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Application of reliability centered maintenance on a drilling system

Master thesis

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Abstract

The first part of the thesis is an introduction of the drilling system where the theoretical background of the drilling system is described. Then the reliability centered maintenance (RCM) methodology is described. RCM is a logic way of identifying what equipment that needs to be maintained with a preventative maintenance basis rather than letting it fail and then fix it basis, commonly referred to as the run to failure (RTF). The maintenance strategies are described in 3.2

Reliability centered maintenance include many different hazard analysis types and techniques. The failure mode, effect and criticality analysis (FMECA) is the main technique in this thesis. The work of conducting a FMECA and failure tree analysis is very time consuming, this thesis will therefore have a main focus on a sub system. The subsystem described in detail is the top drive. A fault tree analysis is used to describe the system boundaries while the FMECA is used to create a risk priority ranking and a risk matrix. A maintenance plan for the top drive is proposed in Appendix B.

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List of abbreviations

RCM	Reliability centered maintenance	FTA	Failure tree analysis
FMEA	Failure mode effect analysis	FMECA	Failure mode, effect and criticality analysis
RPN	Risk priority number	CBM	Condition based maintenance
RTF	Run to failure	MTTF	Mean time to failure
NOK	Norwegian krone	MMS	Maintenance management system
RMS	Rig management system	NDT	Non Destructive Testing

Introduction

Maintenance is an essential part of the drilling industry today. A reliable drilling system is required to ensure progress in the drilling operation. When the drilling system stops functioning, the rig company has to declare downtime; the day rate earned from the operation company decreases or fully stops. Drilling rigs are rented out to operators that own the oil fields at an approximate day rate of 450 thousand dollars per day on the Norwegian sector. This shows the high cost of downtime and highlights the importance of a maintenance strategy to avoid break down.

A good maintenance strategy is based on understanding the system and knowledge of maintenance concepts. The challenge is to choose the right maintenance concept for the specific equipment and operation conditions. The implementation of reliability centered maintenance (RCM) can help decide what equipment that needs different maintenance strategies to ensure a high reliability at a reasonable cost.

In this master thesis a drilling system is described and the reliability centered maintenance (RCM) approach is applied on the drilling system. First the theoretical background of the drilling system is explained. Then the method of RCM is presented. Many types of hazard analysis can be used in the RCM methodology, but the main hazard analysis techniques in this thesis are the Failure tree (FTA) and Failure mode, effect and criticality (FMECA) analysis.

The FMECA analysis in this thesis is focused on the top drive. Failure modes and failure causes are identified and a priority ranking technique is used to rank the failure modes. The priority ranking is a method used to optimize the maintenance strategy.

1.1 Problem statement

The oil and gas industry has a challenge with drilling enough wells to sustain the oil flow from the Norwegian continental shelf. To optimize the drilling operation and avoid downtime the maintenance activities should be directed to where they are needed the most. By identifying the critical maintenance tasks, the maintenance activities can be prioritized.

The following three main questions shall be discussed in the thesis:

- What is the theoretical background for reliability centered maintenance?
- How to implement RCM into the drilling system?
- How to prioritize maintenance activities?

1.2 Goal of the thesis

The goal of the thesis is to apply the RCM methodology to a drilling system. Main activities include literature, field research and risk rating.

As a result this paper can be used for further studies on how to prioritize maintenance activities.

1.2.1 Approach

In the following the approach of the thesis shall be stated. The bullet points below shall be individually discussed and researched in the chapters of this thesis.

- Define the system
- Divide the drilling system into sub systems
- Define a method that can be applied to the drilling system
- Conduct a Failure mode, effect and criticality analysis on one of the sub systems
- Describe failure modes
- Describe failure causes
- Prioritize the failure modes
- Find maintenance activities that can reduce the occurrence of the failure mode
- Create a fault three
- Create a risk matrix
- Describe a maintenance plan

1.3 Delimitations

The following report will define the drilling system, but the focus in this thesis will be on the top drive. Failure mode, effect and criticality analysis will only be conducted on the sub systems of the top drive. Because of time limitations all the sub systems of the drilling system will not be discussed in depth.

Theoretical background

2. The drilling system

Transocean Barents (Fig 1) is a semi-submersible drilling rig. Barents is equipped with a modern drilling system.

Figure 1 Transocean Barents

To understand the main challenges for the maintenance activities on the drilling system it is essential to have an understanding of the system itself. This chapter will give an overview of the main components in the drilling system.

The drilling system consists of four main types of drilling equipment (Bommer 2008):

- Mud pumping and treatment
- The derrick
- Hoisting equipment
- Rotating equipment

Introduction to the drilling system

The drilling system on a semi-submersible rig consists of the derrick (2.2) with the drill floor at the base. The drawwork (2.3 hoisting equipment) is placed at the drill floor. The drawwork is a large winch that lifts the top drive (2.4 rotating equipment) and the drill string. The mud pumps (2.1) are the heart of the drilling system.

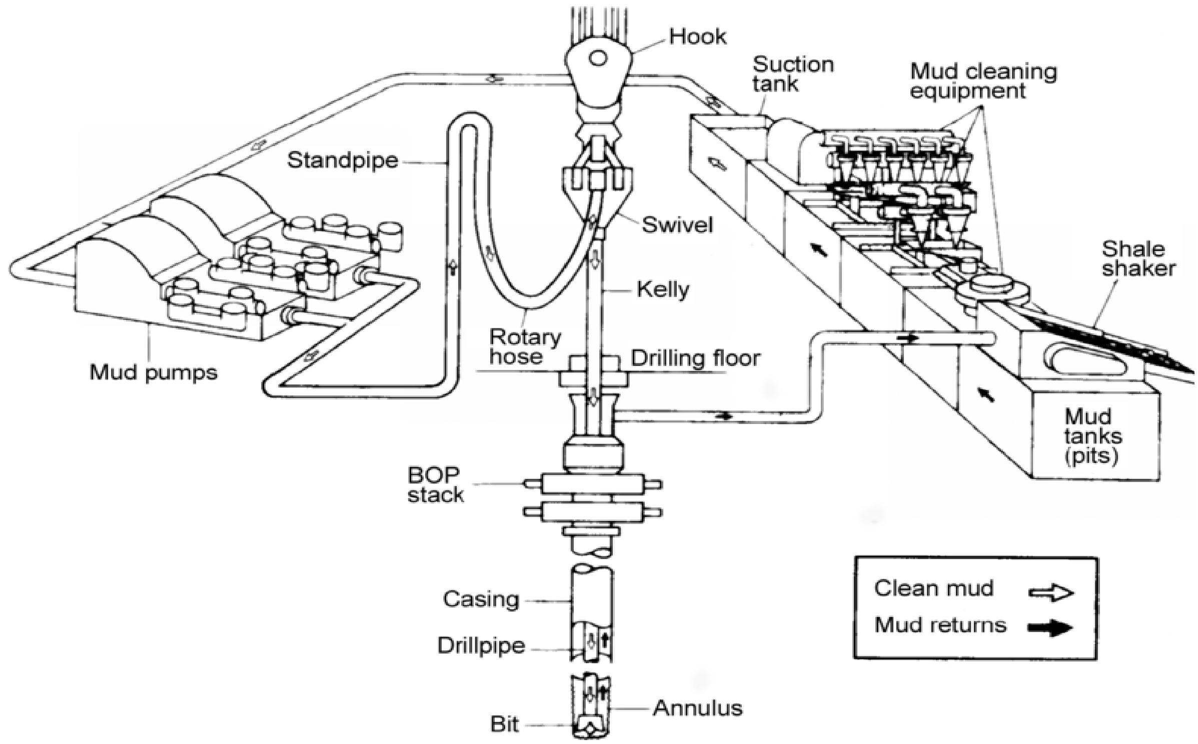


Figure 2 Example of a drilling system

2.1 Mud pumping and treatment

The mud pumps provide the pump pressure to push the mud through the drill string and the bit(Fig 2). The mud goes down through the drill bit where it cleans the hole and transports the cuttings to the surface.

When the mud returns to the surface it is directed to the shale shakers where all the large cuttings are removed from the mud. The shale shakers consist of a vibrating frame that holds screens that mud is filtered through. The shakers are not always enough to keep the properties of the mud. A second cleaning system like a centrifuge is used to get rid of the smaller particles.

Then the mud returns to the pits. A pit is a tank that stores mud and the pit room has several of pits. The pumps suck mud from a pit to complete the mud cycle.

The mud mixing room is where chemicals are added to the mud. The ingredients in the mud are different in water based mud and oil based mud, but the function of the mud stays the same; controlling the pressure in the well, cool the bit and to clean the hole.

Figure 3 Mud pump

The mud pumps (Fig 3) are critical to the drilling system; they provide the pumping power needed to drill. If the mud pumps shut down, the operation has to stop and the driller has to close in the well until the pumps are fixed.

The mud pumps are usually tri-axial piston pumps. They have tree single acting pistons which are driven by a common crankshaft. The three pistons have a phase displacement of 120 degrees to minimize the pulsation in the mud(Skaugen 2011). But to create an even flow a pulsation dampener is required. The pulsation dampener is a vessel with gas inside, normally Nitrogen. When a pulsation damper is installed the volume supplied by the pump during a complete rotation is split into two parts; one is going to circuit needs and the other part is going into the pulsation dampener. The volume in the pulsation dampener is returned immediately to the circuit while the pump is in the suction cycle. This enables the mud pumps to provide a constant pressure. (Gimeno 2000)

2.2 The derrick

A derrick (Fig 4) is a steal beam tower centered directly over the drill floor. All drilling rigs have a derrick which is an important part of the drilling system.

Figure 4 The derrick with a yellow traveling block

The derrick is a framework to hoist the drill (top drive) over the drill pipe. When drilling down there is a need to connect(Markeset 2011)t more drill pipe to the drill string to get deeper. The drill (top drive) is hoisted to the top of the derrick and a new stand is connected to the drill string. One drill pipe is approximately 10 meters long and three pipes are connected to make up a stand. Drill pipe needed for the operation is stored inside the derrick to gain fast and easy access.

When drilling with stands the derrick needs to be approximately 60 meters high to be able to lift the drill over a stand of drill pipe. The advantage of drilling with a stand versus a single drill pipe is large, due to fewer stops and therefore reduced risk of getting stuck. One stand requires one stop after 30 meters, while drilling with one drill pipe requires one stop every ten meters. This is why the derrick is such a high structure.

At semi-submersible rigs and drill ships the derrick provides vertical rails to guide the top drive, the rails keeps the topdrive from swinging back and forth as the rig is moving with the waves. The derrick is also holding up sheaves for winches and a separate winch for a personnel harness to allow safe work within the entire derrick.

There are several kinds of equipment in the derrick. Equipment in the derrick includes:

- Crown block\Traveling block
- Heave compensator (on drill ships, semi-submersible rigs)
- Racking system
- Iron roughneck

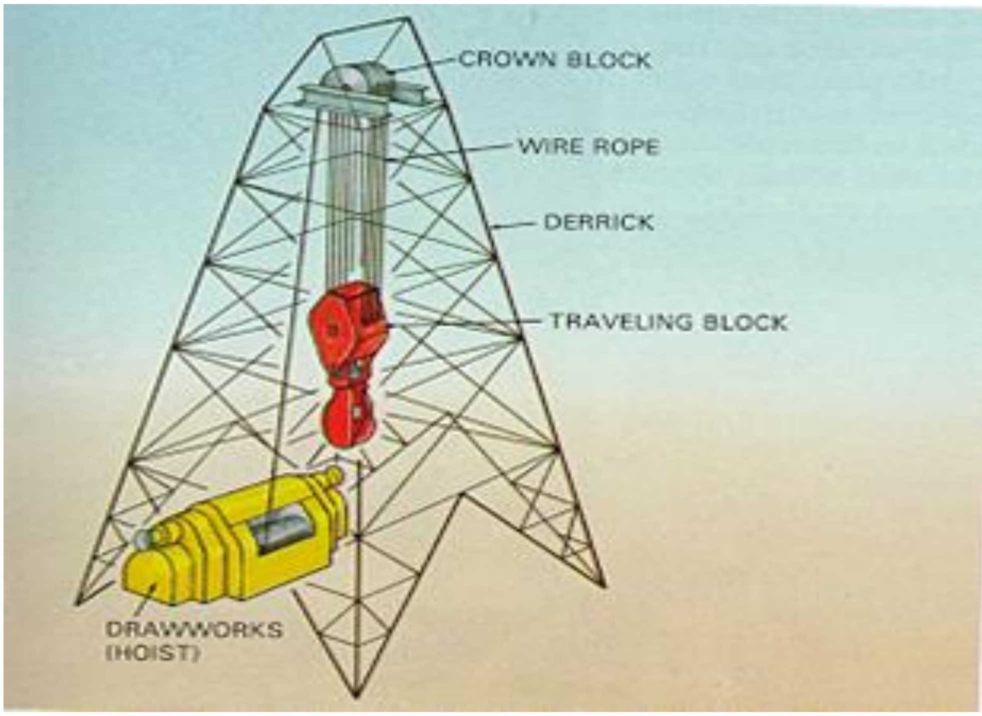


Figure 5 Drilling equipment in the derrick

The Crown block and the Traveling block

The crown block (Fig 5) is the stationary section of a block and tackle that contains a set of sheaves. The drill line is threaded through crown block and connects the crown block to the traveling block. The crown block is stationary and the traveling block is lifted or lowered by pulling or releasing drill line. The combination of crown block, traveling block and drill line gives the ability to lift or lower the topdrive. (Wikipedia 2012)

The heave compensator

A heave compensator (Fig 6) decreases the influence of the waves on the drill bit. Semi submergible rigs and drill ships move up and down with the waves. Without heave compensation the drill bit would hit the bottom and then get pulled off the bottom when the next wave hits the rig.

