.

Pre-Study and Interviews

Different professionals shared their view on possibilities and challenges by using Managed Pressure Drilling. The purpose of this study was to find out if a selection of persons within the MPD community believed in the method, and if so, which challenges the method holds. In addition, the participants' answers formed part of a triangulation with findings found in analyses and relevant theory to be used in section 5. Discussion. The respondents comprised:

- Principal Researcher at Statoil
- Senior Research Scientist, SINTEF
- Research Scientist, SINTEF
- Drilling Engineering Advisor and researcher on human factors
- Senior researchers at DNV GL
- Personnel on the drilling rig Transocean Spitsbergen with hands-on experience, including data operator, drilling supervisor, derrickman and mud engineers

The research was evaluated using the criteria credibility, transferability, dependability and conformability (Patton 2005).

Case Study

Halliburton AS, an oilfield service company and a supplier of MPD, was contacted with the aim of using their Geobalance system as a case for the human factor analyses. With acceptance from the MPD Manager in Sperry Drilling, one of Halliburton's product lines, the author was provided access to information which included:

- System descriptions
- Procedures
- Piping and instrumentation diagram/drawing (P&ID)
- Pictures and figures
- Field cases

This information formed the base for the scenario that will be explained in the next section. Further, MPD operators within the company explained functions and the process of MPD, and helped with the task analysis explained later i the thesis.

While writing this thesis, the author has been working as a Mud Engineer in the offshore petroleum industry. Observations from offshore operation and asking questions during work have aided in understanding drilling technology and well control.

3.3 Data Analysis

The following subsections hold the procedures for the different analyses performed, which includes functional analysis, task analysis, and human error identification.

3.3.1 Functional Analysis

Functional Analysis System Technique (FAST) focuses on identifying system functions that are needed to fulfill a goal. The analysis was used to allocate functions to human and machine, and find out which equipment are critical to control/monitor functions. The procedure was performed as follows:

1. System functions were identified in terms of the main goal phrased as "Maintaining BHP within drilling window".
2. A horizontal chart was organized from left to right answering the question: "How is the function to its immediate left performed?"
   The sequence of functions proceeding from right to left answered the question: "Why is the next function performed?"
3. The diagram was complete when all the how and why questions could be answered by referring to the model.

3.3.2 Allocation of Functions

Allocation of functions was used to allocate functions to human and machine, identify responsibilities, mode of automation, and evaluating the allocation according to Fitts list. The procedure was performed as follows:

1. The functions identified in the FAST analysis were dedicated to human and machines during drilling and lost circulation event, with the different categories:
   - H: Human only
   - M: Machine only
   - H-C: shared between human and computer, human in control
   - C-H: shared between human and computer, computer in control
2. The equipment involved with the functions and the personnel responsible were identified.
3. The allocation was evaluated according to Fitts list (Table 7).

3.3.3Task Analysis

HTA was performed based on information obtained from Halliburton AS. The analysis was to decompose tasks and identify the responsible person of each task. Further, the was used to identify human errors. The procedure was performed as follows:

1. The analysis was planned and prepared
    a. The objective was defined.
    b. The work was organized.
    c. Background information was aquired
2. The overall goal of the task was defined.
3. The task subgoals were determined.
4. Each subgoal was further decomposed. The decomposition continued as far as required with the lowest level as an action that represented what needed to be done. At the point where tasks were split into subtasks, plans were analyzed. These were used to specify how tasks were meant to be executed.
5. The analysis was reported in a diagram.

3.3.4 Human Error Identification

The Systematic Human Error Reduction and Prediction Approach (SHERPA) was used to identify human errors from the task analysis. The analysis was performed to support the thesis main objective. The procedure was performed as follows:

1. The tasks or scenario was described in the HTA.
2. The first bottom level task step in HTA was classified according to the SHERPA behavior taxonomy (See table 8):
    a. Action (*e.g.*, pressing a button)
    b. Retrieval (*e.g.*, getting information from a screen or manual)
    c. Checking (*e.g.*, conducting a procedural check)
    d. Selection *e.g.*, choosing one alternative over another)
    e. Information communication (*e.g.*, talking to another party)
3. Human errors were identified. The associated error mode taxonomy and domain expertise was used to determine any credible error modes for the task in question. For each credible error (*i.e.*, those judged to be possible) a description of the form that the error would take was given.
4. Consequence analysis. The consequences for the well associated with the errors identified in step 3 was determined and described.
5. The recovery potential of the error was identified either as none, immediate or at another stage of the analysis.
6. Probability of error occurring was given a value of Low (L), Medium (M), or High (H).
7. The criticality of the error in question was then rated. Normally, if an error would lead to a critical incident (in relation to the task in question) then it was rated as a highly critical error.
8. Error reduction strategies were proposed. Normally, remedial measures are comprised of suggested changes to the design of the process or system. Remedial measures are normally proposed under the following four categories:
    a. Equipment *(e.g.*, redesign or modification of existing equipment)
    b. Training (*e.g.*, changes in training provided)
    c. Procedures (*e.g.*, provision of new, or redesign of old procedures)
    d. Organizational (*e.g.*, change in organizational policy or culture)

Table 8: The Systematic Human Error Reduction and Prediction Approach (SHERPA) behavior taxonomy (Rausand 2013).

Action Errors	Checking Errors
A1 – Operation too long/short	C1 – Check omitted
A2 – Operation mistimed	C2 - Check incomplete
A3 – Operation in wrong direction	C3 - Right check on wrong object
A4 – Operation too little/much	C4 – Wrong check on right object
A5 – Misalign	C5 – Check mistimed
A6 – Right operation on wrong object	C6 – Wrong check on wrong object
A7 – Wrong operation on right object	**Communication Errors**
A8 – Operation omitted	I1 – Information not communicated
A9 – Operation incomplete	I2 – Wrong information communicated
A10 – Wrong operation on wrong object	I3 – Information communication
Retrieval Errors	**Selection Errors**
R1 – Information not obtained	S1 – Selection omitted
R2 – Wrong information obtained	S2 – Wrong selection made
R3 – Information retrieval incomplete	

4 Results

The overall aim of this section is to present the findings of the work performed in this thesis. Results from the pre-study are first given, in which possibilities and challenges with MPD are discussed. Next, the findings from human factor methods; functional analysis (FAST), task analysis (HTA) and human error identification (SHERPA) are given. These are founded upon the Petroleum Safety Authority (PSA) and Norwegian petroleum standards (NORSOK-S002). Finally, a table is presented with the aim of combining the analyses.

4.1 Results from the Pre-Study

The information presented in this subsection is obtained from different researches and technical professionals contacted by email and phone. Their answers are joined into one text and further used in the discussion to support the thesis objectives. The pre-study itself correlates to the thesis' sub-objective 3 (Section 1.2).

Possibilities with MPD

MPD facilitates reduction of pressure variances in the well which further enables drilling of wells with a tight drilling window that cannot be drilled conventionally. The reduction in pressure variance also reduces risk of losses and kicks as it is possible to change pressure in the well quicker than when traditional methods are applied. In addition, the wellbore pressure can be changed continuously as the actual pore and fracture pressure is revealed during drilling.

MPD provides improved well control due to earlier loss and kick detection when using Coriolis flow meter. This can reduce operational costs as less time is spent on handling such well control situations. As a result, non-productive time (NPT) is reduced. Other factors that can save costs are the ability to drill faster because of lower BHP and trip faster by compensating for swab and surge.

Challenges with MPD

MPD is not widely employed today due to high expenses related to integrating the equipment on the rig, and operational costs as extra personnel and equipment is needed onboard. It is difficult to defend these expenses if the well can be drilled conventionally; therefore MPD is only used on the most challenging wells.

MPD equipment failure can lead to influx if the well is drilled with light mud in static underbalance. These failures could be leakage of rotating control device (RCD), wash out of choke, and failure of the control system leading to wrong opening of the choke. Often, MPD systems have built-in redundancies to such failures. Other failures on traditional equipment may be washing out of drill pipe, kick/loss, pack-off, and power loss on the rig.

As with recent aviation accidents, a significant challenge is when the operators come to depend on the automated system to the point where they lose their skill in operating the system manually. An additional challenge is the competence of the rig team and coordination between the MPD operator and the driller. Today, the MPD operators are usually sitting in a unit separate from the drill floor where communication is done with a radio. To have an effective pressure control, good collaboration between the driller and the MPD operator is essential, especially when ramping up and down the rig pumps. If the mud pumps are ramped too fast, the MPD control system may not follow which in turn could lead to losses or influx. The quality of collaboration is often dependent on how well they are trained and how much they practice together as a team.

When the choke is automatically controlled, pressure variances that could give information to the driller about kick or other well problems may be hidden. Also, if something goes wrong, it is important to fully understand the equipment. This includes understanding the real time models and controlling systems that control the automation. Many operators do not have this understanding.

In an ideal world, the MPD equipment should be integrated in the drilling control system and operated by the driller, such that it would be possible to set in a RCD and change over to MPD modus if needed.

4.2 Results from Analyses

This subsection includes the different human factor analyses performed, and thereby correlates to thesis' sub-objective 2 (Section 1.2). These are functional analysis, allocation of functions, human error identification.

Functional Analysis

Functional Analysis System Technique, FAST, adapted from Handal *et al.* (2013), demonstrates how the MPD system fulfills the goal "Maintain BHP within drilling window" (figure 16). This is considered the most important goal during drilling when it comes to maintaining well control, *i.e.* the prevention of kick and losses. The functions highlighted in yellow are also found in the task analysis presented later in this section and are therefore particularly vulnerable to human errors. The functional analysis will further we used to allocate functions to human or machine.

