Faculty of Science and Technology

MASTER'S THESIS

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Preface

This master thesis is the final part of our master degree program at the University of Stavanger. The thesis is written in cooperation with National Oilwell Varco (NOV) under the department Drilling Systems located in Kristiansand. The main supervisor has been Jan Morten Haavik working as line manager for Drilling Systems and the supervisor from the University of Stavanger, Mesfin Belayneh. I would like to thank both for helpful discussions and inputs during this spring (2014).

At the end I would like to thank our fellow students here at UIS for good times during my years at the university.

Andreas Ims Winther

June 2014

Abstract

Increasing the number of wells drilled into a reservoir leaves less oil in the reservoir as well as exploration of new reservoirs demands to drill new wells. By increasing the efficiency of a drilling rig, more wells can be drilled for the same cost, which brings more oil to the surface. The overall goal of a drilling rig is to have weight on bit, cutting new formation, which is regarded as the Productive Time (PT), referring to reference [1]. To reduce the Non-Productive Time (NPT), the efficiency of the machines and their configuration needs to be evaluated in an efficient way in the design phase of a drilling rig.

Tripping constitutes 20-30% of the total time while operating a drilling rig [2]. Tripping demand no weight on bit, thus this time will be part of the NPT. By reducing the duration of tripping one stand, the efficiency of a drilling rig is increased.

MicroSoft Project (MS Project) is evaluated to be a program with functionalities of great value to evaluate and decrease the duration of an activity, e.g. tripping in. Several operations constitute an activity and the goal is to make the sequence of operations as efficient as possible.

To decrease the duration of an activity, machines and their operations should aim to be executed simultaneously, with short trajectories/distances to travel and high, but safe velocities. The sequence of operations in an activity is restricted by dependencies between the operations that define which operations that can be run simultaneously.

The critical path in MS Project consists of the critical operations with no slack, and defines the duration of an activity. The goal is to set up the correct dependencies and the duration for each operation in an activity to find the critical operations. These critical operations will be the bottlenecks and therefore the operations and machines to improve.

For Rig 1 it is evaluated to be possible to decrease the duration of tripping in one stand from 124 seconds to 104 seconds. Instead of tripping 29 stands per hour it should be equipped with a faster hoisting system which make it possible to trip 34,6 stands per hour.

Even though well parameters allow high velocities lowering the drillstring into the well, the machine configuration may restrict to decrease the duration of tripping in one stand by increasing the velocity of the operation “Lower to stickup”. In that case the machine configuration is the limiting factor.

A lot of the machines on a drilling rig are driven by hydraulic pressure. The department Drilling Systems has been asked to evaluate the requirements for the Hydraulic Power Unit (HPU). They need to evaluate the total flow required [l/min] of hydraulic oil at the time of highest consumption. Each consumer of the hydraulic oil as hydraulic motor(s) and/or cylinder(s) demand a flow [l/min] to operate as intended. The sequence of consumers is a result of the sequence of operations. After the sequence of operations is optimized and illustrated in a Gantt

chart, it can be broken down to a level which illustrates the sequence of consumers through the activity. The sequence of consumers and the flow needed to each consumer results in the hydraulic flow through the activity. The activities evaluated to take place at the same time may coincide such that the maximum flow in each activity must be added to determine the flow required from the HPU.

Nomenclature

ACS	Anti Collision System
AHC	Active Heave Compensator
BHP	Bottom Hole Pressure
CM	Column Racker
CMC	Crown Mounted Compensator
DF	Drill Floor
DFMA	Drill Floor Manipulator Arm
DW	DrawWork
ECD	Equivalent Circulating Density
FB	FingerBoard
HPU	Hydraulic Power Unit
HR	Hydra Racker
HSE	Health, Safety and Enviornment
HTV machine	Horizontal To Vertical machine
KBC	Knuckle Boom Crane
KBC	Knuckle Boom Crane
KPI	Key Performance Indicators
LFB	Lower Finger Board
MD	Measured Depth
MH	Mouse Hole
MS Project	MicroSoft Project
NOV	National Oilwell Varco
NPT	Non-Productive Time
PD	Pipe Deck
PDC	Polycrystalline Diamond Compacts
PIM	Pipe Interlock Management
PT	Productive Time
RN	RoughNeck
ROP	Rate of Penetration
RSS	Rotary Steerable System
RT	Rotary table
TD	TopDrive
TW	Torque Wrench
VPH system	Vertical Pipe Handling System
WC	Well Center
WOW	Weight On Weather
WRT	Wireline Riser Tensioner

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1 Introduction

This thesis presents how to optimize the machines and their configuration on a drilling rig, evaluated as one interacting system. This includes studying the sequence of operations in an activity as tripping in and the hydraulic consumption.

1.1 Background

Large reserves still remain and require a lot of new wells to recover more oil out of the reservoirs. The production rate and ultimate recovery will in many cases be a function of the number of wells. The number of wells is continuously increasing as shown in Figure 1-1. Increasing the drilling efficiency give the opportunity to drill new and more drain holes and thus leave less oil in the reservoir. [1]