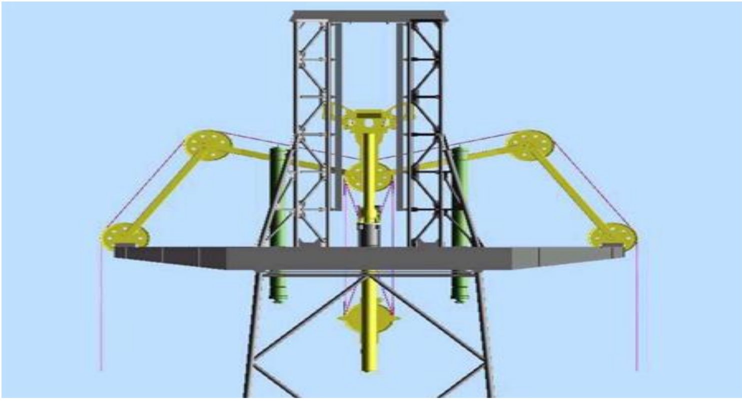


Figure 6 Heave compensator

To drill efficiently the bit needs to be in contact with the formation constantly and this is why a heave compensation system is needed. There are two major types of heave compensators:

- Active heave compensator (AHC)
- Passive heave compensator (PHC)

The main principle in passive heave compensators is to store the energy from the external forces (Waves) and dissipate them or reapply them later. A typical PHC consists of gas accumulators and hydraulic cylinders. When the piston rod in the cylinder extends it will reduce the total gas volume and compress the gas that in turn increases the pressure acting upon the piston rod. (Wikipedia 2013) The main difference of PHC and AHC is that the passive system does not require external power. (Albers 2011)

Active heave compensators (AHC) differ from passive heave compensation by having a control system that actively tries to compensate for any movement at a specific point. (Albers 2011) The AHC consumes a large amount of external power to keep the drill bit at position. New drilling rigs always have both a passive and an active heave compensation system. (Wikipedia 2014)

The racking system

There are many different racking systems but it is usually mounted in the derrick. The drill pipe comes on boats from land and is stored lying down on the deck. Semi-submersible rigs therefor have a deck called pipe deck. When a section of a well is drilled the drill crew picks up the pipe needed from the pipe-deck. The drill pipes are then stored standing tall on the drill floor, secured by the fingerboard (monkey board).

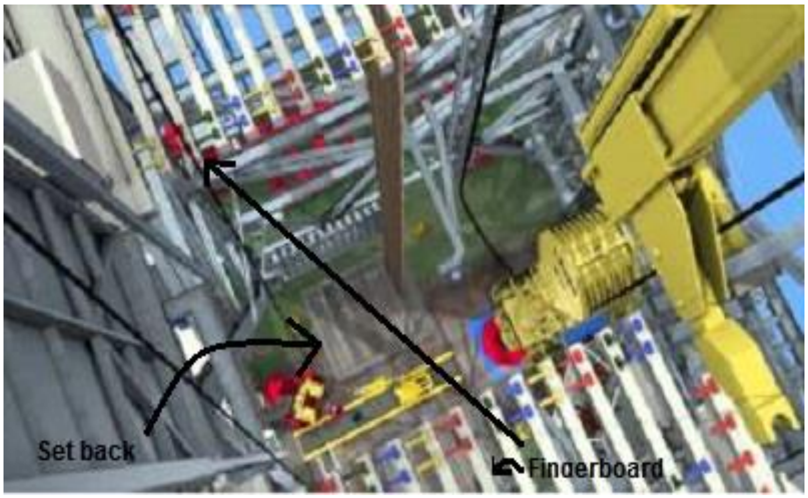


Figure 7 Racking system

The racking system (Fig 7) consists of two hydraulic powered “arms” and a fingerboard. The arms lifts stands in between the well center and the storage place on the drill floor called the set back. The fingerboard is a rack that is mounted approximately 25 meters over the drill floor. The fingerboard is designed to hold the upper part of the drillpipes while they are resting on the setback at the bottom.

Some new rigs have the drill pipe storage on a lower deck. Rigs such as Transocean Barents has the racking system mounted at the cellar deck. The driller can pick up stands directly from cellar deck. This reduces the weight that has to be in the derrick and increases the rigs stability because of a lower center of gravity.

The pipe handling equipment includes an iron roughneck to make up and break connections and drill pipe.

The iron roughneck

The iron roughneck(Fig 8) is the machine that connects and disconnects drill pipe. When drilling deeper the roughneck connect new pipes together to drill further down.

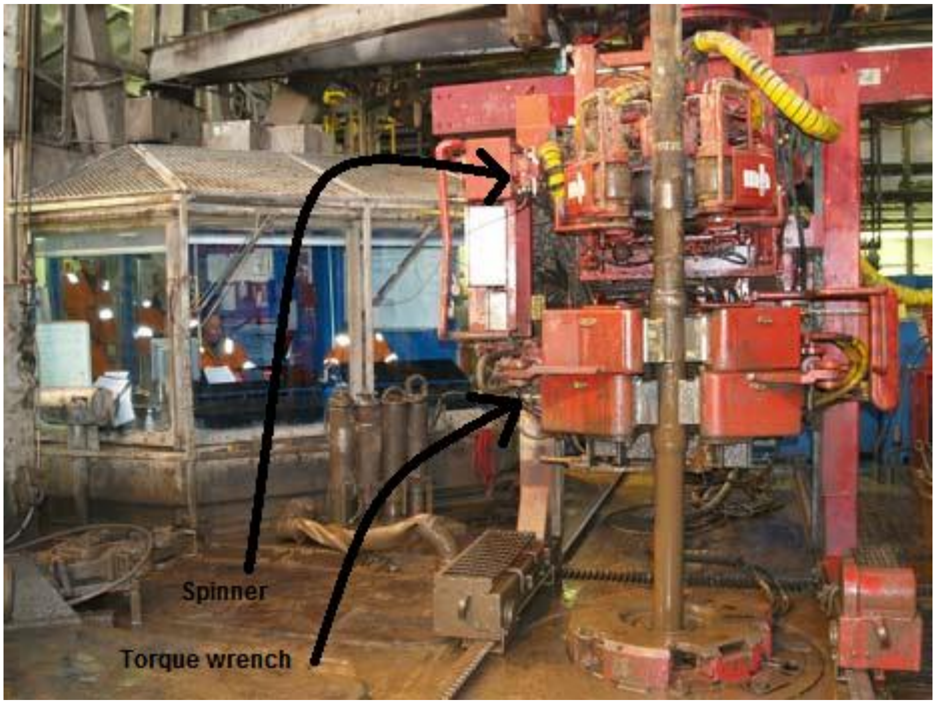


Figure 8 Iron roughneck

The iron roughneck clamps the bottom pipe, providing torque, while the upper clamps turn the top pipe. The drill pipe has one female end with inside threads (Box) and one male with outside threads (Pin). Pipe is strung together by twisting the box and pin pieces together.

When the well is completed or a drill bit needs replacement, pipe is pulled out of the hole and the pipe is simply turned the other way to break it down.

When the torque wrench has broken a connection, the spinner thong spins the pipe out of the threads. When the drill pipe is disconnected, the racking system lifts the drill pipe to the set back and fastens it in the fingerboard.

2.3 Hoisting equipment

The hoisting system consists of either a drawwork or a ram system. The drawwork is basically a big winch that is responsible for lifting and lowering the drill (topdrive). A ram rig is a new concept that is used to hoist the topdrive.

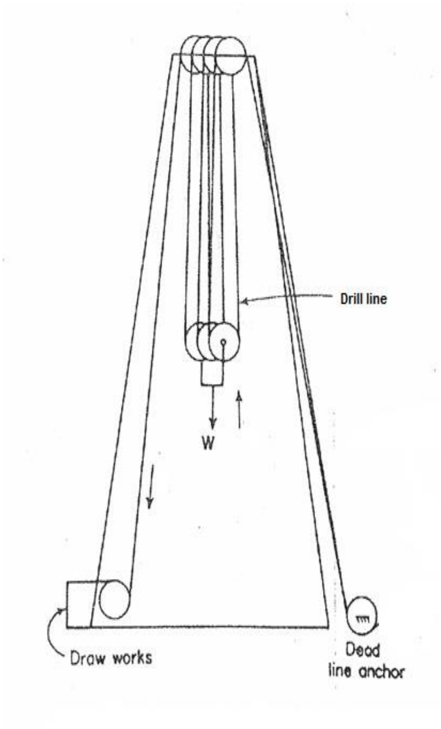


Figure 9 Traditional drawwork and a Ram rig system

At Ram (Fig 9) rigs the drawwork is replaced by a system of hydraulic pistons and rams. The hoisting and lowering of the topdrive is done by two hydraulic cylinders called rams. The hoisting lines are parallel with fixed length wires. One end of the line is anchored at the drill floor and the other at the topdrive. The lines are run over sheaves at the top of the ram. When the ram cylinders extend upward it creates a lifting force on the topdrive. The speed and the traveling distance of the topdrive are twice of the speed of the ram cylinders. If the maximum speed of the rams are 1 m/s the topdrive can move at a speed of 2 m/s. The rams are powered by a hydraulic system with eight to fourteen pumps of equal capacity. The hydraulic pumps are powered by AC motors.(Artymiuk 2006)

The ram rigs are very efficient, but the drawwork system is the most used system in the industry. The drawwork system has proven to be efficient and reliable for many decades.

The drawwork is a powerful winch that can be controlled from the driller's cabin. By winding drill line out or in the top drive (drill) is lowered or hoisted.

Figure 10 Drawworks

The drawwork (Fig 10) holds the drill-line that winds on the drawwork drum to the top of the derrick. The drill-line is moving fast from the drawwork to the crown block and is therefore called the fast line. In the top of the derrick the drill line enters the crown block and continues down to the travelling block and up again from 4 to 6 times. The drill line then continues down from the crown block to the dead line anchor at the opposite side of the derrick. The drill line is not moving at this side of the derrick and is therefore called the dead line. The deadline anchor has a force transducer that shows the tension in the line.(Gusman 2002)

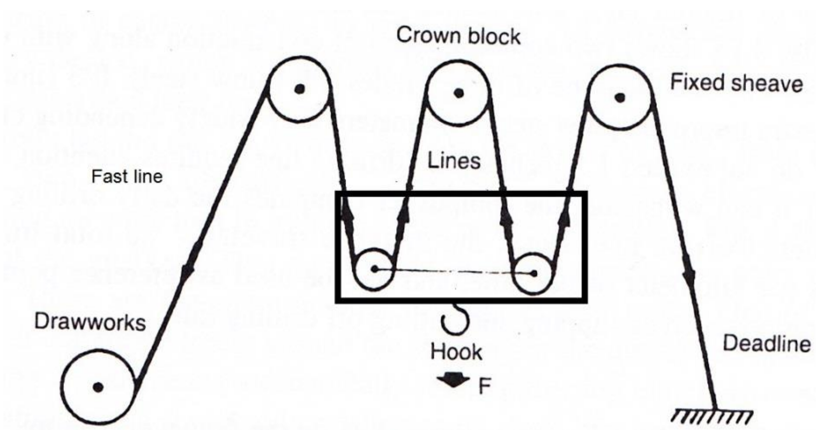


Figure 11 Hoisting equipment

The drill line (Fig 11) has a metal core with six steel wire strands braided around it. The strands in the core normally have a left lay while the strands of the wire rope have a right lay. This makes the drill line stiffer and less prone to rotate. The diameter of the drill line varies depending on the steel grade and type of rig, but generally don't exceed 1.5 inches (3.8 cm). The steel may be of three grades: Plow steel (PS), improved plow steel (IPS), Extra improved plow steel (EIPS). To ensure that the quality of the drill line is acceptable the load and the distance traveled is recorded. The product of load and distance traveled is used as reference points to initiate maintenance operations such as cutting and slipping of drill line.

When performing a slip and cut operation the weight of the traveling block is removed from the drill line by attaching the traveling block to the derrick. Then the drill line is disconnected from the drawwork and approximately 30 meters of drill line is cut off. The deadline anchor is released and 30 meters of new drill line is pulled through the system. The drill line is then reattached to the drawwork and the deadline anchor is tightened to hold the drill line stationary again.

The drawwork is critical to the drilling system; it provides the lifting power for the hoisting system. It provides the function to hoist, lower and stopping the block. Uncontrolled movement may lead to collision, dropped objects or any form of safety hazards. Downtime on the drawwork often results in downtime for the whole drilling operation.

The draw work consists of five main parts: The motors, the reduction gear, the brake and the drum. The motors that drive the cable-drum are usually driven by an electrical motor that is either AC or DC. The motor is connected to the drum by reducing gears and a clutch. The number of gears can be one, two or three speed combinations. The clutch is designed to disconnect the drum from the motor. While the clutch is active the brakes are used and the potential energy is transformed to heat. To keep the brakes cool water is pumped through to dispose of excess heat. (Skaugen 2011).

The drawwork usually have two kinds of brakes: electromagnetic and mechanical. The electromagnetic brakes use a dynamo that is able to produce a current when the drum is rotating. Approximately 90% of the energy produced is disposed of through big resistors. The breaking force of the electromagnetic breaks is proportional to the drum speed and cannot provide an immediate and complete stop. However the breaking power of the electromagnetic breaks provides a much higher breaking power than the mechanical breaks. The mechanical brakes consist of calipers that are placed on both sides of the drum and are used if the drum needs to stop completely or at slow lowering rates. The force applied by the calipers is constant and independent of the rotating speed of the drum. (Skaugen 2011)

2.4 Rotating equipment

Rotating equipment includes those components that turn the bit. A top drive like the one in (Fig 12) is used to rotate the drill string.