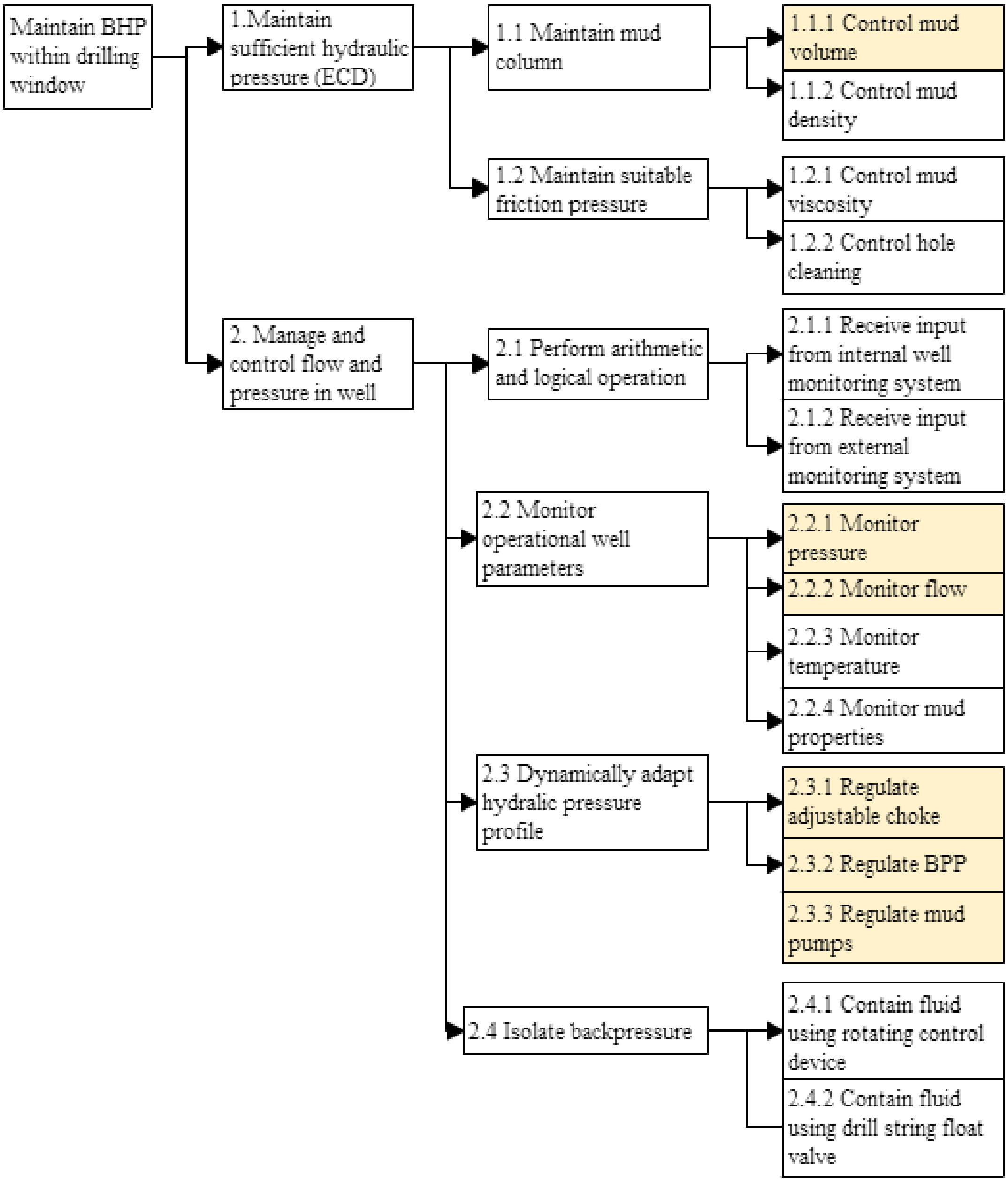


Figure 16: A function tree of an MPD pressure control system with the overall goal Maintain BHP within drilling window. The goal i decomposed into different sub functions. Yellow functions are also part of the task analysis. The tree is adapted from Handal *et al.* (2013).

Allocation of Functions

The allocation of functions analysis distributes functions identified in the previous analysis (Figure 16) to human, machine, or both (Table 9). The functions are allocated when the system is employed during normal drilling operation and in a lost circulation event (Table 6). Further, the table connects the functions to Fitts list (Table 7) with comments. The last row suggests the mode of automation for the two different situations, with the different categories found in Table 5.

Table 9: Allocation of functions to Human (H), Machine (M) or both. The equipment involved, personnel and connections to Fitts list are also described.

	Function	Equipment Involved	Alloc. drilling	Alloc. lost circ.	Description	Personnel	Fitts List	Comments to Fitts list
1.1.1	Control mud volume	Mud pumps	H-M	H-M	The operator gives instruction to mud pumps regarding start/stop and flow rate	Driller	3. Ability to improvise and use flexible procedure	The driller reads signals from the well and may adapts the procedure in response to the information he receives
							6. Ability to exercise judgment	The driller is good at making decisions about flow rate
							f. Ability to apply great force smoothly and precisely	The pumps exert great force when drilling, often 3000-4000 liters per minute are pumped into the well
1.1.2	Control mud density	Mud mixing machine and barite storage tanks	H-M	H-M	Operator monitors mud density and instructs machine to open/close valves. Barite in transferred into mud through mixing machine	Derrick-man Driller	3. Ability to improvise and use flexible procedures	The mud weight of the circulating mud is constantly changing in a non-linear way. This needs to be fixed
							6. Ability to exercise judgment	When density is out of range, the derrickman must make the judgment to adjust the weight
							f. Ability to apply great force smoothly and precisely	Several tons weight materials are usually needed to adjust mud weight, which is best performed by machine

1.2.1	Control mud visc.	Mud mixing machine	H-M	N/A	Human measures viscosity of mud. Viscosity is adjusted by human adding sacks of chemicals via mud mixing machine	Mud engineer Derrick-man	3. Ability to improvise and use flexible	Amount of chemicals added to the mud may vary from time to time
							6. Ability to exercise judgment	Decisions about amount chemicals are made by the mudengineer
							f. Ability to apply great force smoothly and precisely	The machine is mixing the chemicals into the mud
1.2.2	Control hole cleaning	Mud pumps, mixing machine	H-M	N/A	Hole cleaning can be adjusted by increasing viscosity and/or pump rate. See 1.1.1 and 1.2.1	Driller, mud engineer	3. Ability to improvise and use flexible procedures	See 1.1.1 and 1.2.1
							f. Ability to apply great force smoothly and precisely	See 1.1.1 and 1.2.1
2.1.1.	Receive input from internal well monitoring system	Logic unit	M	M	Downhole tools send signals through the mud and to the logic unit	N/A	a. Ability to respond quickly to control signals	Real-time signals are sent to the hydraulic model which is further used to send signals to the controller. Quick adjustments is made if needed
							e. Ability to handle highly, complex, operations	Different signals represent different information, like pressure, temperature, flow etc. Much information is collected at the same time

	Function	Equipment Involved	Alloc. drilling	Alloc. lost circ.	Description	Personnel	Fitts List	Comments to Fitts list
2.1.2	Receive input from external well monitoring system	Logic unit	M	M	Sensors on surface measure different parameters Signals are sent to the logic unit	MPD operator	a. Ability to respond quickly to control signals	Same as 2.1.1
							e. Ability to handle highly, complex, operations	Different information from the external monitoring system is sorted and validated from control parameters
2.2.1	Monitor pressure	Well monitoring system	M-H	M-H	Pressure is measured by sensors and displayed on screen. Operator can observe the screen and monitor parameters	Driller, MPD operator, data operator	c. Ability to store information briefly and then to erase	Sensors send signals to the controller. Real-time measurements are displayed on screen
							1. Ability to detect small amount of visual or acoustic energy	Small changes in pressure can be observed on the screen
							4. Ability to store large amounts of information for long periods	Operators are looking for increasing or decreasing parameter trends
2.2.2	Monitor flow	Well monitoring system	M-H	M-H	Sensors in flowline send signals to display. Observed by operators	Driller, MPD operator, data operator	c. Ability to store information briefly and then to erase it completely	Real-time measurements are displayed on screen

							1. Ability to detect small amount of visual energy	Small changes in flow out/in can be observed on the screen
							4. Ability to store large amounts of information for long periods	Operators are looking for increasing or decreasing trends
2.2.3	Monitor temperature	Well monitoring system	M-H	M-H	Sensors in flowline. Signals sent to display which can be observed by human.	Driller, MPD operator, data operator	c. Ability to store information briefly and then to erase it	Sensors send signals to the controller. Real-time measurements are displayed on screen
							1. Ability to detect small amount of visual or acoustic energy	Small changes in temperature can be observed on the screen
2.3.4	Monitor mud level	Well monitoring system	M-H	M-H	Sensors in mud pits. Signals sent to display which can be observed by human.	Driller, MPD operator, data operator	c. Ability to store information briefly and then to erase it completely	Sensors send signals to the controller. Real-time measurements are displayed on screen
							4. Ability to store large amounts of information for long periods	Personnel are looking for increasing or decreasing trends

