Master Thesis

Possible Implementation of Automated Systems in Drilling Rig Design

Department Mineral Resources and Petroleum Engineering
Chair of Drilling and Completion Engineering

in
Cooperation
with

BAUER Maschinen AG

Author: Klaus Kurz, BSc
Supervised by: Prof. Dr. Gerhard Thonhauser

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EIDESSTATTLICHE ERKLÄRUNG

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Abstract (English)

The implementation of automation technology has changed many industries, with the result of steady increases of economic performance and quality of the manufactured goods. With all the benefits of automated systems, the drilling industry is beginning to follow this trend.

One major precondition to develop autonomous working infrastructure is the understanding of the work flow itself. The technology that is required for such a system brings together different engineering areas. Cooperation of operators and contractors as well as the manufacturers of the key components such as drilling rigs and downhole tools will be essential.

The aim of this work is the documentation and analysis of one of the main operational challenges during the drilling for oil and gas, the assembling and disassembling of the bottomhole assembly. Tripping of regular drill pipes is nearly mechanized and about to be automated. However, the bottommost part of the string still requires a lot of hands-on labor to get it in and out of the well. Reconsidering conventional rig floor design and eliminating manual work steps during that phase will be a milestone on the way to the hands free working infrastructure.

The detailed investigation of the different work steps on the rig floor will provide the basis for further developments and the implementation of new equipment to realize the automated drilling rig. The thesis describes in detail the workflow of BHA handling and also discusses the possibility of future automated handling process.

Abstract (Deutsch)

Die Anwendung von Automatisierungstechnologie hat viele Industriezweige verändert und zu einer Verbesserung der wirtschaftlichen Leistungsfähigkeit geführt mit gleichzeitiger Verbesserung der Produktqualität. All die Vorteile von automatisierten Systemen haben dazu geführt, dass nun auch die Bohrindustrie beginnt, dem Trend zu folgen.

Eine Hauptvoraussetzung für die Entwicklung solcher autonomen Systeme ist das Verstehen des Arbeitsablaufes. Die Technologie, die für ein solches System notwendig ist, führt verschiedene Ingenieursdisziplinen zusammen und verlangt die Zusammenarbeit von Auftraggeber, Auftragnehmer und den Herstellern aller Schlüsselkomponenten wie Tiefbohranlagen und Bohrlochgeräten.

Das Ziel dieser Arbeit ist die Dokumentation und Analyse eines der Hauptaufgabenbereiche die im Laufe einer Öl- und Gasbohrung zu bewältigen ist, der Ein- und Ausbau der Bohrgarnitur (BHA). Die Handhabung von normalem Bohrgestänge ist bereits mechanisiert und wird nun automatisiert. Um den untersten Teil des Bohrstranges in und aus dem Loch zu bekommen sind aber immer noch sehr viel manuelle Arbeitsschritte von Nöten. Überdenken der bisherigen Gestaltung der Arbeitsplattform auf einer Bohranlage und die Beseitigung von Arbeitsschritten, die durch die Mannschaft durchgeführten werden müssen, werden uns der voll automatisierten Arbeitsinfrastruktur ein großes Stück näher bringen.

Die genaue Untersuchung der verschiedenen Arbeitsschritte auf der Arbeitsbühne wird einen Teil dazu beitragen, neue Anlagen zu entwickeln und diese in den Arbeitsprozess zu integrieren um die automatisierte Tiefbohranlage zu verwirklichen. Diese Arbeit beschreibt im Detail den Arbeitsablauf für die Handhabung von Bohrgarnituren und zeigt einige Möglichkeiten auf, wie dieser Prozess zukünftig automatisiert stattfinden könnte.

1. Introduction

Drilling rig manufacturers have come up with new designs that include equipment with higher degrees of mechanization. Handling of drill pipe, for example, is already mechanized so far that it can be done with no or only little physical intervention of the personnel on the rig floor. But there are still a lot of operations that require hands-on intervention of the crew. This is one of the main problems for operators who run such rigs that have automated equipment capable of only a part of the entire work. On one hand, they invest a lot of money for highly developed equipment for the handling of drill pipe. On the other hand they are still dependent on the regular crew and equipment for special operations like installation of BHA.

The first ideas, of what this master thesis should deal with, were the simulation and evaluation of different automation systems that could be used for the installation of bottomhole assembly. It was planned to put the main focus on industrial robots, especially on a prototype of the Norwegian company Robotic Drilling Systems. The interest was on how compatible such systems are with existing rig designs, in particular with the new drilling rig of Bauer Maschinen AG, the TBA 440 M2, that is currently under construction[i]. Unfortunately, there was not much information about the actual working process available. Simulation of such a process without a detailed plan of the work steps is rather difficult and may not deliver meaningful results.

Therefore it was decided to take a step back and focus on the actual BHA assembling process itself. As nether rig operators, rig manufacturers nor downhole tool suppliers had documented a best-practice for the installation of BHA so far, a precise evaluation of the handling process of bottomhole assembly has to be done to provide the fundamental basis for later developments of automation equipment. This would allow a systematic realization of the hands-off working environment on the rig floor instead of developing tools that are capable only of the most obvious manual work steps.

The target of this thesis was to document and evaluate the installation process of bottomhole assembly as precise as possible. The information that is required to design an automated rig floor infrastructure should be defined to collect the right data. In addition to that, an examination of other industry sectors should deliver helpful knowledge how to realize an automated work space.

Automation of BHA handling represents only a part of the work that has to be executed by the rig crew. But the development of a fully automated drilling rig in one stroke would exceed the capabilities of the most manufacturers. Automated systems for the installation of bottomhole assembly will therefore not be the final solution to this problem. However, it would definitely be a milestone on the way to a drilling system that would require personnel only for controlling tasks or supervision, but not to execute the actual work.

[i] The construction of the Bauer TBA 440 M2 was finished in the second quarter of 2013

2. Automation of Industrial Processes

Before starting to discuss possibilities for automating a process, like the installation of bottomhole assembly on a drilling rig, it can help to have a look on other industrial sectors that have already stepped in to the automation technology. The understanding of the challenges and also the possibilities of automatization will be useful to find solutions for new applications.

2.1 Evolution of Industrial Robots

2.1.1 Origins of Industrial Robots

The term *robot* was initially used by Josef Čapek, a Czech artist and writer. It derives from the Czech word "robota", meaning work or hard labor. In his play "R.U.R." he describes a robot as a humanoid machine that serves the people. Later on the terminology *robot* was extended from humanoid machines to machines that could execute certain tasks on their own.[1]

The "Verein Deutscher Ingenieure" (Society of German Engineers) describes industrial robots as "… universally usable kinetic automats with several axes, of which all motions regarding movement sequences and paths or angles can be clearly programmed (without mechanical intervention) and, if applicable, guided with sensors. It is possible to equip them with grippers, tools or other manufacturing devices and they are able to execute handling and/or production exercises"[2].

A clear definition of a robot is difficult. Different industries have a diverse understanding of the nomenclature for robotic systems. One reason for this is that companies want to upgrade their products by calling them a "robot" or "automated" even though it is far away from the technical standard of such machinery.

The request for industrial robots has been driven by a few reasons.

- Performance and productivity
- Risk and safety
- Dependency on human workers
- Costs

Increasing **performance**, keeping it constant and maximizing the **productivity** is probably the most important reason. Monotonous and repetitive steps of procedures are difficult for human workforce to perform as it leads to fatigue and lack of attention resulting in mistakes and accidents. Furthermore, machines can carry out certain steps much faster and with higher precision than humans could ever do. One of the first automated machines to increase productivity was a weaving loom that was built at the beginning of the 19th century, programmable via punched cards[3].

Reducing the **risk** for employees and increasing **safety** is very important in today's society. One result of the industrialization and the technical progress is the arising of hazardous areas in all kinds of ways. Heavy machinery operating at high speeds, contaminated and poisonous mediums, loud noise and extreme temperatures transformed the working area in a dangerous environment. To remove personnel from such working environments machinery was developed to do the job. One example is a remote operator, constructed 1951 for handling radioactive materials[4].

Decreasing **dependency on human workers** will become more and more important. Many companies have difficulties to acquire trained and motivated people. With processes getting more complex, the need for high educated employees is booming. On the other hand, there are branches that still require low skilled, cheap working staff. However, there are not enough educated people to supply the high skill needs, and there are not enough willing to work for low salaries, too. One way to respond to this problem is to replace human with automated systems. Especially in the manufacturing business, great effort is put into the construction of so called "lights-out" factories (there are no workers, so there is no need for illumination)[5]. These plants run completely autonomously, human intervention is only required for monitoring and troubleshooting.

Lowering of **costs** is the ultimate goal as profit is the main drive of every business. The facts that have been mentioned above, like increase in performance and less employees, may lead to an increase of profit. This is the reason why automatization is not only interesting from a scientific or operational, but also from an economical point of view.

2.1.2 History of Industrial Robots

The beginning of the development of industrial robots was in the second half of the 20th century. The first patent was applied in 1951 for a programmable transfer machine by George Devol which today is considered the first industrial robot. The breakthrough came in the 70s when manufacturers started to produce robots on a great scale. This is the time when today's technology leaders, like KUKA Robotics, Comau or FANUC started to manufacture, too[6]. The number of robots in industrial utilization is steadily increasing from there (Figure 1).

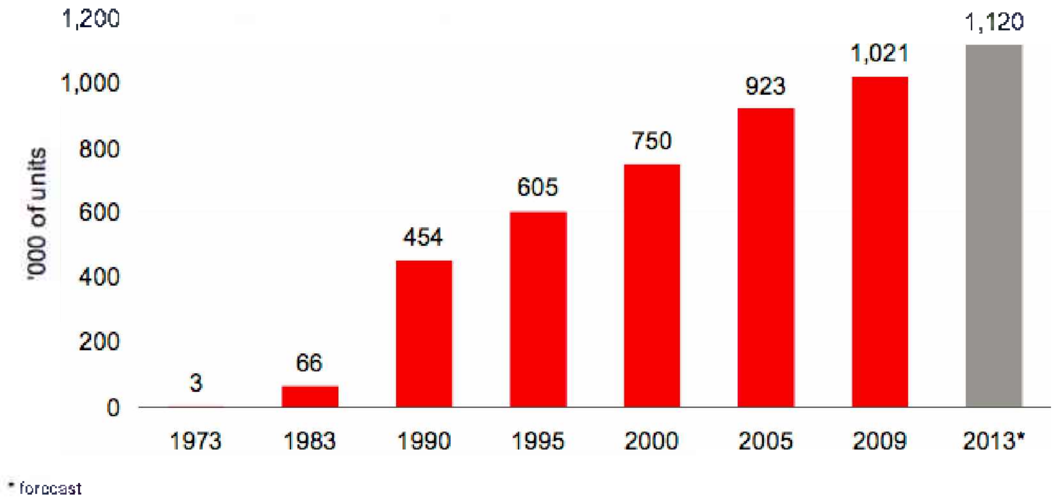


Figure 1: Estimated number of industrial robots worldwide[7]

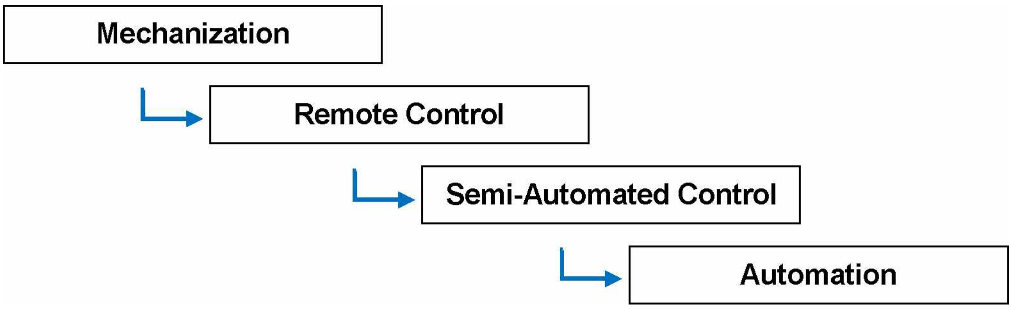
The main drivers for the progress in automation systems have been, and still are, the automotive and electronics industry. During the crises in the car manufacturing business in 2009 the number of annual sales of robots dropped almost half.

Future development analysis indicates that this trend will not stop in the near future. In the year 2008 the margin of one million industrial robots in the global industry was exceeded. In the year 2011 an estimated amount of 160.000 industrial robots were shipped. With the increasing number of units the prizes will continuously decrease where at the same time the implementation of robots will become easier due to the steady development of new programming and control systems. A market is definitely there as the availability of cheap working force, especially in emerging countries, will shrink whereas the demand for cheap consumer products will go up at the same time[8].

2.2 Automation Systems

Automatization systems are designed to carry out certain tasks and replace the human workforce for various reasons. This includes the logistics, too. The most important piece of equipment thereby is the handling device. Depending on the construction type, it will transport things from Point A to Point B and execute the necessary work steps to fulfill a goal. The term handling device is a very broad one, it includes the arm of a digger that is moving material as well as the autonomous robotic arm of a mars rover.

Automatization is the consequent development of mechanized systems combined with modern information technology. The classic approach of developing such system can be described in four steps[9]:



Mechanization of a process is the development and implementation of a tool that will execute certain (or all) work steps that are required to achieve a certain goal. This means that the work will not be done by a human any more but by a machine. Still, without human interaction, the mechanized system will not do anything. It has to be operated by a driver, thereby acting as an extended part of the human body. Interesting here is the degree of mechanization that rates the proportion of the work that can be done with the help of machines.[10]

Remote control is the possibility to operate a machine from a certain distance. Theoretically, with the help of modern sensor and communication technology, this can be from any place around the world. Remote controlled systems bring two big advantages. It removes the operator form the working area which meets safety and working comfort issues. Second, the operator can control more than just one or maybe a few machines that are in his closer range. Tools that are several hundred of meters away can be actuated by simply pushing a button.[11]

Semi-automated control is the point where mechanized systems meet information technologies. With the help of controls, like programmable logic controllers (PLC), the system can execute a defined sequence of work steps by itself. The human operator has to initiate this sequence, for example with a button. The machine will then perform exactly those programmed steps, for example take an iron bar, turn it 180 degrees and put it down on a conveyor belt. There may be a series of different sequences, and those sequences may be adaptable. The machine will do such a routine step by step and then stop, no matter what. It cannot react on unexpected events and it will not proceed with a second run by itself. Still, semi-automated controlled tools will facilitate the operation and improve the performance, especially for procedures that have to be done frequently. The work steps in between those programmed sequences have to be controlled by the operator. [12]

Automation of a system means that the work is autonomously executed by the machinery, human personnel is required only to monitor and intervene in case of a problem. The system is able to react to unexpected situations to a certain degree and can be adapted to changes in the work flow. The degree of automation gives the proportion of work that can be done by automated systems, ranging from the preparation of individual components to the manufacturing of entire products.[13]

2.2.1 Handling Devices

The machinery that is executing certain work steps is the core element of automation systems and can be categorized by their degree of autonomy and flexibility, usually into three groups:

- Manipulators
- Fixed Programmed Industrial Robots
- Flexible or Free Programmed Industrial Robots

A **manipulator** is a piece of equipment that can execute a certain range of tasks. The characteristic of a manipulator is fact that it is not controlled by a program but by a human operator. The purpose of such a device is to carry out extensive physical labor, expand the operating range and take over work in hostile environments. Manipulators can be controlled directly, for example a lifting arm, or via remote control like a bomb disposal robot. The term “automated” is therefore not really suitable as autonomous operation is not possible.

A **fixed programmed industrial robot** is a manipulator that is controlled by a programed routine. It follows a precise sequence of movements that has to be predefined with a sequence control system. This robot receives information about the position via limit switches or sensors that tell the program the position. The programming and equipment is rather simple, however, changes in the work flow require modification of the soft- and possibly even the hardware. Suitable tasks for fixed programmed industrial robots are processes that have to be done in exactly the same way with high number of iterations. Typical applications are loading and unloading activities of different kinds of machines or in an assembly or packaging line.

A **flexible programmed industrial robot** is a manipulator that is controlled by a program. In comparison to those which are fixed programmed, they can be adopted to new working processes by reconfiguring the program instead of a mechanical intervention. Furthermore, it can autonomously react to incoming signals from various sensors like an obstacle that has to be bypassed. To allow complicated motion sequences these robots are usually constructed with more axes than fixed programmed robots to provide contingency. Due to their flexibility, these robots are favored for producing goods with minor number of units and short manufacturing cycles.[14]

2.2.2 Design Characteristics

The design of manipulators for automated systems strongly depends on the application. Although most systems are described as “universally programmable”, this does not mean that it is possible to implement an industrial robot for every imaginable task, at least not in an economic way. Large robots, for example, that are capable of lifting high loads are usually not capable to insert small and sensible electronic components into a circuit board. To choose a suitable system and to avoid expensive over-engineering, some key data have to be kept in mind.

- Number of degrees of freedom and the number of axis
- Working space or working envelope
- Kinematic
- Technical capacities (load capacity, acceleration, speed)
- Technical dimensions (weight, size)
- Accuracy, repeatability and compliance
- Power source
- Effector
- Motion control
- Sensors

The **number of degrees of freedom** (DOF) describes the ability of a manipulator to move around in an area. The maximum number of degrees of freedom is six, three for the ability to move along the x, y and z axis of a Cartesian coordinate system, and three to rotate around these axes. The degree of freedom strongly depends on the **number of axes** of the manipulator, in most cases the number of axis is equal the degrees of freedom. If a manipulator with 6 – DOF can position an item in several different ways it is over-determined and called redundant. This is helpful when the manipulator has to run around unexpected obstacles. But it does not mean that a manipulator has to have a high number of axes. Like in many other technical applications, if a robot with two degrees of freedom will do the job, this will be more cost effective and therefore the better choice.

The **workspace** is a defined area in which a manipulator can handle things. This area is also called the working envelope or the robot workcell. To accomplish an exercise, the robot has to move or treat items in a certain area. This will influence the size and the design of the robot. The size of the manipulator should be big enough to ensure the necessary operating range, but at the same time designed in a way to keep the unit as small as possible. The different designs of manipulators can be divided into Cartesian coordinate systems, also called gantry system, cylindrical coordinate systems and spherical coordinate systems (Figure 2). The working envelope can be extended if the manipulator is set on a mobile installation, for example on rails, which would be considered as the seventh degree of freedom.

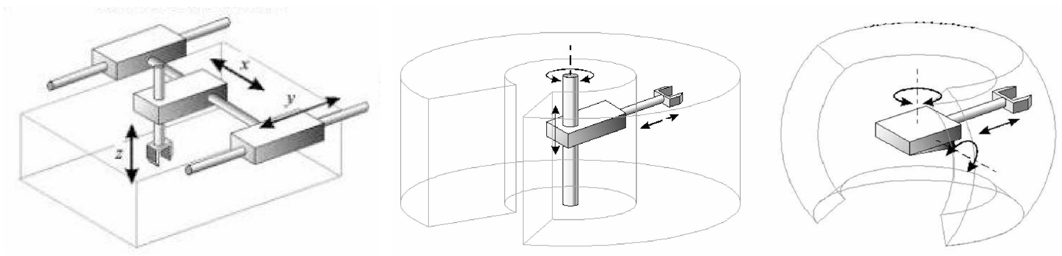


Figure 2: Cartesian (left), cylindrical (middle) and spherical coordinate working envelope[15]

The **kinematic** of a system describes the technical structure, or in other words, how it is built. Most manipulators have a positioning structure and an orienting structure, the intersection is often called the wrist point. The positioning structure does what the name already says, it positions an item or a tool at a desires point. The orientation structure is responsible for the accurate positioning of that item or tool. The denotation of the kinematic type often refers to the positioning structure as there are the main variations (Figure 3). Cartesian or gantry robots are very stiff constructions used for applications with high forces. Plus, the design is rather simple and can operate large work volumes. Delta or parallel robots distinguish with high speed and accuracy. Serial articulated robots are the most common ones and more or less imitate the human hand. They are very flexible and, due to the rather small layout, can be implemented into a work flow much easier than others. Another important type is the Selective Compliant Assembly Robot Arm (SCARA). It is a fast robot that is almost as flexible as an articulated manipulator, but much more cost efficient. These are the four types that are the most common. But in principle, every design that will do the job effectively can be applied.

Figure 3: Gantry robot[16], delta robot[17], articulated robot[18] and SCARA[19] (from left to right)

Technical capacities of the system like load capacities, speed or acceleration have to be defined according to the application. Therefor the boundary conditions of a working process have to be clearly defined as it will have an effect on the efficiency of the robot. It will not make sense to build a manipulator with load capacities up to 1000 kg if it is supposed to paint car parts and is equipped with a paint gun with a weight of 20 kg. The machine will become unnecessarily big, heavy and expensive. A welding robot will never operate faster than the maximum speed that the welding technique will allow to produce a proper weld joint.

Technical dimensions of the robot are important for the implementation. Depending on the size, such machinery can become quite heavy. The automobile industry gives a robot-weight-to-payload ratio of 1:10. This can lead to increased challenges to the substructure.

Accuracy is the ability to execute a certain task like to position a certain object at a defined point. **Repeatability** is the ability to repeat a certain step. If a robot will position a piece always one millimeter too high, it has a high repeatability but a low accuracy (depending on the working demands on the robot, one millimeter may be sufficient, too). **Compliance** describes the stiffness of the construction. Every manipulator will position a heavy part slightly lower than a part with low weight, with the increase of the compliance the system tries to counteract external forces and this difference will decrease. The second problem with compliance is the overshot, the manipulator will have difficulties to stop at the defined stop position and go beyond that point, plus the item will also oscillate in the stop position. Similar to the technical dimensioning of a manipulator, to a high degree these features are achievable but at the same time expensive to implement, a closer examination of the necessity is advisable. Therefor it is important to define the boundary conditions according to the implementation.

The common **power sources** of industrial robots are hydraulic, pneumatic and electric drives, each of those with some advantages and disadvantages. Hydraulic systems are favorable due to their compact installation abilities and the possibility to transfer high forces. At the same time, hydraulic systems tend to cause spilling of hydraulic fluids and require a lot of equipment such as pumps, accumulators, hoses or valves. Pneumatic systems eliminate the problem with spilling fluids, but the compressibility of the medium reduces accuracy. Electric motors do not have the same power-to-weight efficiency, but they can be much better controlled.

The **effector**, or gripper, is the link between the manipulator and the actual task. This can be a welding unit or a paint gun to carry out work steps, this can be a gripper or a suction pad for transport and positioning applications. The diversity in end effector tools is one of the main reasons why manipulators can be used so flexible, especially if the can be interchanged by the robot autonomously.

The **motion control** of an industrial robot can be seen as the brain of the system. This is the key element of an automated system as it is characterized by the fact that it can operate autonomously. The robot is thereby controlled by a program that runs on a PLC. Over different types of user interfaces the system will receive instructions for the tasks in hand. The computing unit is on the input side connected to the sensors that supply the necessary information and on the output side with the pumps, valves, electric motors or whatever mechanism that is driving the robot. In addition to that, the PC can be connected to other automated systems to coordinate the trouble-free interaction and to any kind of network that makes remote operation and configuration possible. [20,21]

Sensors provide the system with the necessary information of the in-situ happening, it serves as the nervous system. There is the internal sensor technology which is implemented in the manipulator. It collects information about the angles of the axis to compute the position of the effector or parameters like gripping forces. Besides that, there is the external sensor technology that observes the interaction of the robot with the surrounding environment. This is essential if the system should be able to react to unexpected changes in the working environment.

2.3 Automation of Industrial Processes

The reasons for automation of industrial processes have already been discussed. The branches with the highest degrees of automation are the automotive, the electronics and the food industry. This chapter should show the possibilities of automated systems on the basis of some examples that are related to practice.

2.3.1 Car manufacturing

As already mentioned, the car manufacturing business is one of the leading industries in the application of industrial robots and automation systems (Figure 5). Figure 4 shows how far this industry is ahead compared to others.

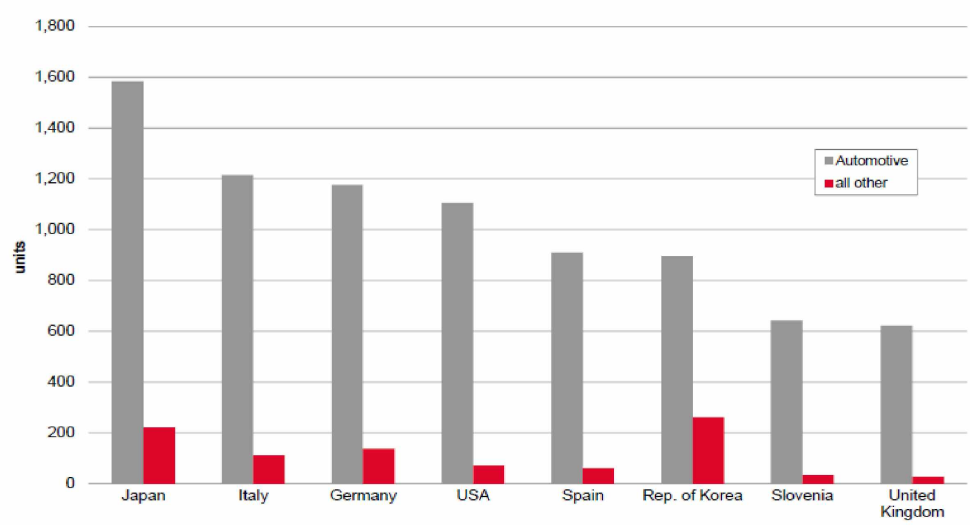


Figure 4: Number of multipurpose robots (all types) per 10 000 employers in 2011[22]

The most common use of robots is for welding. Modern welding techniques allow very low tolerances, small mistakes can lead to failures, or at least increase of durability, of the component and the entire car. The high demands on the welds require highly skilled personnel, which are expensive and difficult to recruit, and great efforts in the quality control. Plus, parts are heavy and cumbersome which makes handling difficult. These problems can be tackled by using robots.

Spray-painting is the second big share of work that is done by robots (Figure 5). The robots used to be driven pneumatically for security reasons as the machinery is working in an explosive environment. Today they are all electric with explosive proof housing of the motors. At the beginning, the system used to imitate the movements of human workers. Now, process simulation software optimizes the painting procedure to get the best possible result, at the same time using a minimum amount of paint and time.

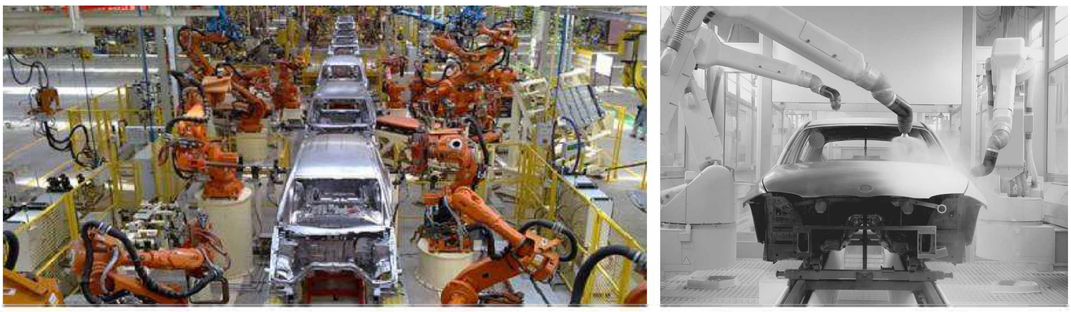


Figure 5: Automated car assembly line (left)[23] and painting robots (right)[24]

The logistics of an assembly line is very complex. A lot of different components have to be at the right time at the right place. The transfer in modern factories is automated. A critical point is the intersection point between transport system and the robot. To pick up an item, the robot needs information about size, shape and position of the item. Especially the position is a problem, as the objects are usually randomly disposed. This phenomenon is called “bin-picking” and challenges especially robots with no or minor sensor equipment.

The main reason why car manufacturing is atomized is to speed up production rates. Assembly lines with robots will run 24 hours, seven days a week without interruptions or a drop in performance. Typical mean time between failure (MTBF) values reported from the industry are around 50 000 hours[25].

Another interesting issue that will concern fully automated rig design is the legal situation in case of failure. Cars that can autonomously back into a parking space are on the market. Sensors measure the distance and the computer directs the vehicle into the end position. But the actual command for motion and especially the breaking of the car has to be given by the driver. Car manufacturers do not want to take over the liability for possible damage during such maneuvers.

2.3.2 Wood industry (harvester)

The forestry processing industry is facing the trend for automation, too. There are certain aspects that can be found in the drilling industry as well and make them comparable to some degree. Wood logging is, like working on a rig, dangerous and exhausting. Still, the only way to cut down a tree used to be hands-on, only with the help of a chain saw. And, also like in the drilling business, the scope of felling a tree is principally each time the same, but with variations of the boundary conditions. Diameter and shape of the tree, inclination and condition of the subsoil may change significantly. As the lumber trade is a very competitive business with contestants from eastern countries that deliver cheap resources, there is not much space for expensive tools if they can't guarantee economic success. As people are rather conservative, there had to be a lot of effort to convince them of the benefits of mechanization and automation. The doubt that a machine could do the job of a lumberjack was quite distinct.

Nevertheless, the huge backwoods in the Nordic countries in combination with a lack of personnel required a change in how trees were cut down. People came up with the idea of constructing a gadget to do this work and developed the harvester (Figure 6). A harvester is a machine that can move even through rough terrain with balloon tires or on continuous tracks. It has a hydraulic arm with the actual cutting device at the end. This cutting device is set at the bottom of the tree. It grabs it and the integrated chainsaw cuts it, a slight pull directs the tree in the desired direction. The tree is then drawn through the cutting device to remove the branches and cut into logs of desired length by the help of a measuring sensor. It still has to be operated by humans, but instead of working in the cold or hot environment, he is operating the harvester in a comfortable cabin. The system is semi-automated as the grabbing and cutting process as well as the debranching and crosscutting of the logs can be programmed and initiated with a button. Manual logging was only possible during daylight whereas a harvester can operate on a 24 hours basis. This is an advantage as the logging is depending on weather conditions and so limited to certain time periods. Right now the producers want to develop their products to a fully automized version, integrating GPS systems with a digital mapping of the forest. It will also include driverless transport vehicles for the removal of the wood.[26]

Figure 6: Harvester cutting tree[27]

2.3.3 Lego Robotic

An indicator that shows how practical the techniques of automation have become is the fact that toy fabricators have start to integrate them into their products. LEGO, the Danish producer of plastic building bricks, has launched a product line in cooperation with the Massachusetts Institute of Technology called LEGO Mindstorms (Figure 7). The key element of the set is what they call the programmable or intelligent brick, a 32 bit processor with a display, USB and Bluetooth interface to connect it to a computer and extra ports for the communication with the components. Such a robot is driven with small electric servo motors and can react to its environment with the help of ultrasonic, touch and even color sensors. The programming is done with the visual programming language LabVIEW from National Instruments which is known in the professional automation industry as well.

Figure 7: Lego Mindstorm[28]

LEGO is offering a special education kit for class room utilization. Students should be able to build and program a fully functional robot in not more than one lesson of 45 minutes.

In fact, LEGO Mindstorm is developing from a toy to a tool. Universities and even companies are using it to test new ideas as it is a relatively cheap way to build first prototypes[29, 30].

2.4 Automation in the Drilling Industry

The history of automation in the drilling industry is a relatively brief one with relatively few success stories[31]. Actually, most of the technology that has been developed should be considered as mechanization. Still, as mechanization is imperative for automation, they will be discussed here as well.

Offshore rigs have a pioneering role when it comes to using new technologies. The reason is rather simple, due to the bigger economic volumes and increased compulsion for success the financial boundary conditions are better than for land rigs.

2.4.1 The Automatic Drilling Machine

The Automatic Drilling Machine (ADM) was a first attempt to automate the drilling process during the 1960s. The concept rig that was build had hydraulic drawworks, top drive and a pipe handler that transferred pipe from a horizontal wrecking position to the rig floor. The procedures where controlled from a cabin, some of the sequences where already semi-automated and could be recalled by the driller. This unit was successfully tested in West Texas. Unfortunately, the project had to be shut down due to financial problems. Still, it was far ahead of its era considering the state of the art at that time.[32]

2.4.2 Iron Roughneck

The first iron roughneck was introduced in the 1970s. It was the first attempt to robotize the work on a drilling rig, therefor there had also been the idea to call it “robotorc”. The connecting and disconnecting of drill pipe, especially during a roundtrip, is the most frequent work that has to be done on a rig floor and is therefore an ideal application for automation. Thereby, the iron roughneck does not only support the crew, it replaces the crew during the connection of pipe and is therefore the first real success in automating rig floor activity. As many other new technologies in the drilling industry, the iron roughneck was mainly used in offshore drilling platforms at the beginning due to the fact that they have more financial resources. That changed and they can be found on many of today’s land drilling rigs, especially in Europe where safety standards are higher than elsewhere.

2.4.3 Pipe Handling Machine

The integration of pipe handling tools to the rig floor is not only a matter of safety. It is driven by the simple fact that the human body is just not capable of moving or guiding heavy tubular. Lifting without winches is not possible at all, but especially the guiding of the drill pipe with bigger diameters or casing on the rig floor and in the monkey board brings the crew to its physical limits. However, automation of pipe handling has been a very slow process. The main reason for this is that such systems used to support the work process, but the crew was still necessary to do the work. An additional crew member was necessary to operate the pipe handling machine. Another disadvantage was that the first designs required intensive maintenance and where not very reliable. So, as long as the work could be done manually, companies did not plan on spending extra money on equipment that would not significantly improve the process.

Today, pipe handling machines can be found on nearly every offshore drilling rig. Even on land drilling rigs, companies change their attitude and are willing to invest money in such tools. The automation of handling pipe is technically possible. First attempts to semi-automate them look promising. Instead of initiating every single work step, the driller can initiate preprogrammed working sequences, for example removing a stand of pipe. But the systems reach their limit when it comes to handling of any tool that cannot be handled the same way as drill pipe, especially bottomhole assembly.[33]

2.4.4 Rig Floor Automation

A place with a lot of potential for automation is the rig floor. As already mentioned, screwing and unscrewing of pipe can be done with the iron roughneck, handling of pipe can be executed with pipe handling machines. Other tools that enable hands-off working are automated slips or elevators. This systems are field tested and can be found on almost all modern land rigs. The big problem is that that those tools are rather inflexible. A lot of manual work is still necessary to adopt slips or automated togs to new pipe diameters.

Rig manufacturers try to develop new tools that will increase the degree of mechanization. Mechanized mud baskets, greasing units or tubular steering devices are in the testing phase. But so far, most of these tools could not convince during testing phases as they are too slow, at least at the moment.

3. Drilling Rig Design

When talking about deep geological drilling operations, for example drilling for hydrocarbons or geothermal, the procedure that is usually being applied is the hydraulic rotary drilling system. The technique was developed at the beginning of the 20th century in Texas and has been further developed until today. Still, the basic principle has not changed. A rotating pipe with a drilling bit at the end is making a hole by breaking earth particles out of the ground. The tensile strength of the drilled material is broken by the shear forces provided by the rotating motion of the drilling bit and the downward force of the weight of the drill pipe (Weight on Bit). At the same time, fluid is pumped to the bottom of the hole through the pipe to remove the cuttings through the annulus and at the same time cool and lubricate the drilling bit.

The machinery, that is necessary to drive the hydraulic rotary drilling process, is the drilling rig. As the drilling process evolved strongly over the last century, also the design of drilling rigs has undergone huge steps of technological developments.[34] This chapter will take a look on the way drilling rigs have been developed and the reasons why they are designed the way they are.

The main components, which are necessary to drill a well and all together interact on the drilling rig, are the hoisting system, the rotary drive mechanism, the fluid or mud system, the power supply, the drill string components handling and the drill string itself.

3.1 Hoisting System

The hoisting system is moving the drill string up and down and keeps the upper part of the drill string in tension during drilling.

3.1.1 Mast or Derrick

The derrick or mast (Figure 8) is optically the most dominating part of a drilling rig, and therefor also kind of a symbol for the oil and gas industry. The mast or derrick has to support the entire dynamic load of the drill string, casing, rod strings, etc. If a top drive is installed, the additional weight of the top drive has to be carried and the torsional force from rotating the drill string is transmitted into the derrick over a torque beam. Furthermore, drill pipe that is set back in the derrick or mast, auxiliary winches and other rig floor equipment initiate force on the construction. Due to the enormous surface of the structure, wind will also apply force on it and has to be considered during operation. Modern land rigs are capable of several hundred tons. Although often used in the same sense, mast and derrick are not the same.

Derrick

A derrick is a trussed framework that has to be erected piece by piece, already in the vertical position. Seated on the four supporting legs that rest on the substructure, it has the hook load in the center of the construction. The dead weight vs. load ratio is very good, but the transport to a new location is not possible or realizable with great effort as it has to be disassembled piece by piece. To reduce relocation costs, standard derricks have become rare and have been replaced by portable masts. Only offshore rigs are still using derricks, as it is a fix installed part of the platform and weight efficient. There are different designs of derrick structures that have been developed over the time. The first were fix installed and made out of wood, but due to severe fire incidents steel derricks became standard. To decrease costs for equipment, stationary constructions were replaced by moveable so that the expensive steel compound did not have to be left at an old well after completing.

Mast

A mast is usually of rectangular or trapezoidal shape. The components are dimensioned in a way that they can be transported by trucks and are assembled horizontally at the rig site. The mast is then connected to the substructure and erected, which looks like a jackknife being opened and closed – therefor the name jackknife mast. Due to the flexural forces during raising the mast and the fact that the acting force of the hook load is often not in the center of the structure, masts are designed stiff and solid. This results in a higher weight and therefor masts are hardly used offshore. [35]

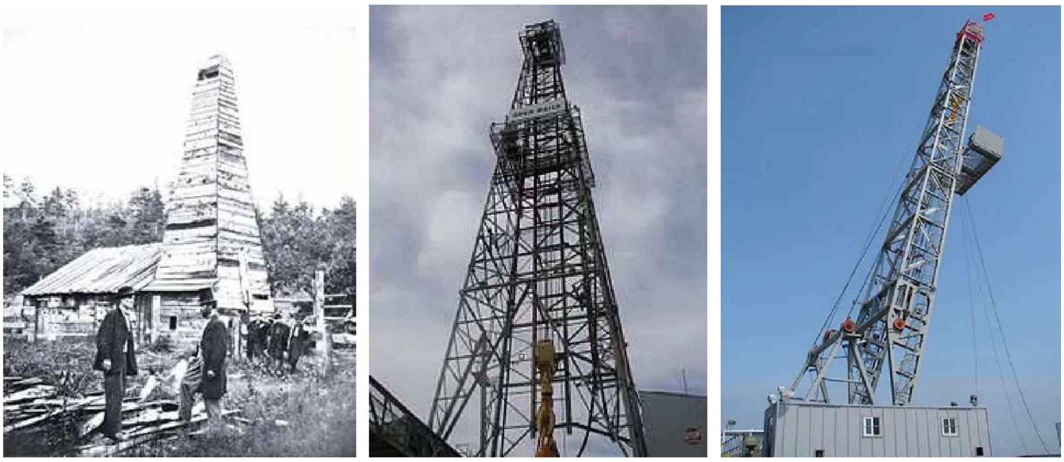


Figure 8: Wooden derrick (left), steel derrick (middle) and mast during the erecting phase (left)[36,37,38]

3.1.2 Hoisting

The hoisting system is moving the entire dynamic load that is acting on the hook of the block up and down along the mast. Conventional hoisting systems are cable operated (Figure 9). A steel rope is driven by a drum and pulls the travelling block up and down. The heavy drum is mounted on the substructure of the rig. The cable goes up to the top of the derrick and is directed by the crown block to the travelling block. To increase the pulling force capacity, crown block and travelling block have several sheaves where the cable is reeved. Actuating the drum, the block is going upward. To hold the block in position or let it down in a controlled manner breaks are used.

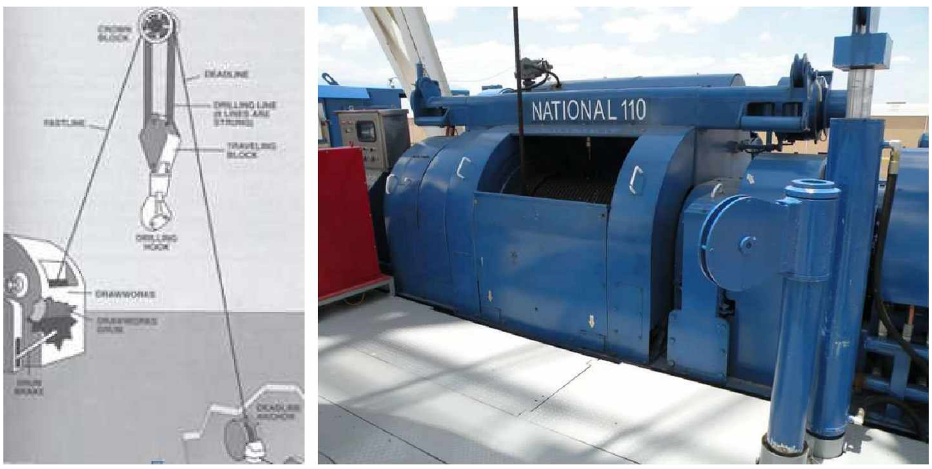


Figure 9: Conventional cable-type hoisting system[39] (left), hoisting drum unit with cathead (left)[40]

Hoisting with Mechanical Drawworks

The drum was initially driven directly by combustion engines, mechanically connected via drive shafts, gear systems and chain or belt transmission (called compound). A simple and solid, though quite cumbersome way of power transfer that dominated the business for long time and can still be found on older rigs, especially on smaller workover rigs.

Hoisting with DC Electric Drawworks

Newer drilling rigs have drums that are driven by DC motors. The electric motor is powered by a diesel-engine AC generator on site or by the local power grid. Therefore, DC motors need rectifiers (SCR) to transfer alternating current from the generators or power grid to direct current for the electric motor. The advantages of the electric motor are better efficiency and flexibility for compact rig designs as the power is transmitted through electric cables to the power load. High starting-torque of electric motors is facilitating operations under enormous loads.

Hoisting with AC Electric Drawworks

At the moment, operators are doing modifications on their rigs by changing their power system from direct current to alternating current. The motor is controlled via variable frequency drive (VFD). The big advantage of AC motors is that they can not only pull but also hold the load in position, acting as an additional break. Also, the motor can be used as a generator and therefor generates electricity when the travelling block is lowered. The regenerative breaking increases power efficiency. The combination of new process control techniques with the AC motor allows the hoisting system to be easy operated, for example with joystick. This is a big work simplification for the driller in comparison to the conventional control station (Figure 9).

Hoisting with Hydraulic Cylinder

An alternative option to the cable operated hoisting system is the hydraulic hoisting system, which is a rather new technique in the rig construction business. Instead of pulling the travelling block up and down with a string hoist, it is pulled by a hydraulic cylinder (Figure 10). The advantages of hydraulic hoisting system are the higher operating speed of the block and the compact construction possibilities. In addition to that they can easily be designed as a snubbing unit. Limitations of the hydraulic system are high working loads and the working height due the fact that very long hydraulic cylinder constructions are difficult to build.

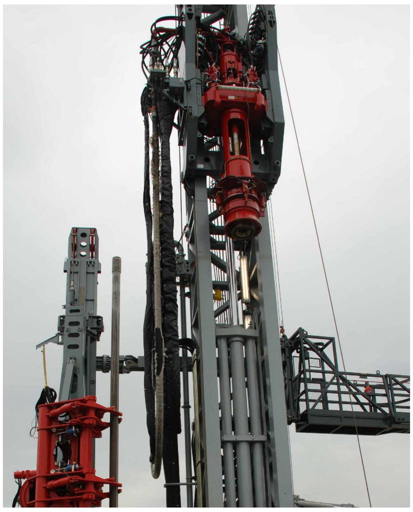


Figure 10: Hydraulic Hoisting System

3.2 Rotary Drive Mechanism

The function of the rotary drive mechanism of a drilling rig is to supply the drill pipe with rotation carried torque. The string is thereby turned clockwise either by kelly drive rotary system or top drive rotary system. A third way is to turn only the bit with a downhole motor. Still, the drilling torque is transferred from the downhole motor through the string to the surface and the kelly drive system or the top drive system have to counteract the force of the twisting.