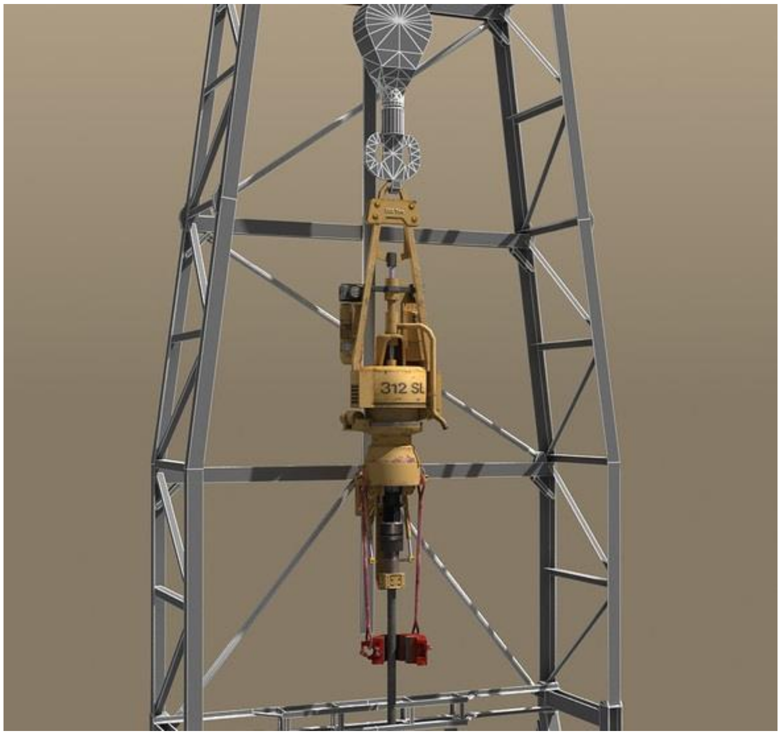


Figure 12 Top drive hanging from the traveling block

The top drive hangs from the traveling block and is able to move up and down the derrick because of the hoisting equipment. The topdrive is a motor that turns a shaft to which the drill string is screwed. The motors are either electrical or hydraulic powered and boasts at least 1000 horsepower to turn the drill string. The topdrive assists in pumping the mud into the drill string by connecting the rotating drill string to a non-rotating flexible hose. The connection between the stationary pipe and the rotating drill string is called the washpipe. The washpipe is a swivel that can easily be replaced if it starts to leak. The flexible hose is connected to the top drive from the standpipe manifold. The standpipe manifold is a set of valves that can direct the mud flow from the mud pumps to the drill string. The top drive is often totally automated and offers rotational control, maximum torque and control over the weight on bit (which is the actual down force from the bit on the formation). The top drive replaces the traditional Kelly and lessens the manual labor involved in drilling.

The predecessor of the topdrive was the Kelly. The rotary table (Master bushing) was used to turn the drill string.

Figure 13 Kelly

Figure 14 Top drive

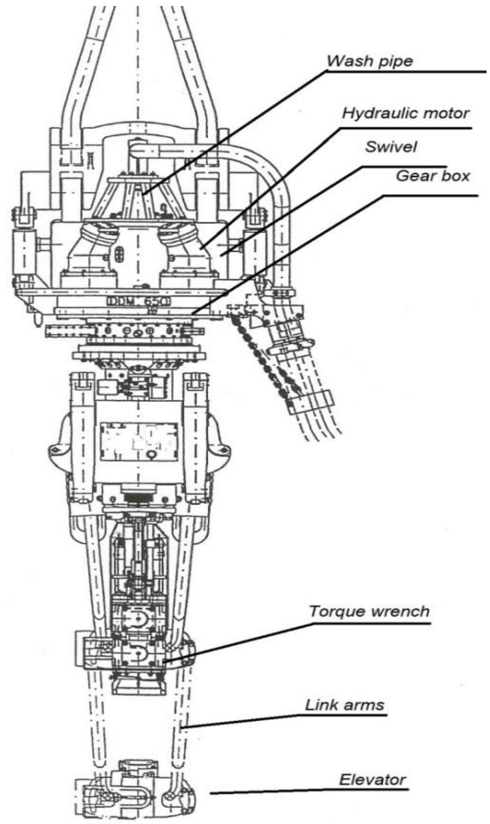
An overview of the Kelly is shown in(Fig 13). Later the topdrive in (Fig 14) has outperformed the Kelly and is now the most common drilling solution offshore. The topdrive has several advantages versus Kelly drilling:

- A top drive is capable to drill with three joint pipes (one stand) instead of just one pipe at the time
- A top drive allows the driller to engage or disengage the pumps quicker while removing or adding drill pipe to the drill string.

While the traditional Kelly could just drill with one pipe at the time, the top drive is capable to drill with three pipes. Three connected drill pipes makes one stand. One drill pipe is approximately 10 metres. Drilling with three pipes decreases the number of connections and reduces the time that the drill sting has to be stationary while adding or removing drill pipe from the drill string. The longer the drill string is stationary in an open hole, the higher the risk is of getting stuck. A top drive therefore reduces the risk of getting stuck. That is the main reason why a top drive is preferred over a Kelly.

Top drives are used in all modern offshore drilling operations, but new rigs usually have both a top drive and a rotary table. The rotary table is often used to correct the direction and turn large strings of casing. (Rigzone)

2.4.1 The top drive



The top drive is built up of:

- The Swivel
- Gear box
- Pipe handler
- Elevator
- Washpipe
- IBOP – inside blowout preventer
- Torque wrench
- Valve unit
- Hydraulic pressure unit (HPU)

These parts are described below. These parts are important for the analysis in Appendix D.

The swivel is the rotating shaft in the heart of the top drive. The rotational force from the motors is exerted from the swivel and down to the drill pipe.

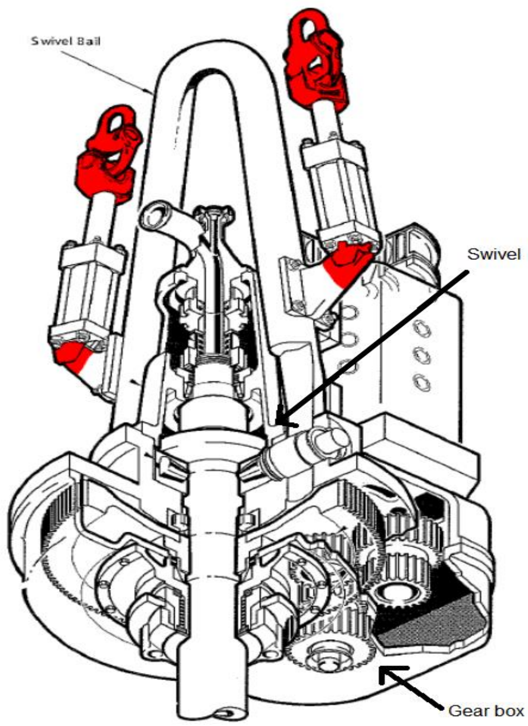


Figure 15 Swivel, gear box and wash pipe

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The gearbox provides several important functions, but one of the most important is to provide a gear reduction in the top drive. A small motor spinning very fast can provide enough power for a device, but not enough torque. The top drive needs a gear reduction because it needs a lot of torque to turn the drill string, but the motor only produce a small amount of torque at high speed. With a gear reduction, the output speed can be reduced while the torque is increased.

At the upper end of the swivel there is a connection between he rotational swivel and a fixed piece of pipe called the gooseneck. This connection is hold together by a wash pipe in Figure 15. This connection offers a stationary pipe and one rotating pipe to connect. The wash pipe is prone to wear and a leak in the washpipe can stop the drilling operation. Therefor the wash pipe is changed and overhauled after approximately 800 hours of operation(Flowtech 2014)

The pipe handler in (Fig 17) consists of two Link arms which can be rotated and tilted to cover 360 degrees around the topdrive. The pipe handler is used to pick up pipe and equipment from the drill floor. In the drilling operation pipe handler is necessary to connect new drill pipes to the drill string. The link arms are powered by the hydraulic system.

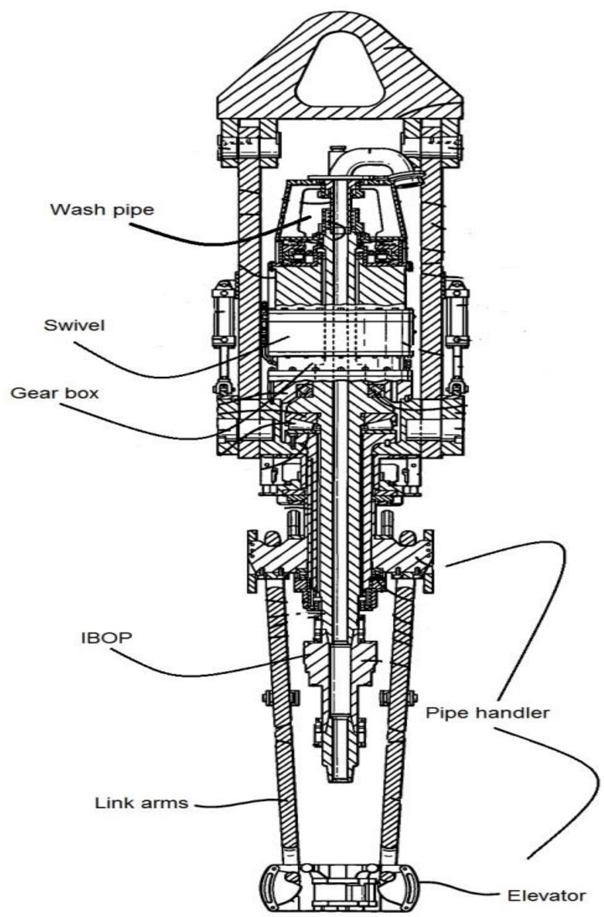


Figure 16 Pipe handler

Elevators come in different shapes and forms. There are pneumatic, hydraulic and manual elevators. The elevator is a lifting device constructed to grip around tool joints. Each pipe has a tool joint and the elevator enables connects around them. This enables faster tripping. Without the elevator the drill string would have to be connected to the top drive between every connection.

In example; the drill bit needs replacement and the drill string have to be pulled out of hole. The drill string is 3000 meters. Instead of attaching the drill string into the top drive, the elevator can latch on much faster. This saves time when tripping 3000 meters.

Typical problem with the elevator is that it does not close\open properly. Important to use an elevator fitted for the specific pipe dimension used. Typical dimensions 5” $5^{1\backslash 2}$”

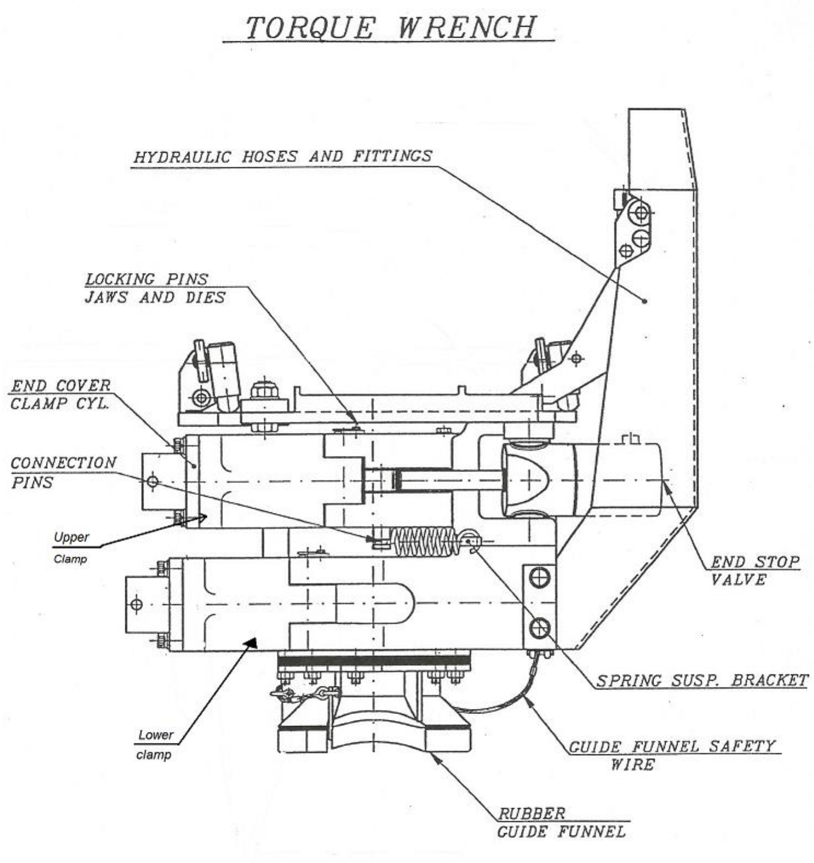


Figure 17 Torque wrench

The torque wrench (Fig 18) clamps the bottom pipe, providing torque, while the upper clamps turn the top pipe. It uses the same concept as the torque wrench on the iron roughneck. The advantage of having a torque wrench attached to the top drive is that it provides the possibility to connect and disconnect the drill string from the top drive at any height in the derrick.

The typical problem with the torque wrench is that dies are worn out or full of dirt.
Scrub with metal brush or change the dies.

The sequence of the clamps and turning function needs to be correctly adjusted.
In example: It does not grip before the turning has started. It is important to center the torque wrench to grip correctly.