	Function	Equipment Involved	Alloc. drilling	Alloc, lost circ.	Description	Personnel	Fitts List	Comments to Fitts list
2.3.1	Regulate adjustable choke	MPD choke manifold	**M**	**H-M**	Choke receive signals from controller whether to open or close. During losses, human gives choke instructions.	MPD operator	a. Ability to respond quickly to control signals	The choke responds quickly to signals from the controller
							3, Ability to improvise and use flexible procedures	During losses, operator gives input to the controller manually
							6 Ability to exercise judgment	During losses, operator decides the setpoints entered to the controller
2.3.2	Regulate back pressure pump	BP pump	**M**	**H-M**	BPP is triggered by decreasing mud pump pressure. During losses, human gives instructions on flow rate.	MPD operator	a. Ability to respond quickly to control signals	BPP is triggered by increasing or decreasing flow from mud pumps
							f. Ability to apply great force smoothly and precisely.	Backpressure pump is used to fine tune the BHP
							3. Ability to improvise and use flexible procedures	During losses, backpressure is regulated by MPD operator
							6 Ability to exercise judgment	During losses, the MPD operator gives instructions to the BPP about flow rate to be pumped

2.3.3	Regulate mud pumps	Mud pumps	H-M	H-M	The operator gives instruction to mud pumps regarding start/stop and flow rate.	Driller	3. Ability to improvise and use flexible procedure	Same as 1.1.1
							6. Ability to exercise judgment	Same as 1.1.1
							f. Ability to apply great force smoothly and precisely	Same as 1.1.1
2.4.1	Contain fluid using RCD	Static MPD pressure control equipment	M	M	Seals off the annulus and diverting all return flow to a designated choke	N/A	N/A	N/A
2.4.2	Contain fluid using DSFV	Static MPD pressure control	M	M	Valve prevent back flow of fluid from annulus into drill string	N/A	N/A	N/A
Mode of automation (Table 5)			3	1	In the crossover from normal operation to lost circulation, function "2.3.1 Regulate adjustable choke" and "2.3.2 Regulate backpressure pump" will change from machine in control to human in control. That means that the choke and the backpressure pump will change from being automatic controlled to be controlled by the MPD operator.			

Task Analysis

A Hierarchical Task Analysis was performed on the scenario “severe losses to the formation” (Table 6). The analysis illustrates the tasks required to achieve the system goal “0.0 Deal With lost Circulation”. The different steps are based on a flowchart obtained from Halliburton AS. Handling losses are a critical well control operation with potential to escalate. The scenario is therefore appropriate for evaluating well control and to identify human errors from the tasks. The process from observing losses to cure losses is illustrated in the following figures. Below each figure, a more thorough explanation is given of each step. In the second level, the person responsible for the different subtasks is identified:

- M = MPD operator
- D = Driller
- O = Other

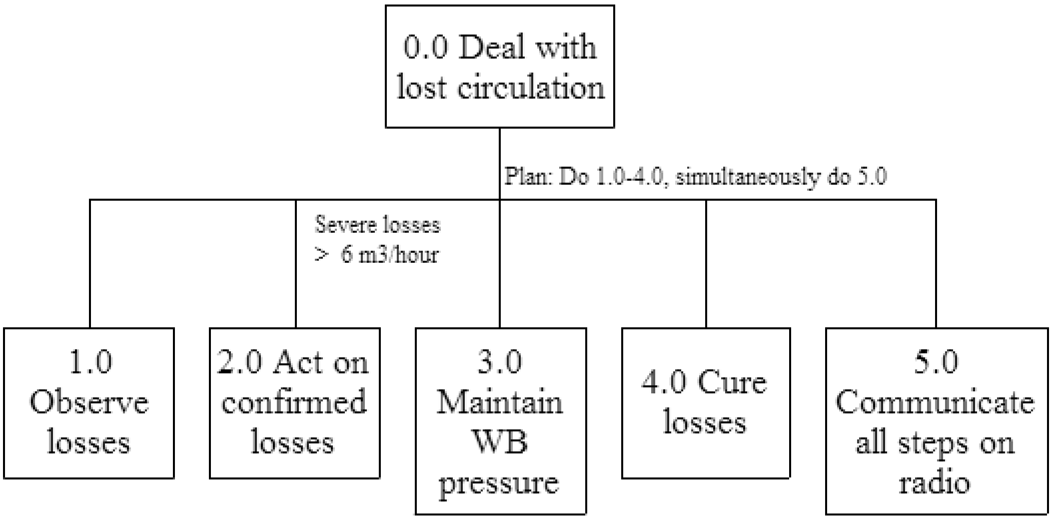


Figure 17: Hierarchical Task Analysis for the event 0.0 Deal with lost circulation.

The operation prior to the scenario is drilling. The event starts by observing losses (1.0) to the formation with following actions (2.0). The losses are calculated to be above 6 m^3 per hour which is categorized as severe. The main task becomes to maintain wellbore (WB) pressure above pore pressure (3.0). At the end of the scenario, the losses are cured (4.0). All tasks performed throughout the operation are communicated on the radio. The main personnel involved are the driller and the MPD operator. In addition, a data operator (or a mud logger) from a third party is monitoring parameters on a separate screen, *i.e.* pressures and mud volume. In addition, he communicates losses or gain on the radio; however this is not illustrated in the analysis (Figure 17).

A lost circulation event is detected by the driller and the MPD operator by hearing an alarm (1.1) and observing a screen (1.2). The alarm starts due to decreasing pit volumes, less mud returns from the well, and a pressure drop in the drill pipe and the casing. The information is communicated to other relevant personnel (1.3), such as the toolpusher (rig contractor) and the drilling supervisor (rig operator) (Figure 18).

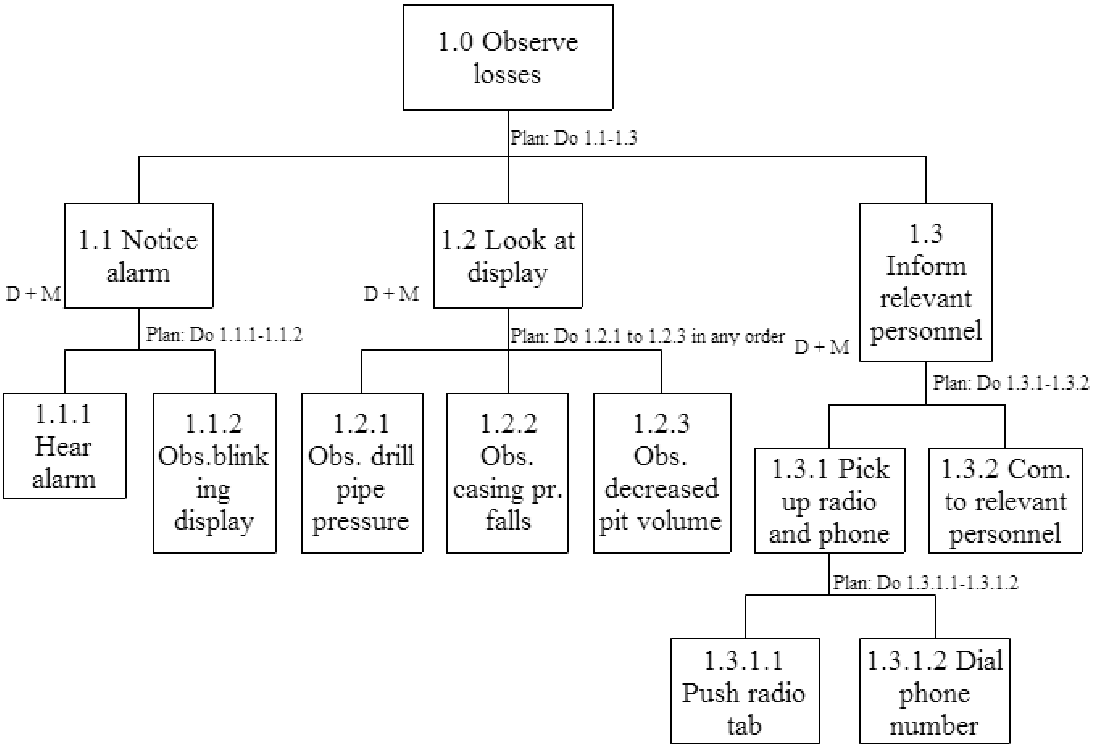


Figure 18: Hierarchical Task Analysis for the subgoal “1.0 Observe Losses”.