3.2.1 Kelly Drive Rotary System

The kelly drive rotary system (Figure 11) was developed hand in hand with the hydraulic rotary drilling technique at the beginning of the 20th century. It is still used today, especially on land rigs. The main part of the kelly drive system is the rotary table. It is integrated in the drill floor and revolves the drill pipe that goes right through the middle of the rotary table into the well. The rotary system can be driven by the drawworks over a shaft that is connected to a ring gear that is connected to the turntable. This is basically the way it used to work hundred years ago besides from small upgrades. Most of today's rotary tables are driven by hydraulic or electric motors, depending on the rig. The revolving movement is transferred to the drill pipe with the master bushing, that sits in the rotary table, the kelly drive bushing, that is connected to the master bushing via form-fit or drive holes, and the kelly, a square or hexagonal drill pipe that fits into the kelly drive bushing.

Although many new rigs use a top drive to rotate the drill pipe, most of them are still equipped with a rotary table. It has auxiliary functions for directional drilling operations, emptying the mud motor, screwing on the drill bit[ii], etc. Therefore, modern rotary tables are often downsized with high torque but only low rotational speed. Depending on the power system of the rig, they are driven by small electric or hydraulic motors. The slips, necessary to hold the drill pipe when it is not connected to the hoisting, are set in the master bushing of the rotary table.

3.2.2 Top Drive Rotary System

The top drive system, also known as power swivel (Figure 11), was first constructed 1981 by Varco, now National Oilwell Varco, with the intention to improve drilling performance while reducing risk at the same time. Drilling from the top of the drill string would remove the kelly drilling equipment from the rig floor. This would eliminate the high risk for the crew when working with this equipment and allow longer pipe ranges to be added during tripping. Like many new technologies that are launched in the oil and gas industry, introduction of this new tool to the drilling process was not easy due to doubts and mistrust of people[41]. However, the top drive turned out to be a big step forward, first mainly on offshore rigs and later on also for land drilling.

Instead of rotating the drill string with a kelly and the rotary table, it is done with one or sometimes even two motors that turn the drill string from the top. The top drive is connected to the travelling block instead of a conventional swivel. The conventional swivel is the connecting piece between the travelling block and the drill string. It has to support the entire load of the string, provide a pressure tight flow line for the drilling fluid and allow the drill pipe to rotate all at the same time. A power swivel has to manage these three tasks and supply the drill stem with torque and rotation. The drilling torque of the top drive is transferred to the mast or derrick with torque beams on which the top drive is attached. If this is not possible, for example if the derrick structure is not able to withstand the forces, the torque can be directed to the substructure with torque rails.

[ii] The drill bit is only screwed to the drill collar with the rotary table, but cannot be made up as the rotary table does not have a torque indicator to apply the suitable make-up torque.

Electric Top Drive

First power swivels were driven by DC electric motors. The power capacities were steadily increasing, the use of locomotive-based engines was necessary to keep up with the requirements from the field. In the 90's, the implementation of AC motors on drilling rigs became popular. Smaller engines, better efficiency and higher starting torque were convincing arguments to build top drives with alternating current power systems. The new designs also tend to be easily transportable and in modular design to facilitate repair and modification tasks.

Hydraulic Top Drive

Hydraulic top drives have become popular due to their small size. The choice between hydraulic and electric top drives is influenced by the available power source of the rig (hydraulic or electric power systems), but mainly dominated by the size. Hydraulic power swivels are installed for smaller rigs as they are small and light, electric AC top drives are used to provide the rig with high working forces.

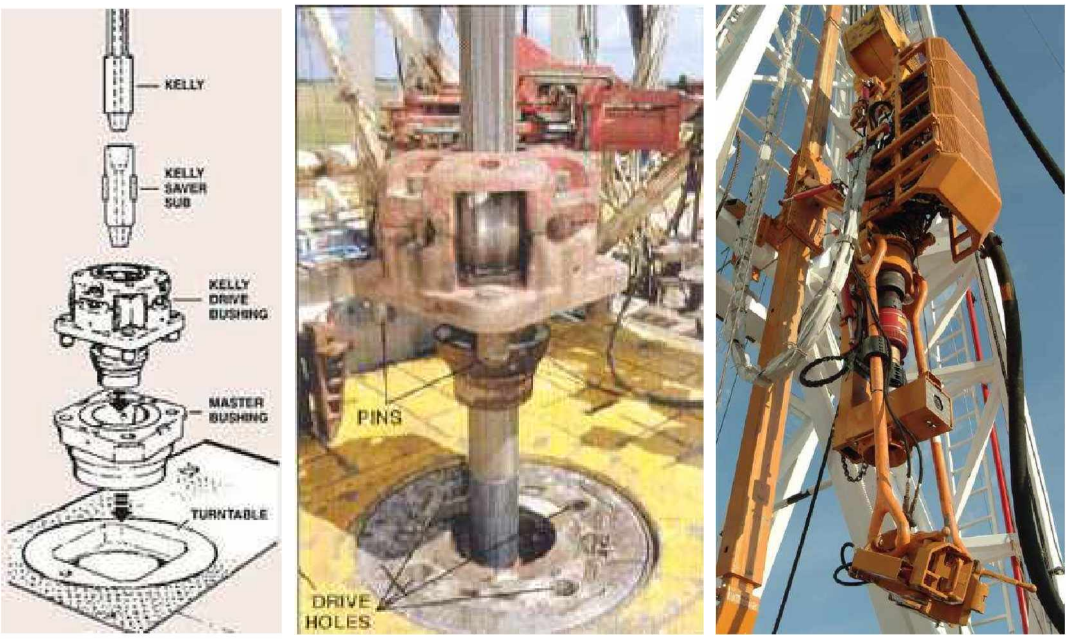


Figure 11: Rotary table with kelly drive (left, middle)[42], portable 250 HP AC top drive (right)

3.2.3 Downhole Motor

The application of downhole motors is a way to rotate the drilling bit. However, this is only applied for certain drilling techniques and cannot replace a rotary table or a top drive. Downhole motors will be described in the chapter "Drill String Components and Handling"

3.3 Hydraulic Circulation System

The use of drill fluid, also known as drilling mud, is one of the key elements of the hydraulic rotary drilling technique. When boring a well, the drilling mud is pumped from the surface through the drill string down to the bit, through the nozzles of the bit in the borehole and then back to the surface. When out of the hole, the fluid is processed and cleaned and the circle starts over again. The drilling fluid has several functions. It has to remove the cuttings that are drilled out by the bit and transport them up to the surface. At the same time, the bit is lubricated and cooled as the drilling generates a lot of thermal energy. To ensure borehole stability it is important to seal the wall of the borehole and counteract the formation pressure of the drilled medium which is done by the hydrostatic pressure of the drilling mud. Certain tools of the BHA use the mud to operate, for example downhole motors or mud pulsers.

3.3.1 Mud Pumps

To get the drill fluid from the mud tank down the hole and back to the surface a lot of hydraulic energy is needed. This is provided by the mud pumps, big reciprocating positive displacement pumps. As the planned wells became deeper and more complex over time, manufacturers steadily had to increase the power rating of their pumps. Power input changed from steam engines at the very beginning to diesel combustion motors and now to electric. The one to three pistons of the pump can be single or double acting. Most common is the single acting triplex pump as it has the smoothest pump pressure output. Depending on the size of the rig, there are two, three or even more pumps on site. The mud pump system requires usually more than half of all the horsepower used in rotary drilling. To increase the efficiency and counteract wear, the mud pumps are nowadays usually pre-charged with smaller electric or hydraulic pumps that push the mud from the tanks to the mud pumps.[43]

3.3.2 Mud Mixing and Storage System

Drilling mud is a fluid, usually water, mixed with additives to obtain the required properties needed for drilling. The mud tank system consists of open steel tanks for the mud and open or closed extra tanks for water. The mud tanks are equipped with different types of agitators to counteract the natural sedimentation of the fluid additives. From these tanks, the drilling mud goes to the mud pumps to be pumped to the rig and down in the well. The mud mixing system is usually a jet-type mixer with a hopper on top to add the mud additives. In comparison to many other industries, for example the construction industry where building materials like cement or plaster are delivered and stored in silos and mixed automatically, the components and additives for the drilling fluid are delivered in 15 kilogram bags and are added manually to the mixing unit.

3.3.3 Mud Cleaning System

When the drilling mud flows back from the well it is usually full of cuttings and dissolved gas that have been drilled out. This foreign matter has to be removed before the fluid can be used again. To clean the mud it has to run through a sequence of equipment that filters out the different substances by size and properties. Common tools are shale shakers for bigger cuttings, degassers to separate any dissolved gas, desander, desilter and centrifuges for smaller cuttings and. On modern rigs, this part works relatively autonomous, human intervention is mainly necessary for repair, maintenance and to make sure that the disposal containers will not boil over.

3.3.4 Surface Circulation Equipment

The surface circulation equipment contains all parts that are necessary to close the fluid circle (Figure 12). This includes the mud hoses and steel tubes that connect the mud tanks with the mud pumps, the suction line, and the mud pumps with the stand pipe on the drill floor, the discharge line. The standpipe, that is in vertical position and attached to one leg of the mast or derrick, is connected with the rotary hose to the swivel or top drive and to the drill string. The mud is pumped down the pipe and then back to the surface, carrying the cuttings. Back on the surface, the mud enters the mud return line that is usually equipped with a flow meter to show the driller the difference between the mud entering the well and the amount of mud leaving the well. The mud return line leads directly to the mud cleaning system and from there to the mud tanks, where the cycle is closed and starts again.[44]

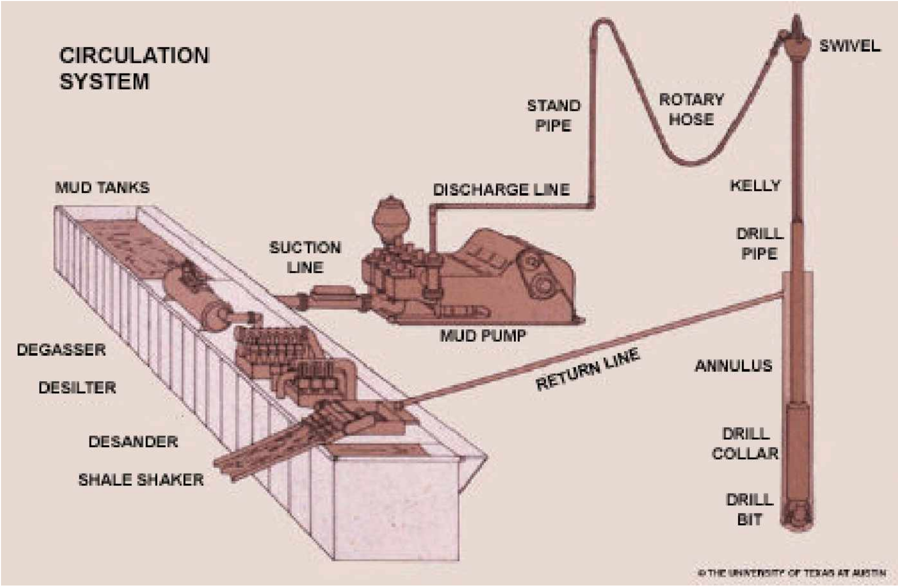


Figure 12: Drilling mud circulation system[45]

3.4 Power Supply

A drilling rig is equipped with a number of machines and several of them consume a lot of horsepower. The mud pumps, the hoisting system and the rotary drive mechanism are the three main power consumers as they do the actual drilling. In addition to that, all the auxiliaries have to be provided with energy, as there are the mud mixing and cleaning system, drill floor and pipe handling equipment, blowout preventers, illumination of the site, accommodation and offices for the crew, hydraulic pumps and so on. But not only is the huge energy request a challenge for the rig operators. The fact that the drilling of deep wells is quite often in areas with little or no infrastructure demanded for autarkic facility layouts.

3.4.1 Prime Movers

A prime mover is “an initial source of motive power (as a windmill, waterwheel, turbine, or internal combustion engine) designed to receive and modify force and motion as supplied by some natural source and apply them to drive machinery”[46]. This makes the prime mover the heart of every drilling rig. At the very beginning of the hydraulic rotary drilling technique the necessary horsepower came from steam engines as these where the only available energy source that was strong enough and relatively independent of infrastructure. Wood, coal or even natural gas could be used to heat up the boiler. Until the 1940’s and 50’s nearly all drilling rigs were steam driven.

Mechanical Rig

This changed when powerful and portable combustion engines became available. Steam rigs were displaced by mechanical rigs[iii]. Especially diesel engines became dominant in the industry as they were more efficient, more reliable and the transport and storage of diesel is much safer than of gasoline due to its low vapor pressure. Plus, they develop higher torque compared to other engines of the same size.

[iii] Rigs with combustion engines and mechanic power transmission are named mechanical rigs

Diesel-Electric and Electric Rigs

Today, diesel engines are still the most common prime movers on drilling rigs, the development of turbo chargers and electronic controlled direct injection keep them state-of-the-art. But instead of powering the rig components directly, the engines are now more and more being used to drive AC generators which deliver the required energy. Electric drilling rigs, or diesel-electric rigs, if powered by diesel generators, are beginning to replace the mechanical rig. Environmental friendly drilling is getting more and more important, so operators are energizing their rigs from the local power grid if the infrastructure is available. Especially near areas of settlement this will reduce exhaust gases and, even more important, noise. The use of public electricity is interesting from an economical point of view, too.

Gas Turbines

In combination with a generator also gas turbines are now being considered as a power source. Gas turbines are constant speed machines which was not well applicable as a direct actuation. But in combination with electric generators they are a considerable alternative as they are environmental friendlier and can be fueled with gas or liquid hydrocarbons that would be wasted otherwise.

3.4.2 Power Transmission

Power transmission is necessary to direct the energy, which is produced by the prime movers, to the actual consumer such as mud pumps or top drive. In some cases it is necessary to convert the original form of the energy to another one. The key features of power transmission in the design of drilling rigs are simplicity and reliability, even in extreme harsh environments. They have to be field serviceable and easy to transport and assemble. Plus, some components serve in explosion-hazardous areas and have to be ex-proof. The means of power transmission are divided in mechanic, electric or hydraulic systems.

Mechanical Power Transmission

Up to the 1960's most of the rigs were equipped with mechanic energy transfer, in some areas there are still a lot of old mechanical rigs around. At the beginning v-belts connected the engines with the machinery, but with the increasing horsepower of the different equipment this technique reached its limits. The belts where replaced by complex arrangements of heavy-duty chains, sprockets, gears and clutches, which could transfer a lot more power. This arrangement is known as the compound (Figure 13). Several engines are compound to the power transmission and the driller can decide whether to link one, two or more engines to the system, depending on the actual situation. The compound supplies the drawworks and rotary table by chain, smaller consumers such as mud pumps, hydraulic aggregates or electric generators can be driven with chains or belts. The big disadvantage of the compound is simply its size. It is big and heavy and therefor difficult to transport. Due to its complexity the assembling and disassembling is time-consuming.

Electrical Power Transmission

A more elegant way is electrical power transmission. Initially developed for locomotives, this technology was used for drilling rigs around 1930 for the first time and is the most common way of energy transmission today. There are many advantages of the system. The components are smaller and can be assembled much quicker, leading to lower costs. Electric systems are more efficient. Less energy consumption is not only cheaper but has lower environmental impacts, too, which is desired by most contractors nowadays. And the electric power transmission is much more flexible. The power is transmitted through flexible electric cables that can be positioned relatively easy, which is a big benefit for the design of drilling rigs. Plus, the prime movers can be placed further away from the rig leading to less noise pollution on the rig floor.

An important step was the implementation of the alternating current silicon-controlled-rectifier system in the 1970s (Figure 15). Before, one DC generator, driven by a diesel engine, was directly connected to one corresponding DC electric motor (Figure 14). With the DC-DC concept each motor required a generator of its own. Including redundancy, this was a lot of equipment on the rig site. With SCRs, diesel engines are connected to AC generators. One control station with several SCRs converts the alternating current from one prime mover unit to direct current for the individual DC motors on the rig. The size and number of prime mover can be adjusted to the power requirements of the rig or it can be powered from a local power grid, if available. AC power can be transported with much fewer losses compared to DC, especially when high amounts of energy have to be transmitted.

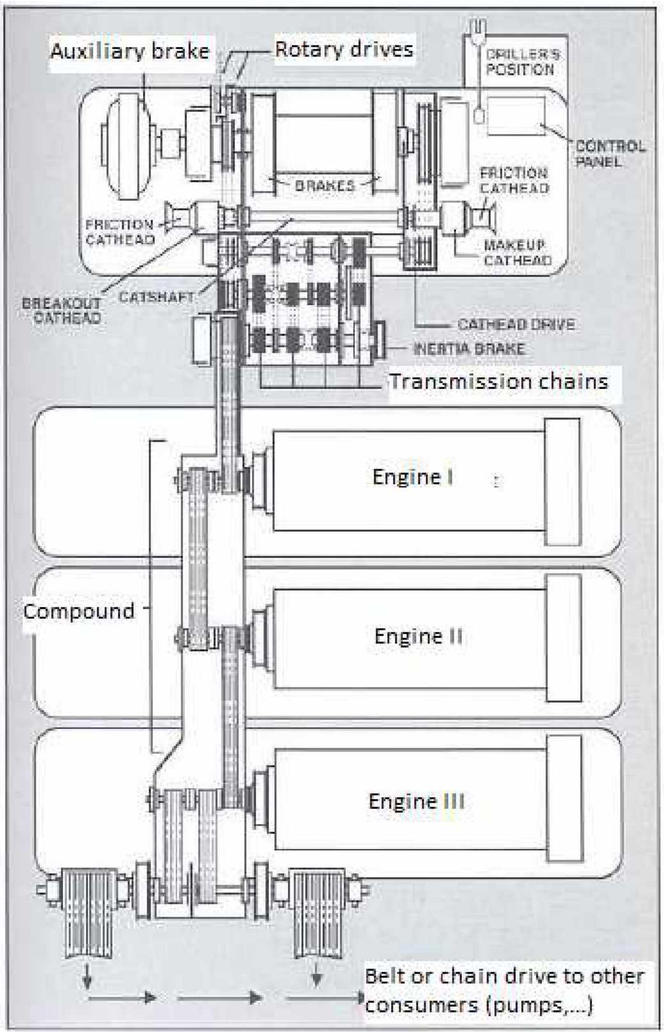


Figure 13: Compound – mechanical power transmission[47]

The latest development in electric power transmission was the application of variable frequency drive (Figure 16). The speed of DC motors can be easily controlled by adjusting the voltage, the speed of AC motors is determined by the frequency. With variable frequency drives, the revolutions per minute of AC motors can be controlled, too. The VFD unit, consisting of a rectifier, a DC bus and an inverter, gets a signal from the drillers control panel and regulates frequency and voltage of the current that runs the motor. The various VFD circuits are usually located in an own container.[48]

DC – DC System

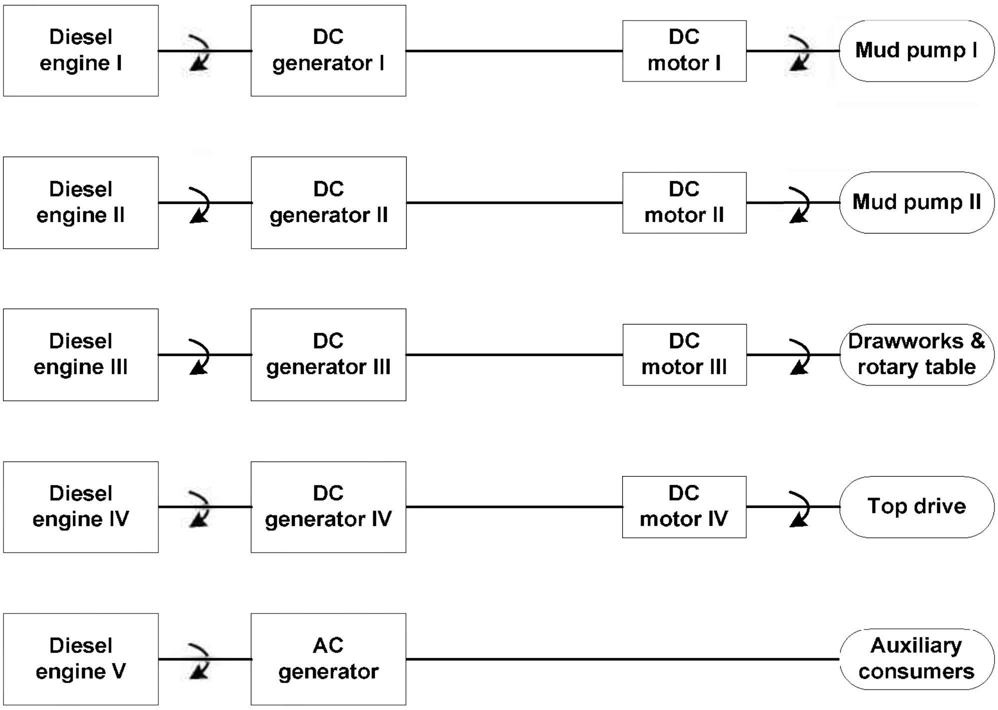


Figure 14: Electrical power transmission, DC – DC system

AC – DC System

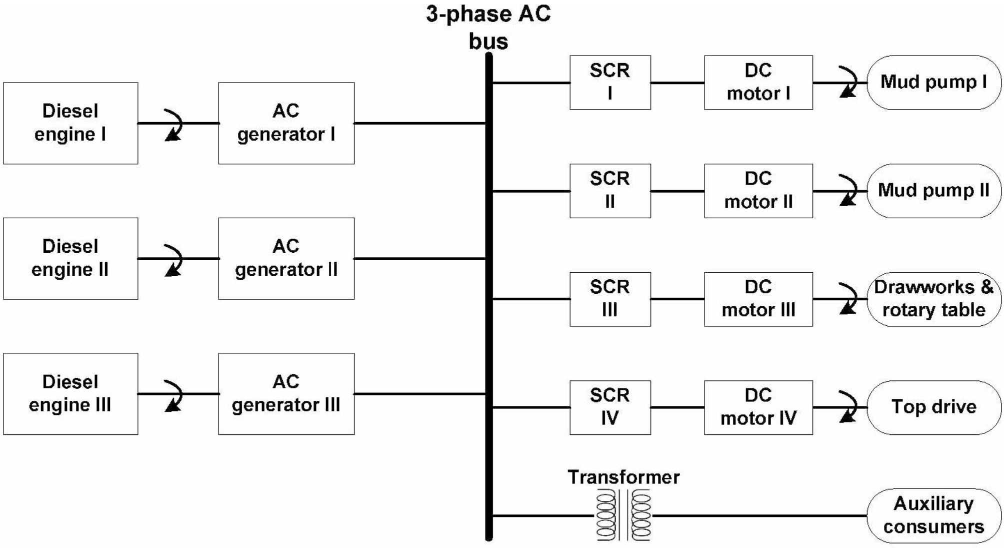


Figure 15: Electrical power transmission, AC – DC system

DC – DC System

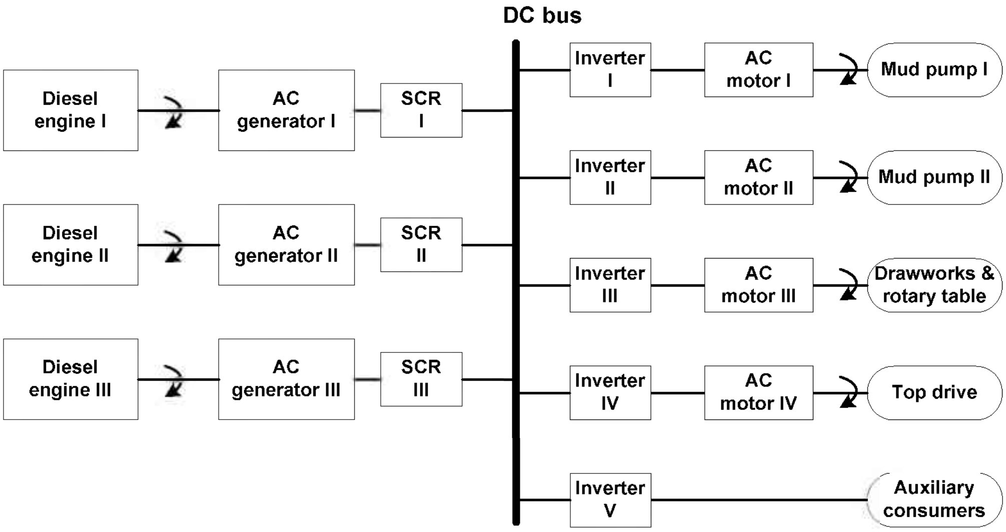


Figure 16: Electrical power transmission, AC – AC system

Hydraulic Power Transmission

The third way of power transmission is with hydraulics. A cylinder or motor is actuated by the pressure of a fluid, usually oil. The fluid pressure is build-up by a pump and then transported to the consumer via tubes and hoses. It is a common method to transmit power from one place to another. Depending on the design of a drilling rig, the proportion of hydraulic power transmission can range from driving only some small auxiliary equipment to providing the entire rig with energy.

Many companies do not want to implement hydraulic power transmission on their rigs. One demur is the spilling of hydraulic oil during connecting and disconnecting of the hoses and in case of leakages. Another concern is that operators want their equipment to be easy operable for the crew. They prefer hammer-proof equipment as this seems to be the only way the crew is willing to handle stuff. Sensitive pieces like hydraulic hoses tend to be damaged above average.

3.5 Substructure

The substructure is the base framework for the drilling rig on which all the equipment is installed. The important requirements for the substructure are the support of all the weight of the entire machinery and drilling load and to provide enough space under the drill floor for the blowout preventer. This has to be checked before selecting a rig for a job.

3.5.1 Self-Erecting, Box-On-Box Design

The main changes in the design of substructures during the last decades were made with the intention to facilitate rig moves. The framework was divided into smaller sections that could be transported from location to location by truck. The individual components could then be assembled with portable cranes. This was the beginning of the box-on-box design. Today manufacturer try to construct all components of the substructure, and also all the other components of the drilling rig, according to the dimensions of standard transport containers in length and weight (Figure 17). The challenge of a containerized layout is to meet the road traffic regulations to ensure transport during rig move to be as cheap and uncomplicated as possible.

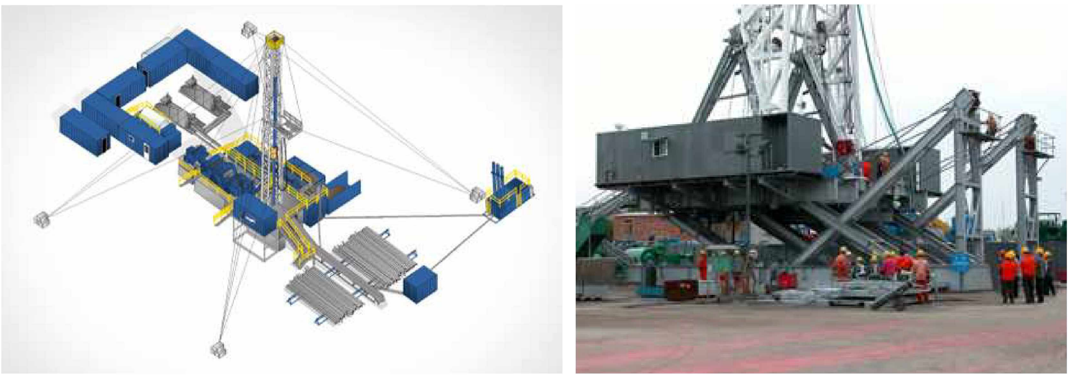


Figure 17: Containerized design of a drilling rig (left)[49], unfolding of a self-erecting drill floor (right)

The actual rig up and rig down procedure is facilitated by self-erecting constructions, at least as far as possible. The target thereby is to have a rig that can be assembled without any auxiliary cranes. Components, like the drill floor, can be assembled on the ground only by the use of the trucks and maybe a fork lifter. The structure is then unfolded with a winch or hydraulic cylinders into the operating position (Figure 17).

3.5.2 Moving Systems

A totally different approach for relocation is to move the entire rig in one piece. In some cases, the distance between two drilling jobs may be a few hundred meters, sometimes not more than ten or twenty meters. This occurs when an oil field is developed with several wells that are drilled form one location to minimize the environmental footprint, for example exploration of shale gas. Instead of disassembling the entire rig and then putting it together a few walking steps away from the original place, the construction is equipped with a moving device and can be sent to the next drilling job in the fully operational position.

Wheel System

There are different methods to execute such a venture. The most common one is to install huge tires at the edges of the rig (Figure 18) and pull it with trucks from Point A to Point B. This is very common for dessert rigs where the broad profile of the tires won't get stuck in the sand.

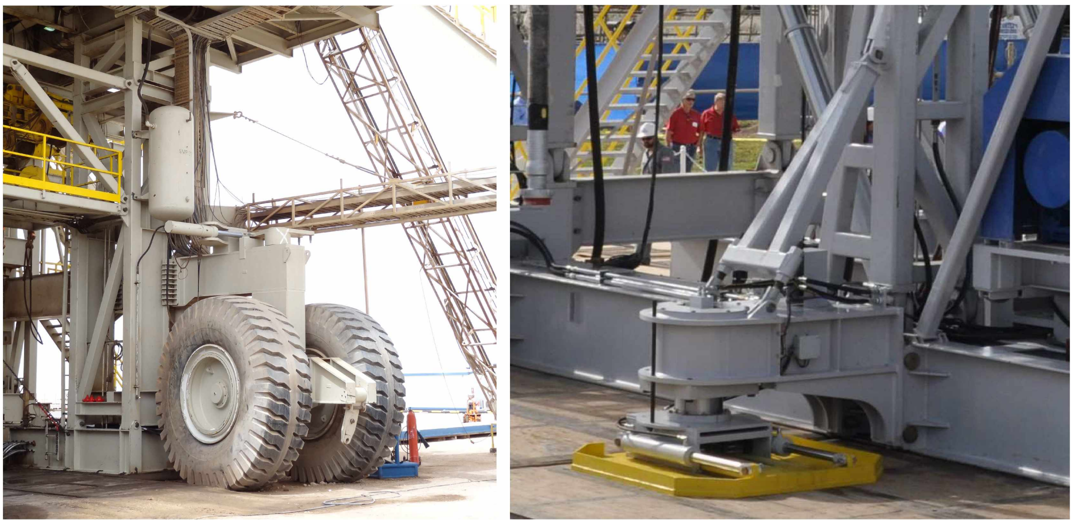


Figure 18: Moving system with tires (left)[50] and walking system (right)[51]

Skidding System

A much cheaper way to push a rig over short distances is the skidding system. The substructure is put on flat, metal panels or rails. These panels are lubricated with grease to reduce friction and prevent corrosion that would bond the substructure and the rails together when the construction is not moved for weeks during the job. The rig will then slide on those rails, pushed by hydraulic cylinders, to the next well. The problem here is that the rig can only be moved along one axis. But in many cases, this is enough.

Walking System

A relatively new technique is the walking system (Figure 18). It is similar to the skidding system, but instead of a fixed track, the hydraulic cylinders push the rig along metal plates that are only a few meters long and attached to the rig. The direction of these plates is variable and therefor the rig can not only walk along one fixe axis but can be directed to a certain degree which makes it more flexible.

One technical requirement for these three moving systems is an enhanced structural stability of the substructure as it is exposed to forces outside the normal range of drilling activity. In particularly for the walking system and the transport with enlarged tires, as the entire load of the construction is concentrated in a few points. The second requirement is that the substructure has to be extended so that all the other equipment, like mud pumps or the catwalk, are attached to the rig. This is not a must but it saves time as these components do not have to be moved extra.

3.5.3 Platform for modular designed equipment

The classic, universal applicable drilling rig is becoming less and less popular. Operators go for rigs that can be adapted to different drilling purposes. Therefore, the substructure is changing into a platform that can be equipped with different drilling components. This would also allow tools from different manufacturers. This brings incredible benefits for the rig operator as he can build together the rig he needs from a set of different models.

3.6 Rig Control System

Operating a rig puts high requirements on the crew, especially the driller. Different heavy machinery with high power has to be controlled simultaneously and with special care to meet the requirements of the operation. As the crew is interacting with the equipment it is even more important to stay focused to avoid accidents. At the same time, the drilling parameters such as hook load, drilling torque, mud flow, etc… have to be monitored and responded to. Mistakes, even small inattentions, can lead to incidents with severe consequences.

User-friendly operability has not been a big issue for a long time. The main function such as the mud pumps, the rotary system and the drawworks with the catheads can be operated from the driller's console (Figure 19). The signals that actuate the equipment are transmitted pneumatic or electric. The brake for the hoisting is controlled with a lever that is connected to the shaft that actuates the jaws. The auxiliary devices like a winch have to be driven directly with controls on the tools. With the working area right next to the well center, the operator is rarely protected by any kind of shelter, thereby exposed to all kinds of hazards on the rig floor like spilling drilling fluid or detached piece parts. Not to mention the fact that standing in wind and weather through an entire night shift will influence the crew's operational capacity and motivation in a negative way.

Figure 19: Driller's console next to the hoisting drum (left) and modern driller's cabin (right)

Manufacturers start to design new drilling rigs not only more efficient but with better working conditions for the crew as well. The conventional driller's console is replaced by a closed cabin (Figure 19) with heating and air condition, thereby removing the driller from the hazardous area on the rig floor. The control devices for the machinery and the information system with all the necessary drilling parameters is arranged more ergonomic so that the driller can concentrate on what he is doing and not on how he is doing it. Joysticks allow a more intuitive operation of the hoisting system or others like pipe handling. Blind spots, like the monkey board, can be equipped with cameras and displayed on the monitor, communication systems connect the driller to the important locations like rig floor, push, mud tanks or the machine room. With electronic data acquisition and monitoring systems, the information displayed in the driller's cabin can be easily monitored from others like the pusher in the doghouse or from a drilling engineer in any office around the world. However, videos from cameras on the rig can only be monitored on the rig and must not be recorded due to labor law regulations.

The next step is to remove the rest of the controls away from the exposed places. Iron roughneck handling is already possible to be done in the driller's cabin or a steering stand in safe distance away from the tool and its hazards. Even more advanced working infrastructures provide driller's cabins with control of pipe handling, iron roughneck, etc… too. As this amount of tasks would be too much for one person, these cabins are usually build for two people, the driller and the assistant driller.

3.7 Drill String Handling

The task of the drilling rig during the drilling of the hole is to hold the load of the drill string and to support it with torque and pump pressure. The main work for the rig and the crew starts when the drill string stops to rotate. The layout has to be adapted many times to react to changing drilling conditions. This begins with the adding of drill pipe to extend the stem as the bit bores deeper and deeper and can come to the tripping of the entire drill string for modifications of the bottom hole assembly such as changing the bit due to wear or changing the entire BHA for a new hole section. The handling of these tools is complicated as they are heavy, cumbersome and require high torque for make-up and break out. In addition to that the string is contaminated with downhole fluids when it comes out of the well and some tools have to be treated with special care so they will not be damaged. The handling of drilling tools is a key element for the evaluation of a drilling operator and the performance of the equipment and the crew. Reducing the time for BHA manipulation means reducing the time required for drilling the well.

The handling of the drill string can be divided into different phases:

- Transport and Storage at the rig site
- Transport onto and from the rig floor (pick up and lay down)
- Handling and assembling on the rig floor

Most of the work concerning drill pipe and BHA handling is done on the drill floor. To enable the assembling and disassembling of the tools special equipment is necessary.

3.7.1 Handling and Assembling on the Rig Floor

Slips

Slips hold the entire weight of the tubular in the borehole when it is not connected to the hoisting system while making a connection. Slips have a cylindrical inside to fit the tubular with jaws to grip it (Figure 20). These jaws have to be serviced from time to time as the teeth of the jaws can be plugged with small metal debris from gripping the metal pipes. The outside is slightly conical so that the jaws will be pushed against the wall of the drill pipe as the slips are forced down into the bushing. Different slips are necessary to cover the entire range of tubular sizes. One slip size can handle up to three drill pipe diameters. Smaller slips consist of three segments, depending on the size the number of segments increases with a maximum of over ten for casing. As the slips can only support a small amount of torque they should not be used to rotate the drill string. Tasks like orientation of the drill string for directional drilling, however, can be conducted.[52]

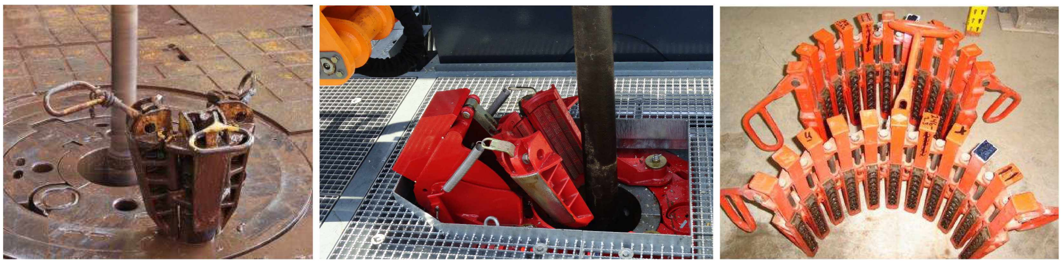


Figure 20: Conventional Slips (left), mechanized slips (middle) and casing slips (right)

Some manufacturers offer remote controlled, mechanized slips (Figure 20) as the handling frequency is rather high. This should improve working conditions and safety. These mechanized slips are actuated hydraulically or pneumatically and controlled by the driller. Nevertheless, manual slips are still the most common ones. In some cases the crew uses them even though mechanized slips are available on the rig floor (Figure 21). The problem is that not all automated slips can be used to rotate the string for directional drilling. Another limitation is that changing the jaws for varying pipe diameter or removing the slips for BHA tools with extended diameter, like stabilizers, is time-consuming with mechanized systems. Removing and changing the manual slips is rather easy.

Elevator

When the tubular is not connected to the swivel or top drive it can still be held by the hoisting system with elevators. The elevator is attached to the block or top drive with two steel bails on both sides. Elevators vary in size and type. Important is to distinguish between drill pipe elevators and drill collar elevators as they have different shoulders to fit the different shapes of the tubular. Taking the wrong elevator for a certain pipe will lead to damage.

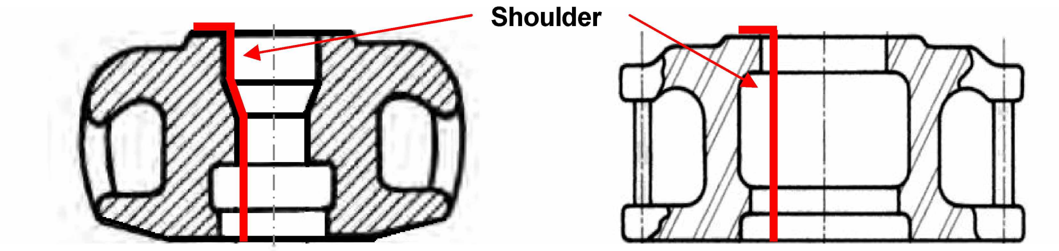


Figure 21: Drill pipe elevator[53] (left) and casing elevator[54] (right)

On many rigs elevators have to be handled manually. This is risky and labor intensive, especially for bigger pipe diameter. New rigs are equipped with mechanized elevators. The bails, that hold the elevator, are modified with hydraulic cylinders on each side. This way they can be pushed from and to the well center which facilitates picking up and handling pipe on the rig floor. This system can be combined with hydraulic or pneumatic driven elevators which open and close by themselves. This type of elevator system can be used hands-free and is controlled by the driller.

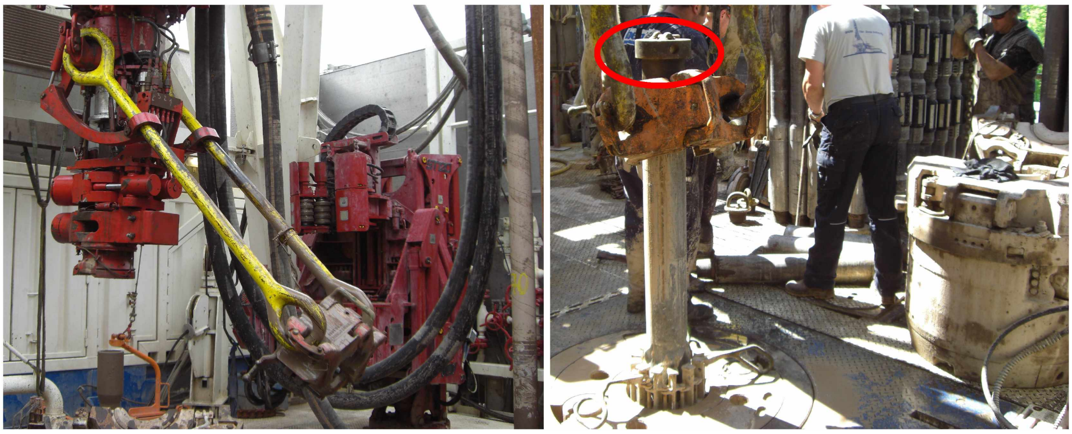


Figure 22: Hydraulic elevator bails (left), stabilizer with casing elevator sub in elevator (right)

Manual Tongs

To make up or breaker out the connections of a drill pipe or a part of the BHA immense amount of torque is required, in extreme cases more than 200 kNm. To apply this amount of torsional moment the crew uses the manual rig tongs in combination with the cathead. Tongs can cover a range of different pipe sizes due to the adaptable lug jaws. During use they are lifted with auxiliary winches as they are heavy, the big tongs can weigh up to 300 kilogram. The rig crew swings them from a parking position on the side of the rig floor to the well center where they are latched to the string for make-up or break out. The lever is then actuated by a cable that is pulled by the cathead, the gripper tightens itself through the turning of the tong in a uniform force distribution around the pipe. It is important that the lever and the cable align in a right angle to achieve maximum torque and also to know the exact value of the torque.

Using the manual tongs is an exhausting venture, especially during tripping. It is considered as one of the most dangerous work steps on the rig floor. The heavy equipment in combination with the high forces for make-up can become a severe hazard for the crew. This starts with the pinching of a finger and can become life-threatening when the human body gets caught between the lever of the tong and another steel body.

Figure 23: Manual tongs (left) and iron roughneck (right)

Spinner (Power Tools)

Tongs can be used to make-up or break a connection, but they still have to be screwed together or apart. Using the tongs is rather inconvenient, manual screwing is only practicable with very small pipe diameter and should be avoided anyway. Chain tongs are common tools to unscrew tubular manually because they can be handled better than heavy manual tongs. Some crews spin a chain around the pipes and pull it with the cathead. With the friction between the chain links and the pipe wall, this will unscrew them rather fast. Still, it can lead to accidents.

Instead of doing it manual, spinners can be used. They are usually mounted at the swivel and rotate the kelly, thereby unscrewing the pipe.

Iron Roughneck

The introduction of the iron roughneck has been one of the biggest game changers in rig floor design. This machine allows mechanized execution of making, breaking, screwing and unscrewing connection of pipe. With remote control, crew members won't have to be around the well center any more. The roughneck is located next to the well center in a waiting position. For operation, it will be moved to the well center. Two sets of jaws, usually hydraulic, are set onto the tool joints, one on the upper and one on the lower. This will break or make-up the connection. On top there are usually rollers that will then screw or unscrew the tubular. Moving of the iron roughneck used to be done mainly with a rail system to support to enormous weight. As rails are hazardous for tripping, new systems use manipulators to guide the iron roughneck around the rig floor.

Handling auxiliaries

To handle all tools on the rig floor a wide range of different auxiliary devices is required. Most of them are necessary to process bottomhole assembly. Different kinds of lifting subs allow the hanging of tools in the elevator which would not fit in due to size or shape. Drill collars, for example, cannot be handled by elevators as they have a plain outside with constant diameter.

During tripping operations of drill string or installation of casing, the pipes have to be unscrewed from the kelly when new pipe is installed or taken out. In this case the entire string is hanging free in the borehole, held in place only by the slips. If the slips fail, the entire drill pipes or casing falls into the well, which results in costly fishing or damage. To ensure that this will not happen, it is advisable to install safety clamps around the pipe, right above the slips. It acts as a backup, holding the tubular employing friction.