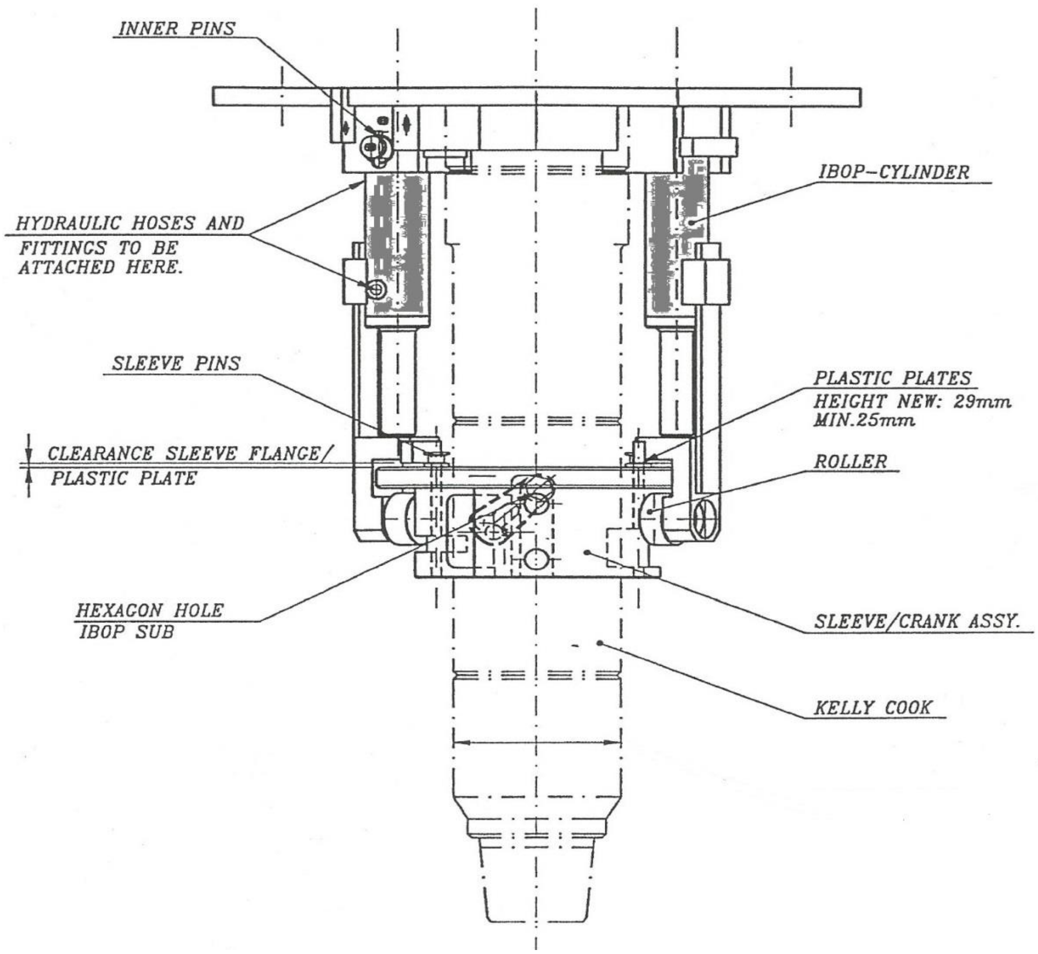


Figure 18 Inside Blow Out Preventer (IBOP)

The inside blowout preventer (IBOP) (Fig 19) is a ball valve that is open\closed by turning the ball 90 degrees. A pipe with a ball valve is called a Kelly cock. To turn the valve a hexagonal pin is inserted into the Kelly cock and turned. The turning force is exerted from the hydraulic cylinders. By pulling the sleeve/crank assembly up/down, the valve change between open and closed position.

The IBOP is an important valve that can open and close the mud flow in to the well.

In example: When tripping down after a bit change it is important to fill the inside of the drill string with mud. The IBOP provides a fast control of directing the mudflow into the drill string.
If the drill string is not filled with mud the outside pressure will be much higher than the inside pressure. This would lead to a risk of collapse.
When inspecting a Kelly cock; be sure that the valve moves completely to the closed and open position

The hydraulic power unit (Fig 20) applies the pressure that drives cylinders and other complementary parts of the hydraulic system.

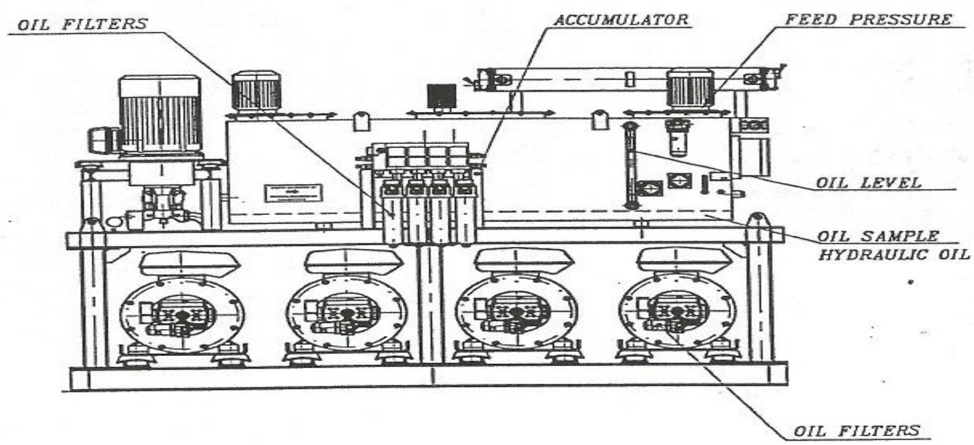


Figure 19 The Hydraulic Pressure Unit

When a hydraulic power unit starts running, the pump pulls hydraulic fluid from a tank and moves it into the accumulator. This process is repeated until the accumulator has the desired pressure. When the accumulator has the desired pressure, the charging valve switches the pump over into circulating fluid. If the pressure in the accumulator drops, the valve switches over to filling the accumulator again. The maintenance on the HPU includes periodical checks of the oil level, oil filters and oil level.(Thomasnet 2014)

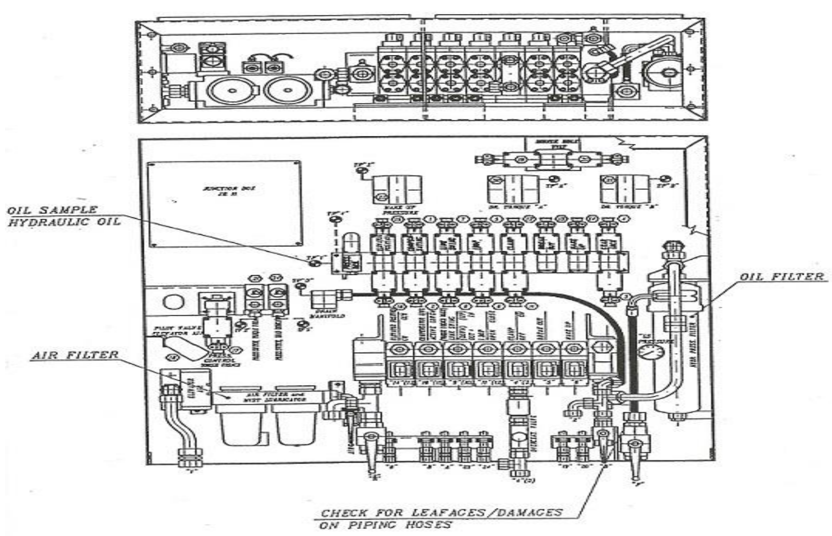


Figure 20The valve unit

The valve unit (Fig 21) directs the hydraulic fluid through the desired circuits. The valve unit is the controller of where the hydraulic pressure is applied. Maintenance on the valve unit includes periodical checks of air and oil filters, visual checks for leakages and oil sampling.

3. The Reliability centered maintenance method

Plant and equipment will not remain safe and reliable unless it is maintained. The main challenge for maintenance engineering is that it is practically impossible to predict exactly when things will fail. A maintenance engineer should use this knowledge to achieve the best possible reliability and safety at the lowest possible cost (Wong 2002).

Reliability centered maintenance was first used in the 1960s. The Airline Maintenance Steering Group's (MSG) logic was a predecessor to RCM. Stanley Nowlan and Howard Heap of United airlines introduced formal RCM to the commercial aviation industry in 1978. They published the first edition of Reliability centered maintenance in 1978.
RCM is a logic way of identifying what equipment that needs to be maintained with a preventative maintenance basis rather than letting it fail and then fix it basis, commonly referred to as the run to failure (RTF).

RCM has three phases:

1. Identify the equipment that needs preventive maintenance
2. Specify the different types of preventative maintenance activities that is needed
3. Ensure that the preventive maintenance actions are executed in a timely manner.

The definition of reliability centered maintenance (Bloom 2006):

A set of tasks generated on the basis of a systematic evaluation that are used to develop or optimize a maintenance program. RCM incorporates decision logic to ascertain the safety and operational consequences of failures and identifies the mechanisms responsible for those failures.

Identifying the equipment that needs preventive maintenance is the most important phase. The second phase is to choose the different types of preventive maintenance activities that are needed for the equipment. The third phase is to execute the preventive maintenance activities in a timely manner.

Disasters can be natural, made by human error or have its origin in the equipment. Natural disasters like storms, tornadoes and earthquakes are part of the ecosystem on earth. We cannot control natural disasters; for the most part they are unavoidable. We can make wave buoys that warn us about large waves and build structures that absorb the energy form an earthquake, but we cannot stop an earthquake or a tsunami from happening. Human error can also result in disasters, but we have a range of tools that can be used to lower the risk. Human errors can be reduced by training and procedures, but human error can never be totally eliminated. Disasters that have its origin in the equipment offer the greatest improvement potential. Nothing is ever 100 percent reliable, but disasters induced by equipment failure allows for the closest proximity to the 100 percent threshold (Bloom 2006).

The RCM use several hazard analysis types to be able to come as close as possible to this 100 percent threshold.

3.1 Hazard analysis types and techniques

There are many different hazard analysis types and techniques but some of the most important ones are:

- Fault tree analysis
- Event tree analysis
- Failure mode and effects analysis (FMEA)
- Failure modes, effects, and criticality analysis (FMECA)

3.1.1 Fault tree analysis

The fault tree analysis is a technique for reliability and safety analysis. Bell telephone laboratories developed the concept in 1962 for the US Air Force for use with the minute man system. The concept was later extendedly used by the Boeing company.(Weibull 2014)

Fault tree analysis (FTA) is a system analyzes technique. The goal of a fault tree analyses is determine the root cause and the probability of occurrence of a specified undesired event. The fault tree is a model that logically and graphically represents the various combinations of possible events.
Fault trees is graphical models that use logic gates and fault events to model the cause- effect relationships involved in causing the undesired event. The graphical model can be translated into a mathematical model if all the failure rates in the system are known.

The graphical model with Boolean logic gates

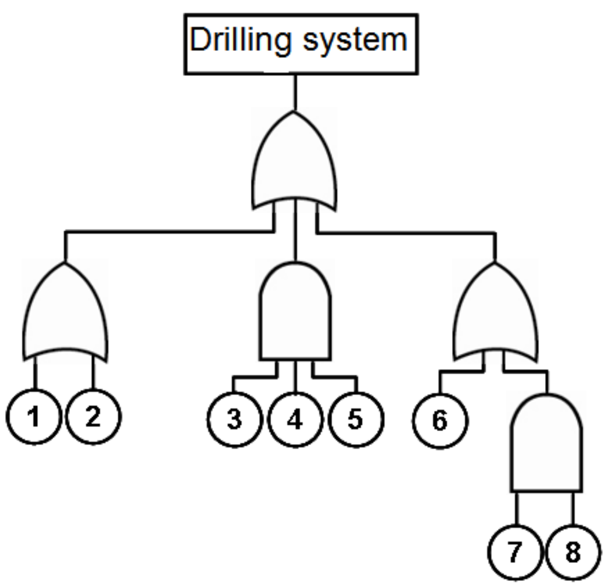


Figure 21 Fault tree

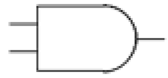
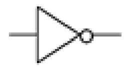
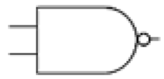
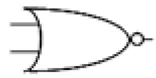
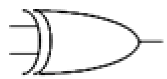
Gate	Symbol	Operator
and		A · B
or		A + B
not		$\bar{A}$
nand		$\overline{A \cdot B}$
nor		$\overline{A + B}$
xor		A ⊕ B

Figure 22 Boolean logic symbols often used in FTA

A fault tree is a model that logically and graphically represents the various fault events that can cause an undesired fault to occur. The analysis is deductive in that it transverses from general to specific causes. The failure tree develops the logical fault paths (Fig 23) from a single undesired event at the top to all of the possible root causes at the bottom. The strength of the failure tree analysis is that it is easy to perform, provides useful system insight, and shows all of the possible causes for a problem under investigation. The graphical model can be translated into a mathematical model to compute failure probabilities and system importance measures. (Ericson 2005)

Fault tree mathematics is based on Boolean algebra, reliability theory and probability theory. The following are some definitions for mathematical terms frequently used in FTA:

Probability of success; Reliability (R) of a component, which is calculated by $R = e^{-\lambda T}$, where λ = component failure rate and T = component exposure time. Also the component failure rate is:

$$\lambda = \frac{1}{MTBF}$$

MTBF = Mean time before failure

The probability for an AND gate is: $P = P_a * P_b * P_C, \ldots P_N$

Where N is equal to the number of inputs to the gate

Probability for an OR gate is:

$$P = \left(\sum 1st\ terms\right) - \left(\sum 2nd\ terms\right) + \left(\sum 3rd\ Terms\right) - \left(\sum 4th\ Terms\right) + \left(\sum 5th\ Terms\right) - \left(\sum 6th\ Terms\right), \ldots \ldots..$$

The reliability of a system can be calculated by combining the reliability of the sub systems. It is often a challenge to calculate the right failure rate for the equipment. The failure rate is an indication on how much wear a similar part statistically has lasted. The reliability measure of the system is therefore a good, but approximate measurement.

In this thesis the fault tree analysis is used to create an oversight of the drilling system rather than calculate the reliability through historical observations.