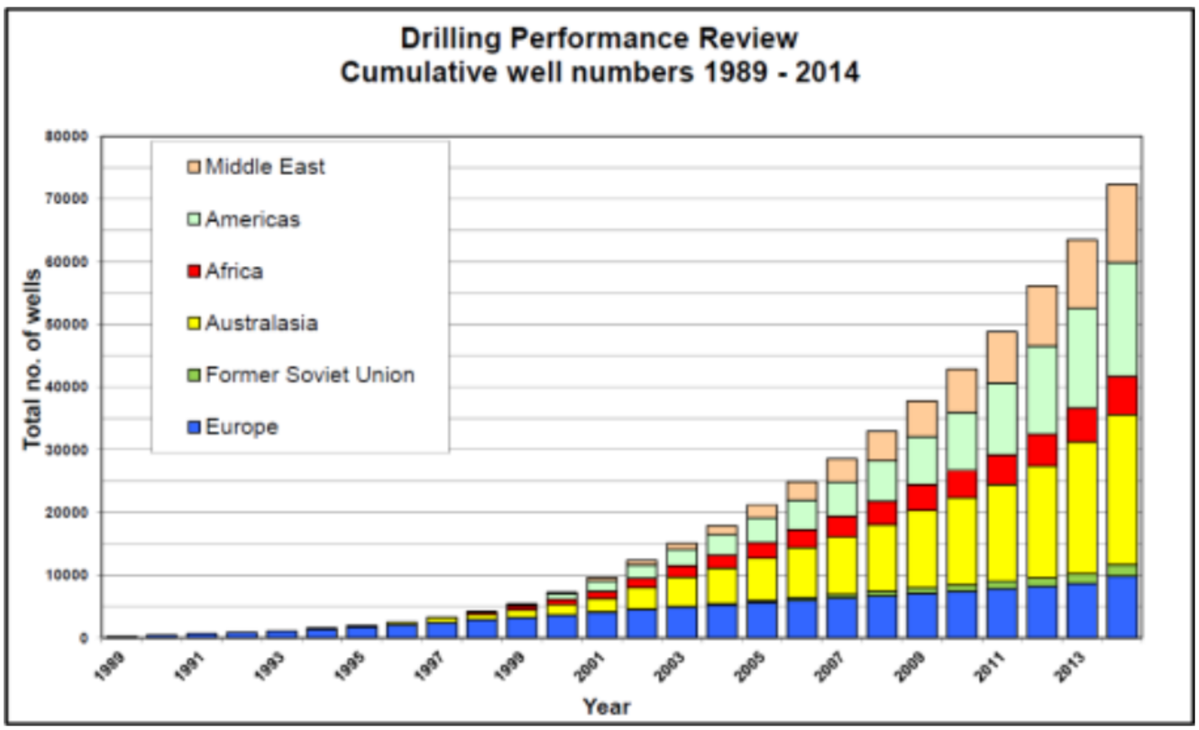


Figure 1-1: Cumulative well numbers from Drilling Performance Review 1989 – 2014. [3]

The drilling industry is facing challenges as the remaining petroleum reserves are found in areas demanding more complex drilling technology. The complex path to reach these reservoirs results in a slow overall drilling progress and considerable time and costs related to Non-Productive Time (NPT). According to reference [1] “An efficient drilling process is characterized by a high percentage bit on bottom time relative to the total time spent in drilling mode. In this respect, all time spent off bottom can be regarded as non-productive time – time subjected to reduction.

Quite obviously, real progress while being in drilling mode can only be achieved with the bit on bottom cutting new formation.”

There is a need for the drilling industry to improve as the remaining oil and gas reserves are more challenging to exploit, both from a technical and economical point of view. Key words challenging the drilling industry are [1]:

- Deep water
- Remote
- Artic
- HPHT
- Mature fields (depleted fields)

During the last 30 years, the industry has seen a dramatic development in complexity. From vertical or low inclined wells 3-4000m long, while now horizontal, 3D curvatures, multilateral wells often twice the length. At the other hand, looking at the drilling process, there has been limited development through these years. [1]

Looking at the development within two main Key Performance Indicators (KPIs), Rate of Penetration (ROP [m/day]) and Non-Productive Time (NPT [%]), there is a radical increase in the drilling efficiency in the late 1990s. Hovda S. [1] believe that “the increased use of Polycrystalline Diamond Compacts (PDC) drill bits and the introduction of Rotary Steerable System (RSS) technology in the late 1990s contributed to the positive trend in this period. See Figure 1-1 and Figure 1-2.

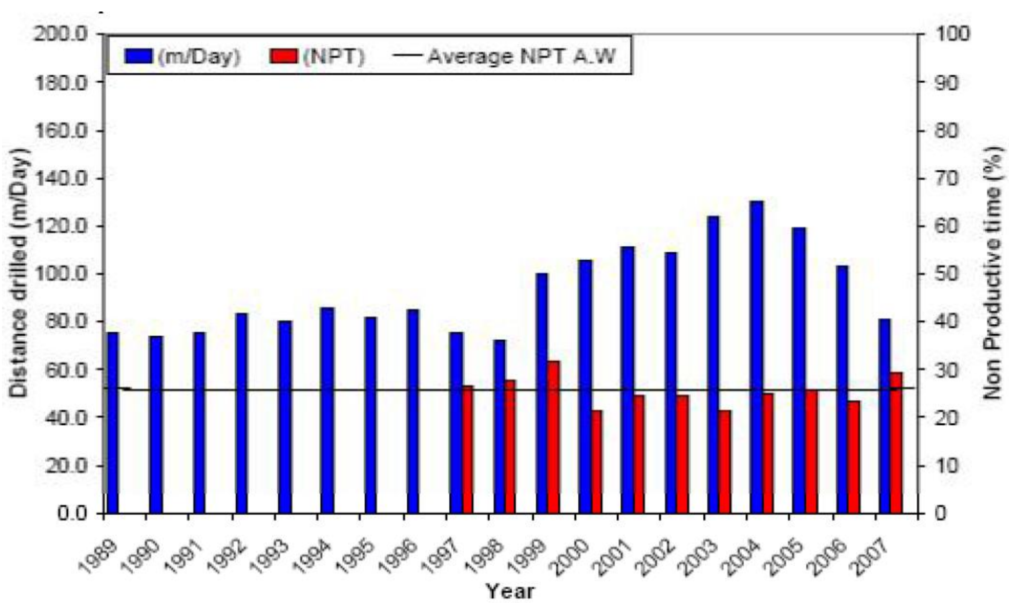


Figure 1-2: NPT and m/day for approx. 5900 wells in Europe from 47 operators in the period from 1989 to 2007. All types of wells. Source Rushmore Reviews. [1]

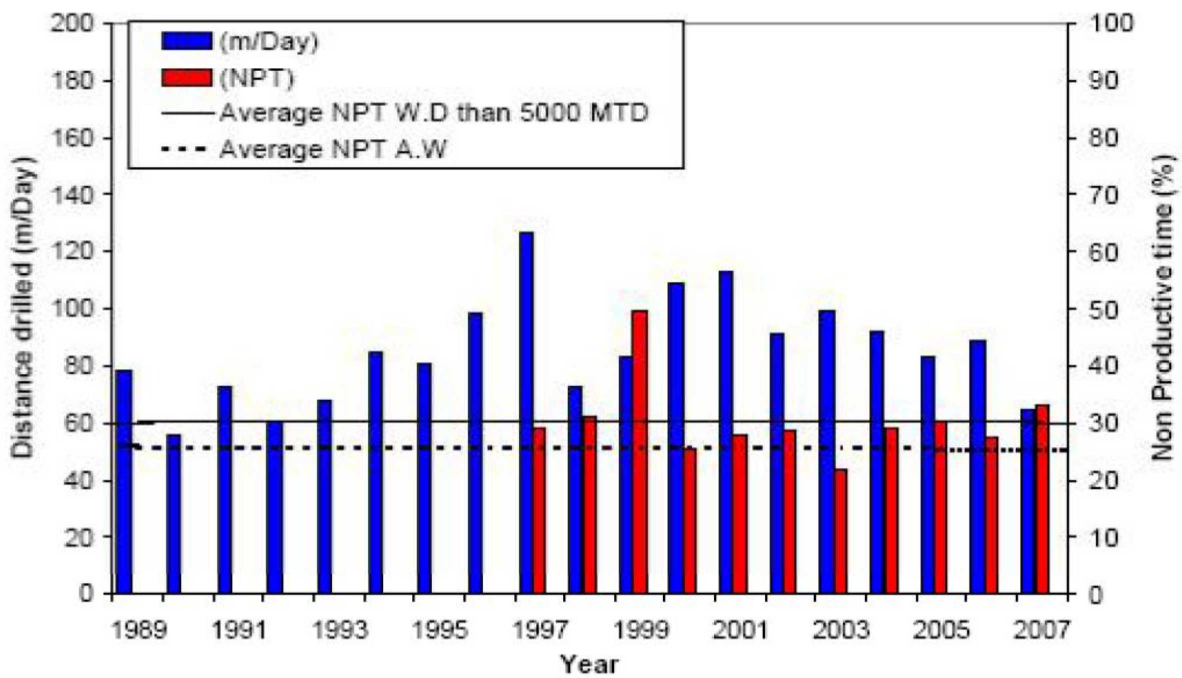


Figure 1-3: NPT and m/day for approx. 5900 wells in Europe from 47 operators in the period from 1989 to 2007. Wells where MD > 5000 m. Source Rushmore Reviews. [1]