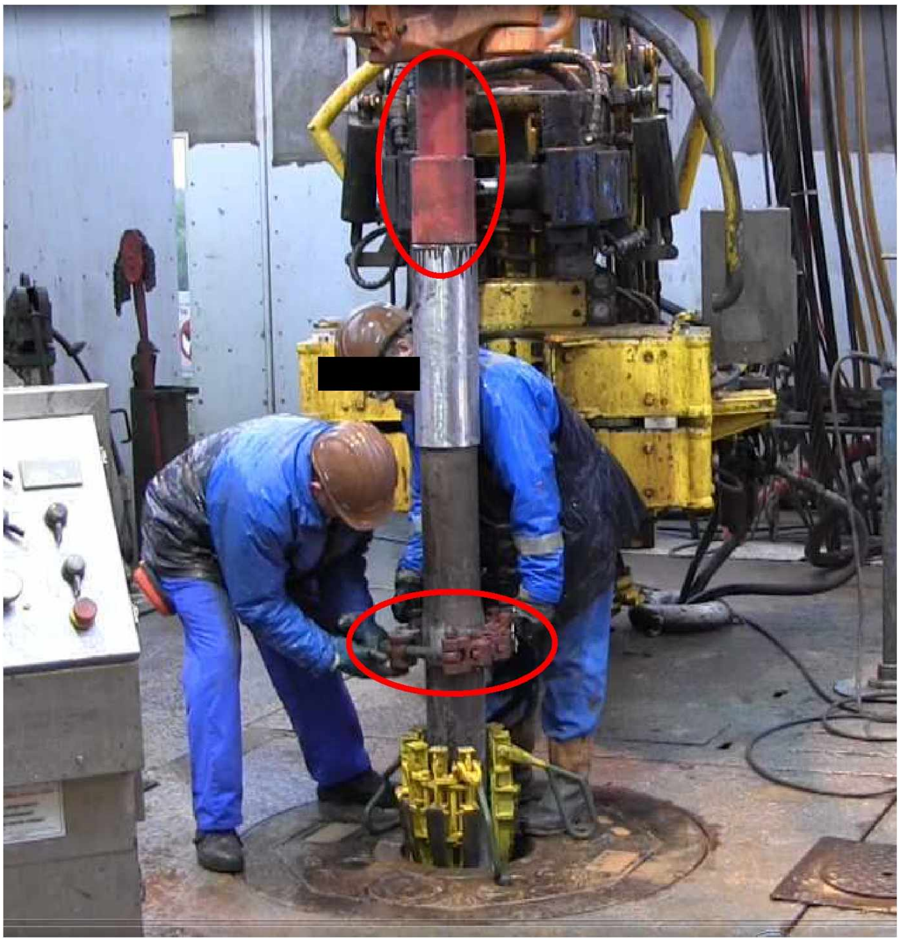


Figure 24: Crew installing safety clamp, lifting sub on top of the string

When the tubular is filled with drilling fluid during tripping, the so called wet tripping, fluid will splash out of the connection when the pipe is lifted after unscrewing it. To protect crew and avoid spilling of the rig floor, mud buckets are used. They are pulled over the tool joints and trap the drilling mud. Mechanized versions are available but not very common.

Landing/Lifting sleeves, also called step-in and step-out guides, look similar to the mud buckets. They fit around the tool joint and have conical openings on both sides. They guide the pin threads in and out of the box threads to avoid collision. The threads, especially WT threads, can hook together which could lift the string and loosen the slips when pulling out.

The shape of the drilling bit does not allow the use of tongs. Therefore, a plate is used to hold it. This plate, the bit breaker plate, is connected to the drill floor or the rotary table with a frame.

Service auxiliaries

The string components and especially the threads have to be maintained. When pulling out of the well, the pipe is covered in drilling mud which is usually very aggressive to metal and would corrode them. So they should be cleaned as good as possible. This is done on the rig floor to prevent spills on the ground. The cleaning is executed with a conventional water hose, in some cases with high-pressure cleaners. Some rigs also use sponge sleeves or a rubber mat with a hole to wipe the mud of.

The threads have to be treated with special care. Grease is used to improve the quality of the connection. This is done with a simple brush that is dipped into the grease bucket. Depending on the condition, cleaning with a rag should be done. To save the threads during transportation, thread protector caps are used.

Figure 25: Step-in guide (left), mud bucket (middle), bit breaker plate (left)

3.7.2 Pick Up and Lay Down

Slide

Every part that has to be transported onto the drill floor will go there over the slide. It is a very steep metal ramp that guides the tools when they are pulled up with the winch. For many drilling rigs, it is the only way to bring equipment up on the rig floor. Long tubular like drill pipes, casing or MWD tools as well as small components such as stabilizers and bits come to the rig floor via the slide. Even auxiliary equipment like wrenches or thread protection caps come this way.

Pipe Set Back Installation

Nearly every conventional land drilling rig does have a board in the mast to set back tubular if they are not used at the moment. Especially during tripping, laying down of every pipe would be very time consuming. Instead, the pipe is stored in the mast, attached to the so called monkey board. However, it is very risky as usually one crew member has to be on the board to handle the pipe. New rigs bypass that risk with mechanized pipe handling equipment that would do the crew members job. Another option is to store the pipe on the ground. Super single rigs with efficient mechanized pipe handlers do not require set back capacity at all and can still trip at reasonable times as well.

Mechanized Pipe Handling

More and more rig manufacturers install mechanized pipe handling systems on their rigs (Figure 26). Especially smaller land rigs that use super single pipe utilize this very fast way of bringing pipe up to the well center without any interaction of the crew, besides from operating the gadget.

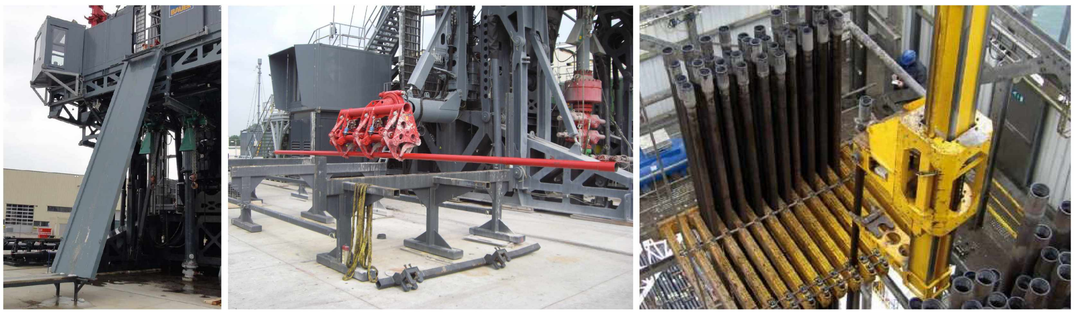


Figure 26: Slide (left), Pipe Handling machine[55] (middle) and mechanized monkey board (right)

3.7.3 Transport and Storage at the Rig Site

A lot of equipment has to be stored on the rig site. Usually two sets of drill strings with different pipe diameters and various BHA sets will be required. In addition to that there are all kinds of additional equipment and maybe the casing string for the next section. Tubular is usually stored on racks, usually near the catwalk. Smaller BHA parts as well as additional rig equipment is shelved in cage boxes and palettes. Transportation is done with a fork lift, to handle pipe on the ground operators prefer the use of lifters with pipe grippers which allow save transport of tubular (Figure 27).

Figure 27: Logistics on the rig site

3.8 Drill String

This is the one part of the drilling rig that is actually drilling the hole. All the other equipment is only there to actuate the drill string. The drill string is composed of numerous components and varies from drilling project to drilling project as it is designed different for each application. The drill string consists of drill pipes that support the weight of the drilling tools and connects them to the rig. It transmits the drilling torque to the bottom and the drilling fluid is pumped down through its hollow body. At the end of the drill pipe are tubes with high dead weight to provide the drilling bit with downward force. They make sure that the uppermost part of the drill string is kept straight and in tension. These are the heavy-weight-drill-pipes and the drill collars. The bottommost part is the bottomhole assembly with the bit. This is the actual drilling set that is making the hole and provides control of the direction. As the drill string is probably the main key factor for drilling performance a lot of effort is put into the development of better and more advanced downhole tools. At the beginning of the hydraulic rotary drilling technique the drill string was not more than some metal pipes that were screwed together and a tool with blades at the bottom, the so called fishtail bit. This has changed over time and the BHA of today is setup of different high technology downhole tools that can be precisely modulated to the requirements of a variety of drilling projects.

4. Drilling Rig Performance

4.1 Demands of the Market

The total available rig count on the US market has been steadily declining for the last years. The tendencies in the residual world look similar. At the same time analysis of future development shows that the number of drilling activities will go up in the next years. The gap between increasing demand and declining supply is an indication for rig manufacturer that new equipment will be required on the market.[56]

The challenges for the design of new drilling rigs will all lead to one target: economic successfully drilling of wells. But this does not necessarily mean that the cheapest equipment will be successful, the overall performance will be crucial.

4.1.1 Diversity of Drilling Operations

It is difficult to give an example of a standard drilling operation. There are so many different variables, offshore or onshore drilling, shallow or ultra-deep wells, vertical, horizontal or deviated wells, etc. The choice of the appropriate type of rig will play an important role on the success of the operation. On the one hand, rigs should be universal applicable to be able to apply for as many contracts as possible, especially as relocation distances should be kept to a minimum.

On the other hand, every part of a rig's capacity that is not used will be a loss for the economic performance. So designing a rig for special types of wells will make them very competitive. Especially bigger development projects that call for wells with similar boundary conditions, for example development of shale gas reservoirs, will tend to devote built-for-purpose rigs instead of built-for-market rigs.

4.2 Key Performance Indicators

The performance of a drilling rig can be rated by the relation between its capacity to drill a well of a required quality as fast as possible and the effort to execute the drilling of the well. This is nothing new. The correlation between input and outcome is a dominant factor for success in any other commercial field. The problem is to remark a precise statement about the performance. A drilling rig is a complex compound of different machinery, variable in quality and size, and is utilized for different jobs ranging from workover operations to the drilling of highly complex wells.

The performance of a drilling rig depends on many factors and measurement is therefore complicated. The layout of the well plan and the geology, the available surface and downhole machinery or the environmental conditions at the drilling site have immense influence on the way a drilling rig will complete a certain job. Nevertheless, the most influencing parameter is the human factor. Many tasks at the drilling site have to be handled by the crew. And even in the case of a high rate of mechanization, the equipment is still actuated by humans and is therefore dependent on the skills of the one who is operating it.

To be able to make qualitative statements about the operating level of a drilling rig it is helpful to implement key performance indicators.

4.2.1 KPI Measurement and Interpretation

To reflect and rate the performance of a tool or of a process, a good way is to put certain parameters into relationship. These values are called key performance indicators, or KPIs. An example for a common known KPI from the everyday life is kilometers per hour. If you take the average km/h during a long drive or the maximum value a car can go, you get a good idea of the driving performance and, most important, can compare it to others. Initially, key performance indicators were used to evaluate economic coherences. Nevertheless, they proved to be quite helpful for monitoring technical processes, too.

To evaluate a drilling rig, there are some specific KPIs defined in the oil and gas industry. The most common is “meters drilled per day”. The problem with this KPI is that it does not consider the specific situation of the drilling job. A certain value of “meters drilled per day” can be good for drilling a complicated well path in hard formations. The same value may be bad for drilling a shallow well in an already known formation. The same problem occurs with many other KPIs. Therefore, a proper analysis of KPIs will be always done in combination with the necessary background information, for example from the morning report.

Depending on the subject that has to be observed, a significant KPI should be defined. Some values give a good overall picture, others can be used to look on a situation in detail. A few examples for common KPIs in the drilling industry are the following:

- Drilling progress , meters drilled per day (or per hour)
- Drilling costs, amount of money (usually dollar) spent per meter of a well
- Tripping speed, meters of drill pipe tripped in or out of the well per hour
- Rig-up time, time required for assembling and dissembling the rig during a relocation
- Safety incident frequency, injuries that occur in a certain period of time
- Productive time, the share of time that is used for the actual drilling operation
- Non-productive time (lost time), the share of time that is used to deal with unexpected events like technical breakdowns or waiting on weather

To come up with useful key performance indicators it is necessary to collect accurately measured data. Taking them from the morning report may be inaccurate in some cases as this form of documentation is done manually and therefore not hundred percent objective. Important facts, like tripping times, are monitored during phases of intense activities and may be inexact as the focus of the crew is on the operation and not on the documentation. Important information may be missing due to a lack of communication between the one who is documenting and the one who is evaluating. And most important, the detailed evaluation of the performance of a drilling rig requires various kinds of data which should be taken every predefined time interval, in many cases this intervals will be a second. This is just too much to be done manually in a consistent way, especially with routine operations. Automated data acquisition, therefor, will play a big role in detailed evaluation of drilling rig performance[57].

4.2.2 KPI Influenced by the Drilling Rig

According to a rule of thumb in the oil and gas industry, forty to fifty percent of the total financial efforts for drilling a new well are related to the drilling rig[58]. This includes day rates for equipment and crew, energy consumption, mud system or costs for rig move. The rest is spent on material like bits, for cement and casing, all kinds of services or the preparation of the well site. This is only a rough approximation as the costs depend on the kind of operation, whether it is a shallow well in a known oil field or a deep, horizontal exploration well. But still, the performance of the drilling rig has a big influence on the economic success of a prospect for oil. Figure 28 shows the different matters of expenses from a quotation for drilling three geothermal wells to give an idea about the driving units for overall drilling costs of a project.

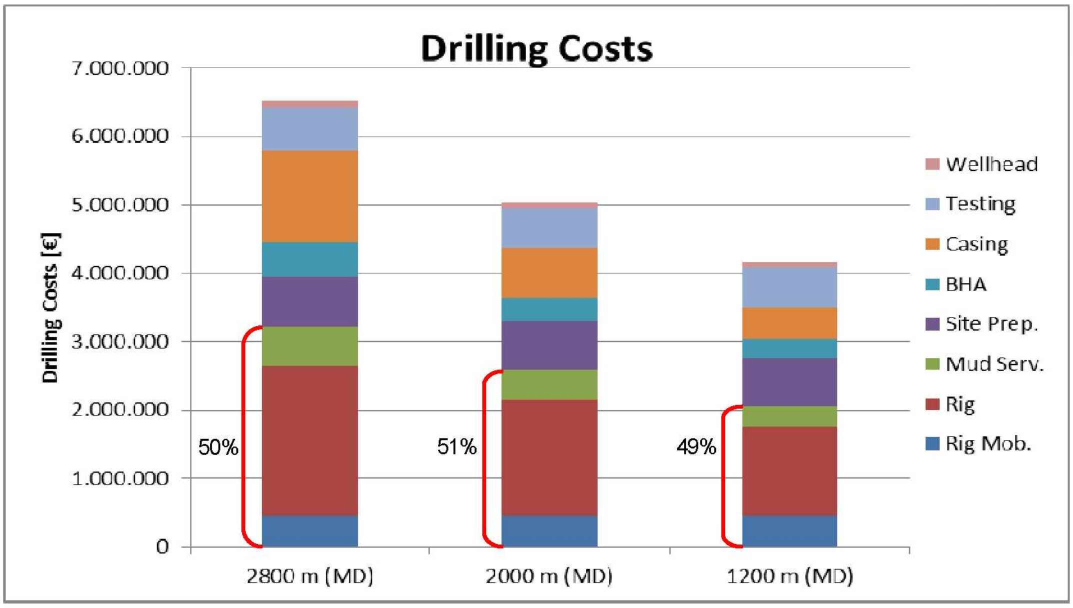


Figure 28: Example of the total costs for drilling geothermal wells

To rate the performance of a rig it is necessary to concentrate on those parameters which reflect only the part of an operation the rig has an influence on. The rate of penetration, for example, will be influenced significantly by the quality of the bit and the BHA. As long as the rig will provide it with sufficient torque, it will not be able to improve ROP dramatically. The same is valid for the life span of the downhole equipment. As long it is installed and operated properly, it will last for a certain period of time, no matter if an old rig or a modern one is revolving it.

In general, a drilling rig can outdo other competitors by being ahead in some specific categories:

- Reducing operating costs
- Decreasing operational time
- Improving health, safety and environment related issues

Reducing operating costs is primary related to the day rates. Figure 29 shows the proportional cost factors of a 25.000 € day rate for a 300 tons drilling rig. The biggest share is the cost for the rig itself which will be derived, among others, from the purchasing price. Operators try to run their rigs 24 hours the whole year which requires four crews for a twelve hour shift system. With 6 people each crew, this is a major cost factor as well as it can be seen in Figure 29. Reducing the personnel to zero is hardly possible, but designing a rig that could be run with less people would bring a potential saving. And as the graph shows, fuel efficiency will not only bring environmental benefits but also financial.

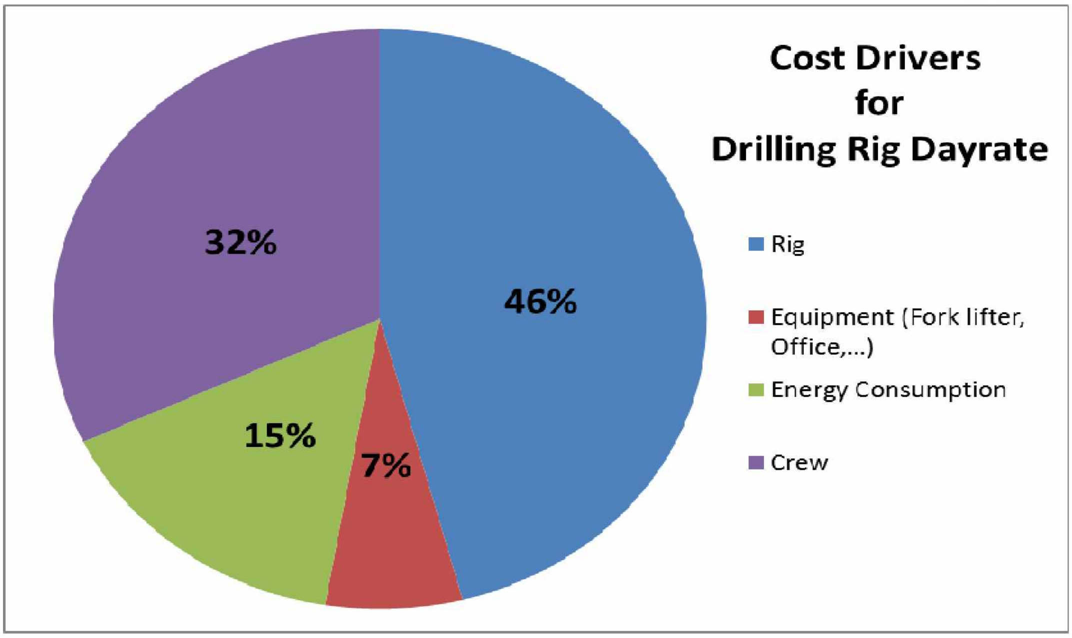


Figure 29: Proportion of the main expenses on the day rate for a drilling rig

Decreasing operational time is the second option to minimize the overall rig costs. As already mentioned, the design of the rig does not influence all processes. So it is important to have a look on those parameters which can be improved by the surface equipment.

Effective handling and logistics of pipe and downhole tools is very important. The faster they can be brought into the well the higher the percentage of time that is spent on actual drilling. Another important role is the rig up and rig down capabilities of the machinery. Easy and fast relocation is characteristic of a rig that can save quite an amount of money, especially in rather populated regions like Europe.

High HSE standards will not only help to keep accident statistics low, but it has influence on the drilling time too. Damage of tools and injuries of the crew will lead to delays. Frequency of technical failures due to false treatment on the surface is a problem. An accident of a crew member will lead to temporal shut down of the operation and brings costly investigations with it.

Improving HSE is one of the hot topics in the business. Working on a drilling rig is, with no doubt, considered as one of the high risk jobs. Accidents have severe consequences and can result in the loss of lives in the worst case. Besides that, the oil and gas industry is very well observed by the media and numerous NGOs. It has the reputation of being very money focused with no scruples of sacrificing human life and the environment for the exploitation of hydrocarbons.

Minimizing the number of work accidents is not only a matter of ethics. The economic consequences have to be considered too. The injury of a crew member is followed by the shut-down of the operation for at least a few hours, depending on the severity up to one or more days. Investigations for the circumstances of the accident and improvement of HSE standards will follow and bond personnel. Plus, all companies, especially those who are listed on the stock exchange, will be rated not only by economic success but also by indicators like work incidents with injuries.

4.2.3 Lost and Hidden Lost Time

Rating of KPIs like “meters drilled per day” is a rather simple way of classification of the performance. Drilling operations are diverse and comparison of such values may not tell the entire story. The analysis of productive and non-productive time goes a little more into detail and gives an idea of the different time consumers during the drilling of a well. Exact drilling data monitoring should help to detect those parts where valuable time is lost due to mistakes.

The most common way is to compare productive time (PT) with the non-productive time (NPT) to detect opportunities for improvement. Productive time is the time of actually drilling the well with the bit rotating on bottom and the pumps on. The residual time is non-productive time, also called flat time as on a time vs. depth drilling diagram the curve will be flat. This is where all the operations like tripping, reaming, running casing and cementing, maintenance and other work is done. So the name non-productive time can be misleading as it contains tasks essential for drilling a well but at the same time unplanned and sometimes unnecessary events that should be avoided, for example shut down of the rig due to an accident. Hence, NPT is where the biggest potential can be found for saving operational time and consequently saving money, especially savings that are related to the design of the rig.[59]

The time spent for such unnecessary events during non-productive time is considered (visible) lost time, or down time. Lost time, such as waiting for equipment, can be detected in morning reports. The investigation of hidden lost time is more difficult (Figure 30). Hidden lost time is the outcome of operations that are not executed at the technical limits and mainly related to human failure or poor equipment. The driller that has to wait for the crew to lift the slips, equipment that has to get onto the rig floor during tripping due to bad coordination, results of tool damage or the inconvenient handling of equipment due to the lack of proper handling procedures are only some of the many examples that can be seen on rig floors. Studies have shown that hidden lost time is responsible for a significant amount of drilling time, in some cases up to 30%. So elimination of the lost time and especially the hidden lost time should be high priority for operators.[60]

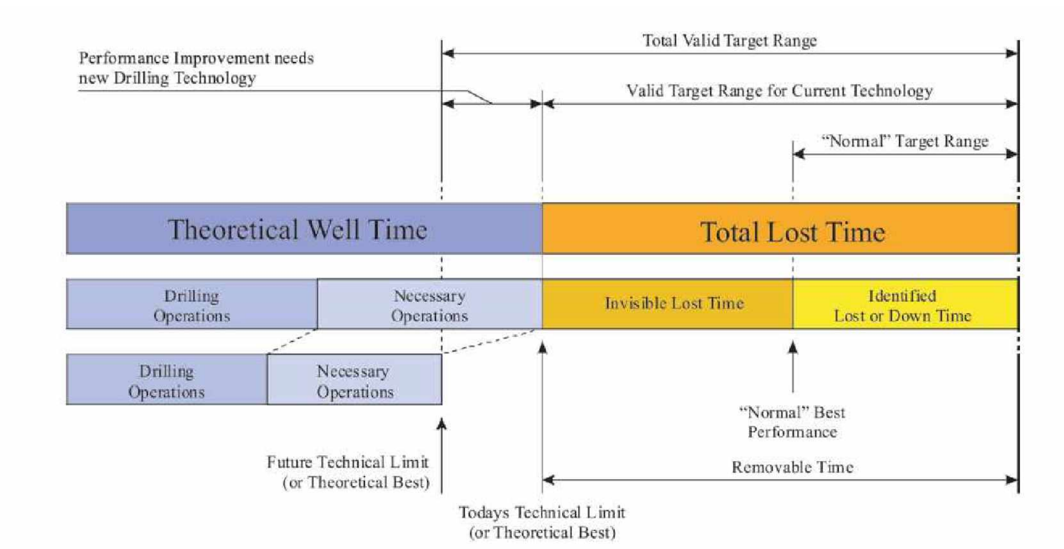


Figure 30: Theoretical well time vs. real well time due to lost time[61]

4.2.4 Best Performance

Best performance is the ultimate goal that people want to reach, no matter which discipline. In the drilling industry, as in all other productive processes, best performance can be achieved with the focusing on two things. Getting rid of the lost and invisible lost time on the one hand and pushing the limits of the machinery on the other (Figure 30).

Benchmarking is the comparison of the performance of competitors, usually those who are working at the highest level. It is the easiest way to find the technical limit of a certain process. Those operators who will drill a well in the shortest amount of time will probably work as close as possible to the technical limit, and therefor set the benchmark for all the others. Still, it is important to compare the overall performance. Not only time, but other criteria like quality of the well or total costs have to be compared, too. If several members of the crew get hurt during the drilling of the well, it might not be the best way of running a rig, even if they run it fast.

The philosophy of **performance drilling** can be compared best to those of sports teams, like formula one. The main goal is to execute the ideal work flow and therefor reach the best results. The interaction of rig and crew is essential. The crew has to be at a very high training level that knows every work step by heart. The workflow is usually very well defined, unnecessary work steps are eliminated. Although the equipment is usually at a high level, operators try to avoid unnecessary machinery on site and keep the system as simple as possible. If a tool will not improve the performance dramatically, it will not be used as it is another part of the game that could fail or disturb the work flow. This is why many rigs that do performance drilling will not have tools like an iron roughneck or automated slips. They could only slow down the process. The problem is that the whole concept is very dependent on the human factor. If one member has to be exchanged, the work of the entire crew will suffer. And performance is nothing without a constant level of doing so. It is not enough to make one very fast slip to slip connection. The time required for this has to be kept stable over the entire time period.[62]

Lean manufacturing comes originally from the car manufacturing business. Since then the ideas have been used in many other disciplines and can help to improving drilling efficiency. The concept of lean manufacturing is to avoid anything that is not essential for a certain goal and concentrate on the actual creation of value. The focus is on the customer and his needs. The things that are important for him are of high priority as he is willing to pay for it. A lot of effort is put into the optimization of the different manufacturing processes, synchronization is very important to avoid downtime. Automation is a key element to execute the physical and mentally exhausting duties. If production systems do not deliver the desired outcome engineers will not only go for small alterations but for radical changes. Instead of having unskilled workers with no authorities the employees are well trained so they can react quickly if necessary. The result is a production that creates the same number and quality using less of everything. Less workers, less resources, less space and less time.[63, 64]

4.2.5 Predictability of Well Planning

The different time intervals that are required to do exactly the same work task are not only a sign that a rig is not working at the optimum. The even bigger problem is that scheduling of drilling projects becomes inaccurate. The time required for a 2000 meter trip to change the bit can only be predicted by using rough estimates. Typical forecasts might be between eight and twelve hours or half a day. Prognosis closer than one hour are rare and only for standard operations that have happened in the last weeks. Cost come up for down time due to waiting on equipment or excessive standby of all kinds of services, a just in time concept is quite far away.

Drilling companies have started to use data warehouse processing. Operations from the past are recorded and documented to use them for future well planning. Still, automated data collection as well as automated execution of the work will significantly improve the precision of project scheduling.

Looking at the bigger picture, the estimation of the time required for an entire drilling project is quite broad, too. Sure, telling the exact amount of days is not possible as so many unknown factors have an influence. Geology, weather, unexpected troubles with equipment lead to intense delays, especially in projects as big as drilling for oil and gas. But companies have to plan their annual budget for exploration, more accurate planning of the amount of days that are required for drilling a well ensures better disposition of financial resources.

4.3 Development in Human Resources

4.3.1 Working Infrastructure

The working environment on a drilling rig is changing. In the past it used to be a rough place to work. Handling of heavy equipment, contact with all kinds of fluids, exposed to the weather, working in shifts on remote places, far away from civilization. Roughnecks used to have the reputation of being tough guys, injuries where part of the business, the missing of a finger nothing unusual.

With the development of technical highly advanced tolls the demands on the crew increased. New tools are often very sensible and require special techniques for handling and implementation. Tool damage became a severe problem as the careful handling of very heavy equipment is not quite easy, especially if the personnel is not used to that. Manufacturers of hydraulic rigs, for example, report that components get damaged during installation and maintenance. The reason for this is that the rather sensitive couplings of the hydraulic hoses are treated with hammers as the crew is used to handle other machines on the rig site like this as well.

New rig designs try to make the working environment a more pleasant place to be. The driller is working in a closed cabin with air condition. The crew is removed from the well center with machinery that can be controlled remotely from a safe distance. Still, a part of the work has to be done hands on, for example installing BHA components.

4.3.2 Shortage in Human Resources

The oil and gas industry, particularly drilling rig operators, have problems recruiting enough personnel for running their operations. Positions with all levels of education are affected, but especially people that are working out in the fields are scarce. Reduction of the crew size of drilling rigs is going to be a big issue.

One characteristic of the drilling business is the up and down of drilling activities. With increasing oil prices, companies start to drill extensively. When the oil price drops, drilling projects are cancelled. The problem for drilling contractors is now that during low times with fewer jobs, a lot of their personnel have to be held on standby or even released to lower costs. During times with high drilling activities, they have problems hiring enough people to run their entire fleet on a 24 hour basis. If core workers are absent due to illness or holidays this becomes even worse. As a result, shifts have to work with reduced members or the free positions are staffed with rental workers with usually no or little experience. The workflow gets affected significantly. The permanent workers are faced with doubled burden as they have to think for the new ones as well, accidents are preprogrammed.

Finding new people becomes more and more challenging. The job on an oil rig is a good chance to make good money with low education level. But less people are willing to accept the working conditions as discussed before. And with the increase of the technical level, crew member-to-be have to be trained better and better before they can be sent on a rig as a full member.

Demographic tendencies will make this even worse in the next years (Figure 31). The aging pyramid in the drilling business is well known. Over the next years the industry will lose a big part of their employees due to retirement. And this goes hand in hand with the loss of knowledge as knowledge management is not practiced very much.

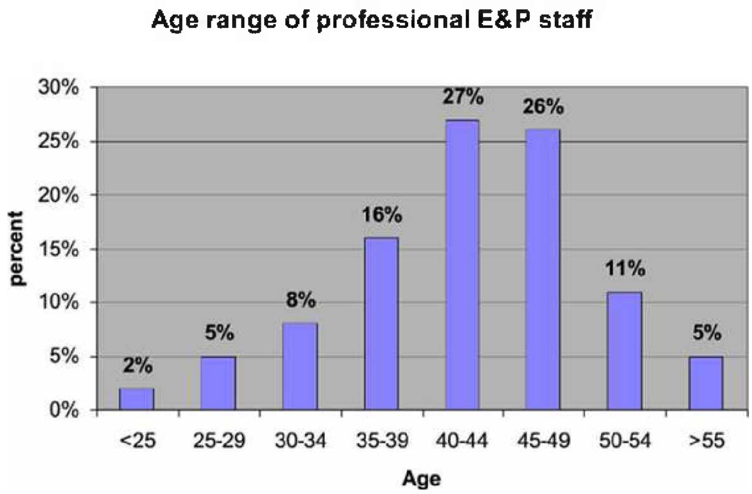


Figure 31: Demographic pyramid in the oil and gas industry[65]

A big share of the global hydrocarbon reserves are located in emerging and third world countries. Companies try to run their rigs there with local staff to avoid the problems of locating personnel from western counties. But finding work force in such countries is not easy. Poor education systems and different working mentality does often not fit to the requirements of running complicated machinery.[66]

5. BHA Handling Analysis

5.1 Documentation of BHA Handling

5.1.1 BHA Handling as Automation Milestone

The mechanization and automation of complex machinery like a drilling rig is not something that can be done in just one step. Some key elements have already been successfully realized. Iron roughneck and mechanized pipe handling were two major milestones on the way to a hands-off working environment on the rig floor. Tripping of drill pipe can be done without the intervention of the crew. But there are still quite a lot of work steps that require human intervention. The installation of BHA is such a procedure that involves a main share of manual labor due to its complexity. Plus, many of the work steps that appear during BHA handling can be applied for other work, such as installation of completion or cementing.

Developing a system that could handle the different sets of BHA strings will not be the finalization of the problem. But it would definitely be a big step closer to a rig floor that will not need the presence of the rig crew.

5.1.2 Reasons for Documentation

At the beginning of the thesis, the original plan was to do a case study about the implementation of an industrial robot on the drill floor and simulate the installation of bottomhole assembly. But already during the starting phase it was realized that the handling process is a rather complex one with many variables. Lifting a bit into a bit breaker plate and guiding the pipe into the threads would be an insufficient simulation scenario. Plus, the question came up whether an industrial robot would be the ultimate solution to our task.

For the automation of a work process it is absolutely essential to know it in every detail. Unfortunately, neither rig operators nor manufacturers of BHA tools had put much effort in the documentation of the working steps that are necessary to bring an operating bottomhole assembly into the well. The material which was found contained information about save handling of tools. Manuals were pointing out the must for protection of personnel with gloves and safety glasses, heavy loads should be lifted with the winch and protected against collision. But a step by step guidance for the correct installation could not be found, and as it turned out, was hardly available.

Therefor one step back was taken and the target redefined. The new goal was the precise breakdown of the bottomhole assembly installation process and its boundary conditions to understand the proceedings and make the development of effective automation practicable.

5.1.3 The Documentation Process

To understand and record the installation of BHA it was decided to observe it on site at an operating drilling rig. Thanks to the permission of ITAG this was done on two rigs of them (Appendix B – Rig 27 and Rig 30 from ITAG) that were operating not too far away from each other. Due to the limited technical auxiliaries and to obtain as much information as possible with only one monitoring person at the rig it was decided to focus on:

- Photo and video documentation of the rig floor
- Interview of crew, company man and members of the service company
- Collecting information about BHA setup, bills of delivery, data sheets of BHA tools and rig equipment…

It was decided to do **video documentation** of the work on the rig floor with a camera. The information that was required was just too much to be manually document by one person with pen, paper and a stop watch. With everything on video file it was possible to study every work step several times to get the details, stop the video and fill in the data sheets for the later evaluation. The second big advantage of the video documentation is the fact that it can be recalled any time for additional information. It happens quite often that during the processing of the collected data additional questions come up that did not appear before or during the field evaluation.

Photo and especially video documentation on a drilling rig requires some preparation. First it is necessary to get the permission to use a camera on the rig. This is critical for two reasons. The rig floor is a hazardous area with possible explosion-prone environment and an explosion proof camera was not available. And second, the filming of the crew during work is due to employment law not allowed. Nevertheless, the project management, the crew and the company man gave their permission to record the work on the rig floor and it was assured via confidential agreement (Appendix C – Confidential Agreement) to keep the material classified. Constant gas detection, especially for H_2S, assured a save working environment.

The camera was mounted on a tripod to prevent camera shaking and uncontrolled moving of the pictures. And with the camera out of the hands, it was possible to make additional notes. The position of the camera was in the driller's cabin as this turned out to be the spot with the best view on the well center (Figure 32). In addition to that, the cabin acts as a barrier against possible gas appearance and the crew members were not disturbed. One idea was to rasterize the rig floor for the recording with white tape. Unfortunately, even the strongest duct tape would not hold on the wet and oily metal floor. Another problem appeared as the camera had to be operated in battery mode as there is no possibility to have access to an electric socket on a rig floor. Therefor it was focused on specific working scenarios instead of letting the camcorder run the entire time.

To get a picture of the logistics at the rig site photos were taken to see how things are stored and transported up to the drill floor (Figure 32).

Figure 32: View of the camera (left) and pictures of the storage of on the rig site (right)

With **interviews of the people on site** it was tried to gather additional information concerning BHA handling and ask them about their personal position regarding mechanization and automation. At the beginning the general opinion was rather skeptical. The phrase "It's just screwing together of tools, there is not much to improve" came up a few times. But in a closer discussion over the days this changed. Particularly the younger crew members, but also all the others, could imagine that an automated system would have some benefits.

Further, additional information about BHA handling could be collected that did not appear in any literature. For example, certain members of service companies do not want MWD/LWD tools to be made up with the iron roughneck to prevent damage.

To **collect information** and to get an idea about the capacities of the rig tools and the logistics on site revision of different documents such as data sheets of BHA tools and rig tools, bills of delivery and the setup of the different bottomhole assemblies was done. The intention was to understand the logistics that is very important for automation. How many backup rig tools and BHA components are on site and where are they stored.

5.1.4 Processing of the Data

The close evaluation was done on three BHA runs (Appendix D – Setup of Documented BHA). The information gathered on site with the video documentation was fed into an Excel file (Figure 33). All files contained information about the setup of the used BHA and a very detailed breakdown of the work steps:

- Begin - time when the work step was initiated
- End - time when the work step was finished
- Δ time - actual time that was required for the work step
- Position - the position number of the BHA tool in the attached list of the BHA setup
- Tool - name of the BHA tool that was handled in that work step
- Lay down/set back - whether pipe was put on the ground or stayed in the mast
- Treatment - the name of the work step
- Necessary machinery and tools - a complete list of the equipment on the rig floor and information about whether it was in active use (for example crew was setting slips), passive use (for example slips are in place to hold the tubular, but not part of the actual operation) or not used at all.
- Work description - a detailed textual description of the work steps
- Comment - commentary describing specific risks, helpful tricks from the crew, etc.

The spreadsheets were the basis for the evaluation of bottomhole assembly installation. It is a quite effective way of plotting a lot of information into one table. By looking at it, the working process can be followed up quite good. The disadvantage of such a table is that it is difficult to present that type of information as it will not fit on a screen or a common A4 page. Therefore a better visualization will be definitely required.

Run #3, 8 3/4" Section

Necessary machinery and tools

Begin	End	Δtime	Position (s	Tool	Lay	Treatment	1 E	2 ES	3 SL	4 SC	5 IR	6 CNF	7 W 2	8 W 4	9 PH	10 Wr	11 TP	12 WH	13 RS	14 JSC	15 MA	16 LC	17 WB	18 BBP	19 BBPF	20 To	21 CH	22	23 MH	CI	CII	CIII	CIV	Work description
07:01:50	07:02:52	00:01:02	40	Drill Collar	LD	Out of hole	o	o										o												o				Drill collar is pulle
07:02:52	07:03:31	00:00:39	39	Drilling Jar	LD	Install jar safety clamp			x	x						o				o										o	o			The jar safety clam
07:03:31	07:04:13	00:00:42	40	Drill Collar	LD	Set into slips	o	o	o											x										o	o			The top of the BHA
07:04:13	07:05:25	00:01:12	40	Drill Collar	LD	Set safety clamps	x	x	x	o						o				x										o	o			Safety clamps are
07:05:25	07:07:00	00:01:35	40	Drill Collar	LD	Unscrew IR	x	x	x	x	o									x	o									o				The remote control
07:07:00	07:07:59	00:00:59	40	Drill Collar	LD	Lift	o	o	x	x										x														The unscrewed dri
07:07:59	07:09:41	00:01:42	40	Drill Collar	LD	Thread Protectors	x	x	x	x							o			x										o	o			To protect the threa
07:09:41	07:14:13	00:04:32	40	Drill Collar	LD	Lift to pipe handler	o	o	x	x			o		x				o	x										o	o			The lower end of th
07:10:18	07:10:52	00:00:34	40	Drill Collar	LD	Cleaning and inspection			x	x								o		x										o				Cleaning of the pip
07:15:13	07:15:45	00:00:32	41	Drill Collar	LD	Open elevator														x														Elevator is manual
07:15:32	07:15:50	00:00:18	40	Drill Collar	LD	Unscrew elevator sub		o	x	x		o	o						o	x										o	o			With the drill collar
07:15:50			40	Drill Collar	LD	Lay down			x	x					o					x														Drill collar is layed
07:16:50	07:20:31	00:03:41	39	Drilling Jar	LD	Put elevator sub on		o	x	x	o	o	o						o	x										o	o			The elevator sub is
07:20:31	07:20:32	00:00:01	39	Drilling Jar	LD	Set in elevator	o	o	x	x										x										o				Top of the jar (and
07:20:32	07:20:50	00:00:18	39	Drilling Jar	LD	Remove safety clamps	x	x	x	o						o				x										o	o			Savety clamps are
07:20:50	07:20:56	00:00:06	39	Drilling Jar	LD	Open slips	o	o	o											x										o	o			Jar is liftet, the slip
07:20:56	07:22:16	00:01:20	39	Drilling Jar	LD	Out of hole	o	o										o		x										o				Drill jar is pulled ou
07:22:16	07:22:32	00:00:16	39	Drilling Jar	LD	Set into slips	o	o	o											x										o	o			The top of the BHA
07:22:32	07:23:33	00:01:01	39	Drilling Jar	LD	Set safety clamps	x	x	x	o						o				x										o	o		o	Safety clamps are
07:23:33	07:25:05	00:01:32	39	Drilling Jar	LD	Unscrew IR	x	x	x	x	o									x	o									o				The remote control
07:25:05	07:25:19	00:00:14	39	Drilling Jar	LD	Lift	o	o	x	x										x														The unscrewed jar
07:25:19	07:27:46	00:02:27	39	Drilling Jar	LD	Thread protectors	x	x	x	x							o			x										o	o			To protect the threa
07:27:46	07:32:37	00:04:51	39	Drilling Jar	LD	Lift to pipe handler	o	o	x	x			o		x				o	x										o	o			The lower end of th
07:32:37	07:33:09	00:00:32	40	Drilling Jar	LD	Open elevator	o	x	x	x					x					x														Elevator is manual
07:28:12	07:28:56	00:00:44	39	Drilling Jar	LD	Cleaning and inspection			x	x					x			o		x										o				Cleaning of the pip
07:32:56	07:37:30	00:04:34	39	Drilling Jar	LD	Unscrew elevator sub		o	x	x		o	o		x				o	x										o	o			With the jar on the
07:37:30			39	Drilling Jar	LD	Lay down			x	x					o					x														Jar is layed down w
07:37:33	07:40:11	00:02:38	38, 37, 36	Drill Collar	SB	Put elevator sub on		o	x	x	o	o	o						o											o	o			The elevator sub is
07:40:11	07:40:43	00:00:32	38, 37, 36	Drill Collar	SB	Set in elevator	o	o	x	x																				o				Set DC with elevato
07:40:43	07:41:07	00:00:24	38, 37, 36	Drill Collar	SB	Remove safety clamps	x	x	x	o						o														o	o			Savety clamps are
07:41:07	07:41:10	00:00:03	38, 37, 36	Drill Collar	SB	Open slips	o	o	o																					o	o			Stand of drill collar
07:41:10	07:44:37	00:03:27	38, 37, 36	Drill Collar	SB	Out of hole	o	o										o												o				Stand of DC (DC -

Figure 33: Screenshot of the excel file with the breakdown of the work steps

5.2 BHA Components

5.2.1 Setup of a BHA string

In the drilling process, the bottomhole assembly (BHA) is the entire assortment of tools that is below the drill pipe (Figure 34). The BHA operates downhole, consisting of the drilling bit, the bit sub, stabilizers, drill collars, heavy-weight drill pipe (HWDP) and crossovers. To improve BHA performance, additional tools are implemented such as mud motors, jarring devices, vibration dampeners, reamers, measure-while-drilling (MWD) devices and logging-while-drilling (LWD) devices.

The purpose of the BHA is to provide axial force to the drilling bit (WOB) and to transfer torque from the drill pipe to the drilling bit to break and loosen the drilled medium. With the right setup it directs the drilling bit along a desired path. With additional equipment (MWD, LWD) the BHA can provide the driller with information about downhole conditions.[67]

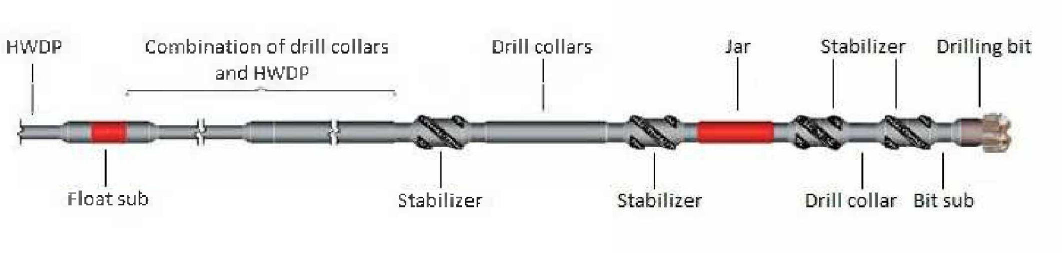


Figure 34: Example for a BHA setup[68]

For the purpose of this work, the bottomhole assembly will be considered everything below the HWDP. The reason for this is that, like normal drill pipe, HWDP can already be handled hands-off.