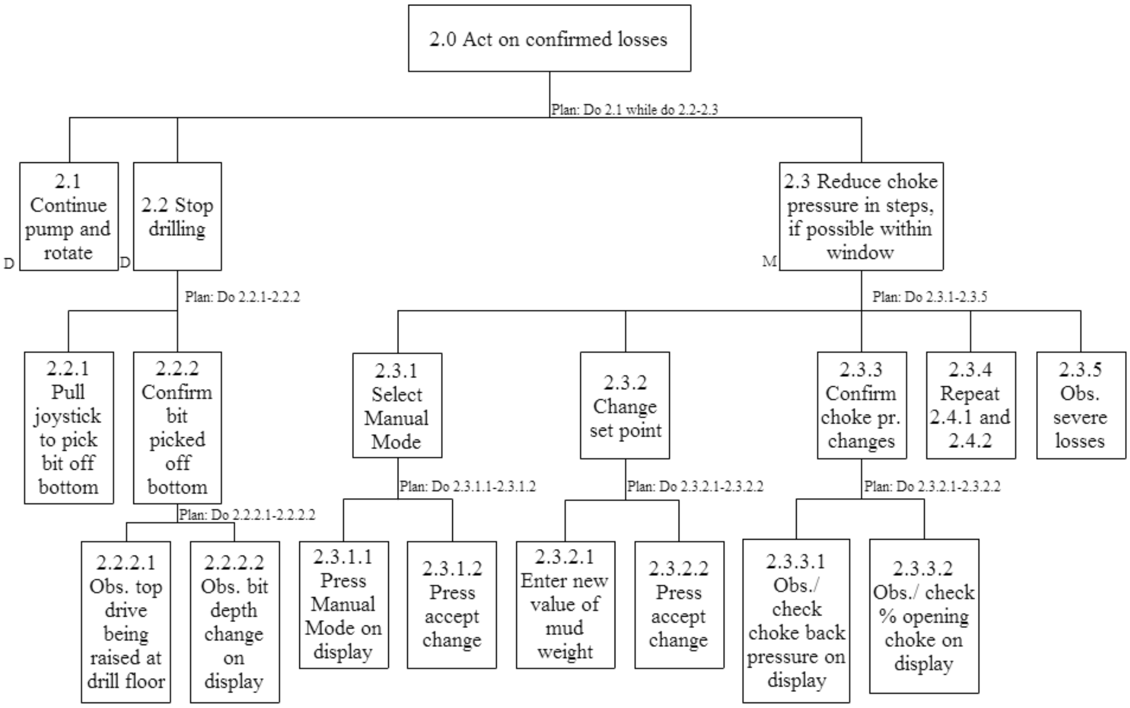


Figure 19: Hierarchical Task Analysis for the subgoal “2.0 Act on confirmed losses”.

The driller continues to pump and rotate the pipe (2.1). However, the bit is raised off bottom such that new formation is not drilled (2.2). To deal with the losses, the MPD operator changes the system to Manual Mode (2.3.1) and reduces the choke pressure in steps by changing the set points on the system (2.3.2). Additionally, this means to increase the opening of the choke. When reducing the choke pressure, the pressure in the well will also decrease. The MPD operator verifies that the choke is responding by checking the back pressure upstream of the choke, and by examining percentage opening of the choke (2.3.3). The steps are repeated until desired pressure is obtained which is should be above pore pressure (2.3). Thereafter, loss rate is observed, which in this case is categorized as severe (Figure 19).

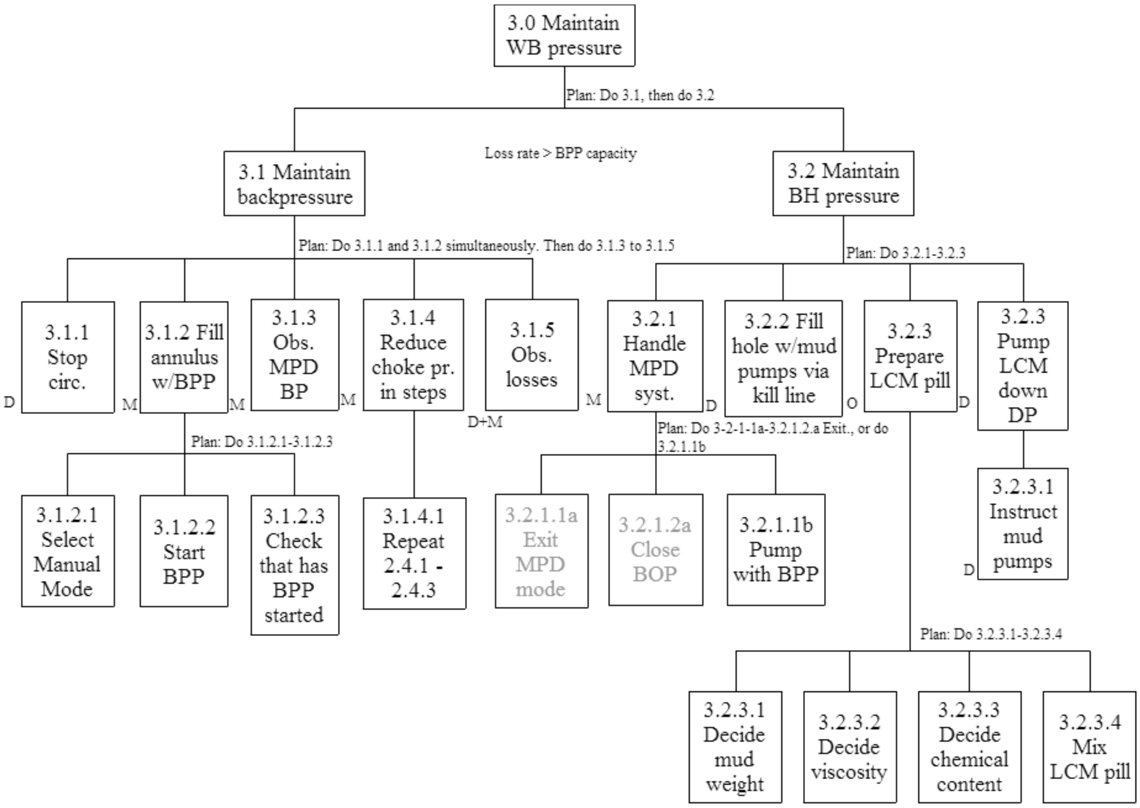


Figure 20 Hierarchical Task Analysis for the subgoal “3.0 Maintain wellbore pressure”.

The first action in maintaining wellbore pressure is to maintain backpressure (3.1). The driller stops to circulate to prevent further losses (3.1.1), which removes the friction pressure. The annulus is filled using the backpressure pump, now operated manually (3.1.2). Again, choke pressure is decreased in steps by increasing the opening of the choke to observe if the pressure in the well holds (3.1.4). However, the scenario states that the loss rate is higher than the backpressure pump capacity. Two options are available: (a) Exit MPD mode and close the BOP (3.2.1.1a). The continued operation is then performed by applying conventional drilling methods. This will not be further elaborated in this thesis. (b) Pump mud into annulus with BPP (3.2.1.1b) while filling the hole through a kill line. The last option will proceed in the HTA. Simultaneously with pumping from BPP and mud pumps down kill line, lost circulation materials (LCM) are pumped through the drillpipe (3.2.3). In such a scenario, the LCM fluid seals off the fractures in the well and losses are stopped.

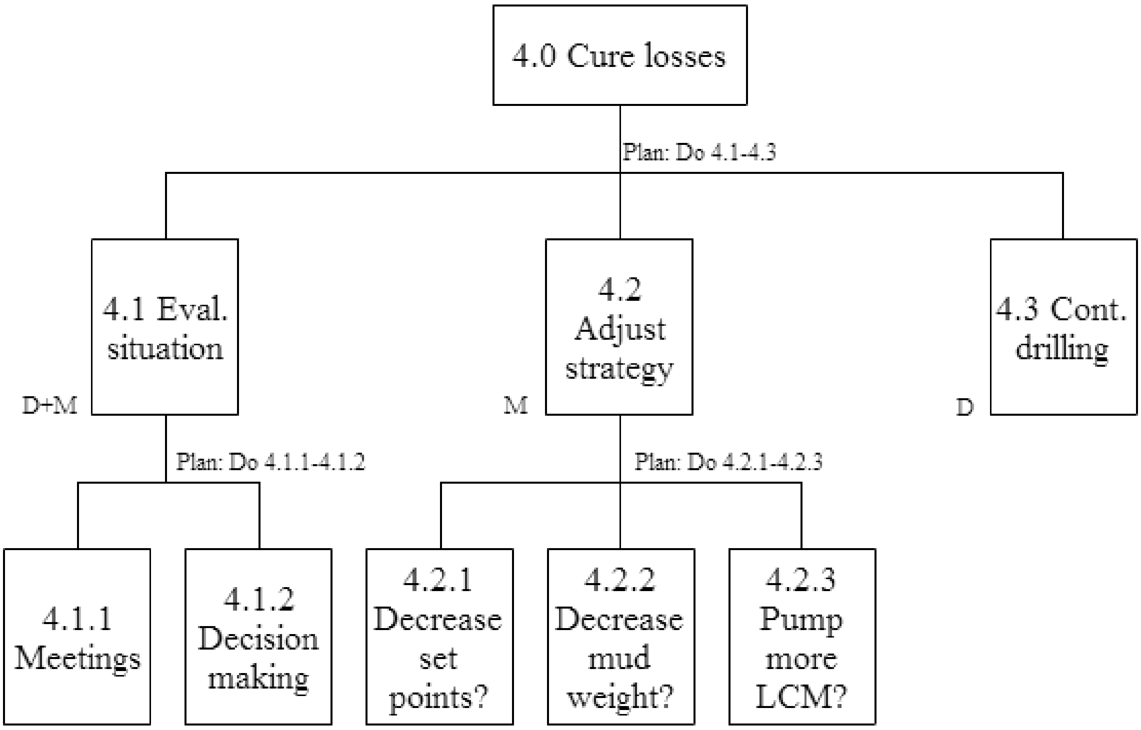


Figure 21 Hierarchical Task Analysis for the subgoal "4.0 Cure losses".

Losses are cured with LC materials. However, to prevent losses to start again, the pressure strategy may have to be changed (4.2). This decision is made in cooperation between onshore and offshore organization (4.1). When the decision is made, the driller and the MPD operator continue the operation to reach the target (4.3).

Human Error Identification

Systematic Human Error Reduction and Prediction Approach (SHERPA) was performed on the lowest level of tasks described in the task analysis (Table 10). The consequences describe how the error will affect the state of the well. Basically, two different scenarios can follow, (a) the losses become worse and/or (b) a kick can occur due to too low wellbore pressure.

Table 10: Systematic Human Error Reduction and Prediction Approach (SHERPA) based on a HTA.