The increasing trend was followed by a reversal from 2003/2004. NPT seems to be more or less flat in this period from 2003/2004, approximately 25%. This NPT costs the industry a lot. The most challenging wells, like deep water and Extended Reach Drilling (ERD) wells, NPT levels can be as high as 40%. [1]

Drilling efficiency measured in m/day has a significant drop from 2003/2004. This drop in efficiency is probably a combination of factors like [1]:

- Complex wells
- Maturing fields
- Rig mechanization
- Stricter HSE
- Stretched capacity

An overall goal of a drilling rig is to reduce the NPT, thereby have more days with weight on bit, cutting new formaiton, and thus increase the ROP [m/day]. This will reduce the number of days and cost to drill a well.

NOV in Kristiansand has specialized producing what is called a drilling package. This consists of machines, structures and systems which is essential on a drilling rig. This thesis will focus on the rig mechanization influencing the NPT. The department in NOV, Drilling Systems, is responsible to put all machines needed into one interacting efficient machine configuration.

Machinery on a drilling rig

A human have the advantage to see and evaluate the situation before execution. A man is flexible to maneuver and choose trajectory to reach the position where to execute the job. This makes the operation and cooperation between humans smoother and less rigid than by machines. Machines have fewer trajectories and need signals from one another, as well as from humans to operate efficient and in a safe manner. It is a challenge to build a system of machines being as efficient as humans because of the rigidity. [4]

The drilling industry has developed from being operated by hand to the use of more machines. Earlier it was not unusual to lack a finger since the drill pipes was connected (made up) by hand. These days there are machines, operated by man, that are in direct contact with the pipes. This makes drilling operations safer.

A machine is more reliable than a human being. Different drilling crews have been measured in ROP, and regardless of well parameters, one crew have performed the double compared to the other. The trend for humans is alternating efficiency from one day to another, as well as through the day. While a machine will perform from start to stop, a human being needs practice and even then will alternate in performance. Machines don’t get paid for what they execute and will perform day after day as long as they are up and running.

Overall, this encourages building machinery on a drilling rig less influenced by human beings, since machines should be more reliable, consistent and less expensive. [4]

Chief executive officer for Statoil considers robotization/automatization capable of reducing the cost of well activities by 30%. [5]

1.2 Problem formulation

As mentioned in chapter 1.1 Background, the drilling cost increase compared to oil prices that are relatively constant. It is important to improve the performance and efficiency of a drilling rig in order to increase productivity and reduce unnecessary cost, while still operate with low risk related to HMS.

The issues addressed in this thesis are:

- How is the performance and efficiency of a drilling rig evaluated?
- Is there an efficient method to illustrate and evaluate the efficiency of a drilling rig?
- Which factors and parameters affect the efficiency of a drilling rig?
- Is it possible to improve the efficiency of a specified drilling rig?
- How can the hydraulic consumption be calculated?

1.3 Objective

In the sales and concept phase of a project in NOV it would be of great value to better understand the effects that different concepts, machines and configuration have on a drilling rig's efficiency in order to make NOV's future drilling rigs even more efficient.

A lot of machines on a drilling rig are driven by hydraulic pressure. It is important to evaluate the requirements for the Hydraulic Power Unit (HPU). The total flow required [l/min] of hydraulic oil at the time of highest consumption need to be evaluated. This is needed to ensure that the machines are given the energy they needed to perform as intended. An efficient method is needed to calculate the maximum hydraulic consumption.

The main objective of this thesis is to:

- Describe the performance and efficiency of a drilling rig.
- Introduce methods to evaluate the efficiency of a drilling rig.
    - Evaluate duration of an activity as tripping in.
- Evaluate the efficiency of a specified drilling rig.
    - Determine the critical operations which is the bottlenecks.
    - Evaluate solutions to increase the efficiency.
- Evaluate a method which is efficient to describe the flow requirement from the HPU.
    - Calculate the hydraulic consumption.

1.4 Structure of the thesis

Chapter 2 - 4 introduces necessary theory. The thesis will start to present essential machines and systems on a drilling rig to be able to understand which functional requirements that are needed. The next chapter will introduce and describe how to evaluate the efficiency of the machinery on a drilling rig and describe tripping as an important factor decreasing the NPT. In chapter 4, the sequence of operations while tripping in will introduce the machines as one interacting system for this activity. The theory behind the hydraulic ringline system is described in chapter 4.

Chapter 5 - 9 presents valuable methods to evaluate the efficiency of the machine configuration on a drilling rig and the associated hydraulic consumption.

2 Drilling equipment, systems and modes of operation

NOV in Kristiansand is specialized to design and produce top-side equipment for a drilling rig. This includes a lot of machines, systems and structures to meet the functional requirements of a drilling rig. This chapter gives an overview of which machines and functions that are used and needed on a drilling rig. Pictures and descriptions of functional requirements is in general gathered from internal NOV technical description documents [2], if not, this is specified with reference number.