5.2.2 BHA components determine boundary conditions

To develop automated systems it is not only necessary to define the necessary work steps. The other crucial part is to clarify the boundary conditions. The question is what has to be handled. To design an efficient mechanized working environment it is important that it can handle all components. If, for example, only 80 percent of all drilling bits can be handled, the system will fail during field testing. If a customer is willing to operate an automated rig, it has to be assured that there is no need of a crew around the well center any more. On the other hand, if the machinery is constructed to handle twice the capacity that it would actually need, entering of the market will be tough, too.

For adequate dimensioning of automated handling equipment the following technical dimensions of BHA tools will be of interest:

- Weight
- Length
- Outer diameter
- Maximum outer diameter (of any overhanging parts)
- Make-up and break out torque

Further information will be required such as:

- Design and shape of the tools
- Adequate handling of the tools
- Logistics of the tools
- Rig equipment that is necessary for handling

5.2.3 Representative BHA Tools

The range of BHA tools is too big to discuss them all. To define standard equipment is not quite easy as they vary in technical dimensions, design, handling requirement and specific characteristics of the different manufacturers. Therefore it was tried to define a set of BHA components that will represent the properties of all the others. If they can be handled, the system should be able to handle the residual, too. These representative BHA tools will be the basis around which the design of automation systems should be done.

To find those representative BHA tools different BHA designs that were collected from operators and catalogues of BHA manufacturers were revised. Then these downhole tools where compared and checked for similarities. The list with the selected components contains the following tools:

- Drilling bit
- Drill collar
- Reamer/Stabilizer
- Jar
- Crossover
- Vibration dampener
- Magnet
- MWD/LWD
- Downhole motor
- AutoTrak
- Bend sub

As already mentioned, searching for recommended procedures for the correct handling and installation of downhole tools was not very successful. Most of the data sheets of the manufacturer give safety advices. Complicated assembling is done under their supervision anyway, so they see no need to print it out. Literature[69] discusses purpose, function and technical background such as pressure calculations. The information that was gathered mainly comes from the documentation on site in combination with the interviewing of crew and service companies. For a few tools (mud motor, AutoTrak) internal instruction sheets existed and were provided by cooperating tool manufacturers.

To define boundary conditions concerning the technical dimensions of the tools the different data sheets were scanned for the smallest and the biggest tool available. In some cases a third tool was selected to show that special designs are available, such as pony drill collars. For better understanding, the minimal possible values were rounded down, the maximal possible values rounded up (length to 0,1 m, weight to 10 kg).

The following will only discuss specific characteristics of each tool, standard procedures like greasing of threads or cleaning of the tool will not be pointed out. The entire handling and data sheet can be seen at.

Drilling Bit

The variation in bit design is significant to ensure the perfect bit for every drilling situation. But the basic forms can be classified into roller cone bits and drag bits. Mechanized handling is difficult due to the shape and sensitivity. Usually, the bit will be changes with every tripping operation.

Handling:

- To connect the bit with the drill string, a bit breaker plate has to be used as the design does not allow the use of tongs. Roller cone bits and drag bits require different bit breaker plates.
- The bit is very sensitive to collision, especially the inserts of PDC bits. When the bit is set down it should be done on a rubber or wooden plate to avoid direct contact with metallic surfaces.
- The bit has to be prepared and checked before using it. The nozzles have to be installed or, if already in place, controlled. The bit should be the right type and size (can be confused with different bit on site) and free of any foreign matter. Before lowering the bit into the well, a flow check is done.
- Recording of bit (serial number, type, nozzles, status of wear etc.) will be helpful for later analysis of performance or, if the bit doesn't work properly, prove correct handling. Usually, photos are made, too.
- Installation of a bit with increased diameter may require the removal of the slips and the master bushing as it might not fit through.
- When the bit is removed from the well, mud samples are taken if present.

Logistics:

- The bit is usually delivered in a transport box. To protect it during handling on the ground and transport onto the rig floor it stays in there until it will be assembled.
- If not in site, the matching bit breaker plate has to be delivered, too.
- The amount of bits on site depends on the infrastructure. Operations in very remote locations will require the storage of the bit and one backup bit for several runs.

Table 1: Technical dimensions of drilling bits

Technical dimension	Minimal possible value	Maximal possible Value
Weight	5 kg	750 kg
Length	0,4 m	0,7 m
Outer diameter	76 mm	241 mm
Max. outer diameter	90 mm	560 mm
Make-up torque	2,5 kNm	85 kNm

Drill Collar

Drill collars are standard components of every BHA design. They have a constant diameter and a plain outer surface. Some have spiral grooves along the tube.

Handling:

- Due to their plain surface and constant diameter, drill collars could fall into the well if slips fail or are lifted accidently. To prevent this, safety clamps have to be used.
- Spinning units with rollers will have troubles if they are applied on an area with spiral grooves.

Logistics:

- Logistics of drill collars is similar to drill pipe. As the number of drill collars may change for different BHA setups, they have to be picked up and laid down a lot during tripping.
- The amount of drill collars on site is determined by the BHA design[iv]. Usually they don't have to be changed. Nevertheless a few backup DC on site will be required.
- Depending on the string setup, so called pony collars can be used. These are conventional drill collars, only shorter.
- Some are non-magnetic to be compatible with magnetic measurement tools. This does principally not influence the handling, but they should not be mixed up with magnetic drill collars.

Table 2: Technical dimensions of drill collars

Technical dimension	Minimal possible value	Maximal possible Value
Weight	250 kg	3200 kg
Length	1,5 m	9,5 m
Outer diameter	76 mm	241 mm
Max. outer diameter	76 mm	241 mm
Make-up torque	3 kNm	130 kNm

Reamer/Stabilizer

Stabilizers are part of every BHA setup. Reamers are designed similar to stabilizers, but they are often more sensible to collision. Due to the shape, mechanized handling is a little tricky, but not impossible.

Handling:

- There is no standard form of reamers and stabilizers. Tools of the same type, the same size from the same manufacturer may still differ in the position of the blades.
- Reamers with inserts or stabilizers with integrated rollers are very sensible to handling.
- Before connecting those to the string, reamers and stabilizers should be checked for correct tool diameter and wear, especially when reusing them. Especially tools with pin to

[iv] Anti-sticking BHA design with over 30 drill collars occurred during research (extreme case)

pin or box to box connections have to be controlled that they are assembled in the right direction (which side is on top, which side on bottom).

- Installation of a reamer or stabilizer with increased diameter may require the removal of the slips and the master bushing as it might not fit through.

Logistics:

- During tripping operations with no big changes of the BHA design, for example a bit change, stabilizers or reamers are often not totally disassembled but remain connected to other components like drill collars to save additional connection and handling time.
- Special BHA components will be delivered as one part, with the reamers and stabilizers already attached.
- The amount of reamers and stabilizers on site depends on the infrastructure. Operations in very remote locations will require the storage of tools for several runs[v].

Table 3: Technical dimensions of reamers and stabilizers

Technical dimension	Minimal possible value	Maximal possible Value
Weight	40 kg	900 kg
Length	1,0 m	2,5 m
Outer diameter	95 mm	254 mm
Max. outer diameter	120 mm	710 mm
Make-up torque	6 kNm	120 kNm

Jar

Jars are commonly used in BHA designs as a backup in case of sticking. They can be applied in combination with accelerators, which are similar to handle (no safety clamp). Jars can be mechanical or hydraulic, but this does not influence the handling on the rig floor.

Handling:

- On surface, drilling jars have to be secured constantly with a mandrel clamp (jar safety clamp) from accidently releasing it. This mandrel is removed right before lowering the jar into the well, with the slips already removed, and installed again the moment it comes out of the well, before the slips are set. The safety clamp is set on the mandrel (section with reduced diameter) and locked with bolts. Over-tightening has to be avoided, the mandrel should be able to move free along the mandrel.
- Due to their plain surface and constant diameter, jars could fall into the well if slips fail or are lifted accidently. To prevent this, safety clamps have to be used.
- When running out of hole, the inside of the jar has to be cleaned. Water is flushed through small vent holes in the shell. The mandrel should be inspected for wear and corrosion.

[v] Anti-sticking BHA design with over 15 stabilizers occurred during research (extreme case).

Logistics:

- The life span of a jar in average is given with 200 to 250 hours of drilling. Depending on the application, a total number of five jars on site will hardly be exceeded.

Table 4: Technical dimensions of jars

Technical dimension	Minimal possible value	Maximal possible Value
Weight	220 kg	2500 kg
Length	7,4 m	10 m
Outer diameter	85 mm	241 mm
Max. outer diameter	85 mm	241 mm
Make-up torque	6 kNm	120 kNm

Crossover

For the mechanical handling of crossovers it is important to keep in mind that they may not have a uniform outer diameter.

Handling:

- Crossovers with pin to pin or box to box threads have to be installed in the right direction.
- Due to their plain surface and constant diameter, jars could fall into the well if slips fail or are lifted accidently. To prevent this, safety clamps have to be used.

Logistics:

- During tripping operations with no big changes of the BHA design, for example a bit change, stabilizers or reamers are often not totally disassembled but remain connected to other components like drill collars to save additional connection and handling time.
- Usually, a series of crossovers are part of the rig equipment. Depending on the BHA setup, additional will be delivered and have to be stored on site.

Table 5: Technical dimensions of crossovers

Technical dimension	Minimal possible value	Maximal possible Value
Weight	10 kg	450 kg
Length	0,3 m	1,5 m
Outer diameter	76 mm	216 mm
Max. outer diameter	76 mm	238 mm
Make-up torque	3 kNm	120 kNm

Magnet

Magnets are integrated to the drill string to collect magnetic debris from the drilling mud. Especially during milling, metal parts occur which are problematic to bring them up to the surface with the hydraulic fluid cycle.

Handling:

- Magnets must never be placed near any measurement tools. The magnetic field could interfere with the calibration of MLWD devices.
- When running the magnet out of the hole, it has to be cleaned carefully from the magnetic debris. Otherwise they could be spoiled all over the rig place during handling.
- The magnetic areas are usually covered with a layer of protection material. Slips and tongs should not be applied there.

Logistics:

- Magnets should be stored separately to prevent interference and false calibration of MLWD tools.

Table 6: Technical dimensions of magnets

Technical dimension	Minimal possible value	Maximal possible Value
Weight	90 kg	650 kg
Length	2,2 m	5 m
Outer diameter	76 mm	203 mm
Max. outer diameter	90 mm	228 mm
Make-up torque	6 kNm	110 kNm

MWD/LWD

MLWD is the notation of a wide range of tubular with different measurement systems integrated. They can be fixed installed or retrievable from a housing string which is usually similar to a non-magnetic drill collar.

Handling:

- MLWD tools are usually rather sensible to handle
- Some MLWD tools have special threats for communication with other tools of the string, for example a transmitter sub. These threads are very sensitive and some service companies do not want them to be connected with the iron roughneck. This would bend the housing and damage the sealing ring. Plus, these threads require a different type of grease.

Logistics:

- MLWD tools must never be placed next to magnetic fields to avoid interference with the measurement devices.
- Retrievable MLWD can be changed at the rig site.

- Some MWLD strings are delivered on the rig site preassembled. The size of the preassembled components will be designed due to the lifting capacity of the pipe handling system

Table 7: Technical dimensions of MLWD tools

Technical dimension	Minimal possible value	Maximal possible Value
Weight	65 kg	2300 kg
Length	1,3 m	9,5 m
Outer diameter	76 mm	241 mm
Max. outer diameter	83 mm	210 mm
Make-up torque	2,5 kNm	75 kNm

5.2.4 Categorization of BHA Components

With the evaluation of the representative BHA tools several similarities can be seen. This leads to the conclusion that all the components can be divided into groups. For this work, four groups were defined:

- String
- Sensible string
- Item
- Special item

String is the group of tubular that can be basically handled like normal drill pipe with conventional pipe handling equipment and the iron roughneck. However, they will require solutions for some special handling features, for example the use of lifting subs to hang them in the elevator.

Components that belong to this group are drill collars.

Sensible string is the group of tubular with special handling requirements. The main difference is that it has special areas on the outside which must not be affected by the gripping unit of the pipe handling system as this may lead to damage. Still, depending on the pipe handling system, some of them can be treated like normal strings, like vibration dampeners. It has to be checked that they are compatible with the gripper arrangement.

In addition to that, some sensible string components require special handling procedures, like installation of a jar safety clamp or the collection of drilling data from MLWD tools.

Components that belong to this group are MWD/LWD tools, AutoTrak, mud motors, vibration dampeners, jars and accelerators, packers, etc.

Item is considered every tool that cannot be handled with the conventional pipe handling equipment due to size or design. It is difficult to define the limit of the dimension as it depends on the available equipment. Theoretically, a magnet with three meter could be handled with mechanized pipe handlers, but it is also important to think about the logistics in the background.

Long tubular will be shelved in some kind of storage box. It will be difficult to keep various components with shorter diameter between longer BHA tools in a sorted manner.

Tools in this group will be stabilizers, magnets, crossovers, vibration dampeners, transmitter subs, etc.

Special items differ from normal items in their design. Everything that will be difficult to handle mechanically is in this group. Tools like drilling bits that do not have suitable surfaces to use conventional gripping devices. Or tools like bent subs that require special installation techniques. They will require tool modification or the development of special handling devices for automation purposes.

Tools in this group will be drilling bits, gauge indicators, cup type testers, bent subs, etc.

Table 8: Technical dimensions of BHA tools[vi]

Tool		Length	Weight	Torque	OD	Max. OD	c OD*	IR**	Additional Info
Drilling Bit	min.	0,40 m	5 kg	2,5 kNm	76 mm	90 mm			Difficult to handle (design), sensible
	max.	0,70 m	750 kg	85 kNm	241 mm	560 mm			Make-up with bit breaker plate
Drill Collar	min.	1,50 m	200 kg	3,5 kNm	76 mm	76 mm	X	X	Safety clamp (plain outer surface)
	max.	9,50 m	3200 kg	130 kNm	241 mm	241 mm			
Stabilizer/Reamer	min.	1,5 m	90 kg	6 kNm	95 mm	120 mm		X	Difficult to handle (design), sensible
	max.	2,5 m	900 kg	120 kNm	254 mm	710 mm			May not fit in iron roughneck
Jar	min.	7,00 m	250 kg	6 kNm	85 mm	85 mm		X	Jar safety clamp has to be installed
	max.	10,00 m	2500 kg	120 kNm	241 mm	241 mm			
Crossover	min.	0,30 m	10 kg	3 kNm	76 mm	75 mm		X	No constant OD
	max.	1,50 m	500 kg	120 kNm	216 mm	240 mm			
Vibration Dampener	min.	3,00 m	250 kg	13 kNm	120 mm	120 mm		X	Check function before use
	max.	4,50 m	1259 kg	120 kNm	241 mm	241 mm			
Magnet	min.	2,00 m	90 kg	6 kNm	76 mm	90 mm		X	Never near magnetic-sensible tools
	max.	3,00 m	650 kg	120 kNm	203 mm	228 mm			Clean before breaking connection (debris)
MWD/LWD	min.	1,00 m	65 kg	2,5 kNm	76 mm	83 mm			Sensibel (pipe handler, iron roughneck)
	max.	10,00 m	3500 kg	75 kNm	203 mm	210 mm			Check function before use
Transmitter	min.	3,00 m	150 kg	5 kNm	76 mm	76 mm	X		Check function before use
	max.	6,00 m	1500 kg	120 kNm	241 mm	241 mm			
Downhole Motor	min.	6,00 m	250 kg	6 kNm	92 mm	Stabilizer			Bent sub adjustment if integrated
	max.	10,00 m	2500 kg	75 kNm	245 mm	Stabilizer			Check function before, deplete after use
Bent Sub	min.	0,40 m	20 kg	6 kNm	76 mm	76 mm	X		May have to be adjusted (with tongs)
	max.	1,40 m	600 kg	120 kNm	216 mm	216 mm			
AutoTrak™	min.	9,2 m	2500 kg	14 kNm	171 mm	310 mm			Sensible (pipe handler, iron roughneck)
	max.	10,6 m	4000 kg	90 kNm	241 mm	445 mm			Includes stabilizer, MWD, transmitter, etc.

* constant outer diameter of the tool; ** connection can be made with Iron Roughneck

Table 8 gives an overview of the technical dimensions that were collected during product research in Chapter 5.2.3 "Representative BHA Tools". Those values that will determine the necessary capabilities of automation systems are highlighted in red.

[vi] Important: The values for the maximum torque correspond to the make-up torque. Theoretically, break-out torque should be the same as make-up torque, but due to drilling activities it can reach higher values. Depending on the company safety standards, a safety margin between 1,5 to 2 is applied to calculate the theoretical maximum occurring break-out torque. This should be the boundary condition for equipment.

5.3 Work Steps for BHA Handling

5.3.1 Breakdown and Visualization of the Work Flow

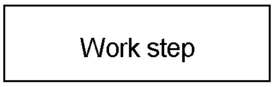
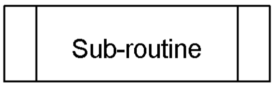
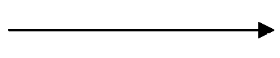
For the mechanization and automation of a process it is important to have an exact idea of how the work is executed. The idea is to define all the necessary work steps for BHA handling. If an automated system is designed that can execute those steps, it should be able to assemble downhole tools. If, for example, a stabilizer has to be installed, the required work steps can be chosen out of a range of predefined actions, and the machinery will do the work

Therefore the data from the documentation were taken to generated flow charts for the handling of the different BHA tools (Figure 35). The benefits of the flowcharts are that it is a good way to document the work that has to be done on the rig floor which will be helpful for the mechanical realization. Plus, the creation of a flow chart helps you to find similarities.

So it is important to define the work steps really precise. It is not enough to have “lowering into the well” as one step but to break it further into “slips open – lower elevator – slips close”. Every action that has to be initiated, such as removing the elevator from the well center, is a work step. The visualization should be that precise that theoretically, someone who has never heard of a drilling rig would be able to execute the operation. Other flow charts can be seen in Appendix F – BHA Assembling Flow Charts .

The flowcharts were designed according to DIN 66001 (Table 9), a common norm used in project management and other fields where visualization of processes is done. This should assure that the flowcharts will be understandable by the different people that will work with them subsequent to the thesis.

Table 9: Symbols for visualization with flowcharts

	…represents the start and the end of a process.
	…represents a point where a decision has to be made that will influence the upcoming steps of the process. Decisions should be stated in a way that the solution is yes or no or other predefined answers. The answer will determine the next step.
	…represents a work step that has to be initiated. If the work step is completed, the process has to be continued according to the arrows.
	…represents a series of work steps, a so called routine. The routine itself consists of several work steps. This is helpful to keep the flowchart arrangement more clearly as repetitive workflows can be plotted compacted.
	…represents the input or output of data to or from the process
	…indicates the way from one symbol to the next

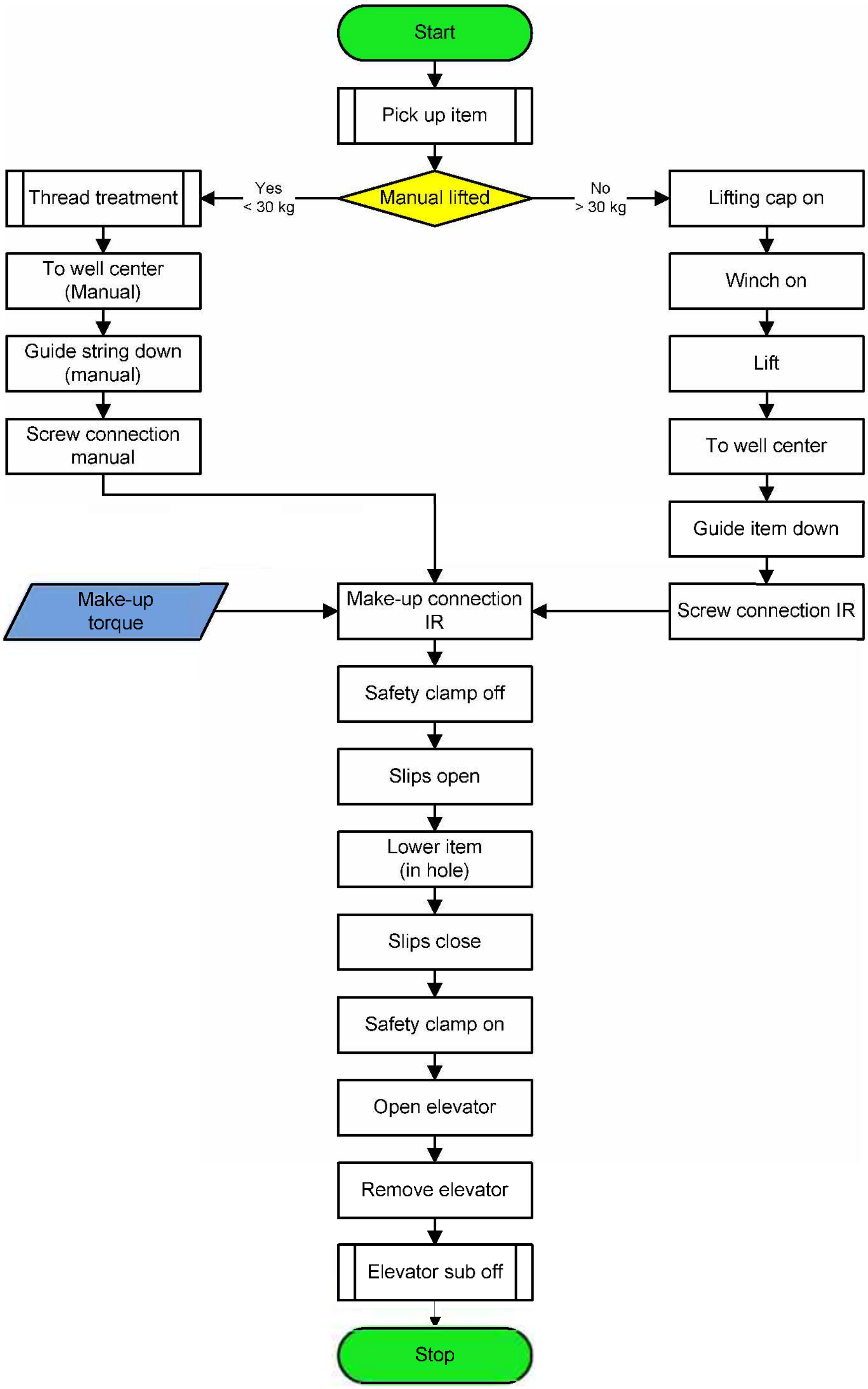


Figure 35: Flowchart with the work steps for the installation of a crossover

The starting point for the assembling is the beginning of the transportation of the tool on the rig floor. This will usually be at the catwalk.

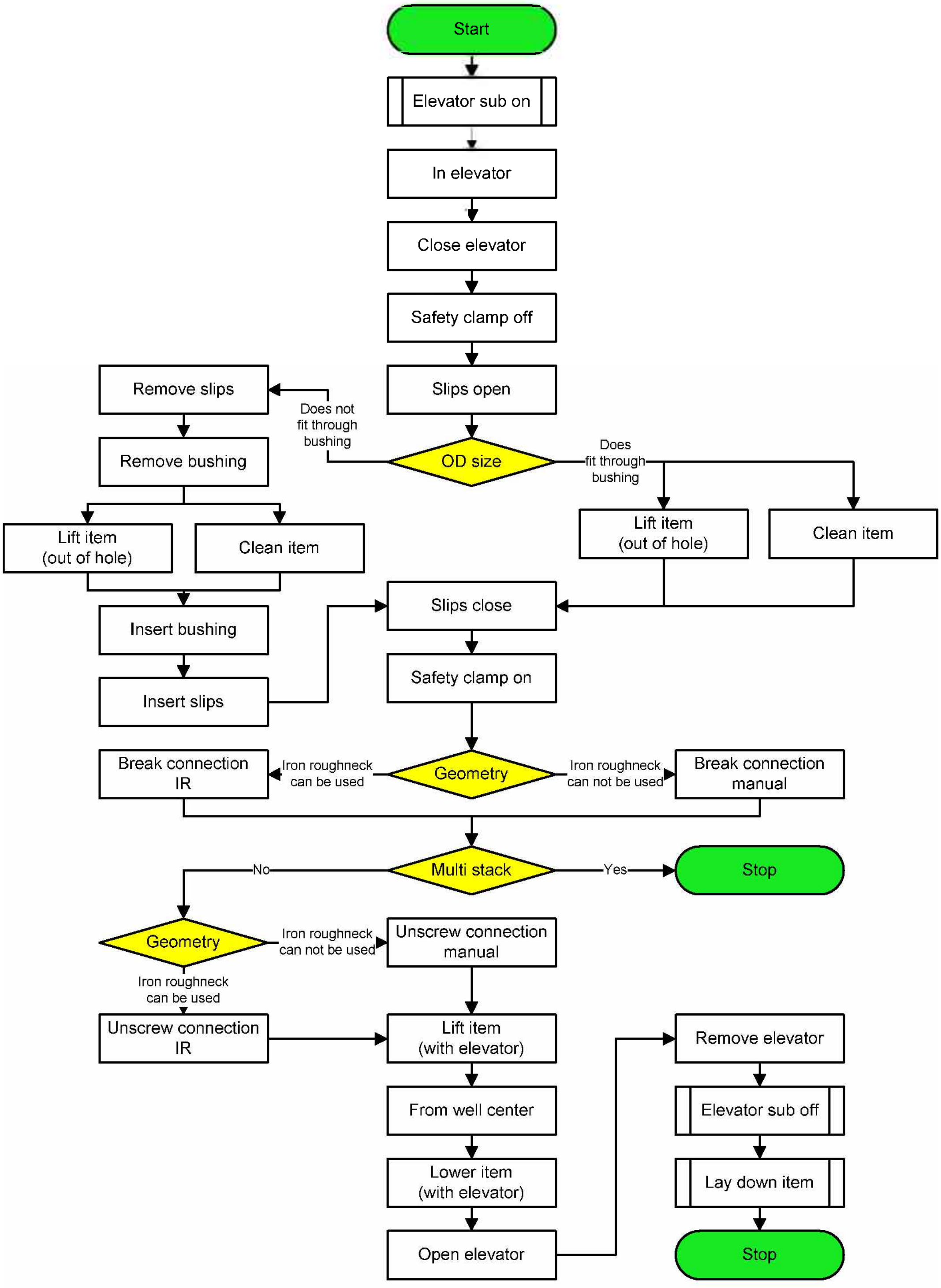


Figure 36: Flowchart with the work steps for the disassembling of a stabilizer

The starting point for disassembling will be when the BHA component is hanging in the slips, with the previous tool, which was positioned above in the drill string arrangement, removed and ready to be pulled out.

5.3.2 Definition and Categorization of the Work Steps

By going through the flowcharts of the different tools some similarities appear. Some have to be executed all the time in the same way, like opening of slips or lubrication of threads. Some have to be executed all the time but in different ways, like making up a connection with either manual tongs or the iron roughneck. And others are tool specific, for example installation of the jar safety clamp.

By doing this step by step a list can be compiled with the different work steps necessary for the handling of BHA. To have a better overview they will also be categorized into different segments:

- Transport
- Assembling
- String handling
- Service
- Modification
- Storage

Transportation is every action that is necessary to bring the downhole tool from the ground (the catwalk) to the well center and, after running it out of the hole again and dissembling it, from the well center away back on the ground.

Table 10: Work steps for BHA transport on a drilling rig.

Work step	Description
Push string	Pushing the bottom of the string in the desired direction. This is necessary to move a tubular to the v-door and the slide or when setting it back.
Pick up string	The procedure of picking up a string (pipe, drill collar, HWDP…) from the catwalk and lifting it onto the drill floor in a position where it is accessible for the elevator
Lay down string	The procedure of taking a string (pipe, drill collar, HWDP…) out of the elevator and bringing it down onto the catwalk
Pick up sensible string	The procedure of picking up a string that is sensible on certain areas and cannot be gripped conventionally (downhole motor, MWD/LWD…) from the catwalk and lifting it onto the drill floor in a position where it is accessible for the elevator
Lay down sensible string	The procedure of taking a string that is sensible on certain areas and cannot be gripped conventional (downhole motor, MWD/LWD…) out of the elevator and bringing it down onto the catwalk
Pick up item	The procedure of picking up any kind of smaller item (bit, stabilizer, elevator sub…) from the ground onto the drill floor
Lay down item	The procedure of taking any kind of smaller item (bit, stabilizer, elevator sub…) from the drill floor and lifting it down on the ground
Thread protectors on	Screwing on thread protectors that protect the threads during handling (at least when the tool is prepared for transport on the rig site)
Thread protectors off	Screwing off the thread protectors that protect the threads during handling (at least when the tool is prepared for transport on the rig site)
Lifting cap on	Screwing on the lifting caps to attach the tool to the winch
Lifting cap off	Screwing off the lifting cap that attaches the tool to the winch
Casing elevator sub on	Screwing on the casing elevator sub that holds the string in the casing elevator

Casing elevator sub off	Screwing off the casing elevator sub that holds the string in the casing elevator
Make-up casing elevator sub	Make-up the casing elevator sub, necessary to prevent the threads from damage
Break casing elevator sub	Breaking the casing elevator sub
Pipe elevator sub on	Screwing on the pipe elevator sub that holds the string in the casing elevator
Pipe elevator sub off	Screwing off the pipe elevator sub that holds the string in the casing elevator
Make-up pipe elevator sub	Make-up the pipe elevator sub, necessary to prevent the threads from damage
Break pipe elevator sub	Breaking the pipe elevator sub
String to well center	Push the string, already in the elevator, to the well center. This can be done with hydraulic elevator bails. Still, guiding the bottom of the string (manually) is advisable to avoid swinging
String from well center	Push the string that is in the elevator away from the well center. This can be done with hydraulic elevator bails. Still, guiding the bottom of the string (manually) is advisable to avoid swinging
Item to well center	Lift the item from any place on the drill floor to the well center. This can be done with a winch (and lifting cap) or, if possible, by hand
Item from well center	Lift the item from the well center away and lay it down on the drill floor. This can be done with a winch (and lifting cap) or, if possible, by hand
Winch on	Hook the winch onto something that has to be lifted
Winch off	Unhook the winch from something that was lifted

Assembling is every action that is required to connect and disconnect the downhole tool properly to and from the string. This also includes the preparation of the components that have to be done during the assembling.

Table 11: Work Steps for assembling and dissembling of BHA on the rig floor

Work step	Description
Jar safety clamp on	Attaching the jar safety clamp on the jar to lock the device. This is done immediately after the jar is pulled out of the hole. The Jar safety clamp is locked with two bolts
Jar safety clamp off	Removing the jar safety clamp that secures the jar during handling. Two bolts have to be unscrewed and the clamp can be removed
Bit breaker plate on bit	Installing the bit breaker plate on the shaft of the bit (drag bits) and lock it with the securing pin
Bit breaker plate off bit	Unlocking the pin and removing the bit breaker plate of the shaft of the bit (drag bits)
Bit + bit breaker plate in frame	Placing the bit with the bit breaker plate on the shaft (drag bits) in the frame
Bit in bit breaker plate	Lowering the string and guiding the bit into the bit breaker plate
Mud basket on	Attaching the mud basket to a string that is full with drilling fluid, right over the connection. This is normally done after the connection has been unscrewed to avoid spilling of drilling fluid all over the rig floor and crew members
Mud basket off	Removing the mud basket from the string
String revolution indicator	The string revolution indicator counts the numbers of revolutions during the unscrewing of a pipe or BHA tool. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread

	and crashes back on the thread groove below when revolving it too far.
Make-up connection IR	Make-up a connection by applying the suitable amount of torque to the connection with the iron roughneck, torque monitoring has to be done. It is important to have a suitable gripping area that will not be damaged by the gripping (MWD, etc.) or cannot be reached by the roughneck (stabilizer, etc.)
Break connection IR	Breaking the connection by applying torque to the connection with the iron roughneck. It is important to have a suitable gripping area that will not be damaged by the gripping (MWD, etc.) or cannot be reached by the roughneck (stabilizer, etc.)
Screw connection IR	Screwing together the connection with the iron roughneck (roller spinner, etc.). It is important to have a suitable gripping area that will not be damaged by the gripping (MWD, etc.) or cannot be reached by the roughneck (stabilizer, etc.)
Unscrew connection IR	Unscrewing the connection with the iron roughneck (roller spinner, etc.). It is important to have a suitable gripping area that will not be damaged by the gripping (MWD, etc.) or cannot be reached by the roughneck (stabilizer, etc.)
Make-up connection man.	Make-up a connection by applying the suitable amount of torque to the connection with the manual tongs and the cathead, torque monitoring has to be done. It is important to have a suitable gripping area that will not be damaged by the gripping.
Break connection man.	Breaking the connection by applying torque to the connection with the manual tongs and the cathead. It is important to have a suitable gripping area that will not be damaged by the gripping
Screw connection man.	Screwing together the connection with the chain tongs or, if possible, by hand.
Unscrew connection man.	Unscrewing the connection with the chain tongs or, if possible, by hand
Bit breaker plate in frame	Installing the bit breaker plate into the frame (or sometimes the bushing) (roller cone bits)
Bit breaker plate off frame	Removing the bit breaker plate of the frame (or sometimes the bushing) (roller cone bits)

String handling is every action that is necessary to move string or tools along the wellbore axis or keep the string in place. For this work, the boundaries were defined between the transport of BHA tools and the handover of the tool to the elevator. However, the points of intersection are often fluent. Lifting subs, for example, are categorized as work steps for transport tasks, but are required during transport and handling.

Table 12: String handling of BHA string on the rig floor

Work step	Description
Slips open	Opening the slips by slightly hoisting the string that is sitting in the slips and lifting the slips to the open position
Slips close	Closing the slips by lowering them into the bushing and thereby vertically locking the string
Safety clamp on	Attaching the safety clamp (or any similar device) to prevent the string from accidentally falling into the well in case of slip failure
Safety clamp off	Removing the safety clamp (or any similar device) that prevents the string from accidentally falling into the well in case of failure of the slips
Guide pipe down	Guide the pin (or box) of the top pipe, that is already in the well center, down into the box (or pin) of the bottom pipe that is hanging in the slips. This will avoid damage due to collision of the connections. Step-in/out guides are used in some cases for better and safer execution
Guide pipe up	Guide the pin (or box) of the top pipe out of the box (or pin) of the

	bottom pipe that is hanging in the slips. This is advisable especially for acme threads to avoid that they will get "hooked" during lifting of the top pipe. Step-in/out guides are used in some cases for better and safer execution
Lift string	Lift the string with the elevator
Lower string	Lower the string with the elevator
In elevator	Pipe is set into the elevator (actually the elevator is set onto the pipe). This can be done manually or with hydraulic elevator bails
Remove elevator	Pipe (casing, elevator sub, etc.) is removed out of the elevator [actually the elevator is removed from the pipe (casing, elevator sub, etc.)]. This can be done manually or with hydraulic elevator bails
Elevator close	Closing/locking the elevator to lift the string
Elevator open	Opening/unlocking the elevator to remove it from the string

Service is every action that is important to keep the tools in operational conditions, before and after the actual drilling. In this case, maintenance of the tools such as re-cutting of threads or changing the inlet of MWD/LWD tools was not considered. Such work is usually done in the shop, or in special cases maybe at the rig site. But it is not really a part of the actual work of the drilling rig.

Table 13: Service of BHA tools

Work step	Description
Clean threads	Removing debris, dirt, old dope… from the threads
Lubricate threads	Apply sealing lubrication (pipe dope) to the threads
Glue threads	Apply glue to the threads to improve the connection. This is done for example with casing or small diameter pipes with low make-up torque
Thread inspection	Inspection of the threads for wear or damage
Clean pipe annular	Cleaning the inside of the string to remove aggressive drilling fluid, especially tools with no clear annulus like MWD, downhole motors, float valves...
Clean pipe outside	Cleaning the outside wall of the string to remove aggressive drilling fluid, especially tools with vent holes have to be cleaned thoroughly
Empty mud motor	Emptying the mud motor after pulling it out of hole. This is done by seating the bit into the bit breaker plate and rotating it with the rotary table until all the mud is out of the mud motor. Flushing it with fresh water will avoid corrosion and damage of the elastomers
Add ball/chip to well	Adding a ball, chip, landing nipple, etc. to the drilling fluid to pump it down and thereby transmitting a signal to a downhole tool. The ball, chip, landing nipple,… is simply induced on the drill floor in the string before connecting it to the next pipe
Adjust bend sub	Bend subs with variable bend degree have to be adjusted. While the housing is kept static, the orientation sleeve is turned to the desired bend angle. The lower bend housing is locked by screwing it upwards and torqueing.
Taking sample	Taking fluid or mud samples from the drill string is done by the mud engineer to analyze downhole conditions. Very important, for example, are the probes taken from the drilling bit when it leaves the hole.
Tool inspection	Inspection of a downhole tool for damage, wear, right size, etc.

Modification is every action that will keep the rig floor and its equipment adapted to the specific working situation. It may not be part of the actual downhole tool assembling, but without the mechanization of those work steps there will be personnel required around the well center.

Table 14: Modification of rig floor equipment

Work step	Description
Bushing in	Installing the bushing (or automated slips) after they have been removed
Bushing out	Removing the bushing (or automated slips) from the well center. This is necessary to run tools with large outer diameter (bit, stabilizer, casing, etc.)into the hole that would not fit through.
Bit breaker plate frame on	Installing the frame, that holds the bit breaker plate in place, on the drill floor (lock them with the retaining pins in the rotary table)
Bit breaker plate frame off	Removing the frame that holds the bit breaker plate in place
Change elevator	Changing the elevator due to change of the outer diameter of the string or change of the shoulder type (casing or pipe elevator)
Change slips	Changing the slips due to change of the outer diameter of the string
Slips in	Installing the slips (or automated slips) after they have been removed
Slips out	Removing the slips (or automated slips) from the well center. This is necessary to run tools with large outer diameter (bit, stabilizer, casing, etc.) into the hole that would not fit through.
Cover borehole	Cover the borehole if the well is empty.

Storage is every action that is necessary for the logistics of auxiliary equipment on the rig floor. In this case, additional rig machinery that may be there as a backup was not considered.

Table 15: Storage of auxiliaries on the rig floor

Work step	Description
Store safety clamp	Storage of safety clamp when not in use
Store jar safety clamp	Storage of jar safety clamp when jar is in the well
Store thread protectors	Storage of different types of thread protector caps
Store bit breaker plate	Storage of different types of bit breaker plates
Store bit breaker plate frame	Storage of the frame that connects the bit breaker plate to the rotary table
Store pipe elevator sub	Storage of pipe elevator subs with different sizes
Store casing elevator sub	Storage of casing elevator subs with different sizes
Store lifting cap	Storage of lifting caps with different sizes
Store elevators	Storage of different types of elevators

5.3.3 Evaluation and Ranking of the Work Steps

Theoretically, the implementation of a mechanized system that executes the work on a drilling rig is possible. It will require the development of new tool, but it is very unlikely to face technical limits. The decision upon the realization of automated systems will be made due to economic reasons.

As it is a rather complex and extensive task to design a hands-off rig floor, this will probably not be done in one stroke but step by step. Therefor it was decided to not only define the different work steps that are necessary for the handling of bottomhole assembly, but also to rank them according to various criteria. This will help to focus the engineering resources on the development of those mechanization tools that have the highest potential for improvement.

Table 16 shows the list with all work steps filtered out that can already be done mechanized. Using that list, it will be easier to detect operations that should be focused on in terms of finding tools for automation. The entire list can be found in Appendix G – Evaluation of Work Steps. The list was implemented into an Excel sheet. Using the "Filter" functions of excel, it is possible to define certain criteria and look for work steps with the defined automation potential.

Table 16: List of all hands on work steps

Work step	Automated	Manual	Rig floor	Hazardous	Time	Frequency	Feasibility	Knowledge	Equipment
Jar safety clamp on		x	x					x	Manual, wrench
Jar safety clamp off		x	x					x	Manual, wrench
Bit breaker plate on bit		x							Manual
Bit breaker plate off bit		x							Manual
Bit + bit breaker plate in frame		x	x						Manual, winch
Bit in bit breaker plate		x	x						Manual, winch
Mud basket on		x	x	x		x			Manual
Mud basket off		x	x	x		x			Manual
String revolution indicator		x	x			x	x	x	Manual, chalk
Make-up connection man.		x	x	x	x			x	Manual, manual tongs
Break connection man.		x	x	x	x			x	Manual, manual tongs
Screw connection man.		x	x						Manual, Chain tongs
Unscrew connection man.		x	x						Manual, Chain tongs
Bit breaker plate in frame		x	x						Manual, winch
Bit breaker plate off frame		x	x						Manual, winch
Safety clamp on		x	x		x	x			Manual, wrench
Safety clamp off		x	x		x	x			Manual, wrench
Guide pipe up		x	x	x	x	x			Manual
Guide pipe down		x	x	x	x	x			Manual
Slips in		x	x						Manual, winch
Slips out		x	x						Manual, winch
Bushing in		x	x						Manual, winch
Bushing out		x	x						Manual, winch
Bit breaker plate frame on		x	x	x					Manual, winch
Bit breaker plate frame off		x	x	x					Manual, winch
Change elevator		x	x	x					Manual, winch
Cover borehole		x	x	x			x		Manual
Change Slips		x	x					x	Manual, winch
Clean threads		x				x			Rag, WD40
Lubricate threads		x				x			Brush
Glue threads		x						x	Scraper
Thread inspection		x						x	Visual, gauge

Clean pipe annular		x				x			Manual, Water hose
Clean pipe outside		x			x	x	x		Manual, Water hose, sleeve
Add ball/chip to well		x	x					x	Manual
Taking sample		x						x	Manual
Tool inspection		x						x	Visual, gauge
Store safety clamp		x	x			x			Manual
Store jar safety clamp		x	x						Manual
Store thread protectors		x	x			x			Manual
Store bit breaker plate		x	x						Manual
Store bit breaker plate frame		x	x						Manual, winch
Store pipe elevator sub		x	x						Manual
Store casing elevator sub		x	x						Manual
Store lifting cap		x	x						Manual
Store elevators		x	x						Manual, winch
Push string		x	x	x		x			Manual, winch
Pick up sensible string		x	x	x				x	Manual, winch, slide
Lay down sensible string		x	x	x				x	Manual, winch, slide
Pick up item		x	x	x		x			Manual, winch, slide
Lay down item		x	x	x		x			Manual, winch, slide
Thread protectors on		x				x			Manual
Thread protectors off		x				x			Manual
Lifting cap on		x	x		x	x			Manual
Lifting cap off		x	x		x	x			Manual
Casing elevator sub on		x	x						Manual
Casing elevator sub off		x	x						Manual
Make-up casing elevator sub		x	x						Chain tongs
Break casing elevator sub		x	x						Chain tongs
Pipe elevator sub on		x	x			x			Manual
Pipe elevator sub off		x	x			x			Manual
Item to well center		x	x	x		x			Manual, winch
Item from well center		x	x	x		x			Manual, winch
Winch on		x	x						Manual
Winch off		x	x						Manual
Count	23	65	71	19	11	40	3	14	
Percent	27	77	85	23	13	48	4	17	

The criteria for ranking the work steps are very alike to the key performance indicators that will evaluate the performance of a drilling rig:

- Automation is available
- Work step has to be done on the rig floor
- Work steps that are considered as especially hazardous
- Frequency of the work step
- Time that is required for the work step
- Special knowledge required for execution of the work step
- Feasibility of the mechanization

For a closer evaluation all work steps were filtered out where **automation is already available** or at least mechanized so far that remote operation is possible. This does not mean that there is no space for improvement. But as those machineries are already implemented on existing rigs the mechanization of those working steps will be considered as realized. Those mechanized tools that are in the field testing phase right now, for example pipe doping units, will stay in the list. Some of them show problems with their performance and may be worth the overthinking of the technique.

From the 84 work steps that were collected, 83 percent are done manually or at least require hands-on duties of the crew. So it can be said that there is a lot of potential for the development of new rig machinery. For the evaluation of the following criteria it will mainly be concentrated on those non-mechanized work steps.