3.1.2 FMEA/ FMECA

Failure mode and effect analysis FMEA is a tool to identify failure modes that will affect the overall system reliability. The FMEA analysis has the capability to include failure rates for each failure mode. By identifying the failure modes and finding their failure rates a qualitative failure analysis can be made of the system.

FMECA is a more detailed version of the FMEA and is known as Failure Mode, Effects and Criticality Analysis. The FMECA requires more information to be obtained from the analysis than the FMEA. Information dealing with detection of possible failures and the criticality of failures differentiates the FMECA from the FMEA.

A FMECA gives the answers to the questions below:

1. How can each part conceivably fail?
2. What mechanisms might produce these failure modes?
3. What can the effects be if these failures did occur?
4. Is the failure safe or unsafe direction?
5. How is the failure detected?

A FMECA may be performed accordingly to the following scheme:

1. Definition and delimitation of the system
2. Define the main functions of the system
3. Describe the operational modes of the system
4. Break down the system into sub systems.
5. Define a criticality ranking

3.2 Maintenance Strategies

3.2.1 Run to failure (RTF)

Run to failure (RTF) is a reactive management technique that waits for an equipment failure before any maintenance action is taken. Few if any drilling rigs use this kind of "no maintenance" approach on all their equipment. A total run to failure methodology is the most expensive method of maintenance management, and drilling rigs usually perform basic preventive tasks like machine adjustments and lubrication. In a total RTF strategy no machines are rebuilt or repaired before the equipment fails to operate. Since there is no attempt to anticipate the maintenance requirements in a true RTF strategy, the maintenance department needs to be ready for all possible failures and have the spare parts ready for every possible failure. This result in a high spare part inventory and require at least all major components for all the critical equipment on the rig. The RTF strategy is still used on non-critical equipment like light bulbs.(Markeset 2011)

3.2.2 Preventive maintenance

Preventive maintenance is based on a time driven method. Maintenance tasks are based on elapsed time or hours of operation. Drilling systems usually have many tasks that are time driven. Checking the oil level and grease bearings are two examples of preventive maintenance that extends the life of drilling equipment. Preventive maintenance management systems assume that machines will degrade over time based on its classification. Drilling companies has collected data on how often different parts breaks down to find the optimum replacement schedule. They base these data on the mean time to failure (MTTF). The goal is to change out the parts before they break. This can save downtime because the task can be planned and secured so that personnel are available and the spare parts are in storage on the planned date. This saves overtime and the risk of waiting for spare parts. The most important difference of predictive and reactive maintenance is the ability to schedule a repair when it leads to the smallest impact on the operation. The operating time gained by implementing a predictive maintenance is often substantial. Operating time is an important factor for the drilling companies. In the Norwegian sector drilling companies often have a day rate of approximately 450 000 dollars. The rigs are operated 24 hours per day and any lost operating time can therefore not be recovered.

The main problem with the time based method is that the condition of the components in the system is not decaying by time but with use. The mode of operating and the variables within the system directly affect the life expectancy of the parts needing replacement. A time based method will never cover all the break downs. As an example; the washpipe on the topdrive can usually rotate for 800 hours before it starts to leak (Flowtech). But those hours does not take into account the pressure inside and the pump rate they are drilling with. The result of this can either be an unnecessary repair or a failure. If the washpipe were replaced too soon the repair would be a waste of time, but if it was too late there would be a lot of extra work.

3.3 Predictive maintenance

Predictive maintenance is not based on time, but at the condition of the component. The condition of components can be monitored by vibration sensors, thermodynamic profiles and oil analysis. There are five nondestructive techniques that are normally used for predictive maintenance management: Thermography, tribology, vibration, visual inspection and process parameter monitoring. (Markeset 2011)

Non Destructive Testing (NDT)

Non-destructing tests use test methods that don't harm the object it is testing. Many test methods are non-destructive, two examples are; Thermography and Magnetic particle testing.

3.3.1 Magnetic particle testing

Magnetic particle testing is accomplished by inducing a magnetic field in a ferromagnetic material and then dusting the surface with iron particles. The surface will produce magnetic poles and distort the magnetic field in such a way that the iron particles are attracted and concentrated making defects on the surface of the material visible.(Engineering ToolBox 2014)

Magnetic particle testing is often used offshore, because it is handy equipment and the testing can be conducted at the drill floor. The link arms should be NDT tested regularly to ensure that there are no cracks in the steel.

3.3.2 Thermography:

Thermography is monitoring of temperature. Thermo graphic profiles are made of the equipment that needs monitoring. A thermo graphic profile consists of images of equipment that are functional. These can be compared with a photo taken later to help to find pending failures. Temperature can also be monitored by thermometers placed on critical points.

3.3.3 Oil analysis:

To keep machinery running smoothly it needs oil. It lubricates the machinery and lessens friction in the system. The oil has to be clean to avoid valves and other pinch points to get blocked by contamination in the oil. A spectrometric oil analysis can detect metals in lubricant oils. If there are a lot of metals in the lubricant it can warn us about wear in the machinery. Spectrometric analysis finds fine metal particles in suspension. These typically come from spinning bearings and fretted splines etc. To complement the spectral analysis, chip detectors can be used. Chip detectors can detect larger metal flakes, which come from fatigue break ups. To capture particles in the lubricant, filters and magnets can be applied.

Oil analysis is a vital part of building an effective lubrication strategy. Used correctly oil analysis is a valuable predictive and proactive tool in ensuring that equipment reliability is optimized and lubrication-relating failures are minimized.

To maintain an accurate oil analysis program six main points has to be considered:

- How to take the samples
- Proper and readable labeling
- Proper sampling equipment and containers
- Proper sealing
- Timely sample submittal and receipt of results/report
- Timely corrective action

Take the sample at the same place every time to ensure consistency in the oil samples. Use a valve specifically for sampling purposes. The valve should be clean and thoroughly flushed before collecting the sample. The best time to take an oil sample is right after equipment shutdown. The frequency of sample analysis depends on the machine type, application, condition and operating environment.

It is important to label the sample directly after it is taken to avoid confusion. The labeling should be easy to read and the oil sampling containers should be clean with proper sealing. The sampling technique should be consistent each time a sample is drawn to send to the laboratory. A laboratory should provide dependable results and an accurate report in a timely manner. When the report is done, personnel should be able to react with a timely corrective action. (Markeset 2011)

3.3.4 Vibration monitoring:

Vibration problems can be detected by placing vibration sensors on the equipment that is in need of monitoring. Vibration sensors are placed on the equipment and a computer uses the Fourier transformation that changes the signal from a time domain into a frequency-domain representation. By studying the vibration frequencies of the machine it is possible to detect failures that are not possible to detect on a visual inspection. By analyzing these frequencies you can detect imbalances or detect broken bearings. An imbalanced machine is the most common cause of vibration and is the easiest to diagnose.
The two most usual reasons for implementing vibration monitoring are that the equipment does not live up to the expected lifetime or that it produces so much noise it becomes both an irritating and in some cases damaging effects on the personnel. Most of the noise problems come from a mechanical vibration. (Markeset 2011)

3.3.5 Visual inspections

Visual inspections are an important part of any factory or drilling rig. Visual inspections are used all the time in all kinds of departments. The visual inspections are an important part of the preventive maintenance. Visual inspections can uncover many problems and help to anticipate the breakdown of equipment. A typical visual inspection includes; Look for cracks, oil leaks, corrosion and physical wear and tear on the components. During a visual inspection it is also smart to listen for sounds that can reveal insufficient lubrication or other mechanical faults.

4. Application of Reliability Centered Maintenance on the drilling system

In the initiating and planning phase the primary system functions are defined. At the next phase called functional failure analysis, the hazard identification techniques are used to analyze the drilling system. The functional failure analysis is the basis of the task selection. The task selection is based on the risk priority number and the risk ranking categories.

The hazard techniques used on the drilling system is fault tree analysis, risk matrix and FMECA.

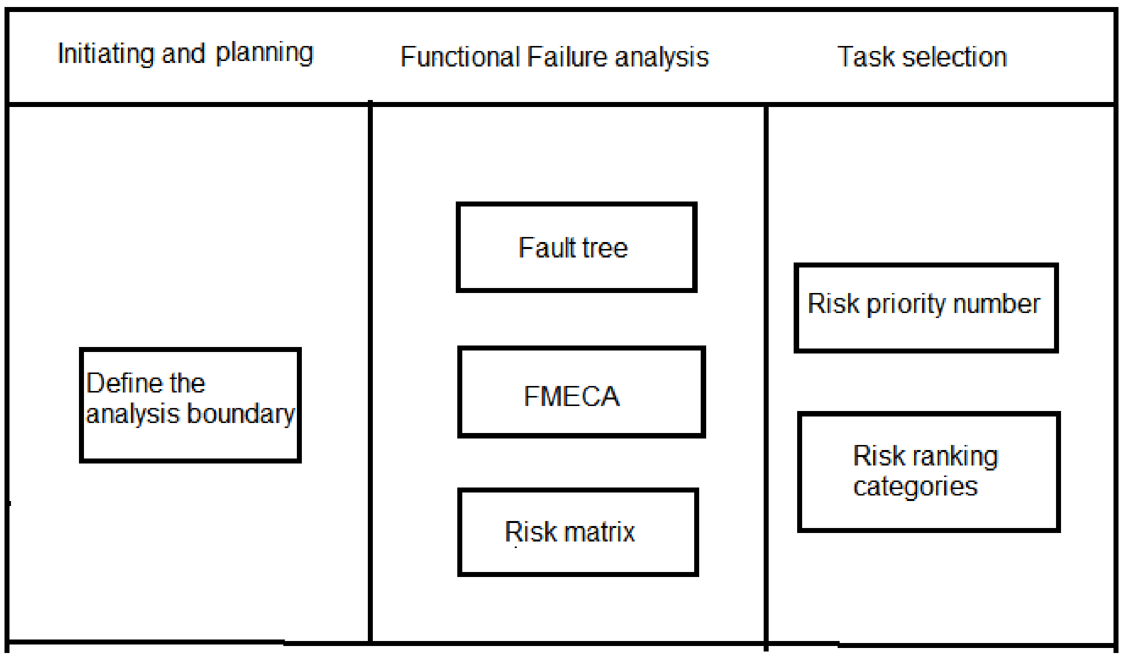


Figure 23 Reliability centered maintenance

The first step is to define the analysis boundry by creating a definition of the system. The fault tree used in 4.1 was made to give a graphical description of the system. Then the FMECA and the risk matrix are explained. The result is a risk priority number and risk ranking categories from the risk matrix.

The reason for using both a risk priority number and a risk matrix is that the RPN gives a risk priority while the risk matrix gives an indication if the existing maintenance is acceptable. If it is not acceptable (category 1 and 2) the risk Matrix gives a due date to fix the problem. The two techniques complement each other and give a better description than one of the analyses does by itself.

4.1 Definition of the system

The drilling system is a complex system consisting of several different types of machinery. The drilling systems are usually made of machines from several different manufacturers. The machines are often supplied through service companies that specialize in a certain type of equipment. Drilling rigs have many suppliers around the world and therefore many variations of drilling systems exist.

In this assignment a general drilling system is defined. In chapter 1, the theoretical part of each part of the drilling system is described.

There are many sub systems in a drilling system. It would take a lot of time to study them all. This assignment is limited to a description of some the most important drilling subsystems with emphasis on the top drive.

Sub systems in the drilling system:

- Mud pumps
- Shakers
- Drawwork
- Racking system
- Iron roughneck
- Heave compensator
- Topdrive

All of these sub systems has to function to keep the drilling rig in operation. Each sub system needs planned maintenance activities to provide optimal performance.

To create a picture of how the subsystems work together it is useful to perform a fault tree analysis.

4.1.1 Fault three analysis

A fault tree analysis is performed to get a better overview over the different sub systems. The fault tree is a graphical description of the system.

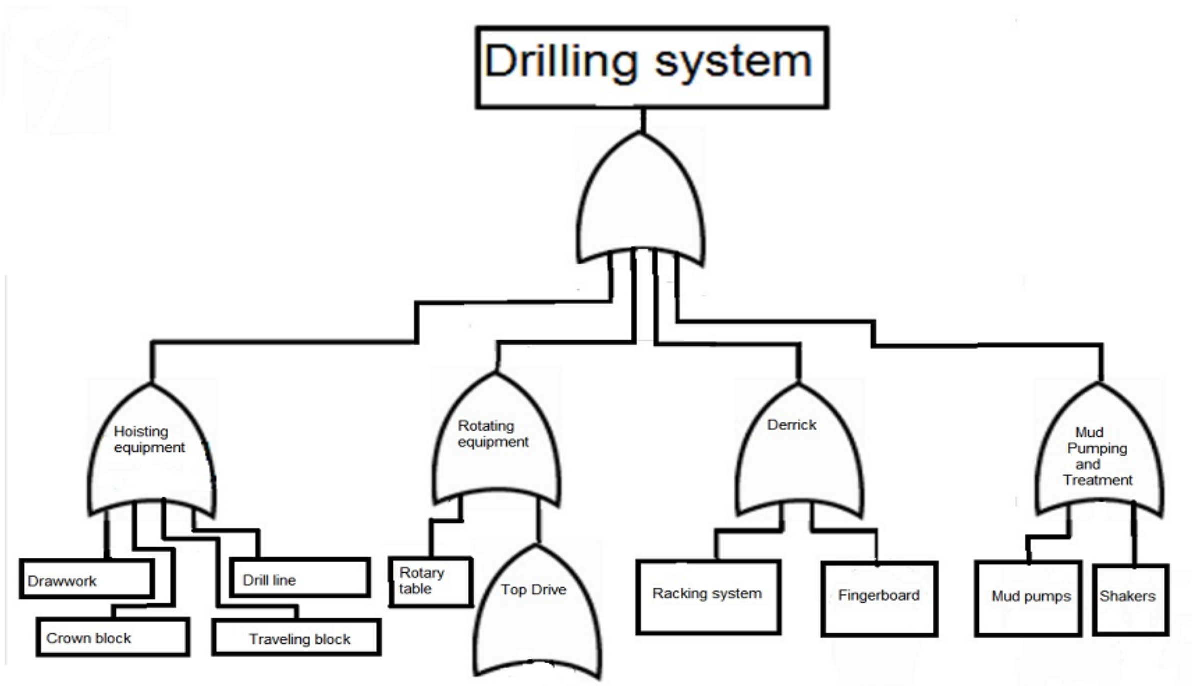


Figure 24 Failure tree of the drilling system

The Boxes contain drilling equipment that is described in chapter 1. The decision gates contain sub systems. The top drive decision gate is left open because the fault tree for the top drive continues from that decision gate.