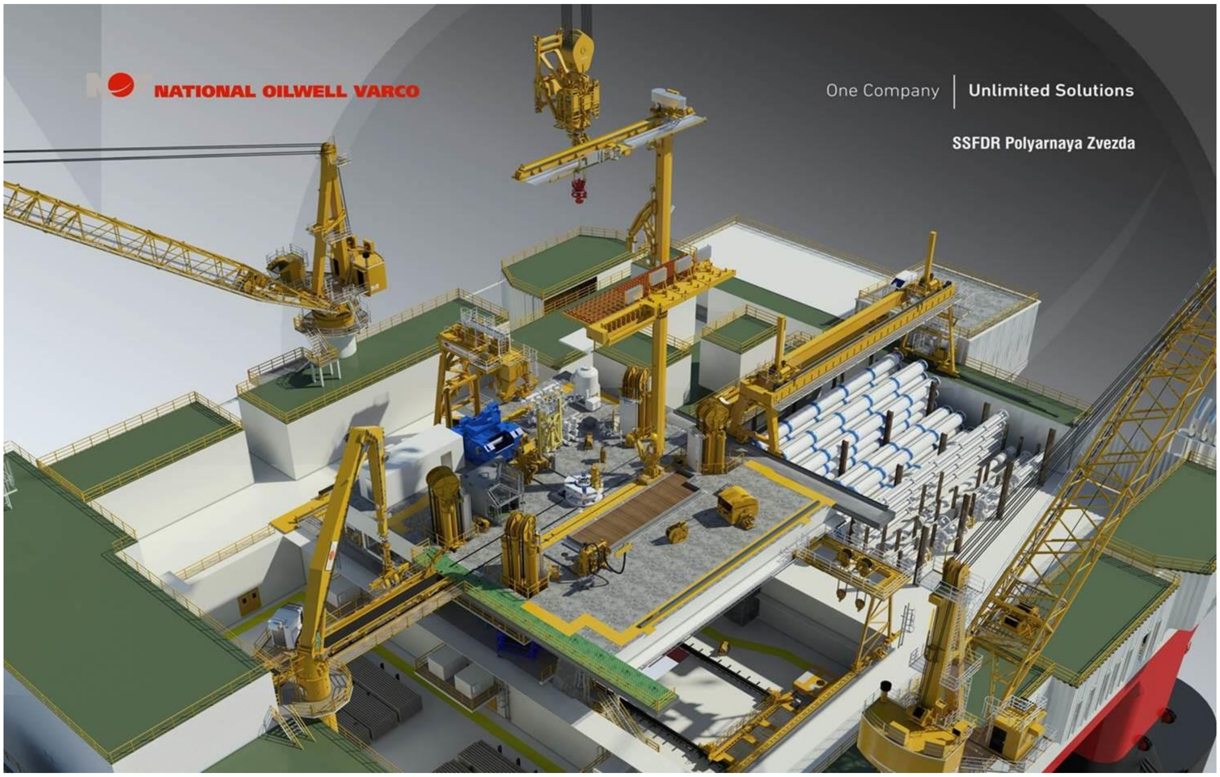


Figure 2-1: Drilling system

2.1 Machines and structures

Drawwork (DW)

The primary function of Drawwork (DW) is to reel out and reel in the drilling line, a large diameter wire rope, in a controlled fashion. The drilling line is reeled over the crown block and traveling block to gain mechanical advantage in a "block and tackle" fashion. The reeling out of the drilling line is powered by gravity and reeling in by a motor. [6]

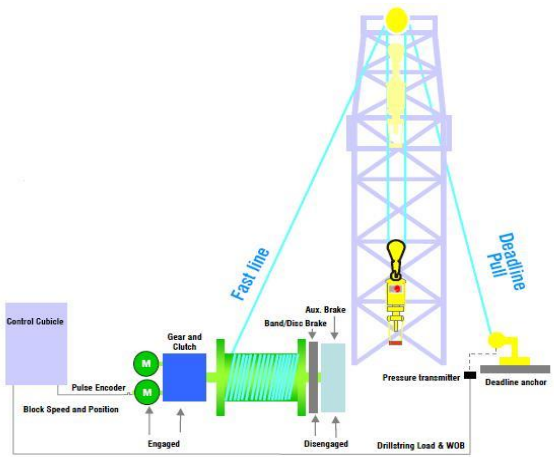


Figure 2-2: Hoisting/lowering system [7]

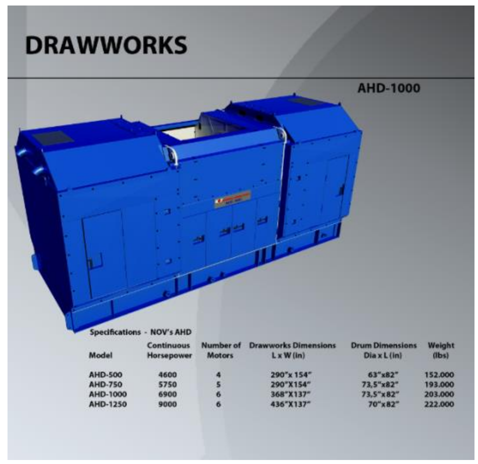


Figure 2-3: DW

TopDrive (TD)

A topdrive shall turn the drillstring. The topdrive is suspended from a hook, so the rotary mechanism is free to travel up and down the Derrick. Compared to Kelly method of turning the drillstring, this enables drilling to be done with three or four joints stand instead of single joints of pipe.[8]

Figure 2-4: TD

Retractable Dolly

The dolly is designed for supporting and guiding of the TD. The dolly is designed to allow the TD to be drilled down to the RT. The Retractable Dolly makes it possible to retract the TD away from WC when running up and down the derrick. The

Figure 2-5: Dolly

dolly connects the TD to guiderails. This acts as a guide and transfers all drilling torque to the guide rail structure.

Elevator

The Elevator is used while tripping in or out, while when actually drilling you connects the drillstring to the Saver sub which is connected to the main shaft in the TD. The Elevator is a clamp able to hold the whole drillstring while tripping in or out. Elevator links are used to connect the elevator to the TD.

Figure 2-6: Elevator and elevator links

Rotary Table (RT)

The Rotary Table (RT) is able to rotate the drillstring. It can be used during drilling operation in case of TD failure. The table is also functioning as a fundament for the slips holding the drillstring when needed, e.g. when connecting new stand to the drillstring. The location of the RT is referred to as the Well Center (WC).

Figure 2-7: RT

Hydraulic Power Slips

Hydraulic Power Slips is designed to be installed into the RT. It can handle casing, drill pipe and drill collar and is a device used to grip the drillstring and suspend it in the RT.

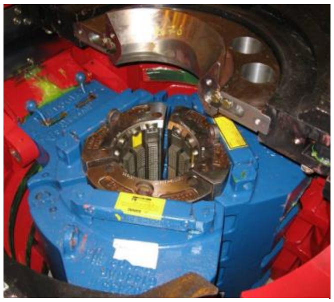


Figure 2-8: Slips

Fingerboard (FB)

Fingerboard (FB) is designed to store various sizes of drill pipe and drill collars in vertical position as part of the Vertical Pipe Handling system (VPH system).

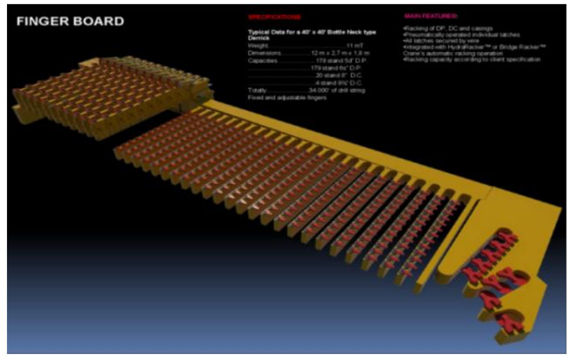


Figure 2-9: FB

Lower Fingerboard (LBF)

The main intension for the Lower Fingerboard (LBF) is to avoid drill pipes/stands to buckle under its own weight during operating and non-operating criteria. It is located beneath the FB. LFB is part of the VPH system. Control of the LFB locking fingers is by the VPH Control system.