The categorization into **work steps that have to be done on the rig floor** and those which could theoretically be done anywhere was driven by the question whether it is necessary to do the entire work next to the well center. All the work that could be done on the ground would lead to less labor and machinery on the drill floor.

When those were filtered out it can be seen that a part of the service of the tools does not by all means have to be done on the rig floor. Cleaning of threads and tools, gluing or lubricating of the connections, taking samples and different inspections could be done on the ground. And, as a matter of fact, some work steps are executed that way.

Connecting those tools that require the use of manual tongs on the ground would be another interesting task to remove from the rig floor. And this is done in some cases, too. Service companies deliver those tools already assembled as far as possible. But some cannot be transported on the rig floor in one piece, for example AutoTrak from Baker Hughes. So it is still important to find a way to mechanize that work step.

Eliminating **hazardous work** steps will directly lead to a decrease of safety incidents. To define them was not so easy. A quantitative evaluation is dependent on detailed accident reports and statistics. Unfortunately, drilling operators do not publish detailed incident analysis and it was not possible to convince anybody to provide such material for a master thesis written with another company.

Therefore, the evaluation was done on basis of interviews. Work steps on a drilling rig are in general hazardous. The focus was put on those with increased risk of incidents, such as handling of manual rig tongs and other heavy equipment or covering of the borehole, which is not dangerous but could lead to accidents if not done.

The **frequency of different work steps** will have a big influence on whether automatization tools will be developed as such machinery is the most effective with repetitive tasks. Plus, the more often a certain action has to be done, the higher the chance someone gets hurt, even if it is “only” the sprain of a finger. So it will be of interest for HSE reasons as well.

This criterion might be the reason why slip handling is already automated. Handling of slips is, compared to other operations on the rig floor, relatively safe and not too exhausting. Manual setting is not slower than the mechanized version and in case the slips have to be changed or removed, manual slips perform even better. But it has to be done over and over again, for every connection. And as it is actuated by the driller, he does not have to wait to move the string for free crew members to unlock remove the slips.

One problem regarding the frequency of work steps appeared. Some actions were not executed as often as they should have been, for example they forgot to mark the pipe to count the revolutions during the unscrewing of the tubular. On the other hand, slips where set too often as the rig crew applied them at the wrong spot of the pipe. It was decided to correct those numbers in the data base to avoid a wrong picture due to individual mistakes.

Figure 37 shows the top 25 work steps regarding the frequency they had to be done during the tripping of a 8 3/8” Drilling BHA (Appendix D – Setup of Documented BHA). It can be seen that a part of the work steps can already be mechanized with available machinery, such as iron roughneck, automated elevators or automated slips. But the bigger part of the work requires hands-on intervention of the crew. Most of them relate to the transport of tools on and around the rig floor. Some work steps will be interesting for rig manufacturers, too. Things like counting of the tubular revolutions during unscrewing or a solution to the manual setting of the safety clamp may be interesting for costumers.

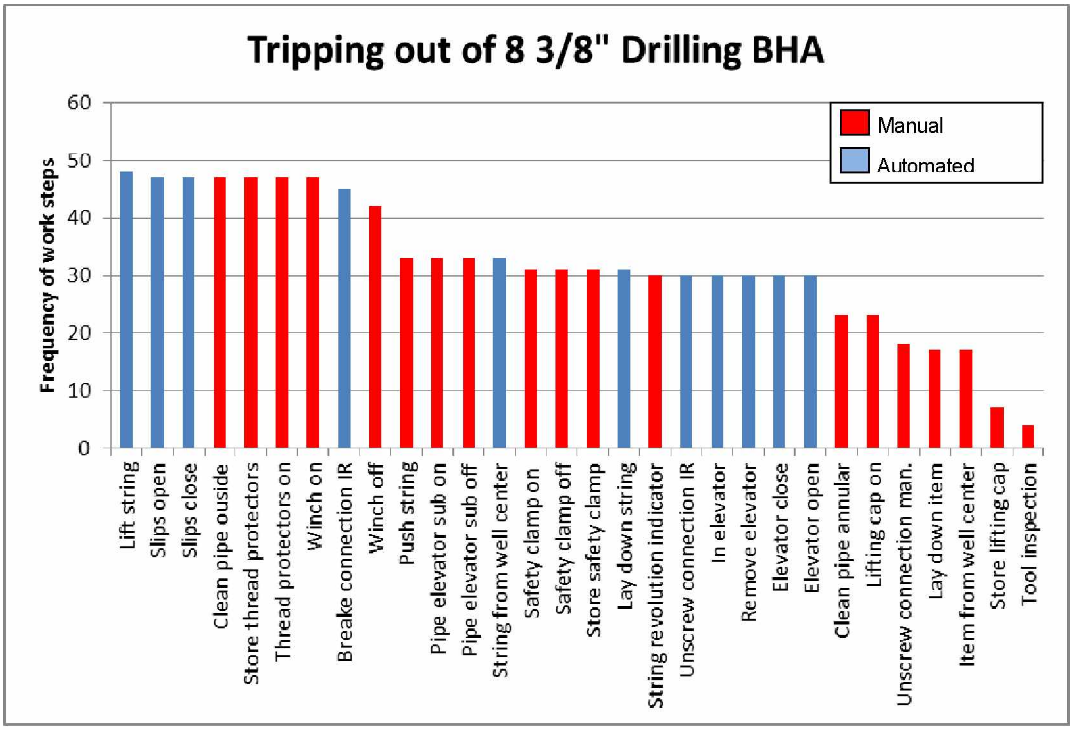


Figure 37: Frequency of work steps for tripping BHA

The **time required for the work steps** will be of high interest in terms of improving the handling performance and therefor reducing rig time. Figure 38 shows how much time is spent for the execution of certain tasks. The graph shows the cumulated times of the operations. The times for transport of pipe and BHA from the ground onto the drill floor could not be recorded as the documentation focus was on the rig floor. Therefore it could not be observed what was happening on the catwalk to follow the entire lay down process.

Figure 38 shows the operations that take the biggest shares of the 2 hours and 36 minutes of operational time. Handling of the safety clamp takes almost a minute. And it has to be done on every smooth tubular. Work steps necessary for tool transportation such as handling of threat protection caps or lifting subs are responsible for another considerable handling period.

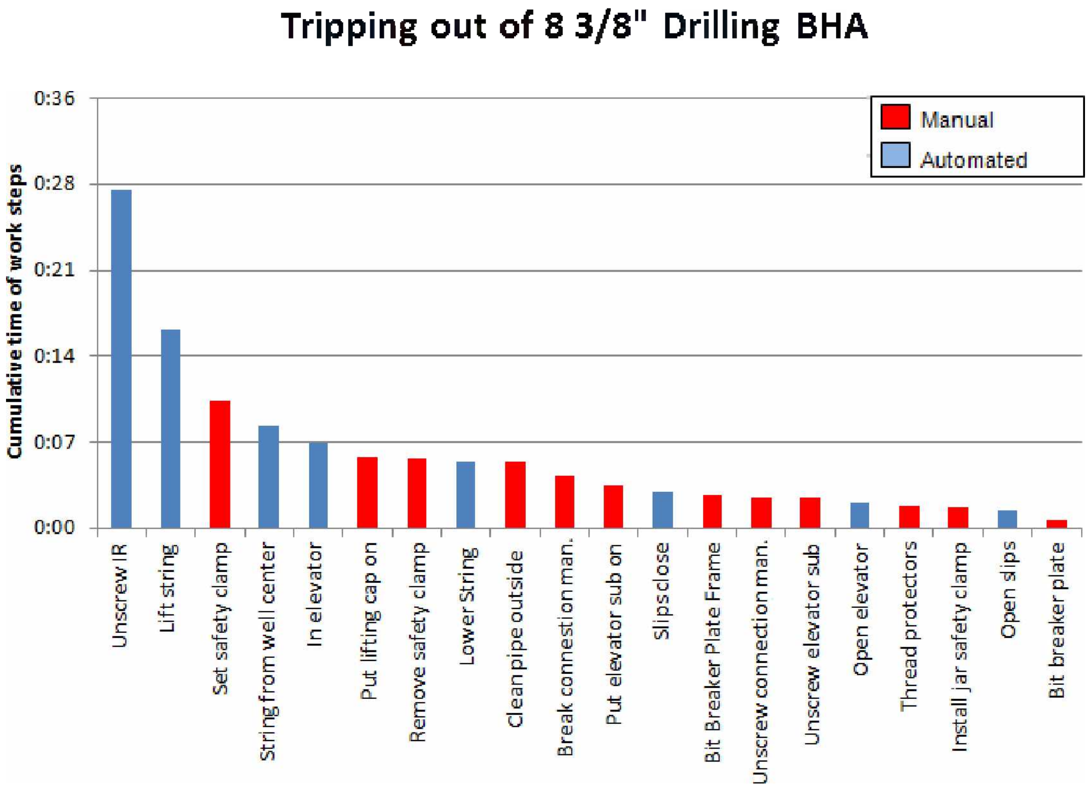


Figure 38: Cumulated times required for work steps

Special knowledge that is required for the execution of certain work steps is difficult to measure with concrete numbers such as time. Still, it was tried to take this into account. Service companies that provide sensible downhole tools, such as bits or MLWD, have company people on site to supervise the assembling process. Plus, such work steps require experienced crew members which might be a problem to get by different reasons. With interviews with different people from the business those work steps were selected that had to be observed by contractors, for example handling of mud motor or taking samples, and non-routine tasks that could lead to severe problems if they are done wrong, like handling of a jar safety clamp.

The feasibility of the mechanization of certain work steps will play an important role on the realization. It is easier to convince both rig manufactures and rig customers to make investments for automated systems if they are cheap and easy to implement, even if they will solve only small problems and not the big ones. On the other hand, hazardous operations like the handling of heavy tools will be done manual as long there is no equipment that can do it economically reasonable.

The installation of a pipe washing system was one of the ideas that came up. Implementation of such a tool would not require that big amount of money, while at the same time relieving one crew member from holding the water hose during tripping out.

The evaluation of this criterion was, again, not done with quantitative means. It was done due to information that was gathered during interviews of drilling manufacturer and operator.

6. BHA Handling Automatization

6.1 Tool Life Cycle

Automatization of the assembling of the BHA tools on the rig floor will not be the only challenge to design a working environment that is not dependent on human interaction. It is important to consider the entire life cycle of the tool on the rig site (Figure 39). An efficient logistic system will require at least the same attention as the mechanization of the installation process. Plus, some components do require different kinds of service. Whether it may be collecting drilling data from MWD tools or cleaning of a filter sub. The necessary work steps for BHA handling have already been categorized in the different stages of the tool life cycle in “5.3.2 - Definition and Categorization of the Work Steps”. Still, things will have to be further discussed to find a suitable solution. Many have the main focus on the automation of the drill floor, but automation of transport, storage and service on site will have a big influence on the success of the entire system.

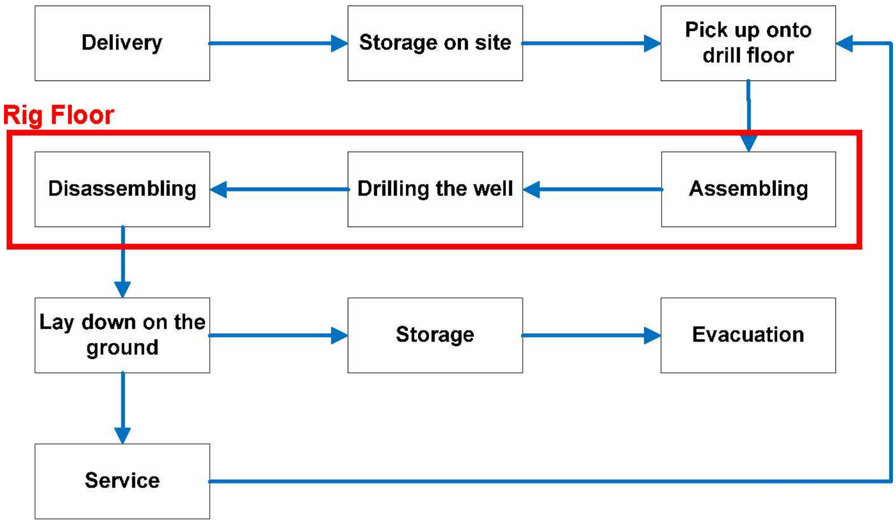


Figure 39: Life cycle of drilling tools

Other industries, which have implemented automated systems, have spatial divided the different stages of the product life cycle. With success.[70] This does not only allow that equipment can be adapted to the individual requirements of the different operations. It is also a good way to prevent dangerous interactions of human and machine. Automated working areas are isolated and cannot be entered during operation. On the other hand, areas, where hands-on intervention of the crew is required, are designed to minimize possible injuries due to moving equipment to zero. Such working area designs are becoming more and more popular on drilling rigs. One example is the Bauer TBA 440 M2.

Figure 40 shows the arrangement of different areas on the rig:

- Service area
- Working area
- Pipe handling area

The **service area** is that part of the rig where the main components like drawworks, power aggregates, hydraulic pumps etc. are located. Intervention of the crew is only necessary for maintenance. Entering of this area during operation is not allowed to avoid accidents.

The **pipe handling area** is that part of the rig where the logistic system for pipe handling and storage is located. During operation, heavy equipment is handling high loads at increased speed. Entering of the crew would be highly risky and is therefore forbidden. Still, access to the tools is possible under certain circumstances, for example in defined areas at the back of the structure. This may be necessary for inspection or other tasks, for example calibration of MLWD tools.

Working areas for the crew does not have to be considered during the design of those parts. So it can be done very compact and process focused as safety issues will not play a dominant role.

The **working area** is the place where the crew will execute the assembling and disassembling of the different downhole components. This is also where the driller will have the main focus on. Industrial robots for the handling of BHA and other tools would possibly be placed here as this is the area where the hands-on operations are performed.

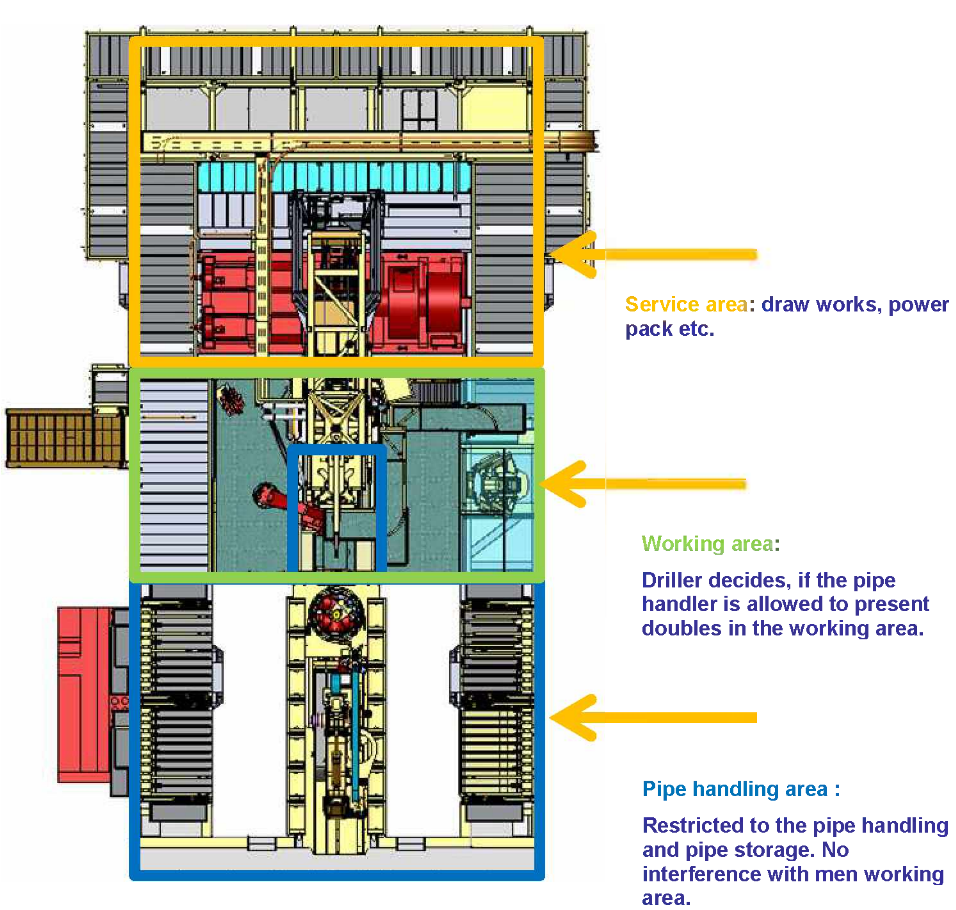


Figure 40: Work space arrangements of new drill floor designs[71]

6.2 Tool Data Exchange

An important but also interesting challenge of automated rig floor design will be the data exchange and management with the system. For the correct handling of downhole tools certain data will be required. Make-up torque is probably one of the most important values, but also tool weight, length, diameter, etc. Right now, these values can be taken from the BHA design list that is generated by the drilling engineer. The list is usually at the rig site office and in the driller's cabin when assembling the respective string. IF a certain component has to be changed in the short run, the values will be taken from similar components. This may fit in most cases but can lead to troubles.

An automated system will require that information as well, but the manual input will be not only laborious but also prone to failure. A data acquisition system that is implemented into the logistic tool cycle might be a promising way to solve that problem. When a tool is delivered on site, the specific data is taken into the system. This can be done with the delivery ticket or maybe with more advanced methods, like an RFID chip that is integrated into the tool. The automated rig floor equipment can recall that data during the installation.

This would not only improve the handling quality of downhole tools, it can be a chance for downhole tools manufacturer as well. The specific data set of a certain BHA component could not only include technical data but also performance evaluation. Tool history and the status of wear of a used drilling bit could help to decide if it could be used again in a certain section. Performance data of a bit that is recorded with automated rig measurement devices could be saved. This could help to analyze the application of the bit later on.

6.3 Offline BHA Handling

An interesting approach to improve BHA handling is to assemble it offline. Instead of installing each component on the rig floor, the BHA is assembled on the ground (Figure 41). The heart of the system is the MBU, the mobile bucking unit. It is basically an iron roughneck that is capable of handling tubular in the horizontal position. The downhole tools are made up into sets which will then be lifted onto the drill floor. The size of those sets is only limited by the capacities of the pipe handling systems.

The biggest advantage is the saving potential of operational time. Tools can be prepared prior to the installation during phases where the crew has time to do that and not during tripping when everybody is in a hurry. This reduces also the risk for crew and equipment as the work can be done without time pressure. Plus, work is removed from the hazardous rig floor, where people should spend as less time as possible.

The system has been tested since 2006 and is now running on different rigs all over the world, mainly on offshore rigs. The average time saving is given with three percent of the total rig time, which is impressive.

Figure 41: Offline assembling of BHA (left), mobile bucking unit (right)

Still, the big breakthrough has not come yet. People criticize that it requires too much space, space that is not available on the crowded rig site. Plus, the problems with handling of downhole tools is not solved, only relocated. And the preassembled sets of BHAs still have to be connected on the rig floor. So the crew will have to be there, and additional workers on the ground for operating the MBU. Not to mention the costs for the equipment.[72]

6.4 Robotic Drilling Systems

Robotic Drilling Systems (RDS), former company name Seabed Rig, is a young Norwegian start-up company with companies like Statoil, National Oilwell Varco or Apache as contributors. The basic vision of RDS is to create a fully automated drilling rig for on- and offshore operations, with no workers on site. The attempt to build such a prototype was driven by the needs of Statoil to face challenges of hostile working environments like the Arctic, deserts or the open see. With the knowledge of building this prototype RDS is trying to create a device able to drill wells completely on its own, with no staff on site, even at the bottom of the ocean.

To realize their plan RDS is working with components of the oil business as well as of the automation business. Soft- and hardware is created with prestigious partners and then put together. Among that partners are NASA with computer software for their mars rovers, Shell with their drilling automation software SCADAdrill or National Oilwell Varco with their rig control system. And the number of oil companies with serious interest in developing automation systems is growing.[73]

Inspiration comes from other highly automated industries such as car manufacturing, steel manufacturing or, as mentioned above, the mars rover program of NASA. The big target is to produce a drilling rig that can be operated from any office by guiding it with targets (drill vertical hole with 2000m) and not with commands (pick up pipe). The drilling operation is controlled by an autopilot, monitored by human that would only take over control if necessary.

RDS is designing robots that will handle various tasks on the drill floor (Figure 42). The robot is three meters tall, has a range of three meters and should be able to perform different tasks with interchangeable hands. So far, about 15 different hands are available, with additional hands in development.[74]

RDS is trying to prove that the implementation of robotic technology on drilling rigs will improve the drilling performance. Manual work steps, like changing the elevator set for different pipe diameter ore pipe tripping, rely on the skills of the crew. Robots execute their work at constant rate that can be pushed to the technical limit. In addition to that they can handle certain tasks simultaneously and will not require a pause of the main operation.

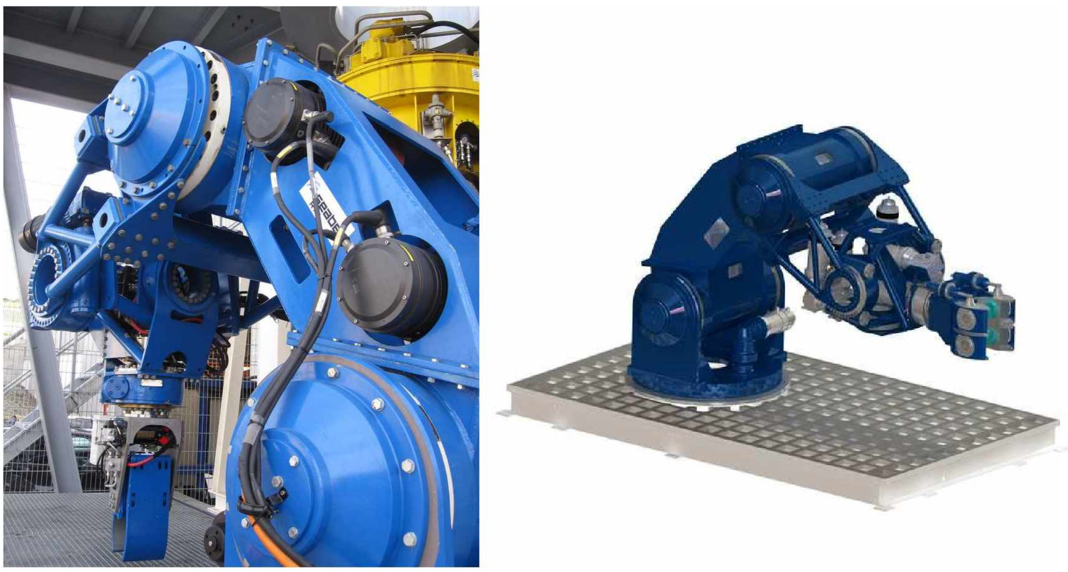


Figure 42: Robotic Drilling Systems rig arm[75]

From an HSE point of view an automated rig floor is essential for minimizing incidents in the drilling industry. The rig floor is a hot spot for injuries being probably the most hazardous area at the drilling site. Minimizing the staff on the rig floor will increase accidents. Robots will also be lifesaving when it comes to major accidents. Taking the explosion of the Deep Water Horizon[vii], automated drilling systems would have reduces the personnel at the offshore platform and therefor lowered the number of dead and injured. Besides, a robot will continue the work, no matter if there is fire next to it or not. He can even initialize actions against the failure while people can start evacuation.

With all this in mind, employees can start focusing on the important tasks. Attention is not wasted on the procedures that make drilling possible, but on the drilling itself. Whereas the automated system can already detect hidden failures, for example worn out threads of drill pipes that would possibly be missed by human.[76]

But not only drilling operations in unfriendly environments are requiring fully automated drilling rigs. The development in shale gas exploration brings new challenges to drilling operations. For exploration of shale gas a high number of wells increase the costs for exploitation of reservoirs. Reducing drilling costs by repetitively drilling similar wells is one of the ways to reduce costs, the common term is well manufacturing.

Another reason for developing fully automated drilling rigs is the dependence on professional staff. Increase in drilling activity and the decreasing number of skilled people on the job market makes it difficult for drilling companies to employ enough staff to run their rigs. Taking a look on the average age of skilled drillers, the situation will get worse as many good qualified employees of the drilling industry will retire in the next years, taking their know-how with them.

6.5 Workshop - Automatization of BHA Handling

As already discussed, the realization of automated rig design requires the cooperation of the different players of the drilling business. Therefore the idea came up of bringing together the different parties that are involved. The planning for the workshop began rather early during the work for this thesis. But it was decided to host it in the finishing phase to compare the results with other experts from the drilling industry (Appendix H – Workshop Summary).

The target of the two-day workshop was to bring together experts with professional expertise in different areas to discuss different approaches to achieve the fully-automated drilling rig. The discussion was focused on the handling of drilling BHA tools. Thanks to the participants, it was possible to bring together different aspects that should be considered when working on an automated drill floor. This included the knowhow about industrial robots and automatization technology, performance measurement, downhole tools and practical aspects from a manufacturer’s, a contractor’s and an operator’s point of view.

The participants of the workshop represented the following disciplines

- Rig manufacturer (Bauer Maschinen AG)
- BHA manufacturer (Baker Hughes)
- Rig operator (ITAG)
- Drilling contractor (Statoil, Shell)
- Automation techniques (Robotic Drilling Systems, UT Texas)
- Data and performance measurement (TDE, Montanuniversity Leoben)

[vii] Deep Water Horizon was a state-of-the-art offshore drilling platform that exploded and sank after a uncontrolled blowout in April 2010. Eleven workers were killed, 16 were injured.

6.5.1 Improving Performance

The two main reasons for the demand for a fully automated drilling rig is the increase of performance and safety. These two issues have to be responded to a certain extend so that the significant financial expenditures can be justified. The increase of performance can be validated by the generated value of the automatization tools, or in other words, how much time it will save during operation. Half of the costs for a new well are spent in the drilling phase. An example of an offshore drilling operation in the North Sea shows that the drilling time, the time during which the bit is actually rotating on bottom and making hole, is beyond 10 percent of the total time. The rest is used for well treatment, tripping, maintenance of equipment and others. So there is definitely potential for process optimization.

The difficulty is now to find the biggest potentials for savings, and this depends highly on the drilling process and the application. On the other hand, some operators claim that they don't see much demand for increasing the working performance on the rig floor, especially when they do performance drilling with highly qualified rig crews in combination with shallow wells. They would rather investigate operations like rig moves as this may be one of the major spending for them. To find a significant statement to compare automated systems to conventional drilling rigs the key is accurate measurement of the work steps.

6.5.2 Human Resources Development

An important reason that requires a high level of automatization is to meet new aspects in the human resources development. Getting the crew away from hazardous areas and reduce risky operations to a minimum has been an important issues for the last years, especially in offshore drilling. Despite the already high degree of mechanization, many procedures still requires manual work or at least involves human interference in some way. Performance is not only measured with time, but also with accidents occurring on site. Many companies follow a zero-incidents policy, although operators report that additional equipment that would reduce the risk of the crew is often cancelled to avoid higher day-rates, especially on land rigs. Safety - yes, but only to the same price.

In addition to that, a drilling rig is not only hazardous for the crew, but also for the equipment. Transport on site and wrong handling of BHA tools has been responsible for a large portion of damages which costs a lot of money. Standardized handling procedures and the fact that automated systems will perform a working sequence always in the same way would eliminate this.

And there is a second reason why companies want to reduce the amount of people on the rig. It becomes more and more difficult to find qualified and experienced people that are willing to take a job in the oilfield. The work on a drilling rig is quite intense, twelve hours shift working, hard physical work in a harmful environment and remote locations where exposed to extreme harsh environmental influences are only the top reasons why people do not want to work as a roughneck any more. And the relationship between employer and employee is not a very sustainable one. Already today operators have difficulties to fill gaps in their crews with poorly trained agency workers to keep their rigs running during peak periods. The hiring of additional crews to run more drilling rigs in case of a possible upcoming boom in drilling activities will bring the operating business to its limit.

However, there might be a downside, too, if future drilling rigs will be fully automated. More effort will be spent on maintenance and repair. And as the equipment of an automated rig floor consists of highly sophisticated gadgets, intervention will required a high level of training and education. Low educated personnel is willing to work under bad conditions as it is the easiest way to make a lot of money, to convince skilled personnel to work under these circumstances will be a challenge. And during the beginning of designing fully automated rigs where new techniques will be tested through semi-automated applications, the personnel capacity will be even higher as I need people to service the machinery as well as the normal rig crew.

6.5.3 Automation through Standardization

To design a fully automated system it is important to know the processes that are required to reach a certain goal, in this case the goal is to bring an operative BHA into the well. Still, this does not mean that I must exactly recreate the processes. Manufacturers tend to find ways to mechanize the exact handling procedure as the crew would do it. They add different tools for every work step to the drill floor which makes the system complicated, prone to failure and at the same time inefficient. Essential for developing a marketable automated system is standardization. Standardization of the process, standardization of the machinery and standardization of the tools, in combination with a long term drilling program with high numbers of similar wells.

Other industries implement autonomous assembly lines only for products that are produced in high quantities, not for individual items. If the same steps are repeated over and over again, automated systems will proof as efficient. Therefor it is necessary to know the handling procedures, identify the necessary work steps and find an effective way to implement them in the automation system, but not necessary replicate the way it has been done so far. Furthermore, it is necessary to implement a certain standard design for the required BHA components as well. But as they would be utilized in higher numbers, especially wear parts, tool manufacturers confirm that they are willing to meet the demands of producing such fit-for-purpose standardized downhole equipment (for example one size OD design of drill string) and provide the operator with the necessary support (for example 3D models of the tools).

Standardization of the necessary handling equipment will help to produce them at a reasonable price. If it is possible to design the machinery in a way that the process of assembling downhole tools can be managed with only a few flexible handling devices, they can be manufactured in a number high enough to bring them on the market. Important features will be the implementation of standard components from the free market. This ensures that the parts require less maintenance as they have been tested in other industries, are easy available in case of failure and can be purchased at a lower price than in-house developments. Modular design will help to implement the equipment on existing rigs as well as on new rigs and will facilitate the adapting of the systems to changes due to new drilling projects, not to mention that also rig moves can be carried out faster. Designing the rig as a platform that can be equipped with the necessary machinery would enable operators to assemble a rig that would meet the requirements of the current job.

6.5.4 Data Transfer

An important issue concerning automatization is data transfer. Information is exchanged between the individual components and especially with the human supervisor. To bring a system to the technical limit, the work steps have to be initiated and coordinated by a computer that initiates and coordinates the process with the help of different sensor data. Measurement data show that mechanized systems that are controlled by men, do not have constant performance and do not work near the possible technical limit. Regulating the equipment by pushing buttons and handling joysticks make the operating level dependent on the driller. And with the increase of steering complexity it gets difficult to work on a constant level over a longer period, even for well trained personnel.

There is a psychological problem as well. People of the oil industry tend to be distrustful to new technologies. They are more likely to be seen as a handicap that has to be treated with caution instead of looking at it as a helpful tool that should be driven to the maximum. People from the field report that is some cases, new tools are not used at all as the crew is not willing to implement it into the workflow. An autonomous control system, on the contrary, will operate the rig on a predictable, 24 hour basis. People only need to monitor the operation and intervene if there is a problem. This can be done from any location around the world, as it is already the case for some offshore applications. This would minimize the manpower on site to a few mechanics for maintenance, logistic issues and technical troubleshooting. The actual work is done autonomously by the computer.

Again, standardization will be playing a big role. Communication between the different handling equipment, sensors, logistics and the controller must subordinate a certain language with common rules, especially as the different components will probably be provided by different manufacturers.

6.5.5 Conclusion

The concept of a fully automated drilling rig can only be realized by the interaction of all contributors, the drilling rig manufacturers and designers of downhole tools as well as operators and contractors. Not only will the developing of new handling machinery, but also a change in the handling process be necessary. The basement for automatization is standardization. Standardization of the downhole tools in terms of design and dimensioning to allow fully mechanized handling as well as standardization of the equipment to allow construction at a reasonable and marketable price. Besides that, operators need long term drilling contracts to justify higher costs for new automated drilling rigs that are more specialized than cheaper conventional rigs. Especially the first automated drilling rigs will rather be fit for purpose rigs than build for market rigs. The high investment will be adventurous if contracts last for only a few years and the rig may then have to be modified for a new application. Then again, if a drilling rig can be designed for a ten to fifteen years contract and a high number of standardized wells, like for developing a shale gas field, contractors and operators may consider investing in totally new BHA and rig designs. By the end, the most overall-cost effective machinery will be the one on future drilling sites.

7. Conclusion

7.1 Automatization in the Drilling Industry

Automatization will become more and more important in the future. The fully automated rig may not be realized in the next few years, but as soon as the automation technology has proofed the increase in performance and safety, there is no doubt that it will achieve a lot of attention in the drilling industry.

The drilling industry has always been skeptical towards new ways of doing the job. With the high costs of drilling operations and the time running, there is not much space for experiments. This is different from other branches. Equipment for car assembling can be tested. You build up a small testing system and start to do trial and error. On a drilling rig, on the contrary, there is not much room for error. It may not only lead to the loss of a lot of money, failures during drilling may lead to environmental catastrophes and the loss of lives.

Still, changes of different variables cannot be denied. To keep the global production rates stable, oil companies will be forced to go for new reservoirs in remote areas with hostile environments. Running rigs in such environments, for example Alaska, with a lot of personnel is not only a logistic challenge but will require high financial benefits for the crew members to get them there.

In general, having enough personnel to keep rigs running will be a problem. This is not only predicted by different demographical diagrams, operators are facing this problem right now. The gap between skilled and unskilled workers is getting wider. On one hand, you have educated people who are not willing to work under the inconvenient circumstances that you find on today's rigs. On the other hand, low qualified work force is from a safety point of view not acceptable on the rig floor. During the documentation the change of the work flow due to rental workers could be experienced. The work load of the regular crew doubled as they had to do their own work and take care of the new guy as well. The number of safety incidents increased directly with the number of external workers.

On the other hand, certain developments in the oil and gas industry bring up chances for new designs. The boom of shale gas all over the world will require an enormous amount of new and cheap wells to be drilled. Therefore new drilling rigs will be required. Well manufacturing, the drilling of similar wells over and over again, is the type of project where automated, build for purpose drilling rigs can prove their advantages.

7.2 Realization of Fully Automated BHA Handling

7.2.1 Automation trough Standardization

Every industry sector that has successfully implemented automation systems was facing one big problem during the starting phase: The lack of standards regarding terminology and technique. Due to the interaction of different engineering areas from different companies all over the world, the definition of certain norms will be imperative.

Automated systems will demonstrate best performance doing repetitive operations. Assembling of downhole tools, however, incorporates a huge range of different work steps that have to be executed on different components. There is not one universal design of a designated type of tool. If, for example, all MWD tools would be constructed due to a certain norm, with predefined dimensions and common arrangement of sensible areas, the development of handling systems would be much more effective.

Fortunately, BHA manufacturers are willing to make changes. Especially during the workshop (Appendix H – Workshop Summary) it could be experienced that they do understand the problem and see it as a chance to be a part of a new way of designing drilling infrastructure.

7.2.2 Target Focused Instead of Process Focused

Although companies put a lot of effort into the development of new equipment that would mechanize the rig floor, they struggle with the acceptance on the market. Many techniques do not come through the field testing phase. They are either too slow in the prototype phase or only applicable to very specific tasks. The reason for this is that engineers often try to reproduce the human work motion. For the development of a thread greasing unit, for example, the focus is on the process by trying to imitate the way the crew would apply pipe dope to the connections. Other industries were more successful in focusing on the target itself, in this case how to get a connection ready to be screwed together. Solutions may include the change of the greasing material that would be easier to apply or different pipe connections that do not need to be greased at all.

7.2.3 Long Term Commitments

Fully automated drilling rigs will require a certain degree of standardization and repetition to be competitive. They will be built for the drilling of special types of wells, like the development of shale gas fields. The acquisition of such a build-for-purpose rig brings economic risks for the operators. Drilling contracts are usually signed for no more than one or two years. To justify the financial expenses for such equipment, companies have to be sure that they keep their rig operating in the long term. Again, it can be seen that the realization of automation depends on the contribution of all participants, manufacturers, operators and contractors.

7.2.4 Setting the Benchmark Right

A basic argument of people that are rather skeptical to automated rig design is that it would never be able to compete with a well-trained crew. If new equipment is tested, the performance is compared with manual operations and, in some cases, slower. This does not necessarily mean that the overall performance is bad. The important thing is to define the benchmark right. Automated systems will not have to compete with the best performance that has been recorded so far, it will have to compete with the standard in the business. Human performance is dependent on the interaction of the rig and its crew, if one variable is changed the system gets disturbed. It can be recorded that due to small changes, such as working the nightshift instead of the dayshift, the same crew will perform a little slower. Automated systems will deliver constant output, twenty-four hours a day, with little or no influence of environmental issues.

7.3 Contribution of this Work

7.3.1 Documentation on Site

The decision to do documentation on an operating drilling rig turned out to be a very productive way of gathering information. To understand a process it is very difficult to rely on written material like literature or handling manuals. In the case of BHA installation, such material was not very precise or not available anyway.

The analysis of drilling operations is very time consuming. Tripping of drill strings is not considered a daily operation. During the two and a half weeks at the rig site three runs could be observed. To record the trips on video turned out to be a very effective way of documenting such an operation by only one person. It would not have been possible to get all the necessary information by making notes. Plus, additional questions that occurred during the analysis phase could be answered by reviewing the video files.

Another advantage of observing a work flow on a real rig is the interaction with the crew, company man and service personnel. They cannot only provide you with information about the ongoing operation but also with their experience from other projects. Working on the rig floor contains so many different tasks and small details of which not even the drilling engineers are aware of. But these details can be crucial for the success of automation equipment.

The documentation on site can not only be valuable for the research in the course of a thesis but also in general for the development and construction of new rig equipment. It closes the gap between manufacturer and operator. It was experienced that the some members of the rig crew have a lot of ideas and proposals for improvement and are willing to pass them on. This would help to make tools more suitable for certain tasks and increase usability.

7.3.2 Define the Goals and Boundary Conditions

During the research at the beginning of this thesis it was discovered that documentation of the work flow for the installation of BHA did not really exist. Only little information could be found on handling manuals, most of them pointing out to obey safety instructions. So far, neither rig operators nor tool manufacturers have outlined the different work steps for education purpose or the evaluation of best practice. Nevertheless, the development and testing of automated systems requires such information to discuss the entire range of BHA handling activities. It would not be enough to just simulate the installation of a random drilling bit or stabilizer to the drill string and then give a meaningful recommendation on the performance. The clear and exact definition of the various tasks and the determination of the boundary conditions such as maximal lengths or loads will serve as a basis for future developments.

7.3.3 Detect Weak Spots on Existing Rig Design

Another benefit of the documentation of different work steps is that it reduces the gap that exists between rig manufacturers and rig operators. It does not only transfer knowledge from the user of the equipment to the producer for upcoming automation projects, it can help detect weak spots of existing drilling machinery, too.

One example is that every item, that has to go up onto the rig floor, will be transported with the winch. Every single item that is too heavy to be comfortably carried in one hand will go up over the slide to avoid accidents. This is not only inconvenient, it blocks the v-door for other operations too. Implementing a second transport system with a lifting basket would improve the situation.

7.3.4 Focus on Tools with the Highest Potential

The automation of the entire drill floor handling infrastructure will probably not be realized in one stroke. Economic reasons and the complexity of the system will not allow such a big step. It may also be that people from the business will not accept such a fundamental change. The achieving of the automated drilling rig will rather be a step by step project. Therefor it is important to filter out the work steps that can already be executed mechanized and define those with the highest potential for increase of different performance parameters. With the evaluation of the work steps it will be easier to find to do so.

7.3.5 Workshop

The workshop turned out to be a very effective way of bringing together different ideas regarding automation. On one hand it was possible to present the results of the thesis to see if this was the right approach to the problem. The fact that the BHA handling process had not been documented so far by any of the participating companies as well as their interest in the findings of this thesis showed the relevance of the work. Especially as the developers of robotic systems, RDS, stated that one of their problems is that they don’t know the boundary conditions and the entire range of demands for their equipment. On the other hand new ideas came up that had not been considered so far. Changes in the design of downhole tools would facilitate the development of mechanized handling equipment. And as it turned out, BHA manufacturers could think about that option.

The opinions of the different participants regarding rig automation where throughout positive, especially towards the end of the two days of the workshop. It was important to structure the seminar as a mutual exchange of ideas and not as a sales event. This created a very constructive dialog.

One of the most important outcomes was that the different parties, who will be involved in the realization of the fully automated rig, see the opportunities of such systems and are willing to contribute their share. This includes cooperation between tool and rig manufacturer to ensure that handling equipment and BHA tools are designed to be compatible. But also collaborations between rig operator and contractor to share the financial risks with long-term contracts for the employment of fully automated rigs.