Task step	**Task descript.**	**Error mode**	**Error descript.**	**Consequence**	**Recovery**	**P**	**C**	**Remedial measures**
5.0	Communicate all steps on radio	I1 I2	The driller or the MPD operator may not give sufficient information on the radio	Dependent on the situation. In worst case, BHP is not maintained resulting in kick and possibly blowout	None	M	!	- Training - Procedure
1.1.1	Hear alarm	A7	Operator or other personnel turns off the alarm instead of increasing volume	Operator does not hear alarm and loss are notices late	1.1.2	L	!	- Training
1.1.2	Observe blinking display	C3	Wrong display is open	Operator does not see the alarm	1.1.1	L	!	- Training
1.2.1 1.2.2 1.2.3	Observe drill pipe pressure, casing pressure falls and decreased pit volume	C1 C3	Operator omit checking display The display shows the wrong window	Operation proceeds and becomes more severe. Could lead to kick if BHP becomes too low	1.1	L L	! !	- Redesign of how the display is set up
1.3.1.1 1.3.1.2	Push radio tap Dial phone number	A8	Operator omit to push/dial	Recovery of loss event is postponed	1.1 1.2	L	!	- Training
1.3.2	Communicate to relevant people	A8	Operator omit to communicate to relevant people	Recovery of loss event is postponed	1.3.2	L	!	- Training

2.1	Continue pump and rotate	A7	The driller stops to pump mud	BHP is decreased to below pore pressure. Influx of gas or fluid to the well	None	L	!	- Training - Procedure
2.2.1	Pull joystick to pick up off bottom	A3	The driller pull the joystick the wrong way	Bit goes down instead of up which gives increased pressure into the well. More mud is lost to the formation	3.1	L	!	- Training
2.3.1.1	Select manual mode	A8	MPD operator omit to tab Manual mode	The choke and BPP do not behave as expected which could lead to longer time to fix the situation	Immediate	L	!	- Training - Procedure
2.3.2.1 2.3.2.2	Enter new value of mud weight Press accept change	A7	Wrong value is entered. Value accepted	Unwanted increase/decrease pressure in well. Make situation worse	2.4.2	L	!	Training
2.3.3.1 2.3.3.2	Obs./check choke back pressure Obs./check % opening choke	C1	Operator does not check the backpressure and choke opening	Unwanted increase/decrease pressure in well. Could lead to more fracturing of the well, or pressure in the well below pore pressure inducing a kick	2.4.3	M		- Extra personnel monitoring operation

Task step	Task descript.	Error mode	Error description	Consequence	Recovery	P	C	Remedial measures
3.1.1	**Stop circulating**	**A4**	**The driller stops the pump too fast for the BPP to start**	**BHP not within drilling window. Initiates a kick and possible blowout**	**None or 3.2.1.1b**	**L**	**!**	**- Training**
3.1.2.1	Select Manual mode	A7	Operator press automatic mode	Incorrect flow to the well	3.1.2.2	L	!	-Training
3.1.2.2	Start BPP	A8 A4	Omit to start backpressure pump Too low flow on pumps	Unable to maintain back pressure, wellbore pressure below pore pressure	3.1.2.3	L	!	- Alarm goes off
3.1.2.3	Check that BPP has started	C1	Operator does not check the backpressure	Unwanted increase/decrease pressure in well. Make situation worse	3.1.3	L	!	- Alarm goes off
3.2.1.2a	Exit MPD mode	A8	MPD operator does not exit MPD mode	Unwanted increase/decrease pressure in well. Make situation worse	Immediately	L	!	- Procedure
3.2.1.1b	**Close BOP**	**A8**	**Driller does not close the BOP**	**A kick on the way results in a blowout with possible damage to humans, environment and equipment**	**None**	**M**	**!**	- Training - Procedure
3.2.2	Decide mud weight	A4	Too high mud weight	Fracture formation more	4.2.3	L	!	- Software simulations
3.2.3.2	Decide viscosity	A4	Too high viscosity	Fracture formation more	4.2.3	L	!	- Software simulations

Combining the Analyses

The FAST analysis identifies functions that are critical to "Maintain BHP within drilling window". This is also regarded as the primary well barrier. Functions that also were part of the task analysis were identified and marked with a yellow color in the FAST tree (Figure 16). Human errors connected to these tasks can therefore be regarded as especially serious as they are correlated to functions that re critical in maintaining primary well control (Table 11).

Table 11: Functions from the FAST analysis also found in the HTA with the person responsible of performing the task. SHERPA illustrates human errors that could take place.

FAST		**Allocating task to:**	**HTA**		**SHERPA**	
1.1.1	Control mud volume	Driller	Many, like 2.1	Continue pump and rotate	A7	Wrong operation on right object
2.1.1	Monitor pressure	Driller and MPD operator	1.2.2	Observe casing pressure falls	C1	Check omitted
2.2.2	Monitor flow	Driller and MPD operator	1.2.3	Observe decreased pit volume	C1	Check omitted
2.3.1	Regulate adjustable choke	MPD operator	2.3.3.1	Obs./Check choke backpressure on display	C1	Check omitted
2.3.2	Regulate BPP	MPD operator	3.1.2.2	Start BPP	A8 A4	Operation omitted Operation too little/much
2.3.3	Regulate mud pumps	Driller	3.1.1	Stop circulate	A4	Operation too little/much

5 Discussion

This section aims to discuss the thesis' main objective; the concept of automation in Managed Pressure Drilling and how it may influence the risk of well control incidents by its effect on human errors. The discussion is based on relevant theory coupled with a pre-study on possibilities and challenges with MPD from different technical professionals' point of view (section 4.1). The Constant Bottom Hole Pressure system, Geobalance, from Halliburton AS was given the role of an example MPD system. The different analyses that will be discussed are functional analysis, allocation of functions, task analysis, and human error identification. In addition, the change in level of automation from a normal operation to a well control incident will be looked upon, with a recommendation of future mode of automation. Finally, this section will discuss strengths and limitations with the methodology.

The thesis' objectives are encouraged by the need for new technologies that facilitate drilling of wells with a narrow drilling window that cannot be drilled with traditional methods. It has been proposed that MPD decreases risk of well control incidents by an improved automatic pressure control in the well and earlier kick or loss detection compared to conventional drilling (Section 4.1). MPD's inherent closed loop setup, coupled with conventional methodologies, naturally lends itself to an automated philosophy (Saeed *et al.* 2012). One of the fundamental motives for introducing automation into complex systems is to lessen the chance of human error; however, this may not always be the case (Reason 1995). The analyses performed in this thesis are founded upon the Norwegian petroleum Standards which states that functional analysis and allocation of functions, including a task analysis shall be performed in the concept phase of design (NORSOK 2008). Further, the Petroleum Safety Authorities requires equipment to be designed such that the possibility of human error is limited (PSA 2008).

5.1 Evaluation of Results

According to (McAndrews 2011), human factors are not adequate addressed in the analysis and control of major accidents in drilling and offshore operations. The qualitative analyses in the following discussion could form part of a human reliability analysis, which is related to the field of human factors. HRA is believed to be a promising path to improved safety and reliability of safety-critical systems in the petroleum industry (Gould *et al.* 2012).

Functional Analysis

The functional analysis, FAST, was performed to identify system functions that were needed to fulfil the main goal, “Maintain BHP within drilling window” (Figure 16). Maintaining BHP within the drilling window is a critical function and the primary well barrier (Figure 4), which means that the pressure exerted by the mud must be situated between the pore- and the fracture pressure (Figure 3). If the operational goal fails and not addressed immediately, serious consequences such as kick, with a further potential of blowout, or losses to the formation could follow. Thus, this is a well-defined goal in regards to the main objective of the thesis; to examine risk of well control incidents. In addition, together with relevant theory in section 2.1.2 and section 2.1.3, the FAST analysis fulfills part of the thesis’ sub-objective 1, to establish an MPD system description, and sub-objective 2, to focus on achieving system goals, such as primary well control. The analysis was further used to allocate functions to human and machine.

The functions were diagrammed into a FAST tree. The main goal described in the previous paragraph was decomposed to its respective sub-functions “1 Maintaining sufficient hydraulic pressure” and “2 Manage and control flow and pressure in the well”. For conventional drilling, only the first sub-function, in addition to “2.2 Monitoring well parameters”, is required to maintain BHP within drilling window. For MPD however, the mud weight is usually close to pore pressure and certain backpressure is necessary to drill the well overbalanced. Consequently, loss of backpressure may degrade the primary well barrier. Control of backpressure is therefore essential for well control, and is dependent on equipment, such as RCD, the adjustable choke, the backpressure pump and mud pumps, drillstring float valve, the monitoring system, and the MPD control unit. These components form part of the second sub-function in the FAST tree.

The FAST analysis may thus demonstrate that maintaining BHP within drilling window is more complex for MPD operations than for conventional drilling. However, as the method allows drilling of wells that cannot be drilled conventionally, adding complexity is suggested to be necessary. Rouse *et al.* (1992) claims that the increasingly complex systems may introduce team-related issues associated with communication, ambiguous information, and decision-making. Lessons learned from previous accidents, for example the Three Mile Island accident, proposes that human errors may be a contributing factor in, what Perrow designates, system accidents in complex systems (Perrow 1984). This gives a drive for further analyses of the MPD equipment.

Allocation of Functions

The allocation of functions was used in this thesis to evaluate allocation of an existing system, and to examine the change in mode of automation that occur when changing from normal drilling to a lost circulation event. The allocation was based on the end-functions from the FAST diagram presented in the previous section, with additional identification of the person responsible for the function. In addition, Fitts list with capabilities of human and machine (Table 7) was used to argue for the allocation.