CatWalk Machine (CWM)

The Catwalk machine is designed for transportation of tubular and material from Pipe Deck (PD) to Drill Floor (DF) and vice versa. The tubular is delivered by the Pipe Handling Crane (PHC) at PD and transported either to interface the Horizontal To Vertical machine (HTV) or Column Racker (CM) for stand-building in Mouse Hole (MH) or to Well Center (WC) to be delivered directly to the TD.

Figure 2-10: CWM

Horizontal To Vertical machine (HTV)

The Horizontal To Vertical machine (HTV) is designed to pick up single tubular from the CWM and rotate them from horizontal to vertical direction. The HTV shall then position the tubular over the Moushole (MH) and lower it until the pipe-end lands on top of the elevated Rabbit, or stab the pipe-end into the box-end of an already present pipe. All handling will be possible to run in the reversed order, i.e. breaking down a previous made stand.

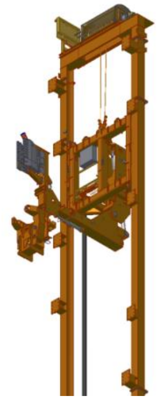


Figure 2-11: HTV

Column Racker (CR)

The Column Racker (CR) is designed to lift and guide drill pipe and drill collar between WC and Fingerboard (FB)/setback. The pipe racking system forms an integrated pipe handling system for easier, safer and faster handling of tubular on every type of offshore rigs. It enables drilling in bad weather and under harsh environment, thus increasing safety and reducing tripping time. CR is part of the VPH system.

Figure 2-12: CR

Hydra Racker (HR)

The Hydra Racker (HR) is NOVs version of a CR which is able to take stands from FB to WC, as well as joints of pipe from CWM to MH.

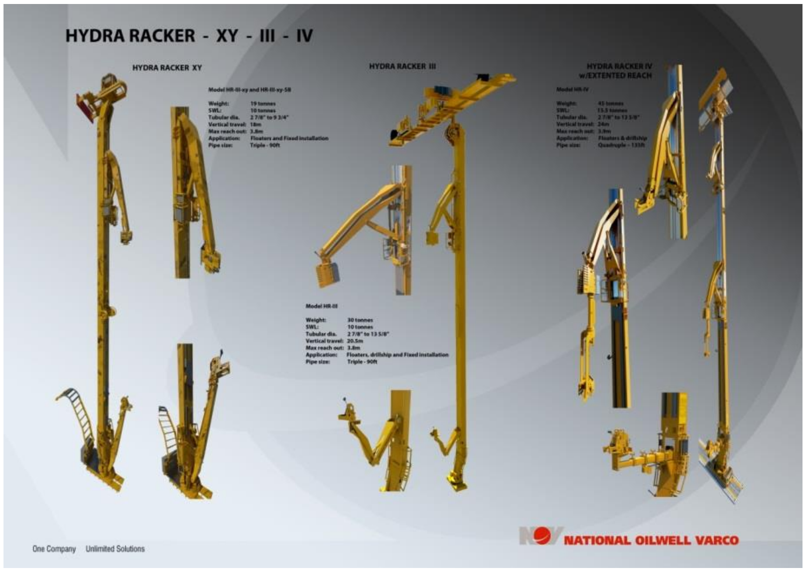


Figure 2-13: HR

Roughneck (RN)

Roughneck (RN) is for applying torque for make-up or break-up of drillpipe. The spinner is part of the RN and shall spin in or spin out drill pipes/stands. A Torque Wrench (TW) is part of the RN. It shall break-out or make-up connection of drill pipes/stands with required torque.

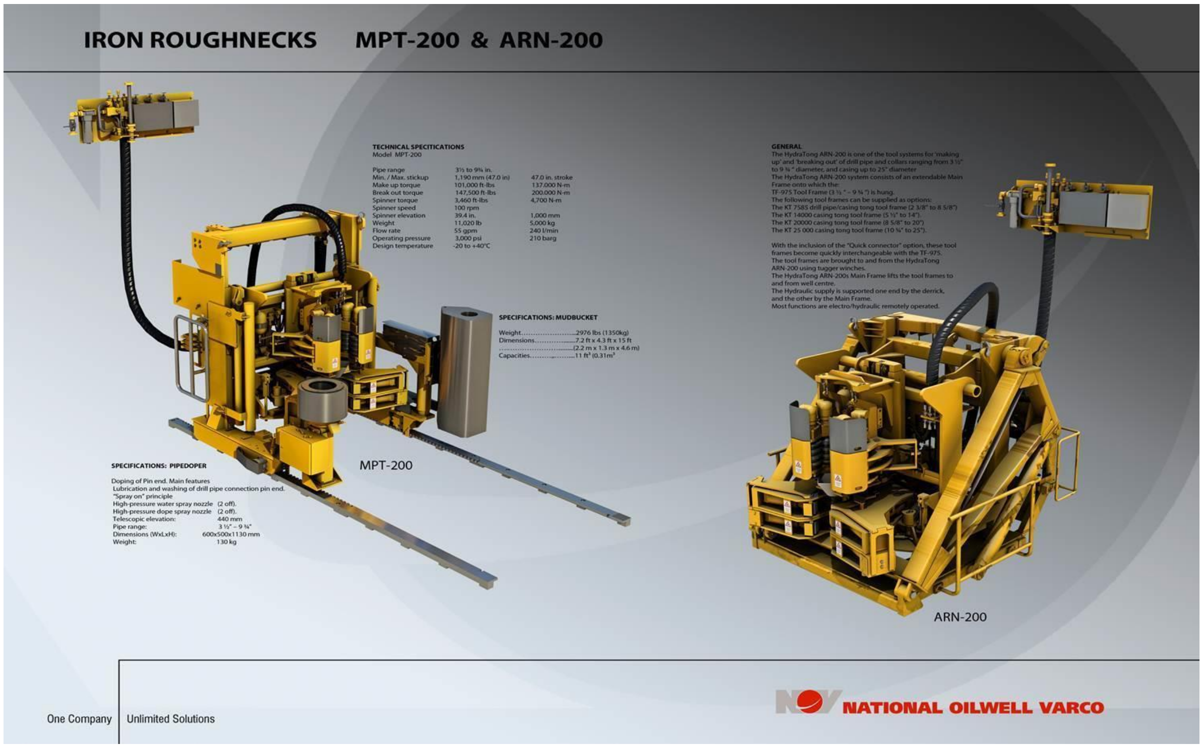


Figure 2-14: RN

Mousehole (MH)

Mousehole (MH) is specially designed for offline standbuilding of drill pipes, casings and collars. The MH is in principle a long tube consisting of main tube and rabbit. The main tube is fixed to drillfloor and cellardeck. The rabbit is running inside the main tube to elevate the stand to right stickup.

Figure 2-15: MH

Drill Floor Manipulator Arm (DFMA)

Drill Floor Manipulator Arm (DFMA) is designed to guide tubular on drillfloor level. It is used for guiding drill pipes, collars and risers to WC, or to setback area.