8. Appendix A – Nomenclature

AC	Alternating current
ADM	Automatic Drilling Machine
BHA	Bottomhole assembly
BxB	Both ends have box threads
DC	Direct current
DC	Drill collar
DOF	Degree(s) of freedom
EMT	Electromagnetic transmitter
HSE	Health, safety and environment
HWDP	Heavy weight drill pipe
ID	Inner diameter
KPI	Key performance indicator
LWD	Logging while drilling
MBU	Mobile bucking unit
MD	Measured depth
MLWD	Measure and logging while drilling
MPT	Mud pulse transmitter
MTBF	Mean time between failures
MWD	Measure while drilling
NASA	National Aeronautics and Space Administration
NGO	Non-governmental organization
Nm	Newton-meter
NOV	National Oil Varco
NPT	Non-productive time
OD	Outer diameter
PDC	polycrystalline diamond compact
PDM	Positive displacement motor
PLC	Programmable logic controller
PT	Productive time
PxB	Pin threads on one side, box threads on the other side
PxP	Both ends have pin threads
RDS	Robotic Drilling Systems
ROP	Rate of penetration
SCARA	Selective Compliant Assembly Robot Arm
SCR	Silicon-controlled rectifier
TVD	Total vertical depth
VFD	Variable frequency drive

WOB	Weight on bit
WT	Wedge threads

9. Appendix B – Rig 27 and Rig 30 from ITAG

ITAG
Drilling & Workover

RIG 27
IDECO E-3000-AC

MAST

Type	L.C. Moore - Cantilever Mast
Clear Height	152 ft (46.3 m)
Max. Hook Load Capacity	1,555,000 lbs (685 t) @14 Lines

SUBSTRUCTURE

Type	L.C. Moore- Raised Floor 32 ft
Setback Capacity	815,000 lbs (370 t)
Rotary Capacity	1,400,000 lbs (635 t)
Height underneath Rotary Beams	26.4 ft (8.1 m)

DRAWWORKS

Type	Ideco E-3000-AC
Max. Line Pull, 2nd Layer	139,000 lbs (618 kN)
Drilling Line	1 5/8 in
Rated Input Power	3,000 HP
Auxiliary Brake	Baylor Elmagco 7838

RIG POWER SYSTEM

Drive	Diesel-electrical-AC
Type of Engines	MTU 12 V 4000 G23
Number	3
Nominal Rated Power (each)	1420 kW
Type of Generators	LEROY SOMER
Number	3 x 2000
Transformer Station (10 / 20 kV Grid)	Fest AG
Power (690V)	5,000 kVA
Wattless Current Compens. (stat. / dyn.)	Yes
Electric- Wave Filter	Yes
VFD / MCC Unit	Bentec

MUD PUMPS

Type (Triplex Pumps)	3 x Wirth TPK 1600

ROTARY TABLE

Type	Ideco LR 375 (37 1/2 in)

TOP DRIVE

Type	Maritime Hydraulics DDM 500-AC
Capacity	500 ton (454 t)
Max. Torque	55,500 ft-lbs (75,300 Nm)
Continuous Torque	49,500 ft-lbs (66,980 Nm)@ 104 rpm
Continuous Torque	32,000 ft-lbs (43,560 Nm)@ 161 rpm

BLOCK

Type	Emsco RA-52-6-500
Capacity	500 ton (454 t)

BLOWOUT EQUIPMENT

Annular BOP	13 5/8"-10,000psi
Ram BOP	13 5/8"-10,000psi Double 13 5/8"-10,000psi Single
BOP closing unit	Cameron C- 324-2-30
Volume	323 gal (1,224 ltr)
Choke- & Kill Manifold	10,000psi WP with Controls
Drilling Spools and Adapters	

MUD TANK SYSTEM

Active Tank System Capacity	4 x 1,258 bbl (200 cbm)
Reserve Tank System Cap. (Vertical Silos)	4 x 943 bbl (150 cbm)
Additional Equipment	LP Mixing System, Mud Agitators, Degasser, Bulk Silos, Double Trip Tank

SOLIDS CONTROL EQUIPMENT

Type	4 xMI SWACO PT Mongoose
Type	1 xDesander(4x10"Cones)
Type	2 xDesilter (16x4"Cones)

ADDITIONAL EQUIPMENT

NOV Iron Roughneck IR- 30120
Power Slips
Feed Off Control System
Drilling Instrumentation
Colour Camera System
Additional Fingerboard
Gas Flare and Kick System
Forklift Mobile Working Platform (Cherry Picker)
Soundproofed Equipment
Anti Collision System (ACS)
Soft Torque Bentec VFD
Soft Pump System

ITAG Tiefbohr GmbH - Itagstraße 5-17 - 29221 Celle/Germany
Phone: +49 5141 914-0 - Fax: +49 5141 914-388
itb@itag-ce.de - www.itag-celle.de

ITAG
Drilling & Workover

RIG 30
WIRTH GH-1250 EG

MAST

Type	M.I.L. Series 500 - Vertical Erection
Clear Height	138 ft (42.0 m)
Max. Hook Load Capacity	551,000 lbs (250 t) @ 10 Lines

SUBSTRUCTURE

Type	M.I.L. - Containerized, Box-on-Box
Setback Capacity	485,000 lbs (220 t)
Rotary Capacity	551,000 lbs (250 t)
Height underneath Rotary Beams	19.4 ft (5.9 m)

DRAWWORKS

Type	Wirth GH 1250 EG - Single Drum
Max. Line Pull. 2nd Layer	71,000 lbs (317 kN)
Drilling Line	1 1/4 in
Rated Input Power	1250 HP
Auxiliary Brake	Baylor Elmgco 6032

RIG POWER SYSTEM

Drive	Diesel-electrical
Type of Engines	3 x Caterpillar 3508 B DI- SCAC
Nominal Rated Power (each)	880 kW
Type of Generators	3 x Leroy- Somer
Apparent Power (each)	1,385 kVA
Voltage	750 V
SCR- & MCC- Unit	Bentec

MUD PUMPS

Type (Triplex Pumps)	2 x Wirth TPK 1300

ROTARY TABLE

Type	National Oilwell C- 275

TOP DRIVE

Type	Bentec TD-500-HT
Max. Speed	230 rpm
Capacity	500 ton (435 t)
Max. Torque	46,500 ft- lbs (63,000 Nm)
Continuous Torque	73,760 ft- lbs (100,000 Nm@100rpm

BLOCK

Type	National Oilwell A 350
Capacity	350 ton (318 t)

BLOWOUT EQUIPMENT

Annular BOP	11" - 10,000 psi
Ram BOP	11" - 10,000 psi Double
	11" - 10,000 psi Single
BOP closing unit	Cameron C 162-1-20 E
Volume	162 gal (613 ltr)
Choke- & Kill Manifold	10,000psi WP with Controls
Drilling Spools and Adapters	According to Requirement

MUD TANK SYSTEM

Active Tank System Capacity	3 x 1,132 bbl (180 cbm)
Reserve Tank System Cap.	4 x 943 bbl (150 cbm)
	LP Mixing System, Mud Agitators, Degasser, Bulk Silos, Double Trip Tank

SOLIDS CONTROL EQUIPMENT

Type	2 x Derrick Linear Motion Shale Shaker

ADDITIONAL EQUIPMENT

Soundproofed Equipment
Iron Roughneck Maritime Hydraulics MH 1898
Power Slips
Feed off Control System
Drilling Instrumentation
Color Camera System
Forklift/ Mobile Working Platform (Cherry Picker)
Anti Collision System (ACS)
Soft Torque Bentec VFD

ITAG Tiefbohr GmbH - Itagstraße 5-17 - 29221 Celle/Germany
Phone: +49 5141 914-0 - Fax: +49 5141 914-388
itb@itag-ce.de - www.itag-celle.de

10. Appendix C – Confidential Agreement

Geheimhaltungsvereinbarung

zwischen

Klaus Kurz,
Reiferdorf 1
4310 Mauthausen, Österreich

- nachfolgend "**Diplomand**" genannt -

und

ITAG GmbH,
Itagstr. 5-17
29221 Celle, Deutschland
vertreten durch Rüdiger Biedorf

- nachfolgend "**ITAG**" genannt -

Präambel:

Der Diplomand erstellt derzeit seine Diplomarbeit im Studiengang Petroleum Engineering.

Zu diesem Zweck generiert er Daten und Informationen über den Einbau von Bohrsträngen und deren Logistik, auch über zwei Tiefbohr-Projekte von ITAG.

ITAG gewährt dem Diplomanden Zutritt zur Bohrlokation in Goldenstedt und erteilt ihm die Erlaubnis, Videoaufzeichnungen über die Lokation und die Bohrung zu machen.

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...., den ....

Ort Klaus Kurz

...., den ....

Ort ITAG

11. Appendix D – Setup of Documented BHA

Type: 8 3/8" Drilling BHA			**Project:** Well A		**Operator:** Operator A
Pos	OD [in]	Tool	Length [m]	Weight [kg]	Handling similar to
1	8 3/8	PDC	0,42	95	Drilling Bit
2	6 3/4	Steering Unit	2,17	800	AutoTrak
3	8 1/4	Modular Stabilizer	1,28	170	AutoTrak
4	6 3/4	BCPM	3,25	800	AutoTrak
5		NM Sub - XO	0,8	200	Crossover
6	6 3/4	MWD Navi Gamma	8,74	2000	MWD/LWD
7	6 3/4	NM Filter Sub	182	600	Filter Sub
8	8 1/4	SST	1,11	150	Stabilizer
9	6 1/2	Float Sub	0,8	180	Filter Sub
10	6 1/2	DC	9,44	1306	Drill Collar
11	8 1/4	SST	1,35	180	Stabilizer
12	6 1/2	DC	18,86	1254	Drill Collar
13	8	SST	1,54	205	Stabilizer
14	6 1/2	DC	18,84	1253	Drill Collar
15	8	SST	1,53	203	Stabilizer
16	6 1/2	DC	18,79	1250	Drill Collar
17	8	SST	1,32	176	Stabilizer
18	6 1/2	DC	18,83	1252	Drill Collar
19	8	SST	1,31	174	Stabilizer
20	6 1/2	DC	18,83	1252	Drill Collar
21	8	SST	1,24	165	Stabilizer
22	6 1/2	DC	18,18	1209	Drill Collar
23	7 3/4	SST	1,23	164	Stabilizer
24	6 1/2	DC	18,16	1208	Drill Collar
25	7 3/4	SST	1,55	206	Stabilizer
26	6 1/2	DC	17,54	1166	Drill Collar
27	7 3/4	SST	1,63	217	Stabilizer
28	6 1/2	DC	18,1	1204	Drill Collar
29	7 3/4	SST	1,92	255	Stabilizer
30	6 1/2	DC	18,23	1212	Drill Collar
31	7 3/4	SST	1,16	154	Stabilizer
32	6 1/2	DC	18,81	1251	Drill Collar
33	7 3/4	SST	1,23	164	Stabilizer
34	6 1/2	DC	18,76	1248	Drill Collar
35	7 3/4	SST	1,54	205	Stabilizer
36	6 1/2	DC	18,46	1228	Drill Collar
37	7 3/4	SST	1,64	218	Stabilizer
38	6 1/2	DC	18,28	1216	Drill Collar
39	6 1/2	JAR	9,88	1800	Jar
40	6 1/2	DC	9,24	1229	Drill Collar
41	5	HWDP	82,82	663	HWDP

Type: 4 1/8" Drilling BHA#1			**Project:** Well B		**Operator:** Operator A
Pos	OD [in]	Tool	Length [m]	Weight [kg]	Handling similar to
1	4 1/8	PDC	0,24	-	Drilling Bit
2	4 3/32	BST	1,58	85	Stabilizer
3	3 1/8	Short DC	1,92	57	Crossover
4	4 3/32	SST	1,50	82	Stabilizer
5	3 1/8	Saver Sub	0,38	-	Crossover
6		XO	0,50	15	Crossover
7	3 1/8	NMDC (Navi Gamma)	9,46	-	MWD/LWD
8	3 1/8	Pulser Sub	0,78	-	Transmitter Sub
9	3 1/8	Saver Sub	0,40	-	Crossover
10	4	SST	1,50	-	Stabilizer
11	3 1/8	Float Sub	0,84	-	Filter Sub
12	3 1/8	Saver Sub	0,82	-	Crossover
13		XO	0,82	-	Crossover
14	3 1/8	DC mit 2 x Stabis	9,05	-	Drill Collar
15	3 3/8	Drilling Jar	7,10	-	Jar
16	3 1/8	DC mit 2 x Stabis	9,15	-	Drill Collar
17		XO	0,36	-	Crossover
18	3 3/8	Accelerator	7,82	-	Jar
19		XO	0,42	-	Crossover
20	3 1/8	DC mit 2 x Stabis	9,03	-	Drill Collar
21	2 7/8	DP WT23	9,58	-	Drill Pipe
22		XO	0,96	-	Crossover
23	3 1/2	DP	9,41	-	Drill Pipe
24	3 1/2	HWDP	9,28	-	HWDP
25		Magnete	5,01	-	Magnet
26		XO	0,56	40	Crossover

Type: 4 1/8" Drilling BHA#2			**Project:** Well B		**Operator:** Operator A
Pos	OD [in]	Tool	Length [m]	Weight [kg]	Handling similar to
1	4 1/8	PDC	0,24	-	Drilling Bit
2	4 3/32	BST	1,58	85	Stabilizer
3	3 1/8	Short DC	1,92	57	Crossover
4	4 3/32	SST	1,50	82	Stabilizer
5	3 1/8	Saver Sub	0,38	-	Crossover
6		XO	0,50	15	Crossover
7	3 1/8	NMDC (Navi Gamma)	9,46	-	MWD/LWD
8	3 1/8	Pulser Sub	0,78	-	Transmitter Sub
9	3 1/8	Saver Sub	0,40	-	Crossover
10	4	SST	1,50	-	Stabilizer
11	3 1/8	Float Sub	0,84	-	Filter Sub
12	3 1/8	Saver Sub	0,82	-	Crossover
13		XO	0,82	-	Crossover
14	3 1/8	DC mit 2 x Stabis	9,05	-	Drill Collar
15	3 3/8	Drilling Jar	7,10	-	Jar
16	3 1/8	DC mit 2 x Stabis	9,15	-	Drill Collar
17		XO	0,36	-	Crossover
18	3 3/8	Accelerator	7,82	-	Jar
19		XO	0,42	-	Crossover
20	3 1/8	DC mit 2 x Stabis	9,03	-	Drill Collar
21	2 7/8	DP WT23	9,58	-	Drill Pipe
22		XO	0,96	-	Crossover
23	3 1/2	DP	9,41	-	Drill Pipe
24	3 1/2	HWDP	9,28	-	HWDP
25		Magnete	5,01	-	Magnet
26		XO	0,56	40	Crossover

12. Appendix E – Data Sheets of BHA Tools

Drilling bit

Types:

There are numerous types of different drilling bit designs, from a handling point of view they can be segmented into two main groups:

- Roller-cone bits
- Drag bits

Specifications:	3 ½" PDC[77]	22" PDC[78]	28" PDC[79]
Length	400 mm	700 mm	700 mm
Weight	5 kg	750kg	900kg
ID	-	-	-
OD	75 mm	240 mm	260 mm
Max. OD	90 mm	558 mm	710 mm
Thread	2 3/8" Reg. Pin	7 5/8" Reg. Pin	8 5/8" Reg. Pin
Make-up Torque	2,5 kNm	85 kNm	160 kNm

Logistics:

- The drilling bit is delivered and stored in a transport box (normally wooden box or some kind of synthetic box). The amount of bits on site depends on the location of the rig. If the drilling takes place in an area with good transport connections to the drilling bit supplier, the bits will be delivered just in time, maybe not even a contingency bit is present (another factor for delivery date is if the bit is a rental or property). If the well is drilled in a remote area, it is possible that the bits and contingency bits for several well sections are stored at the drilling site
- For every bit size the matching bit breaker plate has to be delivered with the bit or be on site (roller cone bits and drag bits have different bit breaker plate shapes).
- The bit is transported onto the drill floor in the transport box with the winch over the slide.

Handling:

- Bit is very sensible to collision, especially the cutters of an insert bit and the threads.
- When the bit is set down, it is recommended to place it on a rubber mat or a wooden pad.
- Bit breaker plate has to fit the bit.
- The inside of the bit has to be free of any foreign matters. Ensure there is no debris that could plug any nozzle.
- Inspection of the bit (cutters, cones, nozzles, bit diameter, status of wear …) before running in hole is necessary. This should be checked again on the drill floor before connecting it to the string to avoid installation of wrong tool.
- Record bit type, size, serial number and condition for later analysis (photography of the condition before running in hole is always helpful)

- Handling of the bit on the drill floor is done with the winch or, if the bit has little weight, by hand (dropping hazard)
- To lift the bit with the winch a lifting cap is screwed on. Depending on the size of the threads, the suitable lifting cap is used.
- The threads have to be cleaned and greased (or glued) before making connection.
- The bit can be screwed on/off with the rotary table.
- The bit is made up/broken out with the manual tongs.
- Apply recommended make-up torque when connecting it to the drill string.
- Depending on the size of the bit, the slips and the master bushing may have to be removed so the bit will fit into the well.
- When the bit is installed it is lowered a few centimeters into the well and tested by pumping drill fluid at a low pumping rate (test the bit nozzles)
- When passing bottlenecks such as rotary table, BOP, casing shoes, tight spots or doglegs tripping speed has to be reduced to prevent damage.
- When the bit is pulled out of the hole, mud samples are taken (if there are any on the bit).
- When tripping out, the bit has to be cleaned with fresh water to remove the aggressive drilling fluids and prevent corrosion.

Required equipment:

- Elevator	Handling	Handle string on drill floor
- Elevator sub	Handling	Connect string to elevator
- Winch	Transport/handling	Pick up bit, handle it on drill floor
- Lifting cap	Transport/handling	Connect winch to the bit
- Slide	Transport	Lift bit (in transport box) on drill floor
- Bit breaker plate	Assembling	Hold bit while assembling
- Bit breaker plate frame	Handling	Connect bit breaker plate to drill floor (rotary table)
- Tongs	Assembling	Make-up/break bit connection
- Cathead	Assembling	Apply torque to tongs
- Rotary table screwing	Assembling	Hold bit breaker plate, rotate for
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Thread lubrication (glue)	Assembling	Improve connection quality
- Water hose	Service	Clean bit
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection

Drill Collar

Types:

- Cylindrical drill collars (standard)
- Cylindrical, spiral grooved drill collars
- Square shaped drill collars
- Non-magnetic drill collars
- Drill collars with elevator recess
- Short drill collar (pony collar)

Specifications:	3" DC[80]	9 1/2" DC[81]	6 1/2" Pony DC[82]
Length	9100 mm	9500 mm	1500 mm
Weight	250 kg	3200 kg	215 kg
ID	38 mm	50 mm	64 mm
OD	76 mm	241 mm	165 mm
Max. OD	76 mm	241 mm	165 mm
Thread	NC 23 P x B	7 5/8 Reg P x B	NC50 P x B
Make-up Torque	3,4 kNm	130 kNm	40 kNm

Logistics:

- Drill collars are stored at the rig site on pipe wrecks. Transport on the rig site is done with fork lifters.
- The drill collar transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift the drill collar with the winch (attached to the drill collar via lifting cap) over the slide up on the drill floor. More advanced ways to bring the drill collar on the drill floor are with the help of pipe handlers. It is also possible to leave the drill collars in the mast if they are required for the following drill string assembly.
- The threads of the drill collars have to be protected with thread protector caps during handling on surface. Drill collars are expensive and their weakest points are the threads, they have to be handled with special care and threat damage while handling has to be avoided. The thread protectors are screwed on right after pulling a collar out of the hole and removed right before running the collar into the well. The thread protectors are stored on the drill floor, normally in an iron cage box. Different protectors are in service for different threads (different thread sizes, different materials for example non-magnetic caps for MWD).

Handling:

- To lift the drill collar with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used. A second way to handle drill collars with the elevator is the use of special drill collars with elevator recesses.
- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when drill collar is set in the slips

- To protect the threads of the drill collar, thread protector caps have to be used during handling, especially when the ends of the drill collars could slug against something.
- The threads have to be clean and greased (or glued) before making connection.
- The inside of the drill collar must be free of any foreign matters that could plug the nozzles.
- The drill collars are screwed on/off with chain tongs or by hand and made up with tongs. If available, this can be done with an iron roughneck, too.
- If the drill collar has spiral grooves, the rollers of the spinning unit should not be placed on the grooves as they could slip through.
- When the drill collar is lifted after unscrewing it, the pin should be guided out of the box as the pin thread could “hook” into the box thread and lift the string that is in the slips.
- Apply recommended make-up torque for connection.
- To protect the threads from damage, it is recommended to count the revolutions of the vibration dampener while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- When tripping out, drill collars have to be cleaned with fresh water to remove the aggressive drilling fluids and prevent corrosion.
- To protect the threads from damage, it is recommended to count the revolutions of the drill collar while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.

Required Equipment:

- Pipe handling	Transport	Pick up/lay down drill collar
- Elevator	Handling	Handle crossover on drill floor
- Elevator sub	Handling	Connect crossover to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Slips	Assembling	Hold crossover in place
- Safety clamp	Assembling	Secure crossover and string
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean pipe outside

Reamer/Stabilizer

Types:

- Stringstabilizer/-reamers, bitstabilizer/-reamers and near-bitstabilizer/-reamers
- Magnetic and non-magnetic stabilizers/-reamers
- Stabilizers/-reamers with integrated blades (one piece), welded on blades or replaceable blades (sleeves)
- Stabilizers/-reamers with straight blades and spiral blades (right and left twisted spiral)
- Stabilizers/-reamers with special features, ex. flexible stabilizer/-reamers
- Blade reamers and rotary rolling reamers

Specifications:	4 3/4" Stringstab.[83]	28" Stringstab.[84]	5 ½" Bitstab.[85]
Length	1575 mm	2400 mm	1575 mm
Weight	90 kg	900 kg	100 kg
ID	38 mm	76 mm	38 mm
OD	95 mm	254 mm	95 mm
Max. OD	120 mm	710 mm	140 mm
Thread	NC26 P x B	7 5/8Reg P x B	NC38 B x B
Make-up Torque	6 kNm	120 kNm	6 kNm

Logistics:

- Reamers/stabilizers are stored at the rig site on palettes and are transported with a fork lifter. The amount of reamers/stabilizers on side depends on the location (close to a supplier or far away) and on the BHA program. It can occur that 20 to 30 reamers/stabilizers have to be stored.
- Reamers/stabilizers are transported on the drill floor with the winch over the slide
- During tripping with no big change of the string setup, for example changing a worn out bit, reamers/stabilizers are stored with drill collars as one piece.
- Reamers/Stabilizers with interchangeable sleeves (blades) are assembled in the shop. The sleeves can also be replaced at the site to replace worn out reamer/stabilizers.
- Thread protectors of the stabilizers have to be handled and stored on the rig floor during usage.

Handling:

- To lift the reamer/stabilizer with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used.
- To lift the reamer/stabilizer with the winch a lifting cap is screwed on (some elevator subs have a lifting cap welded on top).
- Reamer/stabilizer with low weight can be unscrewed and handled manually (dropping hazard).
- Inspection of the reamer/stabilizer (cutters, diameter, status of wear …) before running in hole is necessary. This should be checked again on the drill floor before connecting it to the string to avoid the installation of a wrong or worn out tool.

- Reamers/stabilizers are screwed on/off with chain tongs or by hand and made up with tongs. If available, this can be done with an iron roughneck, too.
- When the stabilizer is lifted after unscrewing it, the pin should be guided out of the box as the pin thread could “hook” into the box thread and lift the string that is in the slips.
- The inside of the reamer/stabilizer must be free of any foreign matters that could plug the nozzles.
- Bit reamer/stabilizer have to be installed in the right direction (box threads on both sides)
- Stabilizers with blade inserts or roller cutters are sensible to collision and have to be handled with special care.
- Stabilizers can vary regarding their length and therefore may not be uniform to another stabilizer of the same size (dimensions change when the threads are recut or new blades are welded on, important for automatization adjustments).
- To protect the threads of the stabilizer, thread protector caps have to be used during handling, especially when the ends of the stabilizer could slug against something.
- The threads have to be clean and greased (or glued) for making connection.
- Apply recommended make-up torque when connecting reamer/stabilizer to the drill string.
- When tripping out, reamers/stabilizers have to be cleaned with fresh water to remove the aggressive drilling fluids and prevent corrosion.
- To protect the threads from damage, it is recommended to count the revolutions of the reamer/stabilizer while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- When passing bottlenecks such as rotary table, BOP, casing shoes, tight spots or doglegs tripping speed has to be reduced to prevent damage.

Required Equipment:

- Slide	Transport	Pick up stabilizer
- Winch	Transport/handling	Pick up stabilizer, handle it on drill floor
- Lifting cap	Transport/handling	Connect stabilizer to winch
- Elevator	Handling	Handle stabilizer on drill floor
- Elevator sub	Handling	Connect stabilizer to elevator
- Iron roughneck	Assembling	Make connection
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Slips	Assembling	Hold stabilizer in place
- Safety clamp	Assembling	Secure crossover and string
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve and seal connection
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean stabilizer annulus and outside
- Sponge sleeve	Service	Clean stabilizer outside

Jarring Tools

Types:

- Hydraulic jar
- Mechanical jar
- Combination of hydraulic and mechanical jar
- Accelerator (intensifier)
- Jars for fishing operations

Specifications:	3 3/8" Hydra Jar[86]	9 1/2" Hydra Jar[87]	9 ½" Accelerator[88]
Length	7450 mm	9912 mm	9912 mm
Weight	225 kg	2500 kg	2500 kg
ID	38 mm	76 mm	76 mm
OD	85 mm	241 mm	241 mm
Max. OD	85 mm	241 mm	241 mm
Thread	2 3/8" API IF PxB	7 5/8 API Reg. PxB	7 5/8 API Reg. PxB
Make-up Torque	6,2 kNm	117 kNm	117 kNm

Logistics:

- Drilling jars are stored at the rig site on pipe wrecks. Transport on the rig site is executed with fork lifters.
- The drilling jar transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift the jar with the winch over the slide up on the drill floor. More advanced ways to bring the drilling jar on the drill floor are with the help of pipe lifters or pipe handling systems.
- The threads of the jar have to be protected with thread protector caps during handling on surface. Jarring devices are very expensive and threat damage while handling has to be avoided. The thread protectors are screwed on right after pulling the jar or accelerator out of the hole and removed right before running into the well. The thread protectors are stored on the drill floor, normally in an iron cage box. Different protectors are in service for different threads (different thread sizes, different materials for example synthetic caps for MWD).
- To secure the jar from accidental firing on surface, a jar safety clamp is installed during handling. When the jar is in the hole, the safety clamp is stored on the rig floor. Jar safety clamp is not required for accelerators.
- The life span of a drilling jar can be taken from the data sheets. During normal drilling applications a jar can be operated for 200-250 recommended rotational hours as a rough average value.

Handling:

- To lift the jar with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used.
- To lift the jar with the winch a lifting cap is screwed on (some elevator subs have a lifting cap welded on top).

- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when the jar is set in the slips
- To protect the threads of the jarring device, thread protector caps have to be used during handling, especially when the ends of the drill collars could slug against something.
- The threads have to be clean and greased (or glued) for making connection.
- Apply recommended make-up torque for connection.
- To protect the threads from damage, it is recommended to count the revolutions of the vibration dampener while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- A jar safety clamp (mandrel clamp) has to be used during handling operations on surface. The safety clamp will be removed right before running in hole of the tool, not until the slips are opened and the tool is in tension. It has to be installed as soon the jar comes out of the hole, before it is set into the slips and the tool still in tension. This is necessary to protect the mandrel section from damage during handling and to prevent the accidental activation of the jarring tool which would be very dangerous for crew and equipment. The jar safety clamp is not used with accelerators.
- The jar safety clamp is installed carefully over the reduced diameter mandrel and locked with bolts. Do not over-tight the bolts, the jar safety clamp must be able to move free along the mandrel.
- When running jar out of hole, they have to be cleaned to remove aggressive drill fluids. Cleaning the inside by flushing water through the vent holes with the water hose is important. Check especially the mandrel part for damage, wear or corrosion.
- When passing bottlenecks such as rotary table, BOP, casing shoes, tight spots or doglegs tripping speed has to be reduced to prevent damage.
- The speeding-up and slowing-down of a drill string with a jar should be done careful. High acceleration forces could cock the tool.
- Never place a drilling jar below high OD tools such as stabilizers, reamers or mills. Make sure that the jar is never used as a crossover. The tubular (drill collar, HWDP…) on top and on the bottom end of the jar should be of the same outer diameter to avoid excessive stress and premature tool failure. If more than on jar is installed, make sure that there is a minimum clearance of 500m between two jars.

Required Equipment:

- Pipe handling	Transport	Pick up/lay down drill collar
- Elevator	Handling	Handle drill collar on drill floor
- Elevator sub	Handling	Connect drill collar to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Jar safety clamp	Assembling	Secure jar from surface uncocking
- Safety clamp	Assembling	Secure drill collar from slip failure
- Slips	Assembling	Hold drill collar in place
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Transport	Clean threads
- Thread inspection	Transport	Thread inspection
- Water hose	Transport	Clean pipe annulus and outside
- Sponge sleeve	Transport	Clean pipe outside

Crossover sub

Types:

- Box to box crossovers (example: bit sub)
- Pin to pin crossovers
- Box to pin crossovers with varying outer diameter (to connect drill string parts with different thread sizes and ensure a smooth outer shape of the string).
- Box to pin crossovers with constant outer diameter (example: connect drill string parts with different thread sizes, saver sub).

Specifications:	3” Bit sub[89]	9 3/8” Crossover[90]	4 3/4” Saver Sub[91]
Length	300 mm	1500 mm	445 mm
Weight	10 kg	450 kg	35 kg
ID	38 mm	76 mm	55 mm
OD	76 mm	216 mm	120 mm
Max. OD	76 mm	238 mm	120 mm
Thread	2 3/8 Reg. BxB	7 5/8Reg x 6 5/8Reg	NC38 PxB
Make-up Torque	3 kNm	120 kNm x 60 kNm	17 kNm

Logistics:

- Crossover subs that are frequently in use are part of the rig equipment and are continuously stored at the rig site. They are stored on the rig floor or, when not needed, on the rig site on pallets or in barred boxes.
- Crossovers that are not stored at the rig site have to be delivered according to the BHA program.
- Special crossovers, like bit sub or saver subs, are delivered with the tools for which they are required (sometimes already screwed together and made up).
- Thread protector caps of the crossovers have to be handled and stored on the rig floor during usage.

Handling:

- Some crossovers do not have a uniform outer diameter (to connect tubular with different diameters)
- Crossovers (with box threads on both sides) have to be installed in the right direction
- Crossovers are picked up onto the rig floor over the slide with the winch.
- Lifting caps are sometimes already integrated in the thread protector caps
- Some crossovers (frequently used crossovers) are stored on the drill floor.
- During tripping operations, crossover connections are sometimes only broken out/made up on the drill floor, assembling and disassembling is done on the catwalk.
- The crossovers are screwed on/off with chain tongs or by hand and made up with tongs. If available, this can be done with an iron roughneck, too.
- When the stabilizer is lifted after unscrewing it, the pin should be guided out of the box as the pin thread could “hook” into the box thread and lift the string that is in the slips.

- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when the crossover is set in the slips
- The inside of the crossover must be free of any foreign matters that could plug the nozzles.
- When tripping out, crossover subs have to be cleaned with fresh water to remove the aggressive drilling fluids and prevent corrosion.
- To protect the threads of the crossovers, thread protector caps have to be used during handling, especially when the ends of the crossovers could slug against something.
- The threads have to be clean and greased (or glued) before making a connection.
- Apply recommended make-up torque for making a connection.
- To protect the threads from damage, it is recommended to count the revolutions of the crossover while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.

Required Equipment:

- Pipe handling	Transport	Pick up long crossovers (> 3m)
- Lifting cap	Transport	Connect crossover with winch
- Winch lift	Transport/Handling	Pick up short crossovers (< 3m) and them on rig floor if heavy
- Elevator	Handling	Handle crossover on drill floor
- Elevator sub	Handling	Connect crossover to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Slips	Assembling	Hold crossover in place
- Safety clamp	Assembling	Secure crossover and string
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve and seal connection
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean crossover annulus and outside
- Sponge sleeve	Service	Clean crossover outside

Vibration Dampener

Types:

- Rubber type shock absorber
- Spring type shock absorber

Specifications:	4 3/4" Shock sub[92]	9 1/2" Shock sub[93]	14" Shock sub[94]
Length	3500 mm	4120 mm	4360 mm
Weight	270 kg	1225 kg	2800 kg
ID	44 mm	76 mm	83 mm
OD	120 mm	241 mm	356 mm
Max. OD	120 mm	241 mm	356 mm
Thread	3 1/2 IF P x B	7 5/8 Reg P x B	8 5/8 H90
Make-up torque	13 kNm	120 kNm	170 kNm

Logistics:

- Vibration dampeners are delivered via truck and stored at the rig site on palettes or pipe wrecks. Transport on the rig site is performed with fork lifters.
- The vibration dampener transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift the shock sub with the winch (attached to the drill collar via lifting cap) over the slide up on the drill floor. More advanced ways to bring the shock absorber on the drill floor are with the help of pipe handlers. It is also possible to leave the vibration dampener together with other tools as one string in the mast if they are required for the following drill string assembly.
- Thread protectors of the vibration dampener have to be handled and stored on the rig floor during usage (different thread protector sizes, different materials for example non-magnetic caps for MWD).

Handling:

- To lift the vibration dampener with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used.
- To lift the vibration dampener with the winch a lifting cap is screwed on (some elevator subs have a lifting cap welded on top).
- To protect the threads of the vibration dampener, thread protector caps have to be used during handling, especially when the ends of the stabilizer could slug against something.
- The threads have to be clean and greased (or glued) for making connection.
- Apply recommended make-up torque for connection.
- When running vibration dampener out of hole, they have to be cleaned to remove aggressive drill fluids.
- To protect the threads from damage, it is recommended to count the revolutions of the vibration dampener while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.

Required Equipment:

- Pipe handling	Transport	Pick up/lay down drill collar
- Elevator	Handling	Handle crossover on drill floor
- Elevator sub	Handling	Connect crossover to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Slips	Assembling	Hold crossover in place
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean pipe outside

Magnet

Specifications:	3 5/8" String magn.[95]	9" String magn.[96]	3 ½"String magn.[97]
Length	2286 mm	2972 mm	5000 mm
Weight	90 kg	650 kg	200 kg
ID	32 mm	76 mm	58 mm
OD	76 mm	203 mm	85 mm
Max. OD	90 mm	228 mm	89 mm
Thread	2 3/8 IF PxB	6 5/8Reg PxB	NC38 B x B
Make-up Torque	6 kNm	109 kNm	15 kNm

Logistics:

- Magnetic subs are stored at the rig site on palettes and are transported with a fork lifter.
- Magnetic subs are transported on the drill floor with the winch over the slide.
- During tripping with no big change of the string setup, for example changing a worn out bit, magnetic subs may be stored with drill collars as one piece.
- Thread protectors of the magnet have to be handled and stored on the rig floor during usage.
- Magnetic subs must never be placed near any measurement BHA tool, the measurement devices could be interfered or damaged.
- When running out of the hole, the caught metal debris have to be disposed at the rig floor (amount of debris can range from around 10 kg up to max 100 kg, depending on the tool size and the application).

Handling:

- Some magnets do not have constant outer diameters.
- To lift the magnet with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used.
- To lift the magnet with the winch a lifting cap is screwed on (some elevator subs have a lifting cap welded on top).
- Magnets with low weight can be unscrewed and handled manually.
- To protect the threads of the magnet, thread protector caps have to be used during handling, especially when the ends of the magnet could slug against something.
- The threads have to be clean and greased (or glued) before making connection.
- The inside of the magnets must be free of any foreign matters that could plug the nozzles.
- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when the magnet is set in the slips.
- The magnets are screwed on/off with chain tongs or by hand and made up with tongs. If available, this can be done with an iron roughneck, too.
- When the magnet is lifted after unscrewing it, the pin should be guided out of the box as the pin thread could "hook" into the box thread and lift the string that is in the slips.
- To protect the threads from damage, it is recommended to count the revolutions of the magnet while unscrewing it. This prevents that the lowest groove of the pin thread

slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- Apply recommended make-up torque for connection.
- When running magnet out of hole, they have to be cleaned to remove aggressive drill fluids. In addition to that, the metallic debris that have been collected have to be removed from the tool and should be collected so the will not be scattered on the rig floor and rig site during handling.
- Magnets must never be located next to any BHA tool with measurement devices. The magnetic field can interfere with the calibration or even damage the tool.

Required Equipment:

- Slide	Transport	Lift magnet on drill floor
- Winch	Transport/handling	Pick up magnet, handle it on drill floor
- Lifting cap	Transport/handling	Connect magnet to winch
- Elevator	Handling	Handle magnet on drill floor
- Elevator sub	Handling	Connect magnet to elevator
- Iron roughneck	Assembling	Make connection
- Slips	Assembling	Hold magnet in place
- Safety clamp	Assembling	Secure crossover and string
- Revolution indicator	Assembling	Count revolutions while unscrewing
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean crossover outside

MWD/LWD

Types:

- Retrievable MWD/LWD and non-retrievable MWD/LWD
- Clear ID MWD/LWD and centrally located MWD/LWD
- Modular MWD/LWD and one-piece MWD/LWD

Specifications:	3 1/8" LWD[98]	9 1/2" LWD[99]	8" PWD[100]
Length	9100 mm	7720 mm	1350 mm
Weight	84 kg	2300 kg	65 kg
ID	20 mm	60 mm	49 mm
OD	79 mm	203 mm	203 mm
Max. OD	83 mm	210 mm	203 mm
Thread	2 3/8 IF BxB	6 5/8" Reg BxB	6 5/8" Reg PxB
Make-up Torque	2,5 kNm	75 kNm	75 kNm

Logistics:

- MWD/LWD tools are delivered via truck and stored at the rig site on pipe wrecks or on the ground on wooden stakes. Transport on the rig site is performed with fork lifters.
- MWD/LWD tools transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift them with the winch (attached to the MWD/LWD tools via lifting cap) over the slide up on the drill floor. More advanced ways to bring the tools on the drill floor are with the help of pipe lifters or with pipe handlers if allowed by the tool manufacturer. Transport has to be done with special care as the tools are sensible.
- The threads of the MWD/LWD tools have to be protected with thread protector caps during handling on surface. The thread protectors are screwed on right after pulling a MWD/LWD tool out of the hole and removed right before running it into the well. The thread protectors are stored on the drill floor, normally in an iron cage box. Different protectors are in service for different threads (different thread sizes, different materials for example non-magnetic caps for MWD).
- The setup of MWD/LWD tools is executed in the shop or on the rig site by the company man of the manufacturer. In a few cases extra adjustments have to be executed on the drill floor.
- Retrievable MWD/LWD tools may be assembled on the ground, in case of a tool change only the interior may be changed. The spare tool (inlet) has to be stored with special care.

Handling:

- Handling of MWD/LWD tools is done under supervision of a company man of the tool manufacturer to assure correct treatment. Wrong handling procedures may affect the downhole performance.
- To lift the MWD/LWD tools with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used. MWD/LWD tools often have separate lifting subs due to their special threads, in most cases they are delivered with the tool.

- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when the MWD/LWD tool is set in the slips
- To protect the threads of the MWD/LWD tool, thread protector caps have to be used during handling, especially when the ends of the MWD/LWD tool could slug against something. MWD/LWD tools often have separate thread protectors due to their special threads
- The threads have to be clean and greased (or glued) for making connection. MWD/LWD tools which can transfer data over the threads have a special type of grease (blue) which is already applied and must stay free of any dirt or fluid.
- Apply recommended make-up torque for connection.
- When making connection, some MWD/LWD tools have to be screwed together with chain tongs and made-up with the manual tongs as the Iron roughneck applies too much force on the tubular. The housing may bend beyond tolerance and damage the inner workings, O-ring seals… Manual tongs distribute the contact force in a more uniform matter around the tool.
- Set tongs, slips and safety clamps only on those segments of the tool where it is permitted and never on sensitive surfaces.
- To reduce possible negative impacts of lifting and making connection to the MWD/LWD tools the different components will be already assembled as much as possible when they are delivered.
- To protect the threads from damage, it is recommended to count the revolutions of the MWD/LWD tool while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- When the pin is guided into the box during the making of connection, avoid collision which could damage the threads.
- When running MWD/LWD tool out of hole, they have to be cleaned to remove aggressive drill fluids. Possible vents may have to be flushed according to the manual.
- Some MWD/LWD tools may be sensible to magnetic influences and have to be handled and stored accordingly. Also the BHA tools close to MWD/LWD should be non-magnetic.
- The MWD/LWD tools should be tested after installation. This is done when the BHA is lowered into the well at a certain depth, at least below the annular fluid level. The MWD/LWD test is done together with the test of the transmitter. When a mud motor is part of the string, the test should be done without the motor if possible.

Required Equipment:

- Pipe handling	Transport	Pick up/lay down
- Elevator	Handling	Handleing on drill floor
- Elevator sub	Handling	Connect string to elevator
- Manual tongs	Assembling	Make-up connection with rest of BHA
- Chain tongs	Assembling	Screw connection with rest of BHA
- Safety clamp	Assembling	Secure the string
- Cathead	Assembling	Actuate the manual tongs
- Slips	Assembling	Hold string in place
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean pipe outside
- Revolution indicator	Assembling	Count revolutions while unscrewing

Mud Motor

Types:

- Turbine downhole motor
- Positive displacement downhole motor

Specifications:	3 5/8" PDM[101]	9 5/8" PDM[102]	9 5/8" [103]
Length	6253 mm	9962 mm	9760
Weight	237 kg	2500 kg	2880
ID	-	-	-
OD	92 mm	245 mm	245
Max. OD	95 mm	250 mm	stabilizer sleeve
Thread	2 5/8"Reg BxNC26B	6 5/8" Reg BxB	6 5/8" Reg BxB
Make-up Torque	6 kNm	75 kNm	75 kNm

Logistics:

- Mud motors are delivered via truck and stored at the rig site on the ground on wooden stakes. Transport on the rig site is performed with fork lifters.
- Mud motors transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift the motor with the winch (attached to the drill collar via lifting cap) over the slide up on the drill floor. More advanced ways to bring them on the drill floor is with the help of pipe lifters or with pipe handlers if allowed by the manufacturer. Transport has to be done with special care as the tools are sensible.
- The threads of the mud motor tools have to be protected with thread protector caps during handling on surface. The thread protectors are screwed on right after pulling the motor out of the hole and removed right before running it into the well. The thread protectors are stored on the drill floor, normally in an iron cage box. Different protectors are in service for different threads (different thread sizes, different materials for example non-magnetic caps for MWD).
- The setup of a mud motor is executed in the shop or on the rig site by the company man of the manufacturer. The components of a mud motor assembly are in many cases already made-up as far as the single components can be handled. In a few cases extra adjustments have to be executed on the drill floor.

Handling:

- Handling of the mud motor is done under supervision of a company man of the tool manufacturer to assure correct treatment. Wrong handling procedures may affect the downhole performance.
- To lift the mud motor with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used.
- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when the mud motor is set in the slips

- To protect the threads of the mud motor, thread protector caps have to be used during handling, especially when the ends of the mud motor could slug against something.
- The threads have to be clean and greased (or glued) before making connection.
- Apply recommended make-up torque for connection.
- Make sure that the master bushing and the slips have the right size range for the string, otherwise they may have to be removed for running the tools into the well..
- The bit is connected to the mud motor as described in “Drilling Bits”.
- Set tongs, slips and safety clamps only on those segments of the tool where it is permitted and never on sensitive surfaces.
- To reduce possible negative impacts of lifting and making connection to the mud motor the different components will be already assembled as much as possible when they are delivered.
- To protect the threads from damage, it is recommended to count the revolutions of the mud motor while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- When the pin is guided into the box during the making of connection, avoid collision which could damage the threads.
- When the mud motor is pulled out of the hole and back on the drill floor, it should be set with the bit into the bit breaker plate on the rotary table. By revolving the rotary table, the residual mud in the motor is removed. Then the tool has to be cleaned with fresh water.
- After assembling, the thrust bearing and the dump valve should be tested to check for wear (see mud motor data sheet).
- The mud motor should be tested after installation, usually together with MWD/LWD and transmitter tools. This is done by lowering the tool so far into the well that the bit box can still be observed. The string is connected to the kelly or top drive and by pumping fluid the mud motor can then be tested (flow test).
- If testing of the mud motor and the bit is necessary in the well the drill string should be slowly rotated and lifted. This prevents damage of the casing or borehole wall.
- Orientation of the mud motor is adjusted with the rotary table or the top drive. When the desired orientation is set, the rotary table or top drive is locked.

Required Equipment:

- Pipe handling	Transport	Pick up/lay down drill collar
- Elevator	Handling	Handle crossover on drill floor
- MWD/LWD Elevator sub	Handling	Connect crossover to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Manual tongs	Assembling	Make-up connection with rest of BHA
- Chain tongs	Assembling	Screw connection with rest of BHA
- Slips	Assembling	Hold crossover in place
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean pipe outside
- Rotary table	Service	Orientation, emptying of mud motor
- Bit breaker plate	Service	Emptying of mud motor
- Bit breaker plate frame	Service	Emptying of mud motor

AutoTrak^{TM}

Specifications:	4 3/4" ATK [104]	9 1/2" ATK[105]
Length	9200 mm	10600 mm
Weight	2600 kg	4000 kg
ID	32 mm	64 mm
OD	171 mm	241 mm
Max. OD	310 mm	445 mm
Thread	4 3/4" T2 PxB	9 1/2" T2 PxB
Make-up Torque	14 kNm	90 kNm

Logistics:

- AutoTrak^{TM} is delivered via truck and stored at the rig site on pipe wrecks or on the ground on wooden stakes. Transport on the rig site is performed with fork lifters.
- AutoTrak^{TM} transport up on the drill floor can be done in different ways, depending on the available machinery. The most common way is to lift the AutoTrak^{TM} with the winch (attached to the AutoTrak^{TM} via lifting cap) over the slide up on the drill floor. More advanced ways to bring the AutoTrak^{TM} on the drill floor are with the help of pipe handlers. Transport has to be done with special care as the tools are sensible.
- The threads of the AutoTrak^{TM} tools have to be protected with thread protector caps during handling on surface. The thread protectors are screwed on right after pulling it out of the hole and removed right before running it into the well. The thread protectors are stored on the drill floor. Different protectors are in service for AutoTrak^{TM} than for other tools
- The setup of AutoTrak^{TM} tools is executed in the shop or on the rig site by the company man of the manufacturer. In a few cases extra adjustment have to be executed on the drill floor.