Control mud volume, mud density, mud viscosity, and control hole cleaning are functions allocated to human and machine, with the human in control (Function 1.1.1-1.2.1, and 2.3.3). These functions are related to mud parameters that are continuously changing throughout the drilling operation. That means that allocating these to humans fit well with the capabilities of using flexible procedures and to exercise judgment. The skills are also important to hold during drilling, as the nature of the well, to some degree, is difficult to predict. Mud pumps and mud mixing machine, are performing the functions with instructions from the operator, which correlates well with the capability of machines to apply great force smoothly and precisely.

The logic unit's functions are fully allocated to the machine (Function 2.1.1-2.1.2). As machines are capable of responding quickly to control signals and to handle highly, complex operations, this allocation is suggested to be sound. Monitoring different parameters is performed both by the machine and the human (Function 2.2.1-2.3.4). If these values are abnormal, an alarm will start. The machine is only monitoring the present situation, which corresponds well with the ability of machines to store information briefly and then to erase it. Information is not directly erased, but the machine does not look back in time. The driller, MPD operator, and data operator are monitoring the signals and looking for trends. They are capable of detecting small amount of changes, and to store large amounts of information over long periods. Understanding some trends often come with experience, which suits the monitoring role well.

The function "Regulate adjustable choke" (Function 2.3.1) is performed automatically from the MPD choke manifold. The choke receives signals from the controller and responds quickly to control signals, which is one of the capabilities of machines in Fitts list. However, during lost circulation, the function of regulating the choke is changed from automatic to manual by setpoints entered by the MPD operator. According to Fitts list, the human operator has the ability to improvise and use flexible procedures, and to exercise judgments, which are capabilities that are needed during losses. The lost circulation event is described in table 6, with a statement that every lost circulation event is unique and requires adjusted procedures. The same arguments can be applied for the function "Regulate backpressure pump" (Function 2.3.2). During normal drilling, the pump is ramped up and down automatically, while it is adjusted manually during lost circulation event. Saeed *et al.* (2012) has specified that these segments are the ones developed for automation during normal drilling.

The last functions in table 9 are to contain fluid using a rotating control device (Function 2.4.1) and contain fluid using a drillstring float-valve (Function 2.4.2). These form the static MPD pressure control equipment, which means that they are set in place to either guide or prevent backflow of mud. No further comments will be made to these as they are not adjustable and intervention is only made if a system failure is detected. System failures are not looked upon in this thesis.

As described in the previous paragraphs, the allocation of functions for the MPD system is evaluated to be sound according to the capabilities described in Fitts list. A different finding where the allocation was not sound could have been used to suggest a redesign of the system, to increase safety, quality, and profits. However, as the literature claims, humans and machines are often complementary rather than comparable (Jordan 1963), and limitations such as psychological needs or interactions are not considered in the list (de Winter & Dodou 2011; Hancock & Scallen 1998). Also, Fitts list is regarded as a scientific theory, and from this perspective, its aim is to explain or predict allocation of functions, and not to be used to guide engineering decision. Thus, more analyses are required to present a more holistic picture of the human-machine interaction.

Changes of Mode in Human-Machine Interface during Well Control Incident

To examine changes of mode in human-machine interface during well control incident refers to the thesis' sub-objective 2 from Section 1.2. Based on the allocation of functions in Table 9, mode of automation can be evaluated according to Table 5. Billings (1997) has already suggested that the MPD system has a mode 3 "Management by Delegation". In this mode the automated system provides closed loop control of individual tasks, such as the choke pressure control. The MPD operator decides setpoints for the pressure in the wellbore, and allows the MPD system to maintain this pressure automatically using a hydraulic model and a controller. During a lost circulation event, the MPD operator overrides the system and has direct authority. Setpoints are continuously entered to adjust the choke manifold and the backpressure pump, which is illustrated in the task analysis performed in this thesis. The mode of automation has therefore changed from mode 3 to mode 1 "Assisted Manual Control". This change is in accordance with the literature proclaiming that today's automatic drilling systems are usually not replaced by the human, but the human and machine are acting together in a joint human-machine system. The performance could therefore be suggested to be improved during normal operation, while the operator can override the system in case of an abnormal operation (Breyholtz & Nikolaou 2012).

Reason (1997) argues that functions that are too difficult to automate are left to the unrelliable operator to handle, which is one of the ironies of automation. Further, the same author suggests that the most successful automated systems with rare need for manual intervention may need the greatest investment in operator training. The factor training is not included in this thesis to evaluate human errors; however, Lorentsen (2012) has described a training sequence needed prior to an MPD operation. This includes classroom training, e-learning programs, and offshore training with simulation practice of different scenarios. A change from mode 3 to mode 1 with manual takeover could thus be suggested to suit the situation if the operators received sufficient information from the system to handle the situation and are well trained. This proposition is made without considering the factors situation awareness, trust, reliance, communication, workload, and mode of confusion which is mentioned in the thesis as underlying causes of human error (Endsley 1995; Parasuraman & Riley 1997; Woods 2010).

Task Analysis

The functional analysis just described is evaluating functions and allocation in a relatively isolated way, therefore a task analysis was performed to demonstrate how functions are attended to in a given situation. This provides a more complete picture of which other tasks that are included in addition to the interaction with machine. The HTA was based on a flowchart obtained from Halliburton AS, and the case was established to be lost circulation (This thesis' sub-objective 1). Lost circulation is classified to be a critical well control situation that could become severe. The scenario is described in Table 6.

The main goal of the task analysis, “Deal with lost circulation, was decomposed into sub-tasks including “1.0 Observe losses”, “2.0 Act on confirmed losses”, “3.0 Maintain wellbore pressure”, “4.0 Cure losses”, and “5.0 Communicate all steps on radio” (Figure 17). The responsible operator was identified at the next level of task decomposition. The task sequence suggests that the interaction between the different systems, the driller, and the MPD operator is complex, because responsibilities frequently changes between the operators. This proposes that the collaborations need to be accurate and well communicated on the radio. As declared in section 2.1.3, the MPD operator is situated in his own control cabin where the MPD equipment is run and monitored, while the driller sits in the drillers’ cabin. Findings from the pre-study (4.1), confirms that interaction between the driller and the MPD operator is seen as a challenge. One of the respondents suggests that the MPD equipment should be integrated in the drilling control system and operated by the driller. The literature agrees that team-work in highly complex systems are prone to errors (Le Bot 2004).

One of the tasks involves closing the blowout-preventer (BOP) (Step 3.2.1.2.a). The author has not found a clear description or procedure on when the driller should close the BOP. According to an MPD operator, this is dependent on the rig operator, for instance Statoil. Without having a reference to this statement, it is the MPD operator who informs the driller that he should close the BOP. As the MPD operator is sitting in his unit trying to fix the problem, the driller cannot see what he is doing and is to some degree kept out of the loop even though communication is continuing on the radio. In worst case, the MPD operator could be trying for too long time to cure the losses while letting the driller know too late that he should close the well in. This stage if therefore highly critical and will be further commented in the SHERPA.

Human Error Analysis

According to Statoilasa (2012), about 60 percent of all well control incidents on a specific rig are related to human errors and misjudgments. The human error identification method, SHERPA was used to identify human errors from the task analysis. This method has been suggested to represent the most promising in terms of performance (Kirwan 2004). SHERPA also includes recovery potential, probability of the error occurring, criticality of the error, proposed error reduction strategies, and consequences for the well if a human error is made. Mainly two consequences to the well were identified from the SHERPA: 1) increased pressure in the well leading to more severe fracturing of the formation, and 2) not being able to maintain bottomhole pressure with the potential of kick.

One of the major concerns during lost circulation is if a failure of keeping the hole full results in a kick (Halle 2010). The combination from the SHERPA analysis of: 1) none recovery, and 2) P = L/M/H, and 3) C = !, is suggested to be categorized as highly severe. The consequences of such a situation are reduced BHP to the state where a kick occurs. If not handled properly, the kick could develop into a blowout with potential damage to people, equipment, and the environment. The detection of kick is suggested to be more challenging when the well also fails to retain mud, as kick detection in an MPD system is based on flow-in and flow-out (Rehm & Paknejad 2008). A similar situation occurred on the platform Gullfaks C, where losses through a hole in the casing reduced the fluid column and led to a kick from the open hole. During that event, the MPD equipment was put on hold while the well control operations continued for almost two months before the barriers were reinstalled (Statoil 2010). Such a highly severe consequence is therefore realistic.

Human errors from the last level on the task analysis “0.0 Deal with lost circulation were identified”. The first part of the task analysis involves detecting losses (1.1.1-1.3.2). Loss of well control signs should be known by all personnel on the platform (Baker & Fitzpatrick 1998). In addition, the pre-study (4.1) claims that MPD offers earlier kick and loss detection. Therefore, it is proposed that the risk of not detecting a lost circulation event is low. On the other hand, (Sheridan & Parasuraman 2005) discusses that trust and reliance to the automation could take the attention away from a subset of tasks giving other tasks a higher focus. The signals may not be detected because of overreliance to, for example, alarms. An additional reason for not paying attention to the screen and alarms could be that the operators rely and trust in someone else watching the operation. The data operator’s task is to monitor screens at all times, however, occasionally he has errands outside the office that may cause for distraction. The literature also describes that lost situation awareness due to automation may lead to extra time for the operator to detect problems and reorient themselves (Endsley & Kiris 1995). These are human-performance shaping factors, which are not evaluated in an analysis in this thesis. However, they form part of the thesis’ sub-objective 3, to discuss advantages and disadvantages in relation to major accident scenario and human errors.