Figure 2-16: DFMA

Pipe Handling Crane (PHC)

The Pipe Handling Crane (PHC) is located at pipe deck and its main purpose is to transport tubular from pipe deck to CWM. It is controlled from the operators chair in the PHC Cabin. The PHC have hydraulic supply from its own HPU located next to the crane.

Figure 2-17: PHC

Wireline Riser Tensioner (WRT)

The Wireline Riser Tensioner (WRT) is installed on a floating drilling vessel to maintain a pre-selected vertical tension in the riser when the vessel is heaving and rolling due to waves, currents and wind.

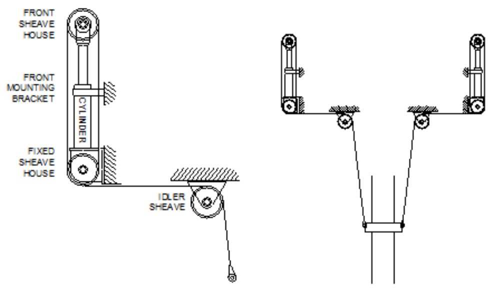


Figure 2-18: WRT

Crown Mounted Compensator (CMC) with Active Heave Compensator (AHC)

The Crown Mounted Compensator (CMC) with Active Heave Compensator (AHC) has a main task to minimize the effect of rig heave on the drill string. The relative movement between drill rig and sea bottom on a floating rig asks for an elastic element in order to maintain a constant bit load.

Figure 2-19: CMC with AHC

2.2 Systems

Anti Collision System (ACS)

The Anti Collision System (ACS) is a safety system. A virtual box represents each machine in the ACS control system. Based on the virtual boxes of all the machines, ACS prevents collision between the machines. If two machines get to close, ACS will prevent collision by reducing the speed, and if necessary stop the machines.

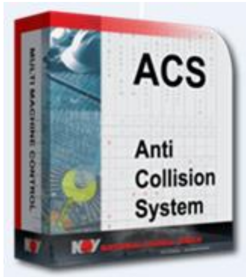


Figure 2-20: ACS software

The ACS will allow collision between machines in certain situations for the rig to be able to operate, e.g. when HTV machine is picking up tubular from CWM. ACS does not relieve the driller from the responsibility of operating the equipment safely, but will be an extra safety guard designed to avoid unintended incidences during normal operation.

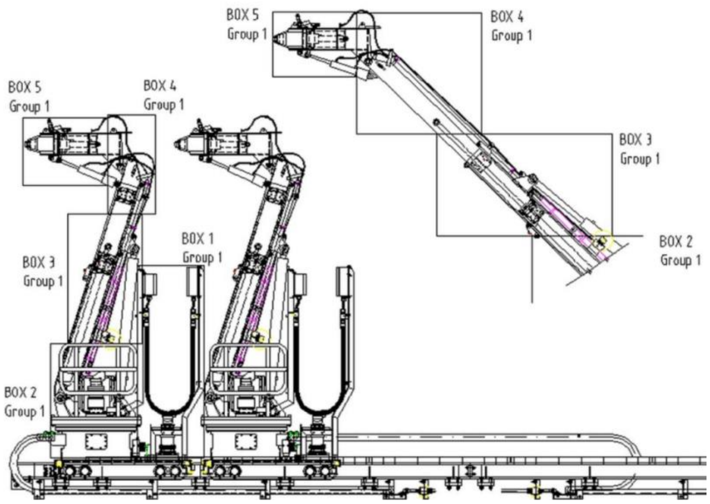


Figure 2-21: ACS principle

Pipe Interlock Management (PIM)

PIM is handling scenarios related to: Do not hoist if both elevator and RN is locked on pipe.

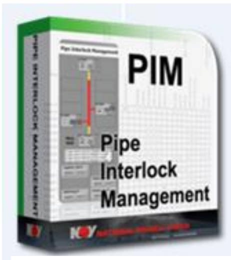


Figure 2-22: PIM software

ACS and PIM

ACS and PIM system is active in all normal operation modes, but not when operated in direct mode or operated hydraulically direct on a machine.

2.3 Modes of operation

Normal mode

Normal mode is the normally used mode during operation. In Normal mode all equipment functions used during handling of drill pipe, casing and riser are available for the operator. Normal mode can be manual or sequenced equipment. The equipment can also have preprogrammed path in Normal mode. The Anti Collision System (ACS) is active in Normal mode.

Manual mode

Manual mode is applicable for all equipment which has more functions than used in Normal mode. When operated in Manual mode equipment functions can be operated individually. In Manual mode equipment can have functions allowing the operator to run along geometrical axis. The Anti Collision System (ACS) is active in Manual mode.

Direct mode

Direct mode is strictly for maintenance and initializing of the equipment. The Anti Collision System (ACS) is NOT active in direct mode.

3 Efficiency of machinery on a drilling rig

The overall goal for drilling is to make a hole which connects the rig and the hydrocarbon reservoir. As described in the introduction, the overall efficiency of a drilling rig was considered regarding Rate of Penetration (ROP [m/day]) and Non-Productive Time (NPT [%]). The productive time for the operator is the time when you actually penetrate the formation [1]. ROP is the length penetrated divided by the total duration, including the NPT. Efficient drilling of a well is recognized as a long length drilled in a short total duration.

Tripping, running/pulling riser, running casing and building stand, are activities which are regarded as NPT, referring to Hovda [1]. An overall goal is to decrease the NPT. An efficient drilling rig is fast tripping, running/pulling riser, running casing and building stand. NOV as a vendor of the machinery top side wants to design efficient drilling rigs which give the customer a low NPT. Drilling Systems is responsible for an efficient interaction between machines as well as the interface between machines and humans. NOV as a vendor must show the customer how efficient different activities can be performed related to their machine configuration.

The efficiency of a drilling rig, regarding machinery top side, is measured by the lowest duration of a specified amount of work for an activity. Typical activities which show the efficiency of a vendor's drilling rig are:

- Tripping in
- Tripping out
- Running riser
- Pulling riser
- Running casing
- Building stand

This thesis will focus on tripping activities, which constitute 20 - 30% of the total time operating a drilling rig and is crucial since this activity demand no penetration of formation, thus tripping will be part of the NPT. On the other hand, stand building is not that crucial as tripping, since a drilling rig is designed to be able to build stand while drilling, thus building stand in that case is not part of the NPT. By eliminating the time used for rigging of equipment, Weight On Weather (WOW), etc., you approximately double the relative time for tripping. I.e. if just the effective time of operation is considered, time for tripping will constitute 45-50%. These values of time for tripping are based on "normal wells" since time for tripping is dependent on Measured Depth (MD), formation, well design, etc. This information relies on information from Statoil to Jan Morten Haavik as part of a project run by him in "NOV Ventures", an educational program in NOV. Odfjell Drilling has also given feedback that tripping constitute 20-40% of total time. For more information of "normal" specified wells from Statoil, se figures below. As an example, Figure 3-1show 11,76% "Make connection", 4,24% "Run in hole" and 4,35% Pull out of hole, which in total give 20,35% for tripping. [2]