Handling:

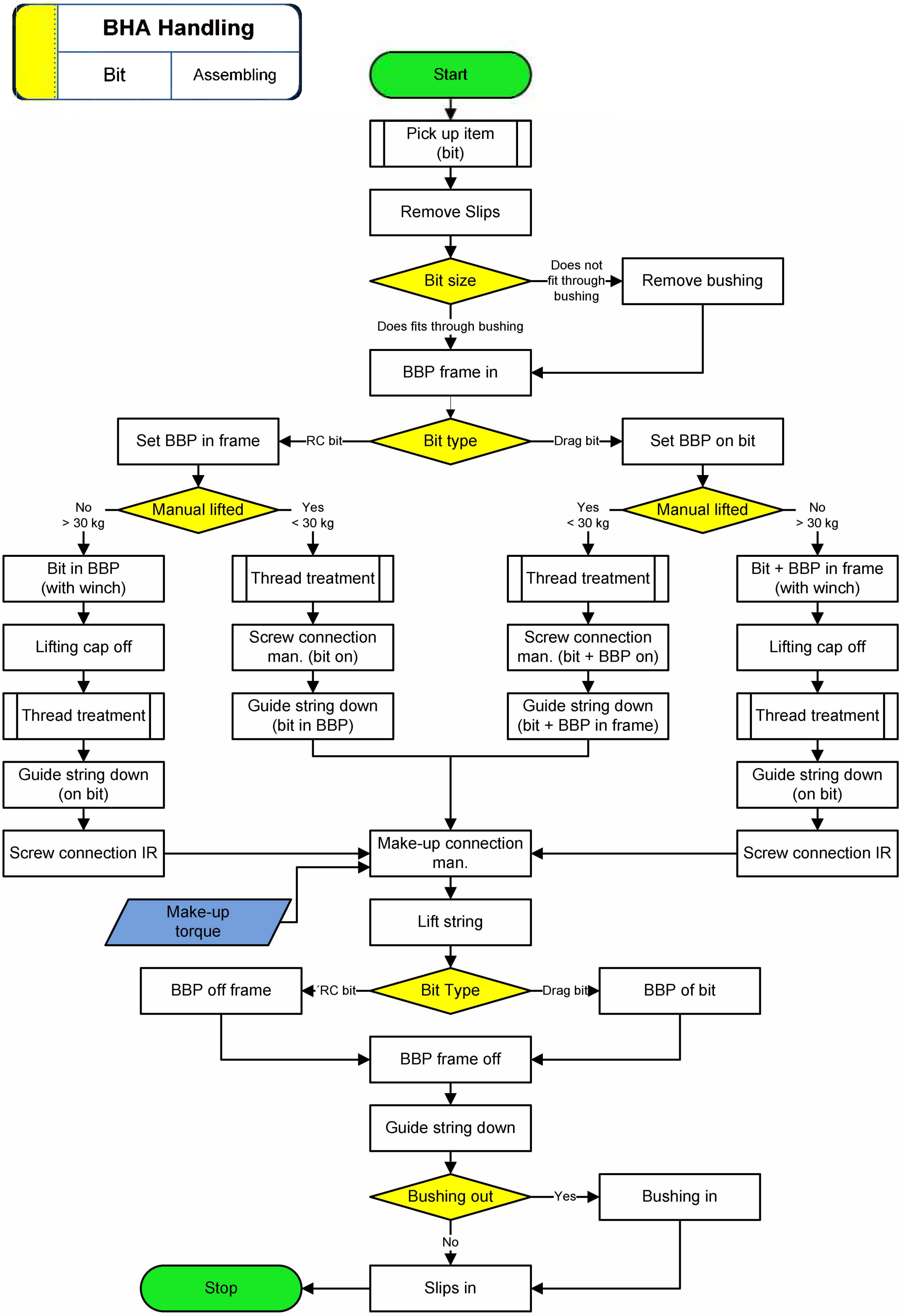
- Handling of AutoTrak^{TM} is done under supervision of a company man of the tool manufacturer to assure correct treatment. Wrong handling procedures may affect the downhole performance.
- To lift AutoTrak^{TM} with the elevator an elevator sub is screwed on. Depending on the elevator (casing elevator or pipe elevator) and the thread size the suitable elevator sub is used. AutoTrak^{TM} has a separate lifting sub due to its special threads, usually they are delivered with the tool.
- Due to the plain outer surface, a possible fail of the slips would result in a lost string in the well. Safety clamps have to be installed as a second safety barrier when AutoTrak^{TM} is set in the slips.
- To protect the threads of AutoTrak^{TM}, thread protector caps have to be used during handling, especially when the ends could slug against something. AutoTrak^{TM} have separate thread protectors due to their special threads.
- The threads have to be clean and greased (or glued) for making connection. AutoTrak^{TM} T2 threads are used for communication between the tools and have a special type of grease (blue) which is already applied and must stay free of any dirt or fluid.
- Apply recommended make-up torque for connection.

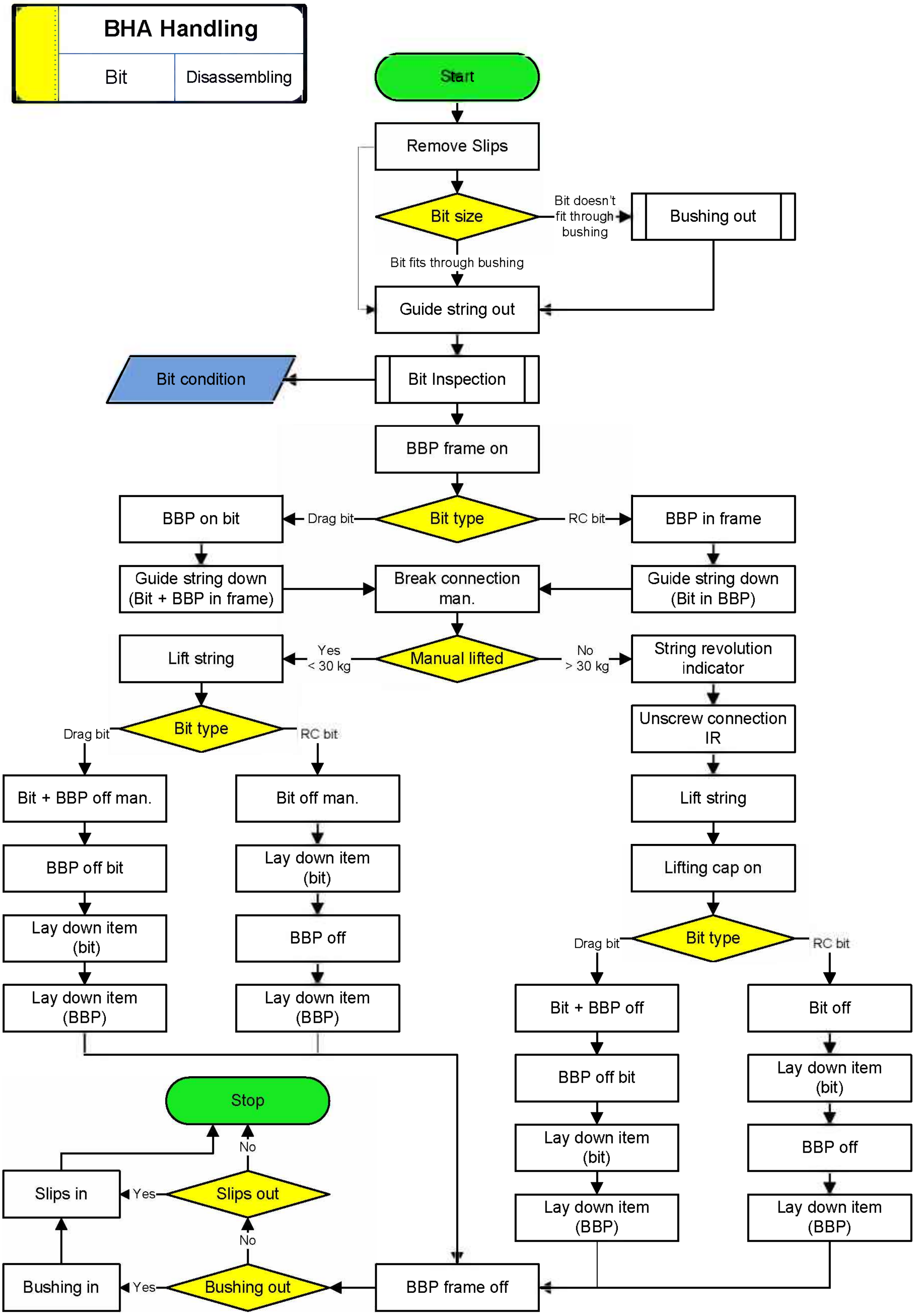
- When making connection, AutoTrak™ has to be screwed together with chain tongs and made-up with the manual tongs as the Iron roughneck applies too much force on the tubular. The housing may bend beyond tolerance and damage the inner workings, O-ring seals… Manual tongs distribute the contact force in a more uniform matter around the tool.
- Set tongs, slips and safety clamps only on those segments of the tool where it is permitted and never on sensitive surfaces.
- To reduce possible negative impacts of lifting and making connection to the AutoTrak™ tools the different components will be already assembled as much far as possible when they are delivered.
- To protect the threads from damage, it is recommended to count the revolutions of the AutoTrak™ while unscrewing it. This prevents that the lowest groove of the pin thread slides over the top groove of the box thread after the last unscrew rotation and crashes back on the thread groove below.
- When the pin is guided into the box during the making of connection, avoid collision which could damage the threads. AutoTrak™ T2 threads are more sensible than other threads.
- When running AutoTrak™ out of hole, they have to be cleaned with fresh water to remove aggressive drill fluids. Possible vents may have to be flushed according to the manual.
- AutoTrak™ may be sensible to magnetic influences and has to be handled and stored accordingly. Also the BHA tools close to AutoTrak™ should be non-magnetic.
- AutoTrak™ should be tested after installation. This is done when the BHA is lowered into the well at a certain depth.

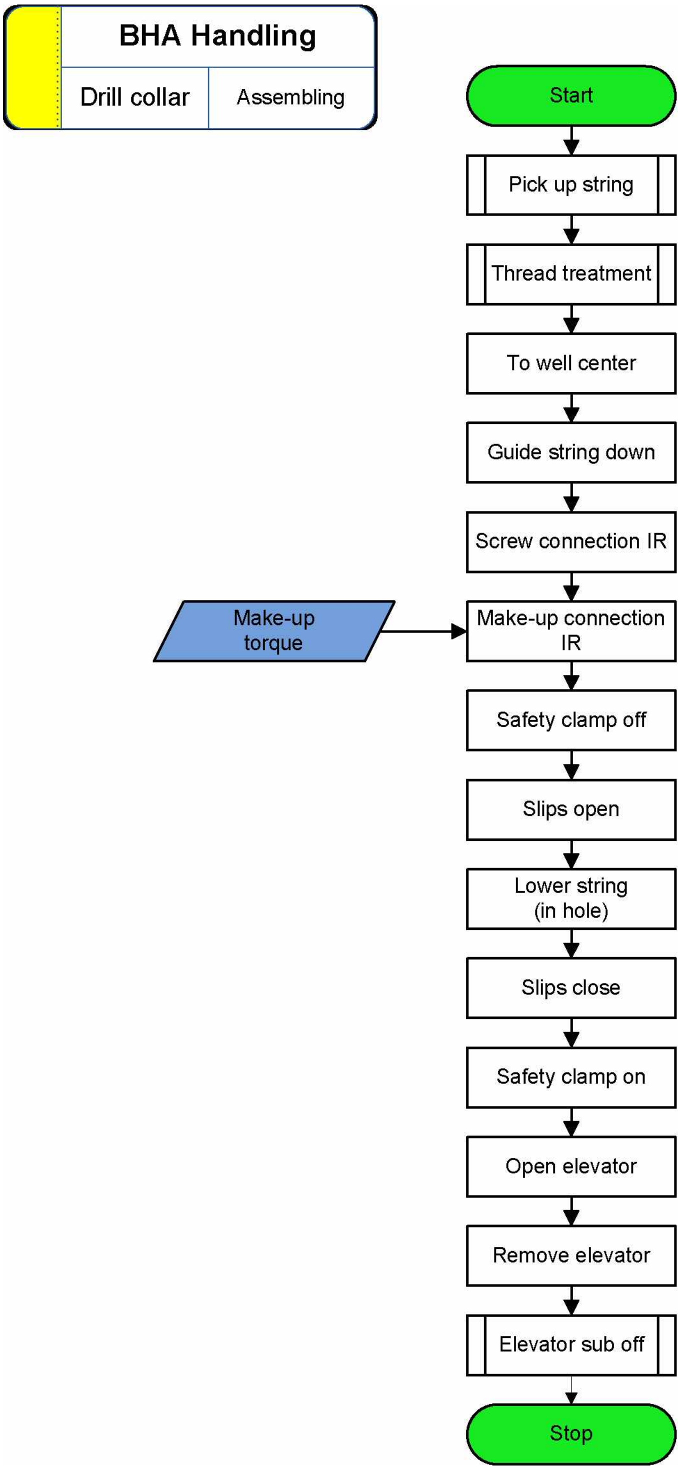
Required Equipment:

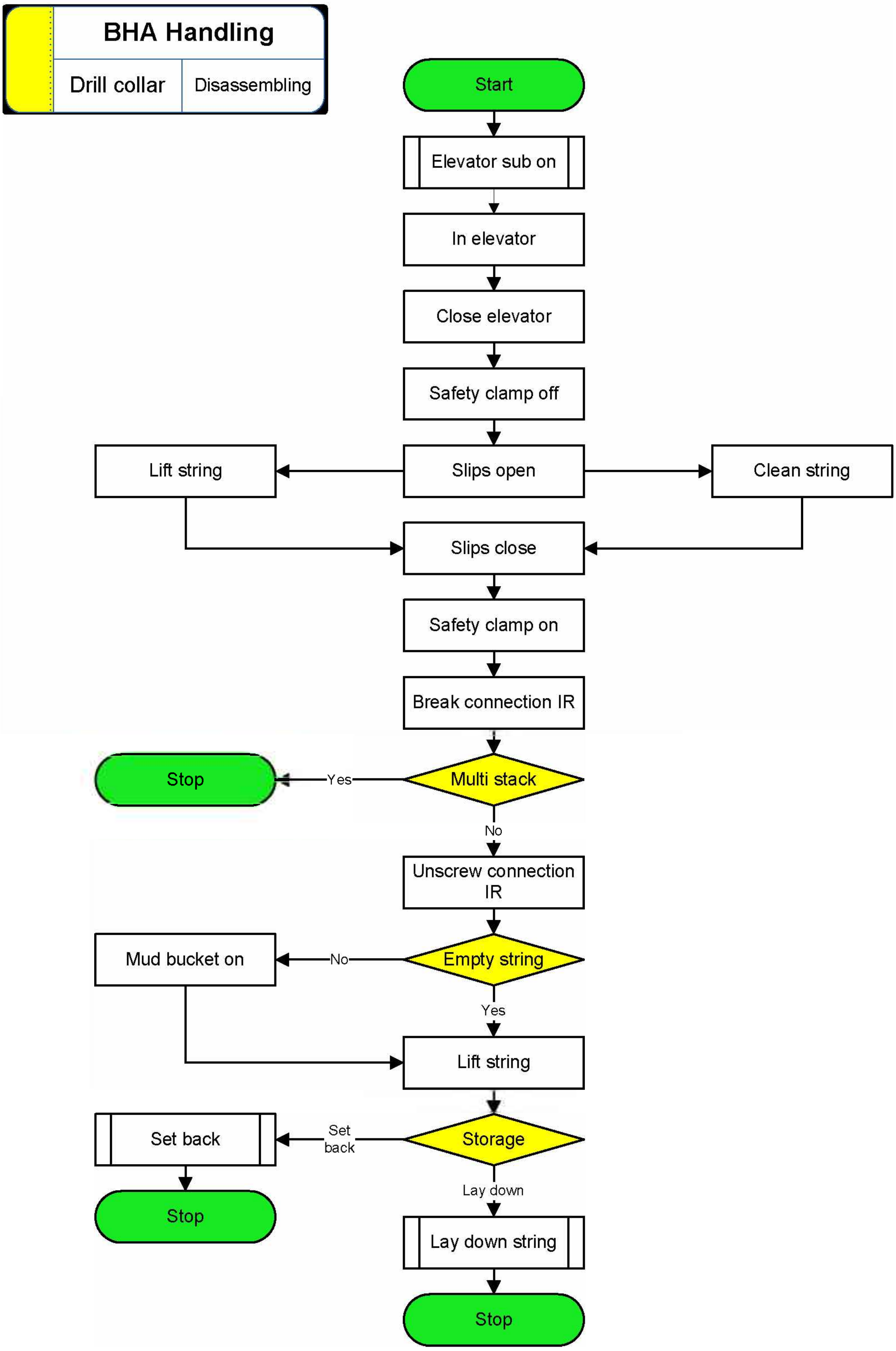
- Pipe handling	Transport	Pick up/lay down AutoTrak™
- Elevator	Handling	Handle AutoTrak™ on drill floor
- AutoTrak™ Elevator sub	Handling	Connect AutoTrak™ to elevator
- Iron roughneck	Assembling	Make connection with rest of BHA
- Manual tongs	Assembling	Make-up connection with rest of BHA
- Chain tongs	Assembling	Screw connection with rest of BHA
- Slips	Assembling	Hold AutoTrak™ in place
- Thread protectors	Transport	Protect threads from damage
- Thread lubrication (glue)	Assembling	Improve connection quality
- Thread cleaning	Service	Clean threads
- Thread inspection	Service	Thread inspection
- Water hose	Service	Clean pipe annulus and outside
- Sponge sleeve	Service	Clean pipe outside

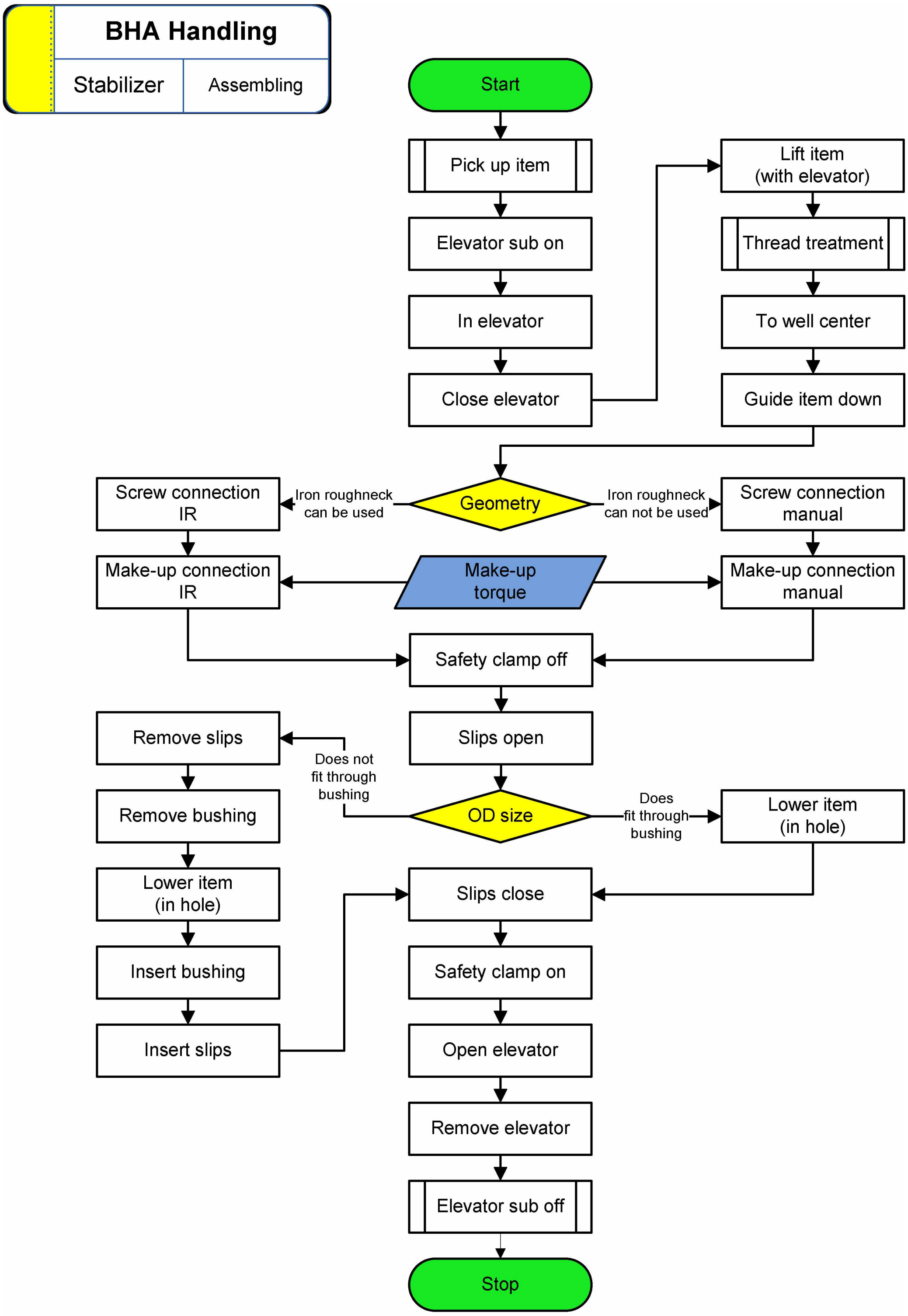
13. Appendix F – BHA Assembling Flow Charts

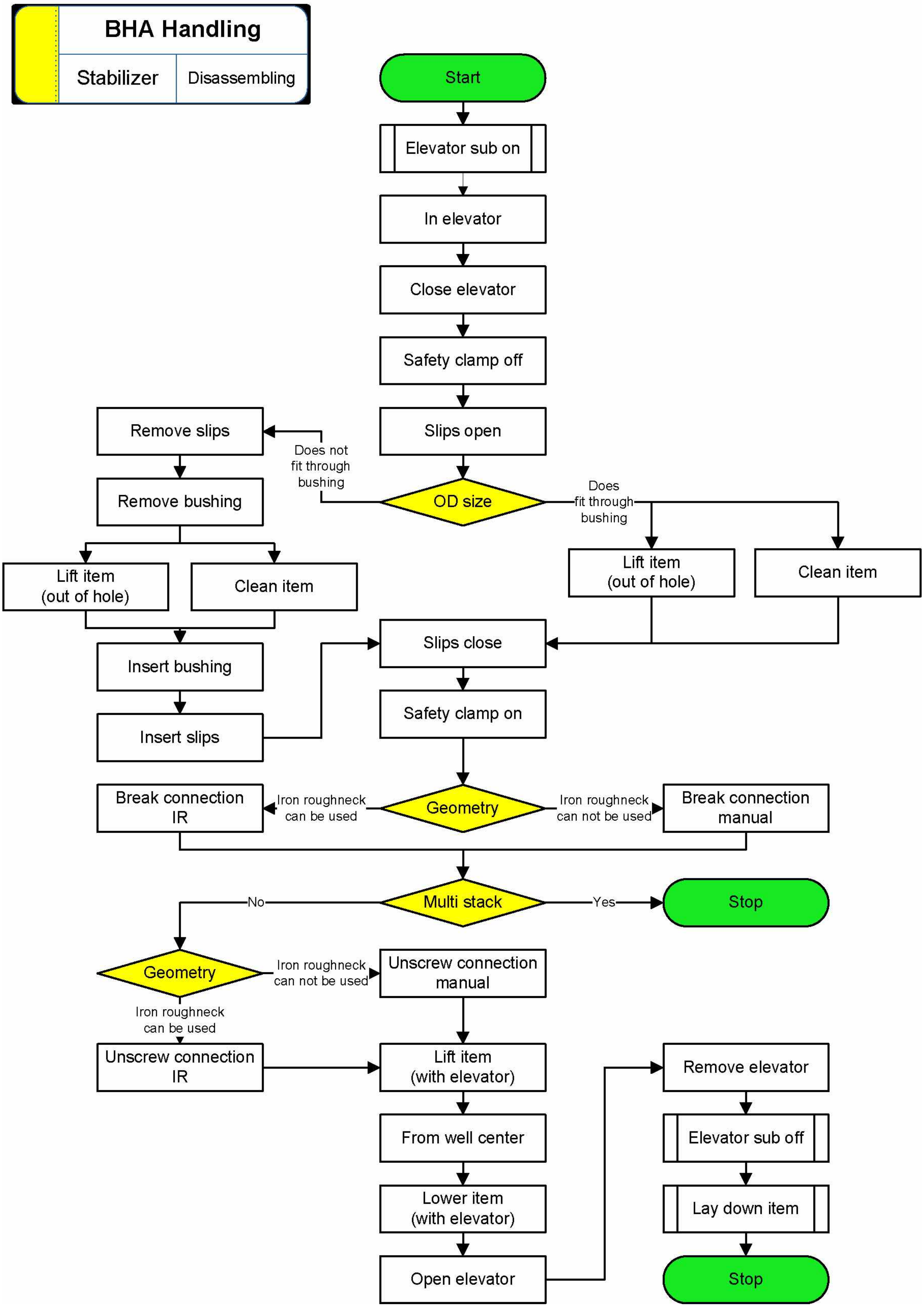



BHA Handling
Bit
Disassembling
Start
Remove Slips
Bit size
Bit doesn't fit through bushing
Bushing out
Bit fits through bushing
Guide string out
Bit condition
Bit Inspection
BBP frame on
BBP on bit
Drag bit
Bit type
RC bit
BBP in frame
Guide string down (Bit + BBP in frame)
Break connection man.
Guide string down (Bit in BBP)
Lift string
Yes < 30 kg
Manual lifted
No > 30 kg
String revolution indicator
Drag bit
Bit type
RC bit
Unscrew connection IR
Bit + BBP off man.
Bit off man.
Lift string
BBP off bit
Lay down item (bit)
Lifting cap on
Lay down item (bit)
BBP off
Drag bit
Bit type
RC bit
Lay down item (BBP)
Lay down item (BBP)
Bit + BBP off
Bit off
Stop
BBP off bit
Lay down item (bit)
No
Lay down item (bit)
BBP off
Slips in
Yes
Slips out
Lay down item (BBP)
Lay down item (BBP)
No
Bushing in
Yes
Bushing out
BBP frame off

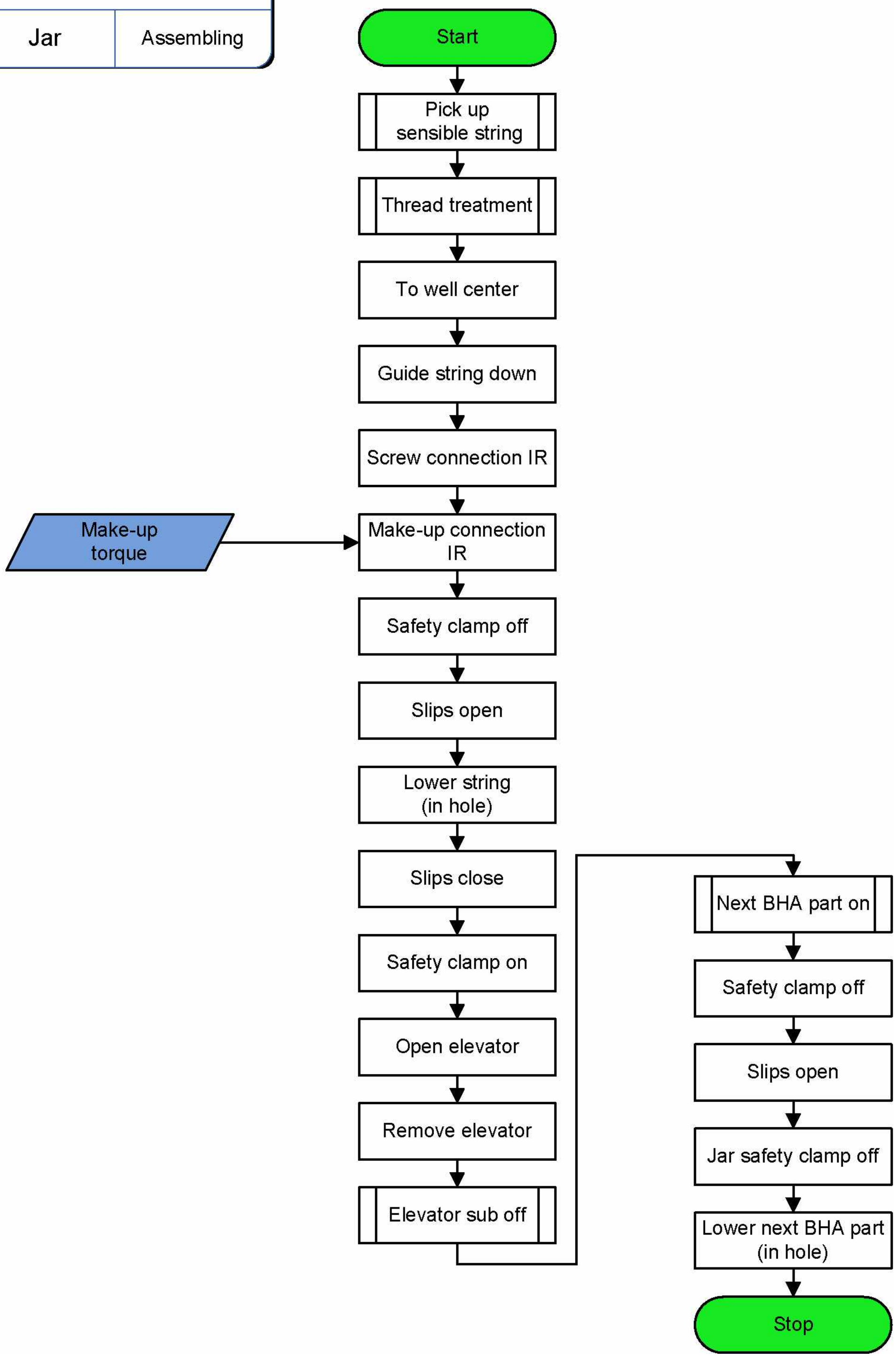

BHA Handling
Drill collar
Assembling
Start
Pick up string
Thread treatment
To well center
Guide string down
Screw connection IR
Make-up torque
Make-up connection IR
Safety clamp off
Slips open
Lower string (in hole)
Slips close
Safety clamp on
Open elevator
Remove elevator
Elevator sub off
Stop

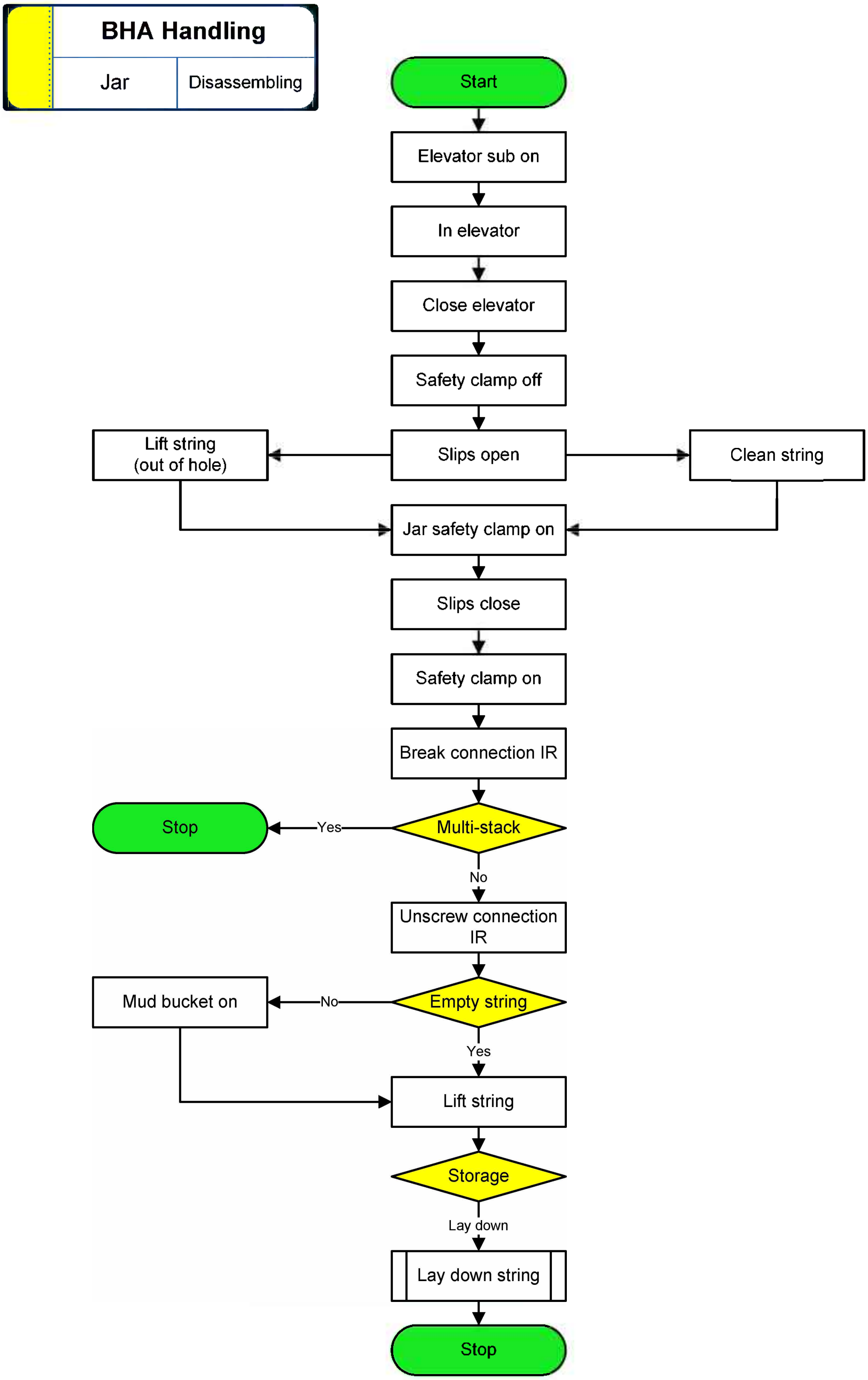

BHA Handling
Drill collar
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Lift string
Slips open
Clean string
Slips close
Safety clamp on
Break connection IR
Stop
Yes
Multi stack
No
Unscrew connection IR
Mud bucket on
No
Empty string
Yes
Lift string
Set back
Set back
Storage
Stop
Lay down
Lay down string
Stop


BHA Handling
Stabilizer
Assembling
Start
Pick up item
Elevator sub on
In elevator
Close elevator
Lift item (with elevator)
Thread treatment
To well center
Guide item down
Geometry
Iron roughneck can be used
Iron roughneck can not be used
Screw connection IR
Screw connection manual
Make-up connection IR
Make-up torque
Make-up connection manual
Safety clamp off
Slips open
Remove slips
Does not fit through bushing
OD size
Does fit through bushing
Lower item (in hole)
Remove bushing
Lower item (in hole)
Insert bushing
Insert slips
Slips close
Safety clamp on
Open elevator
Remove elevator
Elevator sub off
Stop


BHA Handling
Stabilizer
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Slips open
OD size
Does not fit through bushing
Remove slips
Remove bushing
Lift item (out of hole)
Clean item
Insert bushing
Insert slips
Does fit through bushing
Lift item (out of hole)
Clean item
Slips close
Safety clamp on
Geometry
Iron roughneck can be used
Break connection IR
Iron roughneck can not be used
Break connection manual
Multi stack
No
Yes
Stop
Geometry
Iron roughneck can not be used
Unscrew connection manual
Iron roughneck can be used
Unscrew connection IR
Lift item (with elevator)
From well center
Lower item (with elevator)
Open elevator
Remove elevator
Elevator sub off
Lay down item
Stop

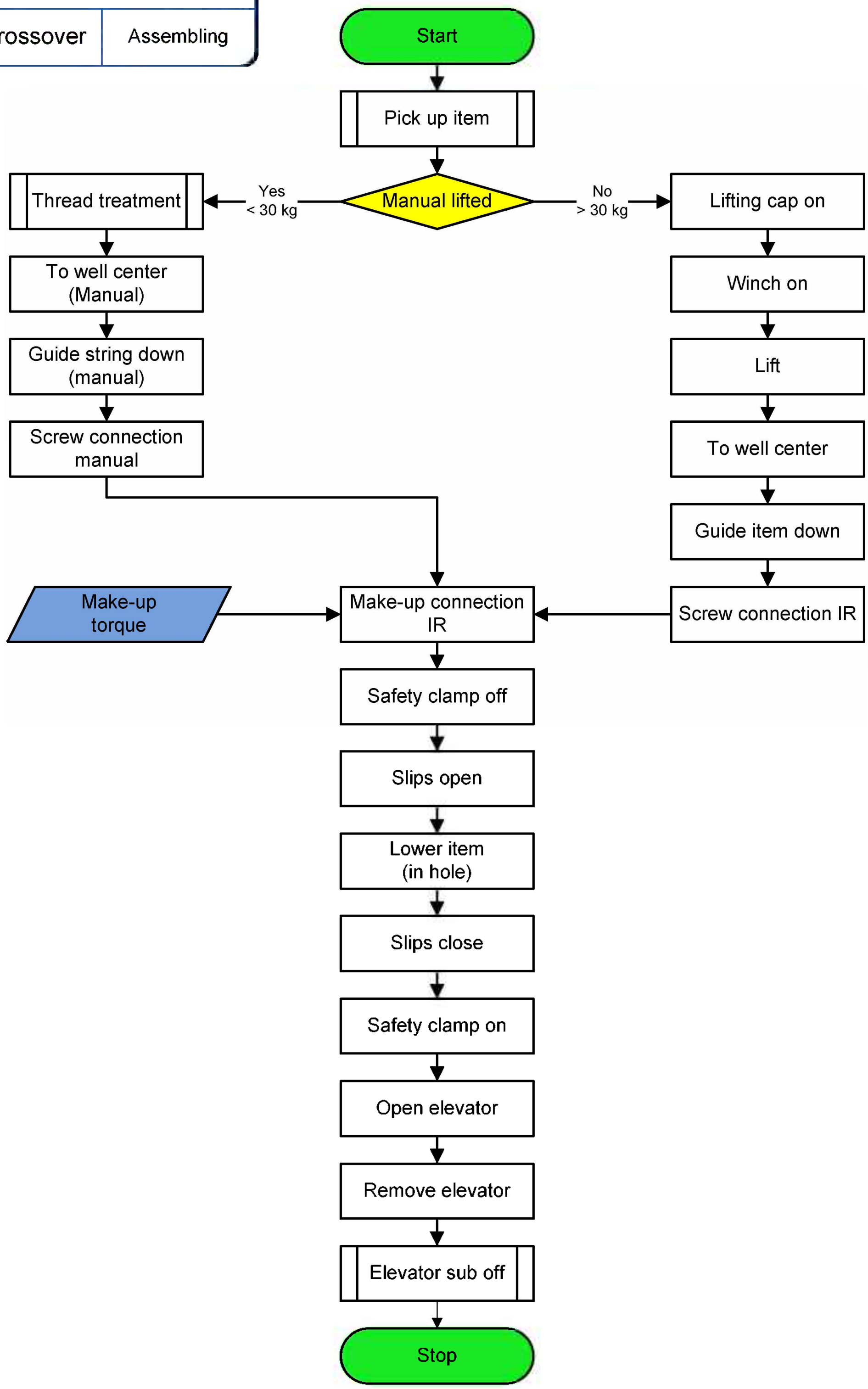
BHA Handling	
Jar	Assembling

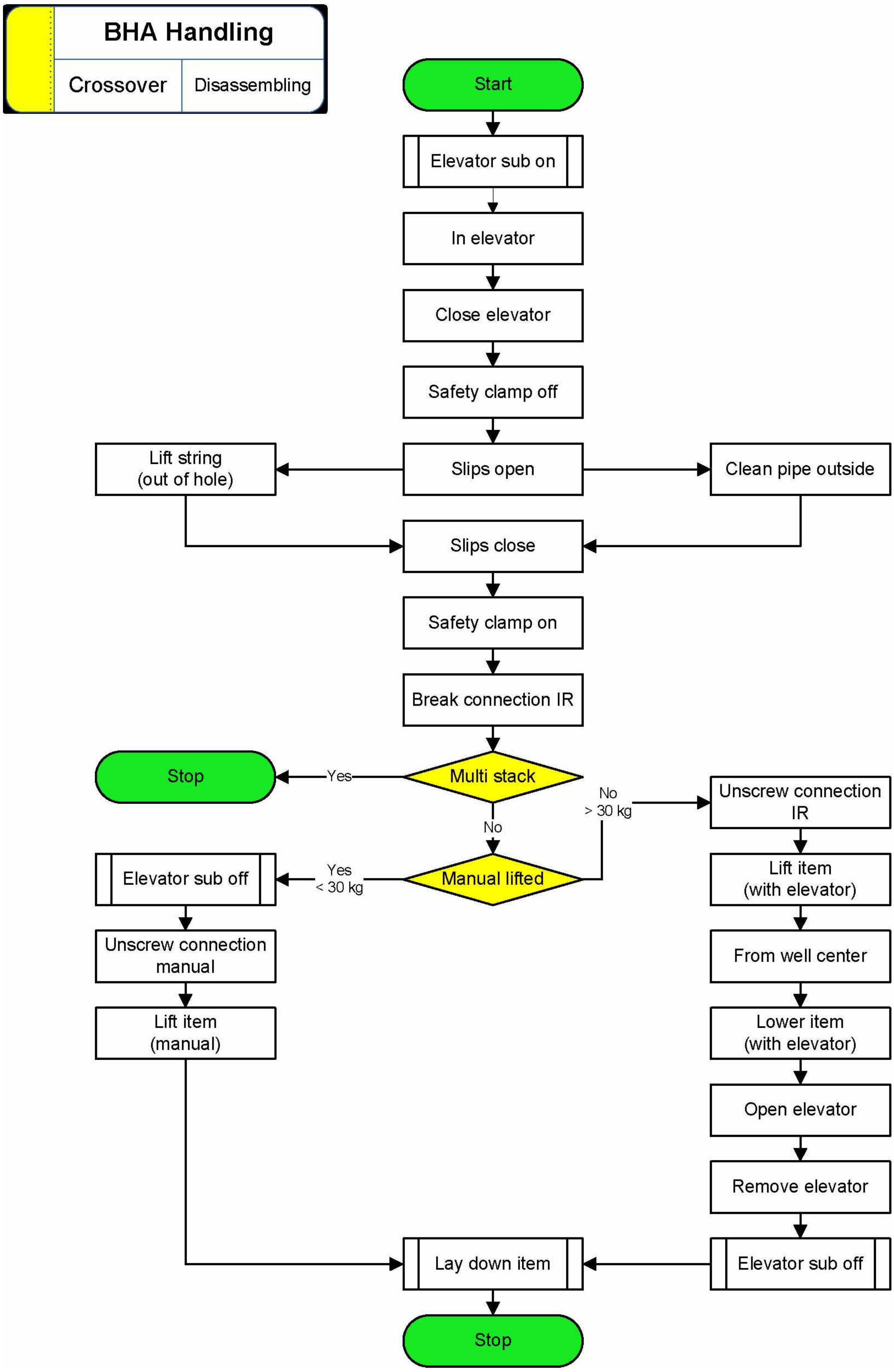


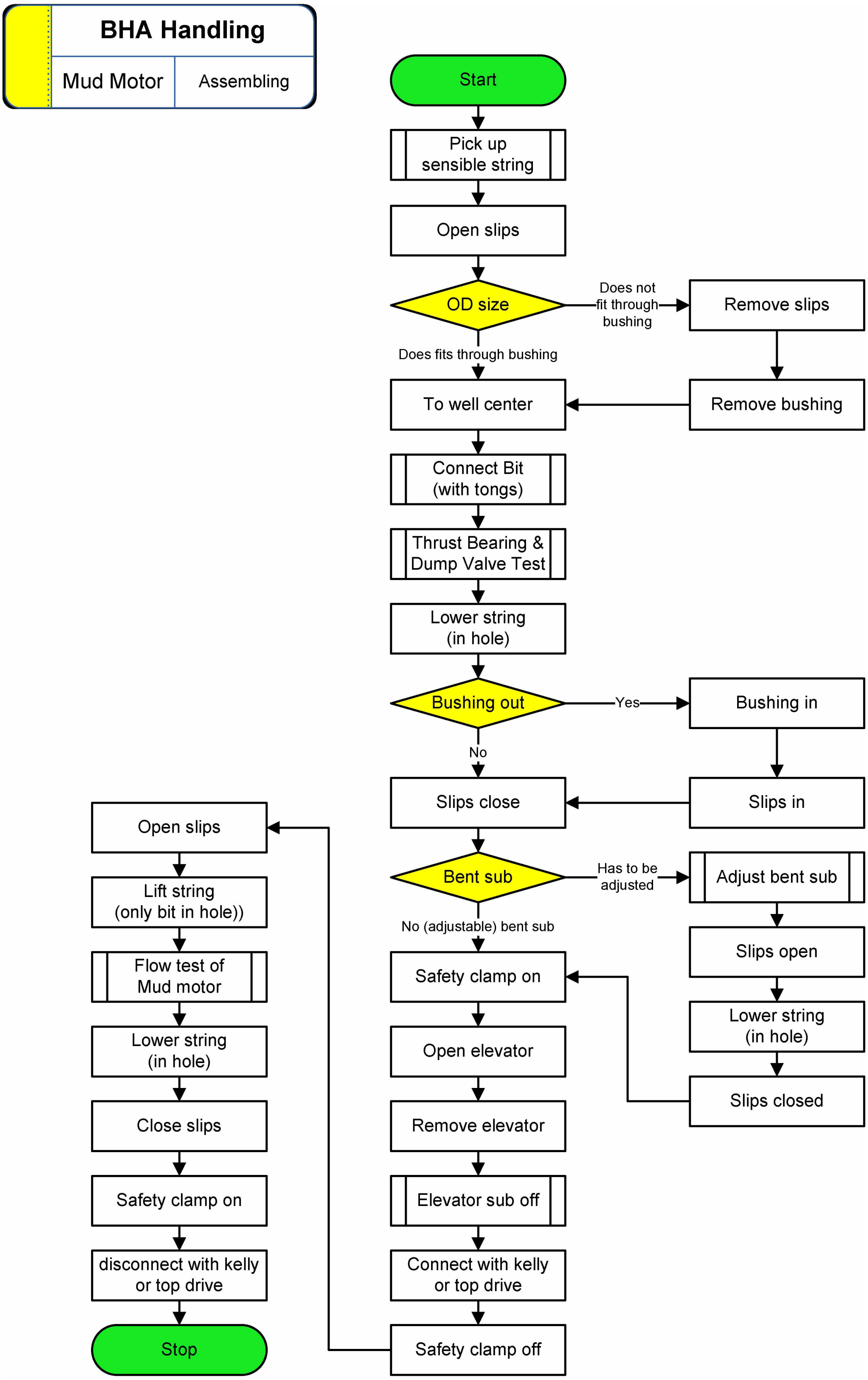

BHA Handling
Jar
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Slips open
Lift string
(out of hole)
Clean string
Jar safety clamp on
Slips close
Safety clamp on
Break connection IR
Multi-stack
Yes
Stop
No
Unscrew connection
IR
Empty string
No
Mud bucket on
Yes
Lift string
Storage
Lay down
Lay down string
Stop