Task steps where human error could result in a highly severe situation are “2.1 Continue pump and rotate”, “3.1.1 Stop circulating”, and “3.2.1.1b Close BOP”. A failure to perform these tasks may have the consequence of not maintaining the wellbore pressure above pore pressure which could escalate into a kick and further to a blowout. Therefore, these errors are categorized as highly severe. A shared link between these task steps is the interaction and communication between the driller and the MPD operator. If the driller halts the mud pumps instead of continued pumping, the backpressure pump, operated by the MPD operator, should engage. However, an inadequate coordination between the pumps could lead to not enough mud volume being pumped into the well. The action “Stop circulating” could be performed too fast and holds the same argument about coordinating the pumps; a challenge that is recognized in Breyholtz *et al.* (2009) and in the pre-study (Section 4.1).

The most severe human error identified is connected to the task “3.2.1.2a Close the BOP”, with the error being not to close the BOP, which involved secondary well control. The reason for this error could be many, both that the MPD operator did not inform the driller that he should close it, or that the procedure did not state well enough at what time the action should be carried out. The literature suggests that if many operators are working in teams, it could be difficult for them to share the same awareness. Failure of deciding when to close the BOP corresponds well with the statement that humans are more prone to make mistaken judgment about the state of the system instead of making slips and lapses (Reason 2008). The findings also agree with the literature claiming that decision making in complex systems may be characterized by ambiguous information, and that communication and coordination are central issues. For an effective operation of dealing with lost circulation, the operators must work together as team and adapt to changing task demands.

Another type of error described in the literature is mode confusion where the operator is not aware of what the system is doing or understands why it behaves differently than expected. An example of this error from the SHERPA analysis is “2.3.1.1 Select manual mode”, where the operator could omit to perform the action and continue the operation in a wrong mode. However, it is suggested that this task will have an immediate recovery when the operator notices that the backpressure pump or the choke is not responding as requested. Reason (2000) also describes latent errors, which are errors likely to be made due to systems or routines that are formed in such a way that humans are disposed to making these errors. The coordination of mud pumps and backpressure pump could be seen as a latent human error as two different operators are involved in the coordination. However, an alternative to the backpressure pump already exists. According to Saeed *et al.* (2013), the rig pump diverter replaces the backpressure pump which in turn decreases the potential of human error. The rig pump diverter is not yet used on the Norwegian Continental Shelf (pers.com. Tim Tønnesen, MPD Manager, Halliburton AS).

In regards to the driller, it has been suggested that automation could result in an increased demand on the user’s memory, or cause the operator to be uncertain as to where he should focus his attention (Woods 2010). During an MPD operation, the driller has more screens to monitor (figure 11) and he has to perform the operation while also remembering his new types of tasks. Another statement is that automation could lead to increased stress and workload during periods of high-demands, such as the event described in the task analysis (Figure 17). It could be proposed that that the procedure of fixing lost circulation is more complex using MPD since a dynamical shift exists between the driller and MPD operator. The operation needs to be coordinated and communicated to more personnel than during conventional drilling. On the other hand, a more fine-tuning of the BHP by the MPD system could be suggested to aid in stopping the losses earlier, and hence benefits dealing with lost circulation.

Combining the Analyses

The feasibility of the combination of analyses performed in this thesis is further discusses. Tasks identified in the task analysis, that also was found in the FAST analysis could be suggested to be particularly vulnerable to human errors. The reason is that these functions are critical for maintaining BHP within the drilling window, or the primary well control. The functions identified were control mud volume, monitor pressure and flows, regulated adjustable choke and BPP, and regulate mud pumps. The human errors identified include action errors and checking errors. From the allocation of functions (Table 9), and from the task analysis itself, it is identified that both the driller and the MPD operator are responsible for these functions. Therefore, together they hold a vital responsibility of maintaining the primary well barrier. What is not illustrated when combining the analyses performed are however, the tasks only made when changing from a normal drilling to a lost circulation event. These include the manual takeover of the MPD pressure control equipment and closing the blowout-preventer. The task analysis is therefore central for accomplishing the thesis’ objectives.

5.2 Future Mode of Automation

The thesis' sub-objective 4 describes that a future mode of automation for MPD systems should be recommended. Different points of views need to be addressed to fulfill this goal, and the author recognizes that it is challenging to predict future developments. However, parts of the literature and learning from other industries, such as aviation, may be helpful. As a reminder, automation is to introduce control system and information technology that gain in reducing the physical and/or mental workload of human operators that are in charge of running the process. In the current drilling industry, humans are usually not replaced by automated systems; instead they are acting in a joint human-machine system (Breyholtz & Nikolaou 2012)

It has been found that in many environments, automation has improved efficiency, enhanced safety, and reduced the operator's workload (Endsley 1999). At the same time, introduction of automation has demonstrated new problems and changed the nature of cognitive work of human operators. Several human performance issues have arisen because automated systems have been designed from a technology-centered perspective (Woods 2010). These include unbalanced mental workload, reduced situational awareness, and trust, both under-trust and over-trust. At times, such factors have led to incidents and accidents. (Parasuraman *et al.* 2008).

A flexible interaction between humans and automation is thought to provide benefits like improved situation awareness, improved workload, and improved overall human-machine performance relative to either human alone or machine alone (Miller & Parasuraman 2007; Parasuraman *et al.* 2008). More recently, the function allocation process has focused on how the human and the automation can complement each other, and jointly satisfy the functions required for system success. This alternative method is called adaptive functional allocation (AFA) (Hancock & Scallen 1996; Scallen & Hancock 2001). In AFA, the control of functions shifts between humans and machines dynamically, based on specified thresholds for environmental factors, operator competence, or psychobiological factors (Parasuraman & Wickens 2008). Such an interpretation could be beneficial to have in mind when designing future MPD system.

In the discipline of drilling technology, standardized procedures without continuous adjustments are not very realistic due to the unpredictable nature of the well. Thus, it is difficult to picture that a fully automated MPD system without human involvement is possible. From a human factor point of view, the author suggests keeping the mode of automation similar to what it is today, mode 3. Then, the automated system provides a closed loop control for individual tasks while permitting the driller to manually take control in a well control incident. In this case, the machine can perform tasks that are beyond human capabilities, or best performed by machines, while keeping the operator in overall authority. This proposition is based on the hypothesis that better performance and SA is seen when keeping humans involved in system operation, than in higher degree of automated system, thus minimizing the out of the loop performance problem (Endsley & Kiris 1995). Also, a higher degree of automation makes it more demanding to manually take control (Endsley 1999). The MPD system is then employed to improve the performance during normal operations, while allowing the operator to intervene to varying degrees in case of abnormal operation

Improvements could, however, be directed to the setup of the different pumps, or the mud pumps and the backpressure pump, and the interface between the driller's equipment and the MPD equipment. Either the equipment could be combined into one unit, or the operators could be situated closer together. This suggests a change in the design from today's situation.

5.3 Strengths and Limitations of the Methodology

This section will evaluate the different methods applied to accomplish the thesis' objectives. First, the pre-study and secondly, the different analyses will be evaluated.

Pre-Study

The pre-study contains technical professionals and researchers' view on possibilities and challenges with MPD. The study was used to map the relevance of the topic explored. The limitation to the pre-study is the number of participants, which is associated with the fact that MPD is not currently a widely adopted method in Norway. More participants, also from the sharp end or those performing the operation, could have increased the consistency and given different opinions. Still, those who contributed to the pre-study are well-known to the concept through their work practice, which suggests that their answers are effective. The results from the pre-study was not directly used for further work in the thesis, however it provided confidence that MPD will have a place in future drilling technology. Thereby, it gives the overall topic of the thesis additional motivation to be studied.

The pre-study adopts a qualitative approach, which means that the standard way of evaluating qualitative research, reliability and validity, are not easily applied. Instead, four criteria are generally used to establish the trustworthiness of qualitative research: credibility, transferability, dependability, and conformability. The credibility of the pre-study is suggested to be high as many of the participants gave similar answers to the two questions. However, the study only contains five participants which is a fairly low number. Hence, some of the statements are not verified. The findings from the pre-study could be transferred to other MPD operations with similar methods applied. However, parts of the study are only usable for constant bottom hole pressure (CBHP) and not for other varieties of MPD (*i.e.* statements about pressure variances). In regards to dependability, factors such as communication and decision-making will be individually specific, and dependent on the environment. The last criterion is conformability, which refers to the degree to which the results can be confirmed or corroborated by others. As many of the statements from the participant cannot be documented or confirmed by other, the conformability is suggested to be low.

Human Factor Methods

The human factor methods applied may form parts of a human reliability analysis and include functional analysis, allocation of functions, task analysis, and human error identification. The first limitation is the time available to confirm the results from the different analyses. The timeframe also restricts the amount of research and number of analyses that could be performed. Another limitation is the lack of practical experience with the MPD system which affects the capability of the analyst, and the understanding of the results. Hands-on practice could have extended the results of the analysis, and contributed to finding different challenges that are currently described in the thesis. In regards to the HRA methods, a lack of relevant evaluation criteria for human-machine interfaces exists. The confidence of the study could have been increased with qualitative methodology.