Time Breakdown Section

Color	Operation	[hh:mm]	[%]
	Drilling rotating	183:01	11.14
	Drilling sliding	15:40	0.95
	Ream upwards (backreaming)	67:15	4.09
	Ream downwards (into hole)	46:17	2.82
	Wash upwards (out of hole)	22:19	1.36
	Wash downwards (into hole)	22:52	1.39
	Run in hole	69:43	4.24
	Pull out of hole	71:25	4.35
	Circulate hole	91:58	5.60
	Make connection	193:05	11.76
	Other operation	858:57	52.29
	Sum	**1642:30**	**100.00%**

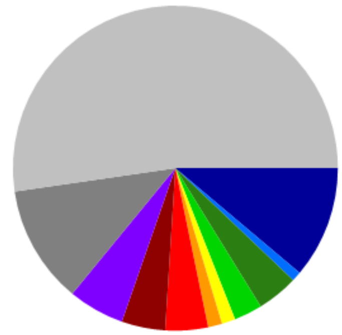


Figure 3-1: Well 1, all sections drilled to Target Depth (TD) 3700m with 32 round trips (trip out and trip in). [2]

Time Breakdown Section

Color	Operation	[hh:mm]	[%]
	Drilling rotating	117:02	14.81
	Drilling sliding	00:00	0.00
	Ream upwards (backreaming)	12:07	1.53
	Ream downwards (into hole)	18:49	2.38
	Wash upwards (out of hole)	04:51	0.61
	Wash downwards (into hole)	08:02	1.02
	Run in hole	23:47	3.01
	Pull out of hole	21:22	2.70
	Circulate hole	44:39	5.65
	Make connection	117:51	14.91
	Other operation	421:53	53.38
	Sum	**790:23**	**100.00%**

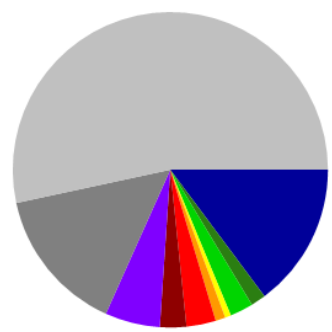


Figure 3-2: Well 2, drilled 36”, 17 ½’’, 12 ¼’’ sections to TD 2200m with 12 round trips. [2]

Time Breakdown Section

Color	Operation	[hh:mm]	[%]
	Drilling rotating	205:49	13.33
	Drilling sliding	19:46	1.28
	Ream upwards (backreaming)	70:55	4.59
	Ream downwards (into hole)	33:51	2.19
	Wash upwards (out of hole)	13:39	0.88
	Wash downwards (into hole)	15:49	1.02
	Run in hole	62:59	4.08
	Pull out of hole	49:47	3.22
	Circulate hole	83:01	5.38
	Make connection	363:45	23.55
	Other operation	625:10	40.48
	Sum	**1544:31**	**100.00%**

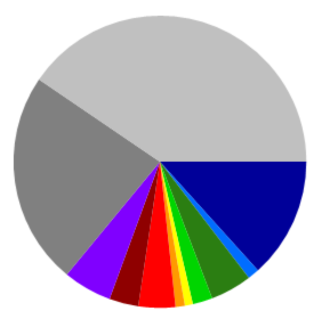


Figure 3-3: Well 3, drilled 22’’, 17 ½’’, 12 ¼’’ 8 ½’’ og 8 ½’’ sections to TD 7000m, with 14 round trips. [2]

Time Breakdown Section

Color	Operation	[hh:mm]	[%]
	Drilling rotating	174:08	13.71
	Drilling sliding	10:48	0.85
	Ream upwards (backreaming)	71:10	5.61
	Ream downwards (into hole)	33:26	2.63
	Wash upwards (out of hole)	31:19	2.47
	Wash downwards (into hole)	30:31	2.40
	Run in hole	60:36	4.77
	Pull out of hole	48:19	3.81
	Circulate hole	67:31	5.32
	Make connection	170:34	13.43
	Other operation	571:23	45.00
	Sum	**1269:45**	**100.00%**

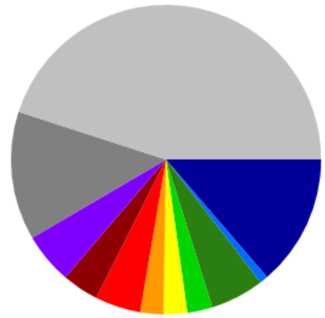


Figure 3-4: Well 4, drilled 26’’, 17 ½’’ og 12 ¼’’ sections to TD 5200m, with 15 round trips. [2]

3.1 Sequence of operations

The department in NOV, Drilling Systems, need to evaluate the sequence of operations in an activity. Drilling Systems is responsible to put all machines needed into one interacting efficient machine configuration for several activities, e.g. the activity tripping in.

Rig: Several activities, as mentioned in the introduction to chapter 3, are part of the functional requirements of a drilling rig.

Activity: An activity needs to be described by a sequence of operations. The activity needs to be described until it starts all over again. The duration of an activity is the time from start of the activity and until it starts all over again. The duration of an activity measure the efficiency of a drilling rig.

Operation: An operation is at a lower level than an activity, meaning that operations constitute an activity. An operation may be a movement to a machine or input from a human operating the machines.

Hydraulic motor or cylinder: A hydraulic motor or cylinder is at the lowest level defined in this thesis. One or several hydraulic motors and cylinders may constitute an operation.