The top drive also has several sub systems. The top drive has many functions and these have to be mapped to conduct a FMECA. The top drive system and the parts it consists of.

<u>The top drive consists of:</u>

- Swivel
- Motor
- Inside blowout preventer
- Torque wrench
- Washpipe
- Gearbox
- Valve unit
- The guide dolly
- The hydraulic power unit (HPU)
- Pipe handler
- Elevator

The connection between the different parts of the system is best explained by the fault three analyses.

The fault tree of the top drive consists of decision gates and boxes. Decision gates show the failure modes. The boxes describe possible reasons for the failure mode to occur. The failure modes are graphically linked to potential causes of failure in the fault three below.

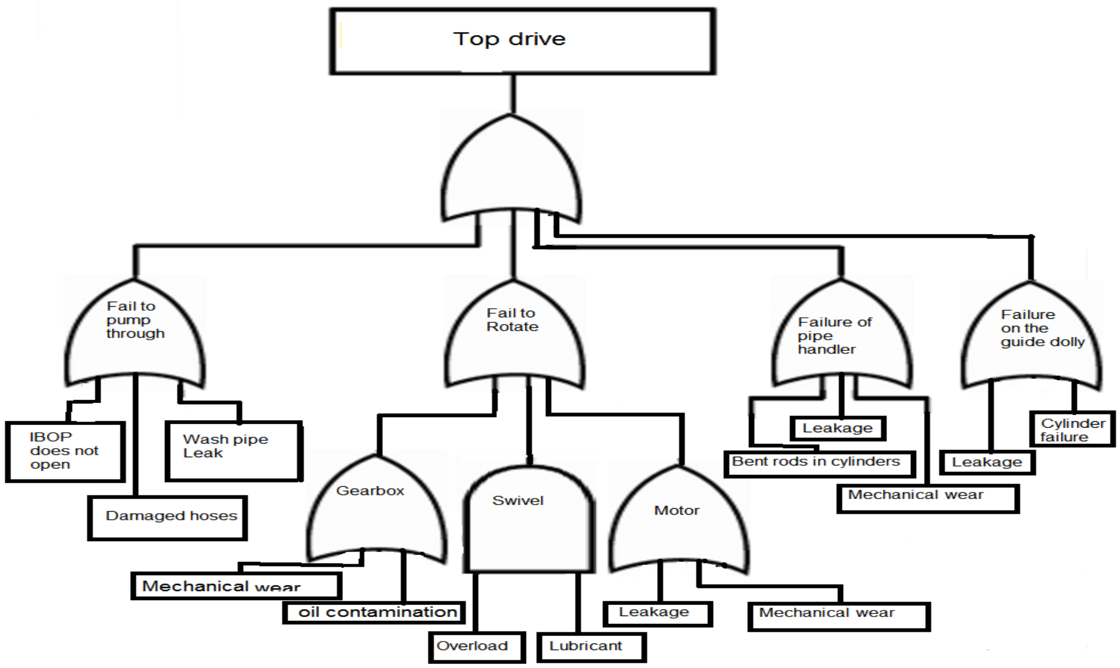


Figure 25 Failure tree of the Top drive

Fig 26 is a less detailed version of the fault three. The complete fault three of the top drive is shown in Appendix A

The identified failure modes of the Top drive are shown in Appendix B.

In Appendix F, the different types of preventative maintenance activities for the top drive are listed.

The failure mode and effect analysis (FMECA) in Appendix D show a more detailed picture of the system.

4.2 Data and approach

The Maintenance Management System (MMS) are tools for planning and scheduling equipment and asset management. MMS is often referred to as CMMS Computer based maintenance management. It is used to collect historical data, managing inventory, descriptions and work orders. Using information about system components and software, maintenance is scheduled, repairs are logged, and inspections of components are conducted. CMMS software notifies operations personnel when maintenance is necessary. There are several different software packages in the industry, but the concept is the same.

Transocean use a maintenance management system called Rig Management System (RMS). The RMS is a full scale CMMS program. The maintenance schedule shows what maintenance activities that are due on specific dates. The system is made to be easy to use when performing maintenance activities, but the failure rates of the different components of the top drive was hidden to the normal user. There were periodic checks that recommended maintenance on a time based schedule. The problem was to obtain the data these maintenance activities was based on.

I traveled offshore to Transocean Arctic and searched for failure rates in manuals. There were many manuals on drilling equipment, but the manuals usually did not give a life expectancy, if there were any, it was an approximate estimate. The data found was insufficient to obtain a full set of failure rates. Another problem with using manuals and data from the manufacturer in the analysis is that some failure rates may contain safety margins and estimates. The data collection process of the failure rates is usually not documented in the manuals.

After searching both the MMS and the manuals in the attempt to find the data needed in a quantitative analysis a different approach was needed. The individual failure rates of the components are not used in this thesis because the data was not representative or available.

A different approach was to collect data by using the experience of people that work with the equipment at a regular basis. On my trip to Transocean Arctic, I asked the Tool pusher, driller and the most experienced roughnecks about failure modes that occur on the top drive. This gave me some tips on the failure modes and a qualitative opinion on the occurrence and severity of them. The data is based on my own experience of working five years at the drill floor and the experience of my colleagues at Transocean Arctic. The data collection could have been broader, but to conduct a meeting with in example ten different drillers is too expensive for the purpose of my thesis.

I searched through several different variation of FMECA to find a suitable analysis to apply on the top drive. In Process Hazards Analysis, Hazard identification and risk analysis (Hyatt 2004), a method that did not require the individual failure rates of the components was described. In this thesis the method from (Hyatt 2004) was customized to fit the drilling system. This FMECA method provides a criticality measure and a risk priority number.

Quantitative analysis has been used at systems where the failure data was unavailable. A qualitative analysis was used at Kårstø to optimize the spare parts inventory. Data of failure rates was unavailable and a group of experts conducted a qualitative analysis and managed optimize the spare parts inventory. (Knut Erik Bang)

4.3 FMECA

The failure mode, effect and criticality analysis is divided up in tree groups and two criticality measures. The tree groups are the potential failure mode, potential cause of failure and maintenance prevention method.

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	D	Risk Priority Number (RPN)	Criticality number (S*O)

The potential failure mode and the potential cause of failure are identified by studying the system. The maintenance prevention method should prevent the potential failure mode from occurring. The FMECA rank the maintenance activities after priority to optimize the maintenance activities.

The full FMECA analysis is shown in Appendix D.

4.3.1 Risk ranking

Economic resources and available personnel is limited, prioritizing the recommendations helps to focus the efforts where they are the most necessary.

Prioritization or risk ranking in this thesis is done by using a combination of:

- Criticality analysis (FMECA)
- Risk matrix

Risk priority number (RPN) is calculated by multiplication of the Severity, occurrence and Detection values. In this thesis the minimum risk priority number value is set to 50. Any value below the minimum risk priority value is considered acceptable risk, or very low priority for further analysis. A RPN value above the minimum risk priority value needs further analysis.

Criticality is a measure of the consequences of a failure mode determined from its severity and the probability of its occurrence.

Severity is a measure of the degree of damage a failure mode inflicts on the various targets.
Occurrence is the frequency of the failure for the drilling process or a part of the top drive. Detection is the ability to detect the failure before it affects the top drive

The levels of Severity, occurrence and detection is assigned an arbitrary value for calculating the Risk priority number (RPN)

Example of the Risk priority ranking:

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	D	Risk Priority Number (RPN)
Failure to rotate	Stop drilling	8	Motor failure	1	Annual check of splines on swivel/motor connection. Inspect and check the HPU and Valve unit.	1	8

The **S**everity of a failure of rotation is significant downtime and major financial impacts. The top drive is inoperable but safe. This gives the failure mode a **S**everity ranking of 8 in Table 1 in appendix C.

This **O**ccurrence of this failure mode is extremely unlikely. This gives the failure mode an **O**ccurrence ranking of 1 in Table 2 in appendix C.

If the top drive stops rotating the driller will notice it immediately. The driller is looking straight at the dill string which is rotating when drilling. The fail to rotate failure mode gives a **D**etection ranking of 1 in Table 3 in appendix C.

By calculating the product of the **S**everity, **O**ccurrence and the **D**etection rankings we can create a Risk priority number.

The risk priority number (RPN) of the failure to rotate mode is S*O*D = RPN

S=8, O=1, D=1
Risk priority number (RPN) =8*1*1= 8

The Risk priority number is used to choose which potential failure mode that needs to be attended first and which maintenance activities that might be prioritized last. When the risk priority number is high it might be necessary to implement new maintenance prevention methods or increase the frequency of the maintenance activity. The risk priority number can also be used to identify excessive maintenance. If the risk priority number is low, there might be excessive maintenance.

4.3.2 Criticality number and Risk matrix

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	Criticality number (S*O)
Failure to rotate	Stop drilling	8	Motor failure	1	Annual check of splines on swivel/motor connection. Inspect and check the HPU and Valve unit.	8

The criticality number calculated at the right side of the FMECA is a product of the severity and occurrence of the failure mode. The Criticality number is then used to place the failure mode into a risk matrix.

<u>Transformation of Criticality number into Risk rating categories:</u>

- 25 or less is category 4
- 50 or less is category 3
- 75 or less is category 2
- 75 to 100 is category 1

Failure mode	Potential cause of failure	Criticality number	Risk rating categories
Failure to rotate	Motor failure	8	4
	Gear box failure	24	4
	Swivel failure	8	4
Lubricant system failure		32	3

The tables with all the failure modes are shown in full size in appendix E.

As an example: Failure to rotate has a severity of 8 and an occurrence of 1. With a risk ranking of 4 the failure mode is placed in the green box with number 4 in the lower right of the risk matrix.

Risk matrix		**Severity**			
		1	**2**	**3**	**4**
Occurrence	**4**	**4**	**2**	**1**	**1**
	3	**4**	**3**	**2**	**1**
	2	**4**	**4**	**3**	**2**
	1	**4**	**4**	**4**	**3**

The failure mode failure to rotate has a risk ranking of 4 and is acceptable as is, no migration is required

Number	**Category**	**Description**
3	Acceptable with procedures and controls	Should be verified that procedures and controls are in place
4	Acceptable as it is	No migration is required

The full table of risk ranking categories for the risk matrix is shown in Appendix E.

All the failure modes in this thesis classify to a risk ranking of 4, except the lubrication system that is classified as 3. The lubrication system is acceptable with procedures and controls, but these should be verified.

4.4 Selection of maintenance strategy

The second step in RCM is to specify the different types of preventative maintenance activities that are needed.

Most of the parts on the top drive need a periodic maintenance strategy. Activities like lubrication, visual inspections and oil sampling fits into a periodic schedule. Some of the equipment needs to be tended more often of than others. The maintenance activities should therefore be divided into groups.

- Group A of maintenance is done every 3 months
- Group B is done every 6 months
- Group C is done annual
- Group D is done every five years

In the maintenance plan in Appendix F, the different types of preventive maintenance activities that are needed for the top drive is listed.

Predictive maintenance like oil sampling, thermography and vibration monitoring could be used to detect impending failures. Oil sampling is important to avoid oil contamination and should be applied to all drilling systems. Thermography can detect changes in temperature in machines, but is not often used on top drives. Vibration censors could be used on the top drive, but the vibration from the drilling process would most likely disrupt the vibration trend.

4.5 Result

The result of the FMECA analysis was identification of tree failure modes that should be prioritized in the maintenance plan. The frequency of the high priority maintenance activities should be increased or new maintenance activities should be implemented. The three failure modes that have the lowest RPN may have a potential to reduce the maintenance frequency. By increasing the frequency of the high priority activities and lower the frequency of the low priority activities the maintenance system is optimized. The highest priority failure modes are shown in the table below.

High Priority	
Failure mode	Risk priority number (RPN)
Lubrication system failure	64
Torque wrench failure	60
Elevator failure	60

The FMECA analysis in this thesis ranks the lubrication system as the highest priority. While the Torque wrench and the elevator has the second highest RPN. The lubrication system, elevator and torque wrench should be prioritized in the maintenance plan.

The Lubrication system

The lubrication system has the highest RPN in the analysis and a risk ranking of 3. The maintenance on the lubrication system should be based on both periodical and predictive maintenance. The periodical schedule should contain visual inspections and lubrication. Oil sampling is a part of the predictive maintenance. The theory for oil sampling is described in 3.3.2. Since the lubrication system has the risk ranking of 3 in the risk matrix, the procedures and controls for oil sampling should be verified.

Example of maintenance that should be done more frequently:

In the derrick there are often lubrication centrals. These holds ten grease nipples or more and each of them are attached to a hose that leads the grease into bearings. These hoses and fittings have to be checked. They are often plugged by old grease.

The Torque wrench

The torque wrench failure mode has two possible failure causes.

- The clamps do not grip on the tool joint
- Sequence failure

Both the potential cause of failure result in severity rank 3. The failure of the torque wrench has a slight effect on the drilling operation. If the torque wrench fails to break out the connection in the top drive, an old fashioned rig thong can be used to break it out. In the analysis the clamps that do not grip have an occurrence of 5, while the occurrence of sequence failure is 2.