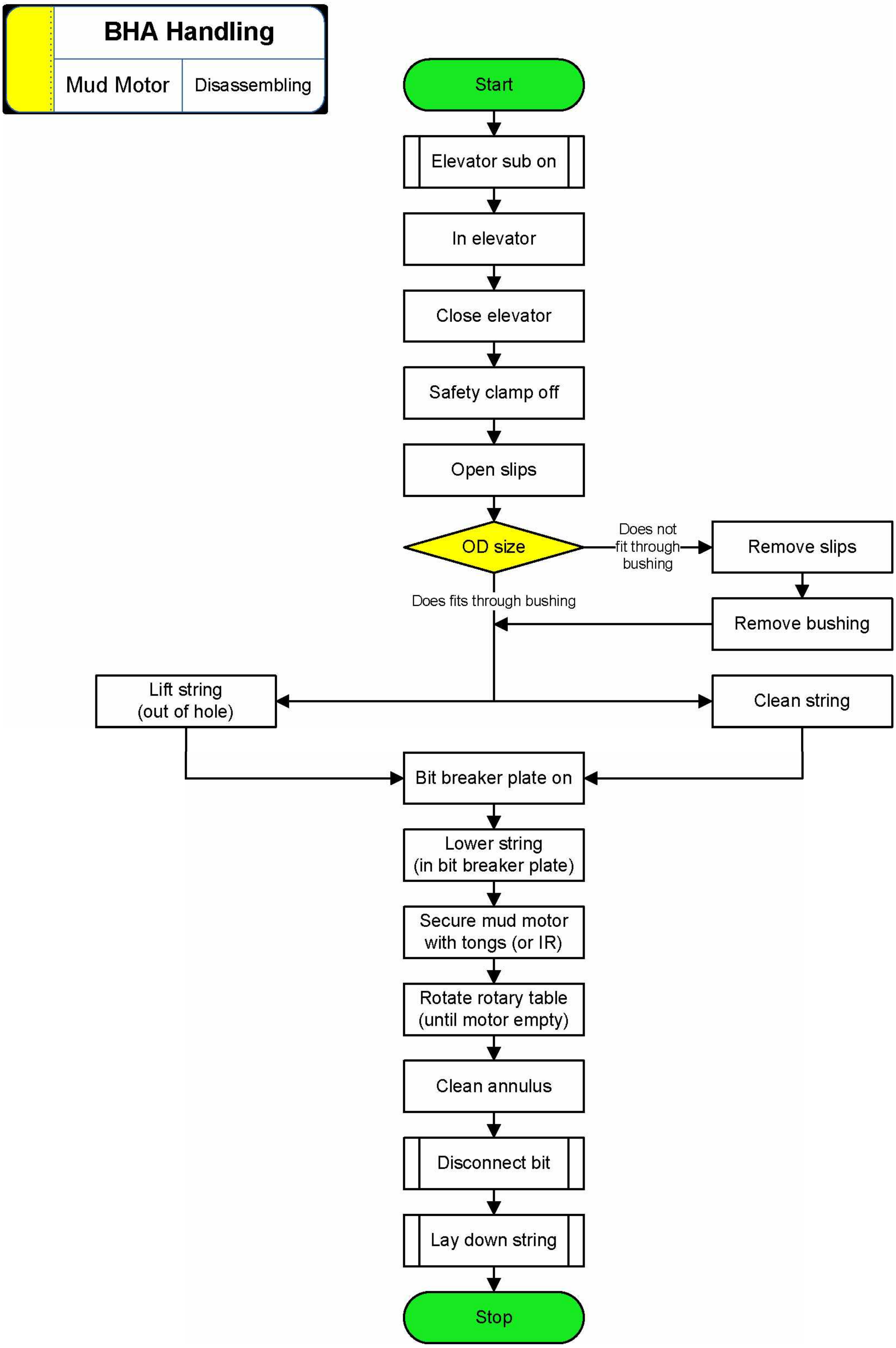
BHA Handling

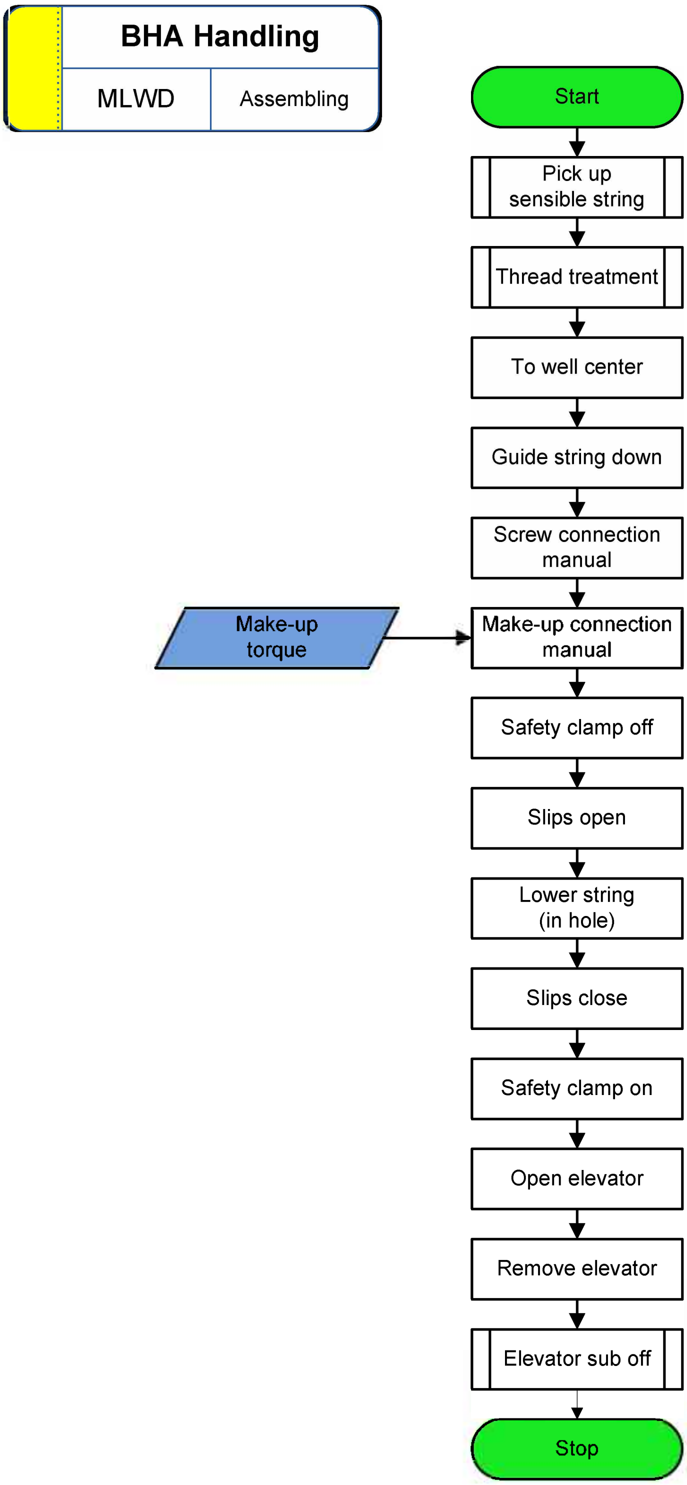
Crossover | Assembling

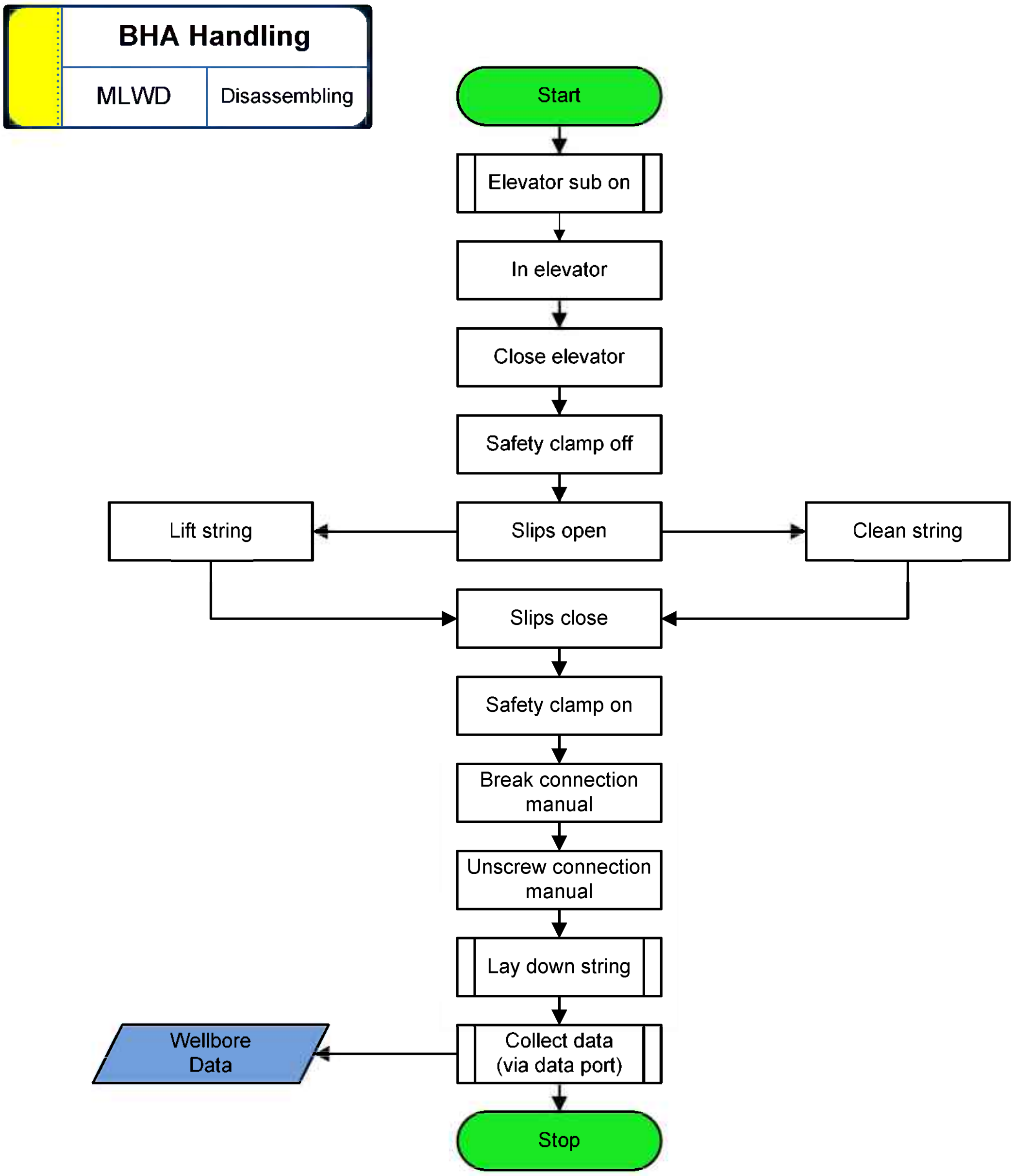


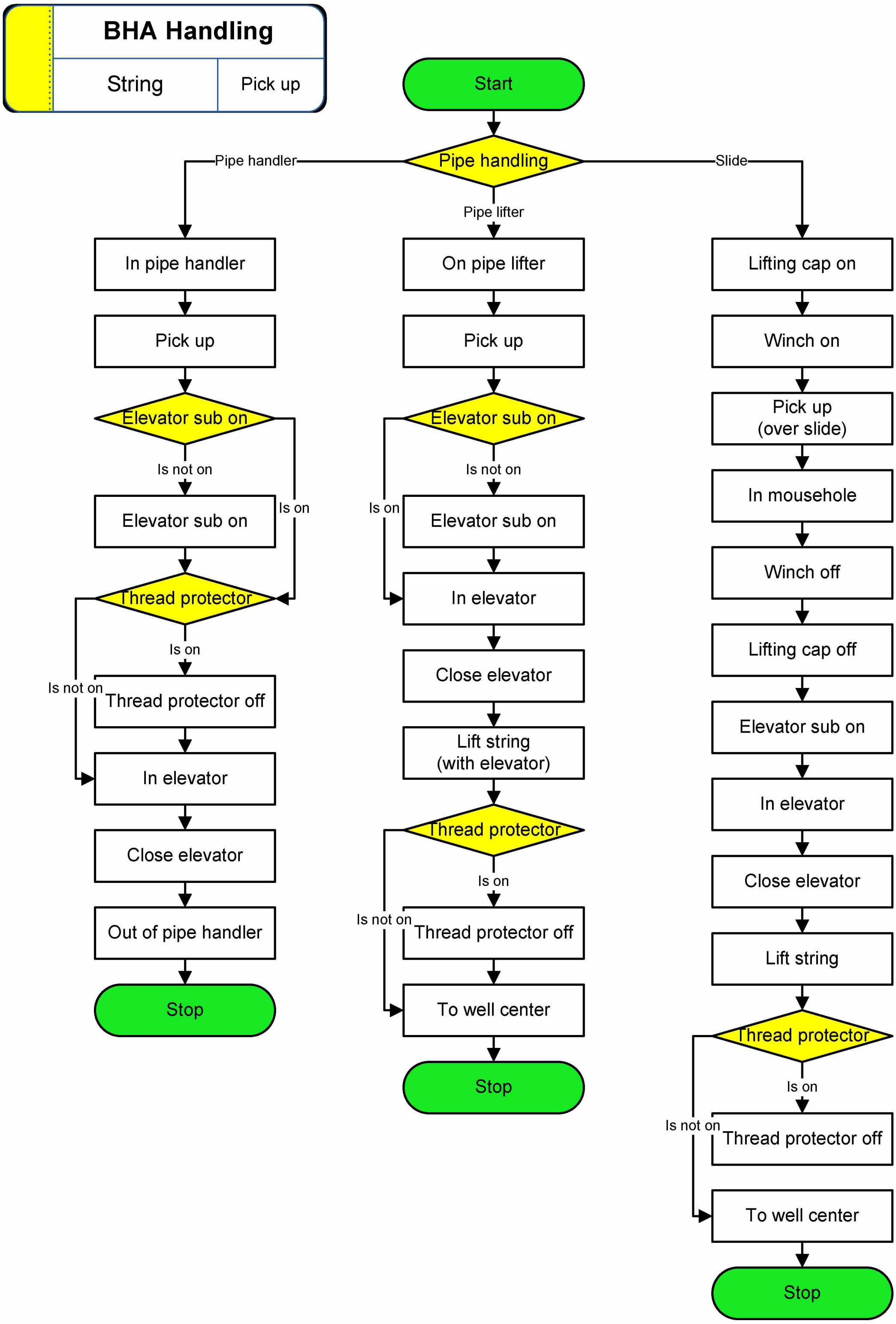

BHA Handling
Crossover
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Lift string (out of hole)
Slips open
Clean pipe outside
Slips close
Safety clamp on
Break connection IR
Stop
Yes
Multi stack
No
> 30 kg
Unscrew connection IR
No
Elevator sub off
Yes
< 30 kg
Manual lifted
Lift item (with elevator)
Unscrew connection manual
From well center
Lift item (manual)
Lower item (with elevator)
Open elevator
Remove elevator
Lay down item
Elevator sub off
Stop

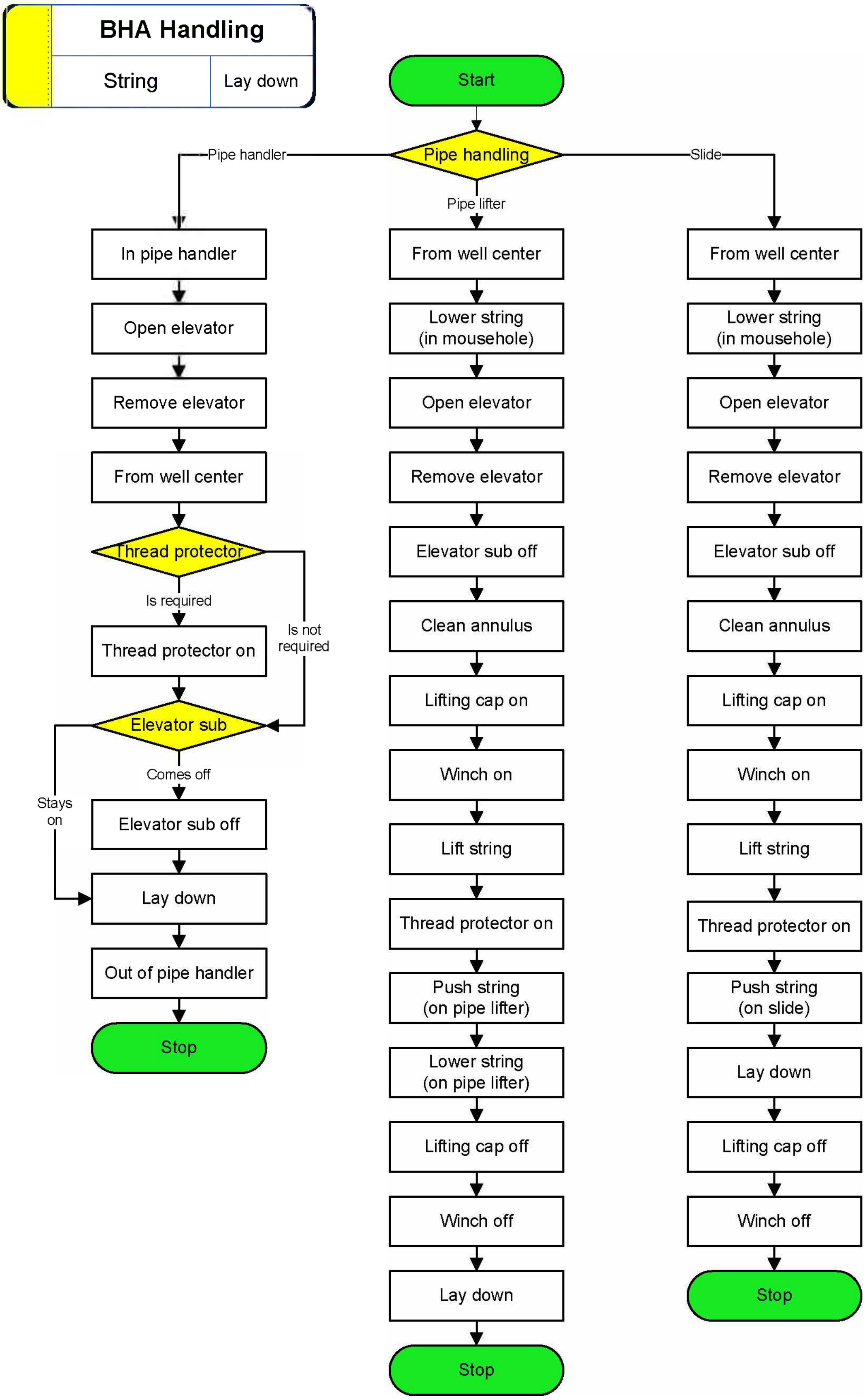

BHA Handling
Mud Motor
Assembling
Start
Pick up sensible string
Open slips
OD size
Does not fit through bushing
Remove slips
Does fits through bushing
To well center
Remove bushing
Connect Bit (with tongs)
Thrust Bearing & Dump Valve Test
Lower string (in hole)
Bushing out
Yes
Bushing in
No
Slips close
Slips in
Bent sub
Has to be adjusted
Adjust bent sub
No (adjustable) bent sub
Slips open
Safety clamp on
Lower string (in hole)
Open elevator
Slips closed
Remove elevator
Elevator sub off
Connect with kelly or top drive
Safety clamp off
Open slips
Lift string (only bit in hole))
Flow test of Mud motor
Lower string (in hole)
Close slips
Safety clamp on
disconnect with kelly or top drive
Stop

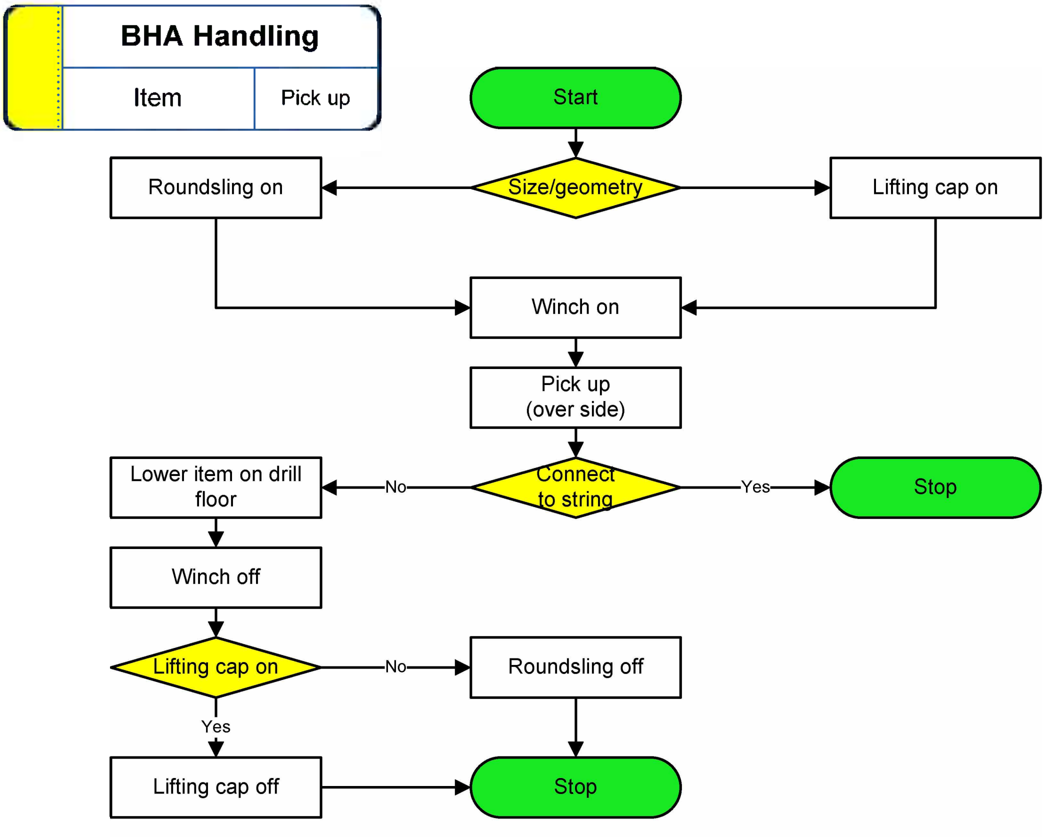

BHA Handling
Mud Motor
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Open slips
OD size
Does not fit through bushing
Remove slips
Remove bushing
Does fits through bushing
Lift string (out of hole)
Clean string
Bit breaker plate on
Lower string (in bit breaker plate)
Secure mud motor with tongs (or IR)
Rotate rotary table (until motor empty)
Clean annulus
Disconnect bit
Lay down string
Stop

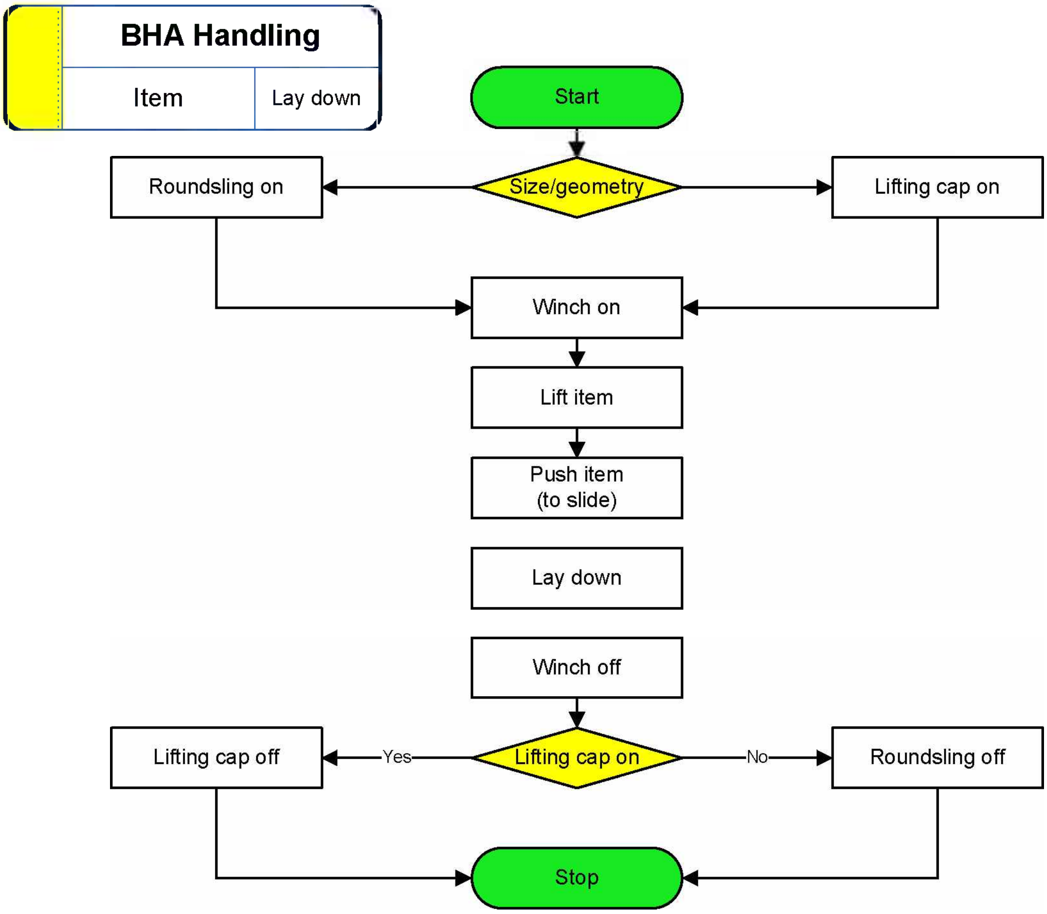

BHA Handling
MLWD
Assembling
Start
Pick up sensible string
Thread treatment
To well center
Guide string down
Screw connection manual
Make-up torque
Make-up connection manual
Safety clamp off
Slips open
Lower string (in hole)
Slips close
Safety clamp on
Open elevator
Remove elevator
Elevator sub off
Stop


BHA Handling
MLWD
Disassembling
Start
Elevator sub on
In elevator
Close elevator
Safety clamp off
Lift string
Slips open
Clean string
Slips close
Safety clamp on
Break connection manual
Unscrew connection manual
Lay down string
Wellbore Data
Collect data (via data port)
Stop


BHA Handling
String
Pick up
Start
Pipe handling
Pipe handler
Pipe lifter
Slide
In pipe handler
Pick up
Elevator sub on
Is not on
Is on
Elevator sub on
Thread protector
Is on
Is not on
Thread protector off
In elevator
Close elevator
Out of pipe handler
Stop
On pipe lifter
Pick up
Elevator sub on
Is not on
Is on
Elevator sub on
In elevator
Close elevator
Lift string
(with elevator)
Thread protector
Is on
Is not on
Thread protector off
To well center
Stop
Lifting cap on
Winch on
Pick up
(over slide)
In mousehole
Winch off
Lifting cap off
Elevator sub on
In elevator
Close elevator
Lift string
Thread protector
Is on
Is not on
Thread protector off
To well center
Stop


BHA Handling
String
Lay down
Start
Pipe handling
Pipe handler
Pipe lifter
Slide
In pipe handler
Open elevator
Remove elevator
From well center
Thread protector
Is required
Is not required
Thread protector on
Elevator sub
Comes off
Stays on
Elevator sub off
Lay down
Out of pipe handler
Stop
From well center
Lower string (in mousehole)
Open elevator
Remove elevator
Elevator sub off
Clean annulus
Lifting cap on
Winch on
Lift string
Thread protector on
Push string (on pipe lifter)
Lower string (on pipe lifter)
Lifting cap off
Winch off
Lay down
Stop
From well center
Lower string (in mousehole)
Open elevator
Remove elevator
Elevator sub off
Clean annulus
Lifting cap on
Winch on
Lift string
Thread protector on
Push string (on slide)
Lay down
Lifting cap off
Winch off
Stop


BHA Handling
Item
Pick up
Start
Size/geometry
Roundsling on
Lifting cap on
Winch on
Pick up (over side)
Connect to string
No
Yes
Lower item on drill floor
Stop
Winch off
Lifting cap on
No
Roundsling off
Yes
Lifting cap off
Stop


BHA Handling
Item
Lay down
Start
Size/geometry
Roundsling on
Lifting cap on
Winch on
Lift item
Push item
(to slide)
Lay down
Winch off
Lifting cap on
Yes
No
Lifting cap off
Roundsling off
Stop

14. Appendix G – Evaluation of Work Steps

Category	Work step	Automated	Manual	Rig floor	Hazardous	Time	Frequency	Feasibility	Knowledge	Equipment
Ass	Jar safety clamp on		x	x					x	Manual, wrench
Ass	Jar safety clamp off		x	x					x	Manual, wrench
Ass	Bit breaker plate on bit		x							Manual
Ass	Bit breaker plate off bit		x							Manual
Ass	Bit + bit breaker plate in frame		x	x						Manual, winch
Ass	Bit in bit breaker plate		x	x						Manual, winch
Ass	Mud basket on	x	x	x	x		x			Manual
Ass	Mud basket off	x	x	x	x		x			Manual
Ass	String revolution indicator		x	x			x	x	x	Manual, chalk
Ass	Make-up connection man.		x	x	x	x			x	Manual, manual tongs
Ass	Break connection man.		x	x	x	x			x	Manual, manual tongs
Ass	Screw connection man.		x	x						Manual, Chain tongs
Ass	Unscrew connection man.		x	x						Manual, Chain tongs
Ass	Bit breaker plate in frame		x	x						Manual, winch
Ass	Bit breaker plate off frame		x	x						Manual, winch
Handl	Safety clamp on		x	x		x	x			Manual, wrench
Handl	Safety clamp off		x	x		x	x			Manual, wrench
Handl	Guide pipe up		x	x	x	x	x			Manual
Handl	Guide pipe down		x	x	x	x	x			Manual
Mod	Slips in		x	x						Manual, winch
Mod	Slips out		x	x						Manual, winch
Mod	Bushing in		x	x						Manual, winch
Mod	Bushing out		x	x						Manual, winch
Mod	Bit breaker plate frame on		x	x	x					Manual, winch
Mod	Bit breaker plate frame off		x	x	x					Manual, winch
Mod	Change elevator		x	x	x					Manual, winch
Mod	Cover borehole		x	x	x			x		Manual
Mod	Change Slips		x	x					x	Manual, winch
Serv	Clean threads		x				x			Rag, WD40
Serv	Lubricate threads	x	x				x			Brush
Serv	Glue threads		x						x	Scraper
Serv	Thread inspection		x						x	Visual, gauge
Serv	Clean pipe annular		x				x			Manual, Water hose
Serv	Clean pipe outside		x			x	x	x		Manual, Water hose, sleeve
Serv	Add ball/chip to well		x	x					x	Manual
Serv	Taking sample		x						x	Manual
Serv	Tool inspection		x						x	Visual, gauge
Store	Store safety clamp		x	x			x			Manual
Store	Store jar safety clamp		x	x						Manual

Store	Store thread protectors		x	x			x			Manual
Store	Store bit breaker plate		x	x						Manual
Store	Store bit breaker plate frame		x	x						Manual, winch
Store	Store pipe elevator sub		x	x						Manual
Store	Store casing elevator sub		x	x						Manual
Store	Store lifting cap		x	x						Manual
Store	Store elevators		x	x						Manual, winch
Transp	Push string	x	x	x	x		x			Manual, winch
Transp	Pick up sensible string		x	x	x				x	Manual, winch, slide
Transp	Lay down sensible string		x	x	x				x	Manual, winch, slide
Transp	Pick up item		x	x	x		x			Manual, winch, slide
Transp	Lay down item		x	x	x		x			Manual, winch, slide
Transp	Thread protectors on		x				x			Manual
Transp	Thread protectors off		x				x			Manual
Transp	Lifting cap on		x	x		x	x			Manual
Transp	Lifting cap off		x	x		x	x			Manual
Transp	Casing elevator sub on		x	x						Manual
Transp	Casing elevator sub off		x	x						Manual
Transp	Make-up casing elevator sub		x	x						Chain tongs
Transp	Break casing elevator sub		x	x						Chain tongs
Transp	Pipe elevator sub on		x	x			x			Manual
Transp	Pipe elevator sub off		x	x			x			Manual
Transp	Item to well center		x	x	x		x			Manual, winch
Transp	Item from well center		x	x	x		x			Manual, winch
Transp	Winch on		x	x						Maunal
Transp	Winch off		x	x						Manual
Total	84	23	65	71	19	11	40	3		
%		27	77	85	23	13	48	4		

15. Appendix H – Workshop Summary

Workshop

Automatization of the Rig Floor: BHA Handling

23rd – 24th of January 2013

1. Disclaimer

Limitation of liability

The content of this workshop reflects the personal view of the author.

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2. Summary

The target of the workshop was to bring together experts engaged in the oil and gas industry with professional expertise in different areas to discuss different approaches to achieve the fully-automated drilling rig. The discussion was focused on the handling of drilling BHA tools. Thanks to the participants, it was possible to bring together different aspects that should be considered when working on an automated drill floor, in combination with knowhow about industrial robots and automatization technology, performance measurement, downhole tools and practical aspects from a manufacturer's, a contractor's and an operator's point of view.

Improving Performance

The two main reasons for the demand for a fully automated drilling rig is the increase of performance and safety. These two issues have to be responded to a certain extend so that the significant financial expenditures can be justified. The increase of performance can be validated by the generated value of the automatization tools, or in other words, how much time it will save during operation. Half of the costs for a new well are spent in the drilling phase. An example of an offshore drilling operation in the North Sea shows that the drilling time, the time during which the bit is actually rotating on bottom and making hole, is beyond 10 percent of the total time. The rest is used for well treatment, tripping, maintenance of equipment and others. So there is definitely potential for process optimization.

The difficulty is now to find the biggest potentials for savings, and this depends highly on the drilling process and the application. On the other hand, some operators claim that they don't see much demand for increasing the working performance on the rig floor, especially when they do performance drilling with highly qualified rig crews in combination with shallow wells. They would rather investigate operations like rig moves as this may be one of the major spending for them. To find a significant statement to compare automated systems to conventional drilling rigs the key is accurate measurement of the work steps.

Human Resources Development

An important reason that requires a high level of automatization is to meet new aspects in the human resources development. Getting the crew away from hazardous areas and reduce risky operations to a minimum has been an important issues for the last years, especially in offshore drilling. Despite the already high degree of mechanization, many procedures still requires manual work or at least involves human interference in some way. Performance is not only measured with time, but also with accidents occurring on site. Many companies follow a zero-incidents policy, although operators report that additional equipment that would reduce the risk of the crew is often cancelled to avoid higher day-rates, especially on land rigs. Safety - yes, but only to the same price.

In addition to that, a drilling rig is not only hazardous for the crew, but also for the equipment. Transport on site and wrong handling of BHA tools has been responsible for a large portion of damages which costs a lot of money. Standardized handling procedures and the fact that automated systems will perform a working sequence always in the same way would eliminate this.

And there is a second reason why companies want to reduce the amount of people on the rig. It becomes more and more difficult to find qualified and experienced people that are willing to take a job in the oilfield. The work on a drilling rig is quite intense, twelve hours shift working, hard physical work in a harmful environment and remote locations where exposed to extreme harsh environmental influences are only the top reasons why people do not want to work as a roughneck any more. And the relationship between employer and employee is not a very sustainable one. Already today operators have difficulties to fill gaps in their crews with poorly trained agency workers to keep their rigs running during peak periods. The hiring of additional crews to run more drilling rigs in case of a possible upcoming boom in drilling activities will bring the operating business to its limit.

However, there might be a downside, too, if future drilling rigs will be fully automated. More effort will be spent on maintenance and repair. And as the equipment of an automated rig floor consists of highly sophisticated gadgets, intervention will required a high level of training and education. Low educated personnel is willing to work under bad conditions as it is the easiest way to make a lot of money, to convince skilled personnel to work under these circumstances will be a challenge. And during the beginning of designing fully automated rigs where new techniques will be tested through semi-automated applications, the personnel capacity will be even higher as this requires people to service the machinery as well as the normal rig crew.

Automatization through Standardization

To design a fully automated system it is important to know the processes that are required to reach a certain goal, in this case the goal is to bring an operative BHA into the well. Still, this does not require the exact recreation of the processes. Manufacturers tend to find ways to mechanize the exact handling procedure as the crew would do it. They add different tools for every work step to the drill floor which makes the system complicated, prone to failure and at the same time inefficient. Essential for developing a marketable automated system is standardization. Standardization of the process, standardization of the machinery and standardization of the tools, in combination with a long term drilling program with high numbers of similar wells.

Other industries implement autonomous assembly lines only for products that are produced in high quantities, not for individual items. If the same steps are repeated over and over again, automated systems will proof as efficient. Therefor it is necessary to know the handling procedures, identify the necessary work steps and find an effective way to implement them in the automation system, but not necessary replicate the way it has been done so far. Furthermore, it is necessary to implement a certain standard design for the required BHA components as well. But as they would be utilized in higher numbers, especially wear parts, tool manufacturers confirm that they are willing to meet the demands of producing such fit-for-purpose standardized downhole equipment (for example one size OD design of drill string) and provide the operator with the necessary support (for example 3D models of the tools).

Standardization of the necessary handling equipment will help to produce them at a reasonable price. If it is possible to design the machinery in a way that the process of assembling downhole tools can be managed with only a few flexible handling devices, they can be manufactured in a number high enough to bring them on the market. Important features will be the implementation of standard components from the free market. This ensures that the parts require less maintenance as they have been tested in other industries, are easy available in case of failure and can be purchased at a lower price than in-house developments. Modular design will help to implement the equipment on existing rigs as well as on new rigs and will facilitate the adapting of the systems to changes due to new drilling projects, not to mention that also rig moves can be carried out faster. Designing the rig as a platform that can be equipped with the necessary machinery would enable operators to assemble a rig that would meet the requirements of the current job.

Data Transfer

An important issue concerning automatization is data transfer. Information is exchanged between the individual components and especially with the human supervisor. To bring a system to the technical limit, the work steps have to be initiated and coordinated by a computer that initiates and coordinates the process with the help of different sensor data. Measurement data show that mechanized systems that are controlled by men, do not have constant performance and do not work near the possible technical limit. Regulating the equipment by pushing buttons and handling joysticks make the operating level dependent on the driller. And with the increase of steering complexity it gets difficult to work on a constant level over a longer period, even for well trained personnel.

There is a psychological problem as well. People of the oil industry tend to be distrustful to new technologies. They are more likely to be seen as a handicap that has to be treated with caution instead of looking at it as a helpful tool that should be driven to the maximum. People from the field report that is some cases, new tools are not used at all as the crew is not willing to implement it into the workflow. An autonomous control system, on the contrary, will operate the rig on a predictable, 24 hour basis. People only need to monitor the operation and intervene if there is a problem. This can be done from any location around the world, as it is already the case for some offshore applications. This would minimize the manpower on site to a few mechanics for maintenance, logistic issues and technical troubleshooting. The actual work is done autonomously by the computer.

Again, standardization will be playing a big role. Communication between the different handling equipment, sensors, logistics and the controller must subordinate a certain language with common rules, especially as the different components will probably be provided by different manufacturers.

Conclusion

The concept of a fully automated drilling rig can only be realized by the interaction of all contributors, the drilling rig manufacturers and designers of downhole tools as well as operators and contractors. Not only will the developing of new handling machinery, but also a change in the handling process be necessary. The basement for automatization is standardization. Standardization of the downhole tools in terms of design and dimensioning to allow fully mechanized handling as well as standardization of the equipment to allow construction at a reasonable and marketable price. Besides that, operators need long term drilling contracts to justify higher costs for new automated drilling rigs that are more specialized than cheaper conventional rigs. Especially the first automated drilling rigs will rather be fit for purpose rigs than build for market rigs. The high investment will be adventurous if contracts last for only a few years and the rig may then have to be modified for a new application. Then again, if a drilling rig can be designed for a ten to fifteen years contract and a high number of standardized wells, like for developing a shale gas field, contractors and operators may consider investing in totally new BHA and rig designs. By the end, the most overall-cost effective machinery will be the one on future drilling sites.

3. Participants

Baker Hughes	Jörg Lehr
Bauer Maschinen	Stefan Hackl
	Maximilian Trombitas
	Franz-Xaver Both
	Klaus Kurz
	Manuel Ostermeier
	Lothar Schirmel
ITAG	Rüdiger Biedorf
Montanuniversität Leoben	Gerhard Thonhauser
ADS	Florian Aichinger
Robotic Drilling Systems	Lars Raunholt
	Kenneth Mikalsen
Shell	Martha Luise Rodbro
	Rick de Bruijn (via conference call)
Statoil	Bjørn Brekne
UT Texas	Mike Reis (via conference call)

4. Agenda

Wednesday, 23.January 2013

12:00 – 12:30	Opening by Sebastian Bauer
12:30 – 13:30	Lunch
13:30 – 16:30	Introduction Presentations
	Rig Automation (Maximilian Trombitas)
	BHA Handling (Rüdiger Biedorf)
	Rig Floor Automatization & Well Manufacturing (Rick de Bruijn)
	Rig Performance Measurement (Gerhard Thonhauser)
	Automated Wellbore Construction (Jörg Lehr)
	Robotic Drilling Systems (Kenneth Mikalsen)
	Bauer Drilling Rigs - TBA 440 M2 (Hackl Stefan)
20:30	Dinner

Thursday, 24.January 2013

09:00 – 12:00	BHA Handling
	Representative BHA Tools (Klaus Kurz)
	BHA Handling Work Steps (Klaus Kurz)
12:00 – 12:45	Lunch
13:00 – 14:45	Automated Drill Floor vs. Offline BHA handling
	Offline BHA Assembling (Klaus Kurz)
15:00 – 16:00	Summary

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