The functional analysis method FAST was used to map system functions critical for primary well control. This is a well-documented method which is easy to learn and easy to implement. It is more descriptive than analytic and provides a robust approach for identifying the functional architecture of the system. FAST does not give any scenario description which makes it unsuitable to use it without further analyses (Rausand 2013). As the method was employed in this thesis to give an overview and identify critical components for maintaining well control, the method is proposed to be a rigid choice. The analysis also gives a supportive start when examining human-machine interactions, and allocating functions to either human or machines.

The allocation of functions’ main aim is to provide rational means to determine which system-level functions should be carried out by humans and which to be carried out by machines. In the design phase, allocation of functions is useful for determining the degree of automation that is optimal for a system. In this thesis, however, the method was employed to evaluate if the allocation of an existing system was sound. This was accomplished by comparing the functions against Fitts list. The procedure itself was easy to follow and well-structured. Additionally, the different capabilities of humans and machines in Fitts list were not difficult to associate to the set of functions. However, the evaluation of the results is more a challenge due to some limitations of the method. For example, the allocation does not display the direct interactions between the different operations, and therefore, does not say enough about workload, or if the interaction is good or not. Still, the allocation of functions gave a well indication of change in mode of automation from normal drilling to a lost circulation event, which was part of the objectives.

An additional limitation of Fitts list is that it does not consider the psychological needs of the human (affective and emotional requirements, job satisfaction, motivation, fatigue, stress, working under time pressure), temporal effects (learning, contextual variations), individual differences, safety, economic utility, availability, maintainability, the rapid evolution of technology, social values, task complexity, and interconnectedness between functions (de Winter & Dodou 2011; Hancock & Scallen 1998). Some of these factors could have an impact on how the driller and the MPD operator perceive the surroundings and how they act in different situations. In a HRA, these factors are identified as performance shaping factors, which are factors that may influence human performance, and thereby human error or reliability. HRA are using these factors to increase or decrease the probability of human error.

The task analysis, HTA, was used to decompose the tasks needed to be performed in order to deal with lost circulation. HTA is an easy to learn method where the analyst is given insight into the main task being analyzed. The procedure is flexible such that the tasks can be analyzed to any required level of detail. On its own, the method does not provide results for evaluating applicability; however, it highlights which tasks to be performed by different operators. The hierarchical structure of the analysis enables the analyst to progressively redescribe the activity in great degree of detail. However, this can be time-consuming work and dependent on the capabilities of the analyst. The resulting overview may be complex. HTA is most commonly used as a starting point for further analyses, like SHERPA, and the method is therefore suitable for the thesis' main objective: to evaluate human errors. A scenario analysis could also have been performed using STEP-diagram, as a part of a CRIOP analysis. The latter was developed for the offshore industry (Johnsen *et al.* 2004). However, CRIOP does not give a detailed enough analysis for this thesis.

The human error identification method, SHERPA, was applied to identify credible human errors for each task in the HTA. SHERPA is a structured and comprehensive method that is well documented and supported by a checklist for each step. However, despite the fact that SHERPA is a structured technique, a great deal of reliance lies upon the judgment of the analyst as to which errors is credible in any given situation. The method is simple and does not require in-depth knowledge of human reliability or cognitive psychology. The latter is also seen as a limitation as it does not consider cognitive components of the error mechanism. Lastly, it only considers error at the "sharp end" of the system operation, which suggests that the analyses should be supplemented with SPAR-H, which is a structured approach to identify and assess the potential for human error in complex tasks including calculating the probability of errors (van de Merwe *et al.* 2012).

6 Conclusions and Further Work

The aim of this thesis was to examine automated Managed Pressure Drilling (MPD) and how it may influence the risk of well control incidents by the influence on human errors. The MPD system, Constant Bottom Hole Pressure, supplied by Halliburton was used as a case, with the critical well control incident, lost circulation, used as a scenario. MPD was introduced to the petroleum industry following a demand of new technologies to drill narrow mud window formations, such as depleted reservoirs. In addition to the traditional mud column, MPD utilizes applied pressure from surface in a closed circulating system as the primary well barrier. More accurate pressure control equipment, and earlier kicks and loss detection methods are believed to mitigate risks of well control incidents, hence an increase in safety. Currently, MPD is only used on the most challenging wells due to high operational costs.

Experience from various industries, such as the aviation industry, have demonstrated that automation of previously manual operations may introduce new types of hazards and risks. For instance, changes in task demands, workload, trust and reliance in the automation, and mode confusion could influence the risk of human errors. However, incorporating the human element in risk assessment is thought to increase safety and enhances the quality of the drilling operation. The Facility Regulations in Petroleum Safety Authority states that equipment shall be designed such that the possibility of human errors is limited. The Norwegian petroleum standard (NORSOK S-002) requires during the concept phase that a functional analysis, allocation description functions, and a task analysis should be performed.

During the functional analysis, it was established that maintaining BHP within drilling window is more complex for MPD operation than for conventional drilling. The MPD system requires a dedicated control system, and a dynamic and static pressure control equipment, with its respective components, to achieve automatic influence. The segments developed for automation are the backpressure pump and the automatic choke, which lends to mode 3 “Management by Delegation. The allocation of function analysis identifies that a manual takeover of the backpressure pump and the MPD choke is motivated by a lost circulation event, which changes the management style to mode 1 “Assisted Manual Control”. An additional finding in both the allocation of function method and the task analysis was a frequent and dynamic change in task/function responsibility between the driller and the MPD operator. The increase in complexity of the system and change in mode of automation, coupled with team-work previously not found in traditional drilling methods may, suggest that an enhanced focus on communication, ambiguous information, and decision-making is vital.

The most severe consequence for the well identified in the human error identification method, SHERPA, was that bottomhole pressure was not maintained, such that occurrence of a kick develops into a blowout. Failure of filling the well adequately with mud, with the driller not closing the blowout-preventer, were established as possible causes. When excluding system failures, these events could be traced to miscommunication and mistaken judgments, or an inadequate procedure. It has not been found a clear description as to when the driller should close the blowout-preventer if losses become too severe. This discovery is, however, limited by the information available, and time to confirm the results. These findings combined with factors such as increased memory demand, more screens to pay attention to, and changed types of tasks could suggest that handling lost circulation is more complex for an MPD operation than a traditional procedure. In addition, the interaction between the driller and the MPD operator with their respective tasks may introduce new types of human errors that could influence the risk of well control incidents. Still, the MPD equipment offers a more precise adjustment of the BHP proposing that some well control incidents are less challenging to handle.

A future mode of automation in MPD systems is recommended to be similar to today’s situation. A flexible interaction between humans and automation is assumed to provide benefits like improved situation awareness, improved workload, and improved overall human-machine performance relative to either human alone or machine alone. The operation is then enhanced during normal conditions, while allowing the operator to intervene to varying degrees in case of abnormal operation. Upcoming drilling practices is believed to change, and MPD is regarded as a necessary building block in the automated drilling scenario. Other industries, such as the nuclear energy industry, have come further than the petroleum industry in integrating human factors into major accident risk analysis. An encouragement to pursue this development is suggested, as incorporation of the human element in major accident risk analyses is viewed as a promising path to improved safety and reliability of safety- critical systems.

Further Work

Although the results presented here have demonstrated the effectiveness of adding the human element in addressing risks, it could be further developed in a number of ways. Further work is suggested as follows:

- A complete Human Reliability Analysis should be performed to increase the confidence, which means to include performance-influencing factors (*e.g.* SPAR-H) and human error probabilities for each error mode (*e.g.* THERP). These could be used to quantify the potential of credible human error, identify causes of human error to support development of preventative measures, and improving the value of a risk assessment by including the human element (Swain 1990).

- The human-machine interaction, or more specific the human-human-machine interaction, should be further analyzed as this was identified as vulnerable for the operation to deal with lost circulation. With the existing system, elements such as procedures and training should be looked upon. These are components of organizational factors (Skogdalen & Vinnem 2011). NORSOK Z-013 states that an evaluation of the effect of human and organizational factors shall be performed. This may range from a qualitative discussion to a detailed analysis of human and organizational errors, depending on the criticality of such aspects for the risk picture

- The redundancies of the MPD system should be examined in regards to well control. Failure modes and effect analysis (FMECA) can be used to evaluate the reliability, in addition to hazard and operability (HAZOP) to evaluate all deviations the system may have (Rausand 2013).

- Finally, it is recognized that the industry is swiftly changing, also within the development MPD technology. Zhou *et al.* (2011) has described a switched control scheme which is believed to attenuate kicks while drilling into the reservoir. Another research propose to enhance well control by using wired drill pipe telemetry which enables more accurate downhole data compared to the traditional mud pulses (Gravdal *et al.* 2010). Landet (2011) is modeling control of MPD from floating rigs suggesting that the practice will expand to not only platforms. The Human Factor community should follow-up this development to provide consultation from a safety point of view.

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References

8 Appendix A

AFA	Adaptive functional allocation
BHA	Bottomhole assembly
BHP	Bottomhole pressure
BOP	Blowout-preventer
DAS	Data acquisition aystem
ECD	Equivalent circulating density
FAST	Functional analysis system technique
LC	Lost circulation
LCM	Lost circulation materials
HMI	Human-machine interface
HRA	Human reliability analysis
HRI	Human error identification
HTA	Hierarchical task analysis
MPD	Managed pressure drilling
MWD	Measurement while drilling
NPT	Non-productive time
P&ID	Piping and instrumentation diagram/drawing
PSA	Petroleum Safety Authority
RCD	Rotary control device
SHERPA	Systematic human error reduction and prediction approach
ROP	Rate of penetration
SA	Situation awareness
TVD	True vertical depth
WB	Wellbore