To reduce the occurrence of clamp failure, the frequency of cleaning the dies in the torque wrench should be increased. It often helps to scrub the dies with a steel brush and wash them with a high pressure water gun.

The Elevator

The Elevator failure mode is an important failure mode to analyze. The potential effect of the failure is failure to lock around drill pipe. The elevator is used in many different operations. In example when picking up pipe or tripping in or out of the well. The occurrence of an elevator failing to lock around a drill pipe has an occurrence of moderately low likelihood. Occasional failures are likely because the fittings and the hoses from the top drive to the elevator is prone for damage.

The occurrence of damage to the hydraulic hoses can be reduced by fastening them to the link arms and visually inspect them on a regular schedule. The visual inspections of the elevator should be increased and the possibility to add a function test should be considered.

Failure modes with low RPN that are identified in the analysis:

Low Priority	
Failure mode	Risk priority number (RPN)
Hydraulic pressure unit failure	7
IBOP failure	7
Swivel failure	8

The Hydraulic Pressure Unit, IBOP and swivel has a low RPN, and the possibility of reduced maintenance frequency should be considered.

An example of how the result from the analysis could be used in maintenance optimization;
Transocean Arctic is sailing in to Westcon Yard in July 2014 for a 5 year classification. The schedule for maintaining the drilling system at the yard is very tight. Future breakdowns can be prevented by focusing the maintenance activities on the most critical part of the system. If they were following the maintenance plan defined in Appendix F, a D-service should be performed when they enter the yard. D-service includes stripping down the whole top drive including the power swivel and NDT test all load bearing parts.

The FMECA in this thesis rate swivel failure with an Occurrence of 1. Occurrence ranking 1 states that the failure mode is extremely unlikely. Stripping down the power swivel includes a risk of getting the swivel surface damaged. The swivel is made of massive steel and the swivel will work properly as long as it is lubricated.
Stripping down the swivel on the top drive every five years is an example of a maintenance activity that could be done at a lower frequency. Stripping of the power swivel could in example be reduced to every 10 years, or until an especially heavy load has occurred during the drilling process.

By reducing the frequency of low prioritized activities the maintenance personnel can focus on high priority tasks. Instead of stripping down the power swivel, the maintenance crew should work on the lubrication system. In example; Replace old/damaged pipes and check fittings.

4.6 Comparison of results versus existing MMS

The results of this thesis are not very different from what you get out of a maintenance management system. Both the thesis and a MMS have a criticality ranking and a maintenance plan with a priority ranking. The MMS systems used in the industry are more detailed than this thesis. Drilling companies use computer analysis to keep track of all the historical failure data. The grade of detail in a computer program is very high. The accuracy of the data that is inserted into the program therefore needs to be high. The challenge is to gather a complete set of failure rates on every component in the system. If the data that is needed to create a complete quantitative analysis is unavailable, the option is to make a quantitative analysis. A qualitative analysis performed by experts, can give just as good results as a quantitative analysis.

In Transocean's rig management system (RMS) there are many details and procedures. They have done a good job building up the maintenance management programs. The maintenance plan schedules the maintenance and spare parts are automatically ordered and ready in stock when needed. This thesis has a simpler maintenance plan than the drilling companies use. The maintenance plan in appendix F is extracted from an old binder I found in the back of the drilling cabin while searching for failure rates.

4.7 Uncertainties

The analysis in this thesis has uncertainty regarding the qualitative interpretation of the severity, occurrence and detection of the failure modes. To increase the certainty of the data in the analysis, a wider range of experienced personnel could be questioned.

The occurrence and detection of failure modes can differentiate between different drilling systems. In this thesis the analysis is applied to a drilling system based on Transocean Arctic.
The analysis should be applied to a specific system. If the method presented in this thesis were applied to a real life drilling system, the rig company would have to gather the drillers and tool pushers that work at the specified rig. These experts can rank the failure modes presented in this thesis. By collecting knowledge from experts, a precise qualitative result can be found.

Ranking maintenance activities has no final answer. Analyzing the system enable us to rank the most important activities on that specific time. After some time the occurrence of the failure modes may change. Risk ranking should therefore be updated regularly.
The analysis of the system could have been more detailed with actual failure rates. The main problem was to find failure rates on the component level. In the rig management system for Transocean Arctic I found criticality ratings on different jobs that was attached to the top drive, but the data behind the criticality number was not accessible. Manuals and books regarding the topdrive only have approximate estimates of the failure rates of components.

4.8 Discussion

Reliability centered maintenance is a vide term and there are many different approaches to applying it to a system. The RCM methodology is a necessary and effective tool that can be adapted to any kind of industrial system. There are many available hazard analyzes in the RCM methodology, but the FMECA is a well-known and widely used method in the oil and gas industry. The drilling system is an interesting system to analyze, but it is a large and complex system. To apply a FMECA on the drilling system is a large task, so it was necessary to focus on a sub system to narrow it down. The top drive is an interesting subject to analyze since it is used at all modern drilling rigs. The drilling system is chosen because of my experience with the drilling system as a roughneck.

This thesis has focused on the actual parts of the top drive. The most severe effects of failures in the analysis have a severity ranking of 8. This leads to significant downtime and major financial impacts. None of the failure modes I have studied is classified as the maximum severity ranking. A severity ranking of 10 is defined as Injury or harm to operating personnel. Falling objects is not included in this thesis, but falling objects are the most dangerous hazard on the drill floor. The top drive is hoisted 40 meters above the drill floor, if there are any loose parts falling from the topdrive to the drill floor it can be fatal. During a drilling operation there is a lot of vibration in a top drive. Periodical checks for potential falling objects are important to avoid falling objects on the drill floor.

Most of the maintenance on the top drive is performed while it hangs in the traveling block. This makes the top drive hard to access without a man rider. A man rider is a winch built to lift personnel. When performing maintenance on equipment that is used in the height, it is very important to bring all the tools used for the job back down.

4.9 Future work

The RCM methodologies in the current thesis dos not cover the whole drilling system. Related future work should deal with the development of a complete RCM program for a specific drilling company. The top drive could be further analyzed using other hazard analysis techniques to get a broader view of the system.

Summary and conclusion

The drilling system is a large system to analyze. The analysis in this thesis was performed on the top drive which is a sub system. To complete a full analysis of the drilling system, all of the sub systems described in 4.1 would need to be analyzed. The challenge of this thesis has been to find a method that could be applied to the drilling system without a complete set of failure rates for the individual components in the topdrive. A lesson learned during the assignment was that it is not straight forward to collect a full set of failure rates for a system. The same problems with data will probably occur when analyzing different parts of the system too. There are many versions of failure mode, effect and criticality analysis (FMECA). The FMECA in this thesis is a customized version of the method used in (Hyatt 2004). The drilling system maintenance schedule can be optimized by reducing the frequency of less important maintenance, and adding maintenance to activities with a high priority.

The FMECA provide a risk priority number and a risk ranking. There were three failure modes that have a risk priority number over 50 which is the minimum risk priority value. These failure modes were, torque wrench, the elevator and the lubrication system, of which the latter had the highest RPN value. Any value below the minimum risk priority value is considered an acceptable risk. A RPN value above the minimum risk priority value needs further analysis. In order to lower the RPN one can add new maintenance activities or increase frequency on existing activities. In results 4.6 there is a description of the high priority failure modes and examples of maintenance activities that can be added. The three lowest rated failure modes was the swivel, the valve unit and the hydraulic pressure unit. The maintenance frequency on these failure modes should be decreased if possible to free up time for other projects or save money.

The results from both the FMECA and the risk matrix rank the lubrication system as the most critical. In the risk matrix the lubrication system got a criticality ranking of 3 while the rest of the failure modes were ranked as class 4. A ranking of three is acceptable, but the procedures should be checked. Rank four is acceptable as it is, and no risk migration is necessary. The conclusion from the risk matrix is that the oil sampling and lubrication procedures should be verified.

To verify that the procedures are followed at the rig floor, the drill crews should be informed that the lubrication system has priority. The driller should verify that the roughnecks know how to perform the lubrication procedures correctly. The last part of the RCM methodology is to ensure that the preventive maintenance actions are executed in a timely manner. By performing the maintenance correctly and in a timely manner, break down of equipment will be minimized.

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Fig 18 Maritime Hydraulics Torque wrench manual.

Fig 19 Maritime Hydraulicks Inside blowout preventer manual

Fig 20 Maritime hydraulics - Hydraulic pressure unit manual.

Fig 21 Maritime hydraulics- Valve unit manual.

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Appendix A

Fault three

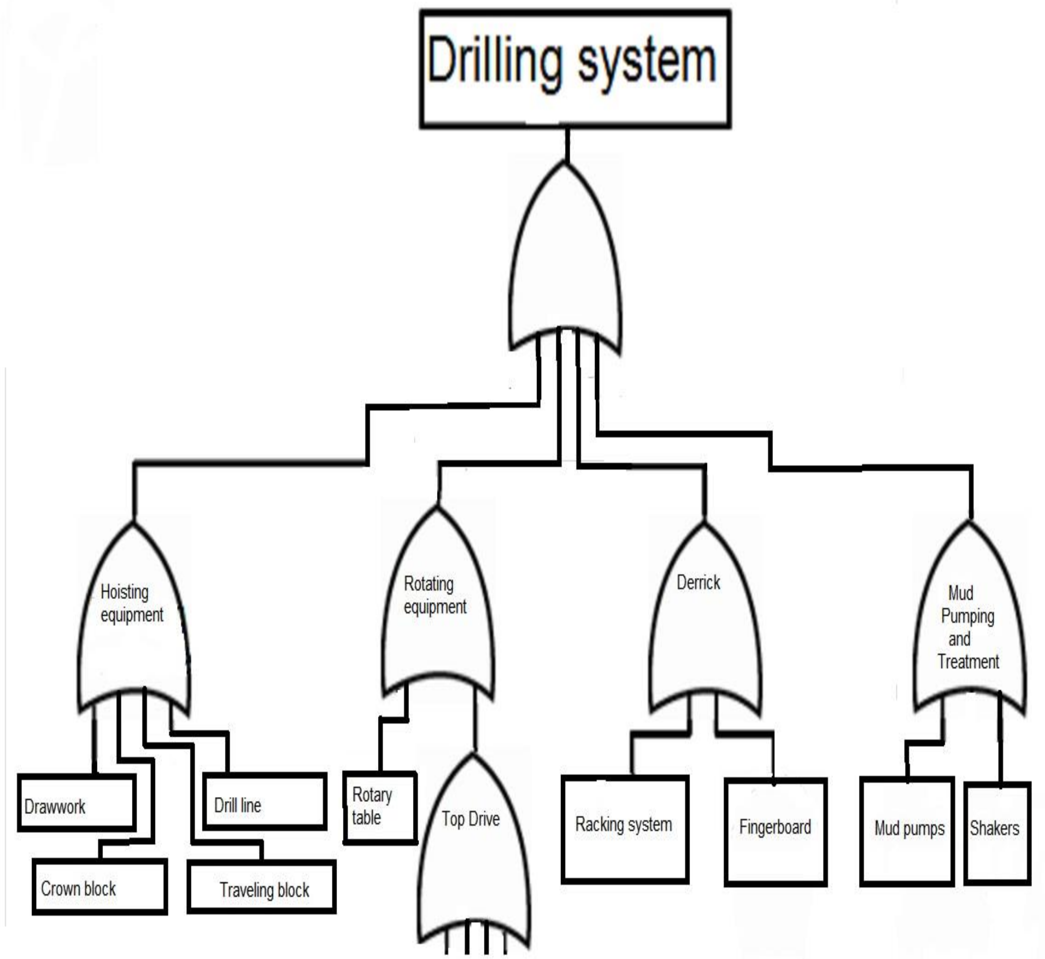

Figure 26 Failure tree of the Drilling system

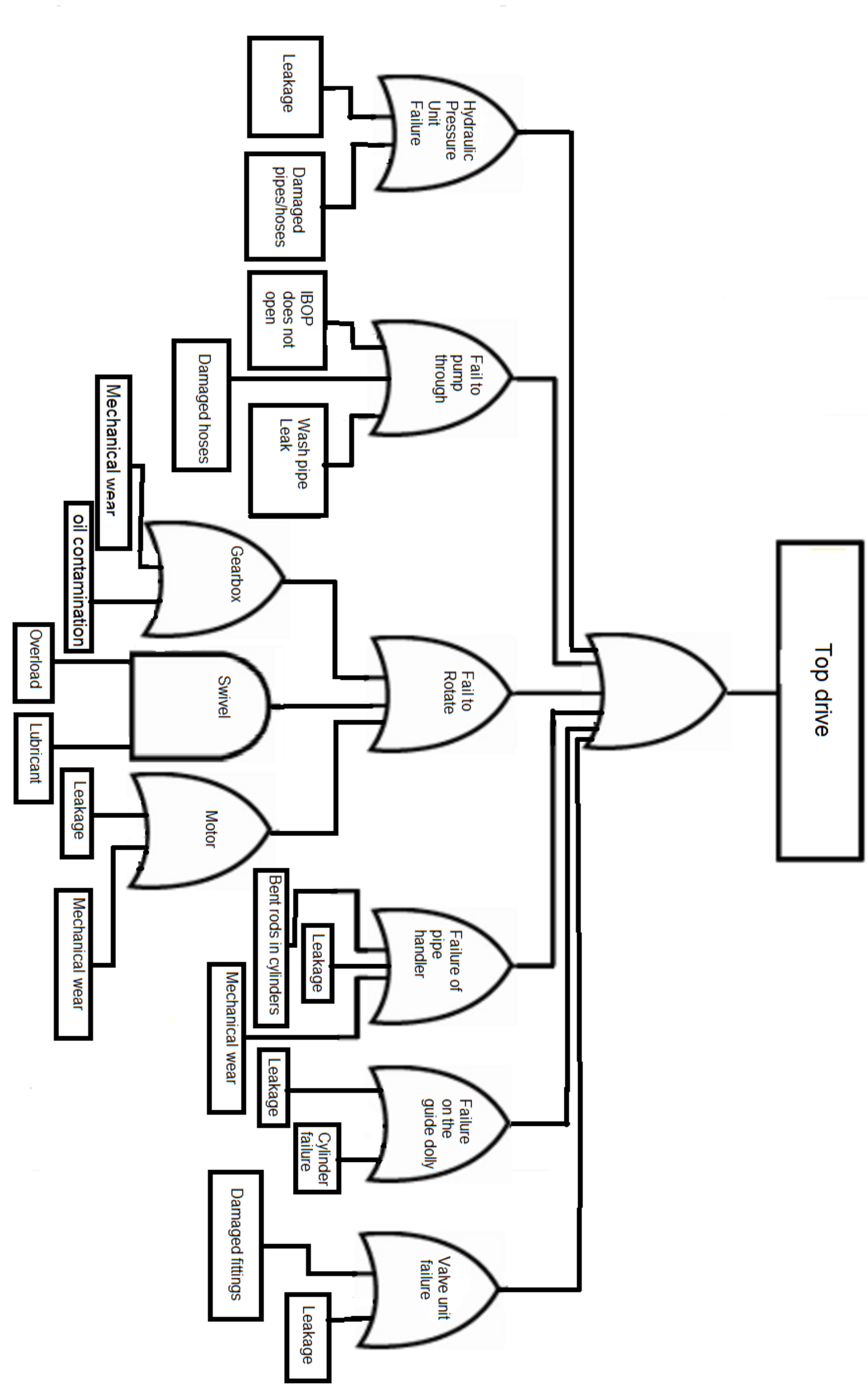

Figure 27 Failure tree of the top drive

Appendix B

Identification of Top drive failure modes

- Fail to rotate
  - Electrical/hydraulic motor shutdown
- Fail to pump through top drive
  - fail open/close inside blow out preventer
- Top drive tilt failure
  - Tilt cylinder fail
- Lubricant systems fail
  - Leakages, damages,
  - particles in the oil
- Fail on pipe handler
  - Torque wrench fail: Torque wrench fails to break or make connection
  - Elevator fail: Elevator does not open/close
- Hydraulic power unit
  - Leakages
- The valve unit
  - oil sample of hydraulic oil, air filter, oil filter, leakages\damages on piping/hoses
- The guide dolly:
  - Wear and tear of boogie wheels, side rollers, dolly arm bolts, cylinder bolts

Appendix C

Severity, Occurrence and Detection ranking

Table 1 Severity values used in Risk Priority Number calculations

Effect	Rank	Criteria
None	1	Might be noticeable to the driller. Improbable / not noticeable on the operation
Very slight	2	No effect on the drilling process. Insignificant / negligible effect on the operation
Slight	3	The driller will probably notice the effect but the effect is slight
Minor	4	The drilling operation might be affected. It will have a minor negative impact on the operation
Moderate	5	Impacts will be noticeable throughout the drilling operation. Reduced performance with gradual performance degradation.
Severe	6	Disruption to the drilling operation. Top drive is operable and safe but performance is degraded.
High severity	7	Significant downtime. Top drive performance is severely affected
Very high severity	8	Significant downtime and major financial impacts. Top drive inoperable but safe
Extreme severity	9	Failures resulting in hazardous effects highly probable. Safety and regulatory concerns
Maximum severity	10	Injury or harm to operating personnel. Failure resulting in hazardous effects almost certain. Non-compliance with government regulations.

Table 2 Occurrence ranking used in Risk Priority Number calculation

Occurrence	Rank	Criteria
Extremely unlikely	1	Failure highly unlikely
Remote likelihood	2	Rare number of failures likely
Very low likelihood	3	Very few failures likely
Low likelihood	4	Few failures likely
Moderately low likelihood	5	Occasional failures likely
Medium low likelihood	6	Medium number of failures likely
Moderately high likelihood	7	Moderately high number of failures likely
High likelihood	8	High number of failures likely
Very high likelihood	9	Very high number of failures likely
Extremely likely	10	Failure almost certain

Table 3 Detection ranking used in Risk Priority Number calculation

Detection	Rank	Criteria
Extremely likely	1	Driller will almost certainly detect the existence of the defect
Very high likelihood	2	Driller have very high probability of detecting existence of failure
High likelihood	3	Has high effectiveness for detection of the failure
Moderately high likelihood	4	Has moderately effectiveness for detection
Medium likelihood	5	Has medium effectiveness for detection
Moderately likelihood	6	Has moderately effectiveness for detection
Low likelihood	7	Has low effectiveness for detection
Very low likelihood	8	Has very low effectiveness for detection
Remote likelihood	9	Driller has very low probability of detecting the existence of the failure
Extremely unlikely	10	Driller will almost certainly not detect the existence of the failure

Appendix D

FMECA

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	D	Risk Priority Number (RPN)	Criticality number (S*O)
Failure to rotate	Stop drilling	8	Motor failure	1	Annual check of splines on swivel/motor connection. Inspect and check the HPU and Valve unit.	1	8	8
		8	Gearbox failure	2	Oil analysis	1	16	16
		8	Swivel failure	1	Top swivel bearing, visual check for mud/dirt and correct clearance. Lubrication Oil samples Function test	1	8	8
Failure to pump through the topdrive	Stop drilling	7	IBOP valve failure	1	Visually inspection. Check if Kellycock is complete open\closed Check all hydraulic hoses and fittings	1	7	7

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	D	Risk Priority Number (RPN)	Criticality number (S*O)
Lubricant system fail	Stop drilling Equipment break down Downtime	8	Leakage Particles in the oil	4	Visual inspection Check for leakages, damage and loose parts etc. Oil analysis	2	64	32
Fail to tilt	Downtime	4	Leakage on hydraulic pipes/fittings, Damaged cylinder	3	Visual inspection Lubrication	5	60	12
Torque wrench failure	Downtime	3	Clamps do not grip.	5	Visual inspection	4	60	15
		3	Sequence failure	2	Function Test torque wrench	4	24	6
Failure on pipe handler	Downtime	6	Mechanical wear Bent rods in the pneumatic cylinders Damage/leakage on the hydraulic system.	2	Visual inspection Lubrication Function test pneumatic cylinders for bent rods Check hydraulic hoses and fittings for mechanical damage and leakages	1	12	12

Potential failure mode	Potential effect of failure	S	Potential cause of failure	O	Maintenance prevention methods	D	Risk Priority Number (RPN)	Criticality number (S*O)
Elevator fail	Failure to lock around drill pipe	6	Failure to close\open correctly	4	Visual inspection Check inserts, lubrication Check hydraulic Hoses and fittings	1	24	24
Extend retract the dolly	Failure to center top drive over rotary Downtime	4	Failure to extend/retract the top drive Mechanical wear Bent rods in the pneumatic cylinders	2	Visual inspection Lubrication	1	8	8
Failure on Hydraulic power unit	No hydraulic pressure	6	Leakages Damaged fittings	3	Visual inspection Hydraulic oil sample	1	18	18
Valve unit failure	Function failure of hydraulic equipment	6	leakages\damages on piping and hoses	2	oil sample of hydraulic oil, Clean air filter and oil filter	1	12	12

Appendix E

Risk matrix

Failure mode	Potential cause of failure	Criticality number	Risk rating categories
Failure to rotate	Motor failure	8	4
	Gear box failure	24	4
	Swivel failure	8	4
Failure to pump through the topdrive		7	4
Lubricant system failure		30	3
Top drive tilt failure		12	4
Torque wrench failure		15	4
Pipe handler failure		12	4
Elevator failure		24	4
Extend\retract Dolly failure		8	4
Failure on the hydraulic power unit		18	4
Valve unit failure		12	4

Table 4 Risk ranking categories for the risk matrix

Number	Category	Description
1	Unacceptable	Should be migrated by administrative or engineering controls to a risk ranking of 3 or less within a specified time period. (Six months)
2	Undesirable	Should be mitigated to a risk level of 3 or less within a specified time period. (12 months)
3	Acceptable with procedures and controls	Should be verified that procedures and controls are in place
4	Acceptable as it is	No migration is required

		Severity			
		1	2	3	4
Occurrence	4	4	2	1	1
	3	4	3	2	1
	2	4	4	3	2
	1	4	4	4	3

Appendix F

Table 5 Existing Maintenance plan Top drive

Table 7 is the maintenance activities extracted from Transocean Rig management system (RMS)

Maintenance activity	Period
Oil sample	30 days
Mechanical check	30 days
Pre/post jarring inspection	30 days
Check torque on Bondura bolts	90 days
Mechanical check	90 days
Oil sample	90 days
Cleaning NDT	90 days
Change oil check	90 days
Inside Blowout preventer – check /replace	180 days
Hydraulic motor spline inspection	180 days
Electrical check	180 days
Annual inspection NDT	360 days
Electrical check	360 days
Mechanical annual service	360 days
Classification NDT	1800 days

Maintenance plan

The following maintenance activities are extracted from an old binder found in the back of the driller cabin at Transocean Arctic. The binder was marked Ross rig, and included simple maintenance plan. The maintenance plan below is a result of extracting maintenance activities for the top drive from the binder.

A-service (every 3 months)

- Visual inspection
- Lubrication
- Oil samples

B-service (every 6 month)

- A-service
- Inspection and check of components
- Function test of equipment

C-service (Annual)

- B-service
- Inspection/NDT test of all accessible load bearing parts without stripping down the power swivel
- Inspection of all accessible parts in drive assembly without stripping down the power swivel

D-service (Every 5 years)

- Ship the topdrive onshore
- C-service
- Stripping down the power swivel/NDT-test of all load bearing parts.
- Recertification of equipment

A-service (3 months)

Torque wrench:

Visual inspection to discover wear/tear/leakages
Lubricate all lubrication points

Swivel:

Check Oil level and pressure; take oil sample of swivel oil
Grease all lubrication points, including top swivel bearing

Gear box:

Check Oil level and pressure; take oil sample of gear oil
Grease all lubrication points

The drive motors:

Hydraulic DDM: check for oil leakages on motor base
Electric DDM: Grease nipples on DC-motor and change purge air filter

The valve unit:

Check oil filter and take oil sample
Check air filter and mist lubricator

The guide dolly:

Grease all nipples

The hydraulic power unit:

Check oil level on hydraulic oil tank
Check feed pressure on the power unit (p.u)
Take oil sample
Check oil filters
Check for leakages
B- Service (every 6 months)

In addition to A-service, the B service contains a thorough inspection of components to discover defects, malfunctions, wear and damages, followed by a function test of equipment.

The function testing requires tests of:

- The pie handler functions
- Rotation
- Power unit
- Guide dolly retracting system

B and C service includes an A-Service.
B-Service includes an inspection of locking wire of bolts and screws.

Torque wrench

- Inspect funnel rubber for wear
- Inspect funnel safety wires
- Check save sub outside diameter. Original 197 mm. Minimum 190 mm
- Open torque wrench lower and upper half
- Inspect locking of pins and jaws\dies
- Inspection of spring suspension bracket and connection pins for wear\damage
- Inspect suspension and safety chain for wear\damage
- Inspect quick-couplings on manifold
- Inspect all hydraulic hoses and fittings
- Check that all bolts are secured with locking wire
- Inspect end stop valve on torque cylinder for wear
- Check for leakages on clamp\torque cylinders
- Check bolted connection on end cover and clamp cylinder
- Check alignment on torque wrench

The inside blowout preventer (IBOP)

- Tilt out the IBOP cylinders by removing inner pins and inspect them.
- Check the plastic plates in the end of the cylinders. Replace if the hight of these are 25 mm or less (new is 29 mm)
- Inspect rollers
- Remove sleeve and crank assembly. Inspect the crank\sleeve for cracks\wear
- Inspect sleeve pins
- Visual inspection of Kelly cock
- Inspect hexagon hole on IBOP sub for wear\damage
- Inspect clearance between sleeve flange and plastic plate
- Check hydraulic hoses and fittings

The pipe handler

- Function test pneumatic cylinders, check for bent rods
- Check that all screws are secured with locking wire
- Check all hydraulic hoses and fittings for leakages and damage

The swivel and gearbox

- Check the top swivel bearing, visual heck for mud\dirt and correct clearance.
- Inspect gear lock assembly.
- Function test of compensator link, relief valve
- Check all hydraulic hoses and fittings for damage and leakages.
- Check that all screws are secured with locking wire

The drive motors

- Electrical DDM: inspect all cables on DC motor for wear and tear.
  Check air filter on DC motor

- Hydraulic DDM: Check all hoses and fittings for wear\damage and leaks

The valve unit

- Check all hydraulic piping, hoses, fittings for leaks\damage and wear.
- Check supply Pressure (P), Return pressure (R), Drain pressure (D) and pilot pressure.

The guide dolly

- Check the boogie wheels outside diameter
- Check the connection on DDM\Dolly for cracks and wear.
- Centering of DDM to well-center
- Check all hydraulic hoses and fittings for damage\wear and leakages

The Hydraulic power unit

- Check all hydraulic hoses and fittings for damage\ wear and leakages.
- Check accumulator precharge

Other equipment

- Inspect service loops for wear and tear
- Check safety chains for service loops.
- Check drain accumulator precharge on DDM
- Inspect junction boxes for leakages and corrosion.

C-Service (Annual)

- B-Service
- Disassembly of all accessible loadbearing parts without stripping the power swivel
- Inspection of all accessible parts in main drive assembly (pinion, main wheel, gearbox, pinions on hydraulic motors, O-rings)
- DC-motor: Inspection of pinion and motor base. Check for air\water leakage.