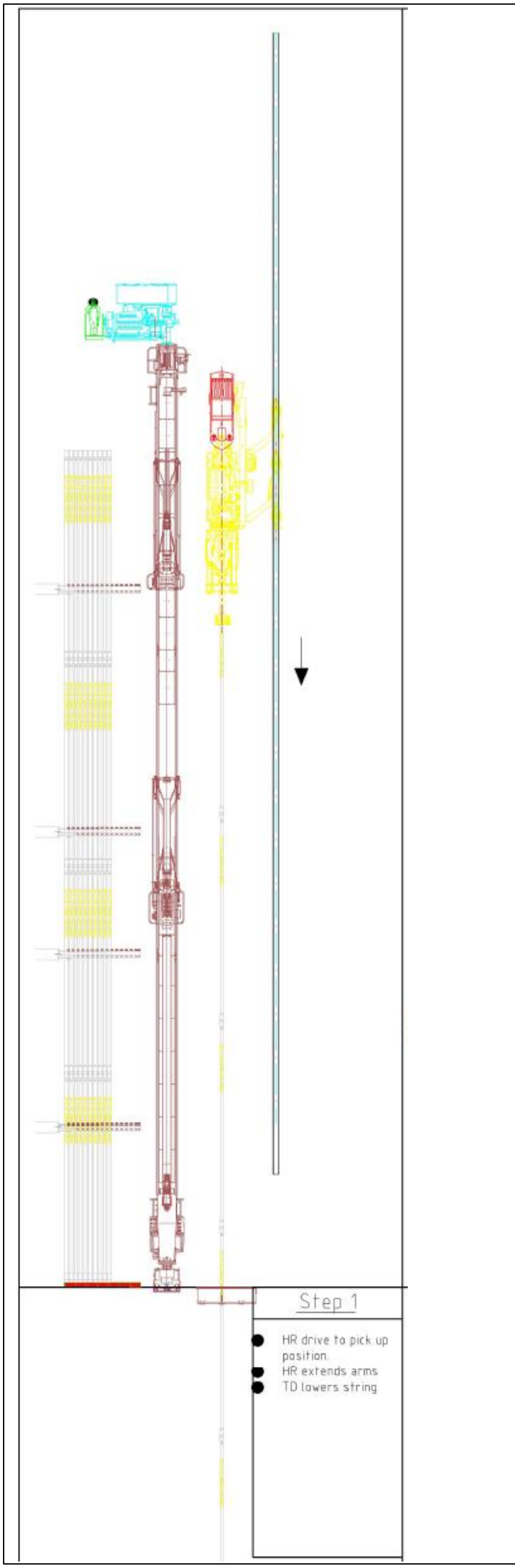
3.1.1 Tripping

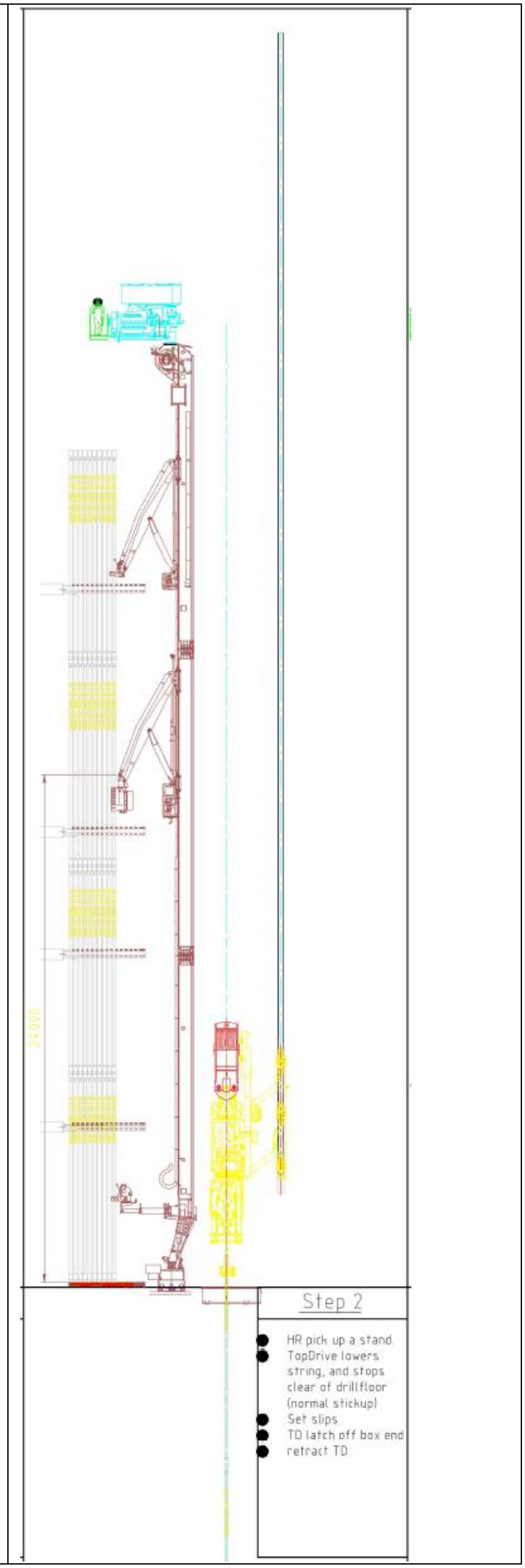
Tripping in is one activity which is described by a sequence of operations. Tripping in is when you go back into the wellbore with the drillstring. Tripping out is the opposite. Tripping pipe is the act of pulling the drillstring out of the hole or replacing it into the hole. A pipe trip is usually done because the bit has dulled and must be replaced. [9]

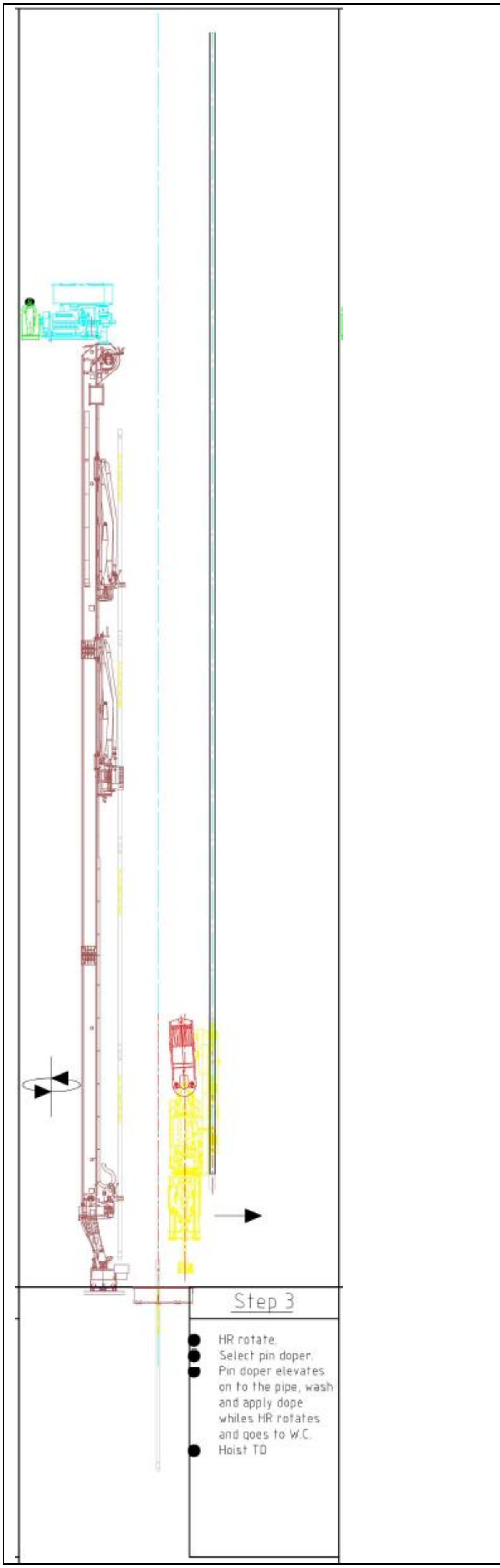
During tripping operations, three or four single joints of drillpipe or drill collars will remain screwed together and stood back upright in the Derrick and placed into Fingerboards. This is a relatively efficient way to remove the drillstring from the well when changing bit or making adjustments to the bottomhole assembly, rather than unscrewing every threaded connection and laying the pipe down to a horizontal position. [10]

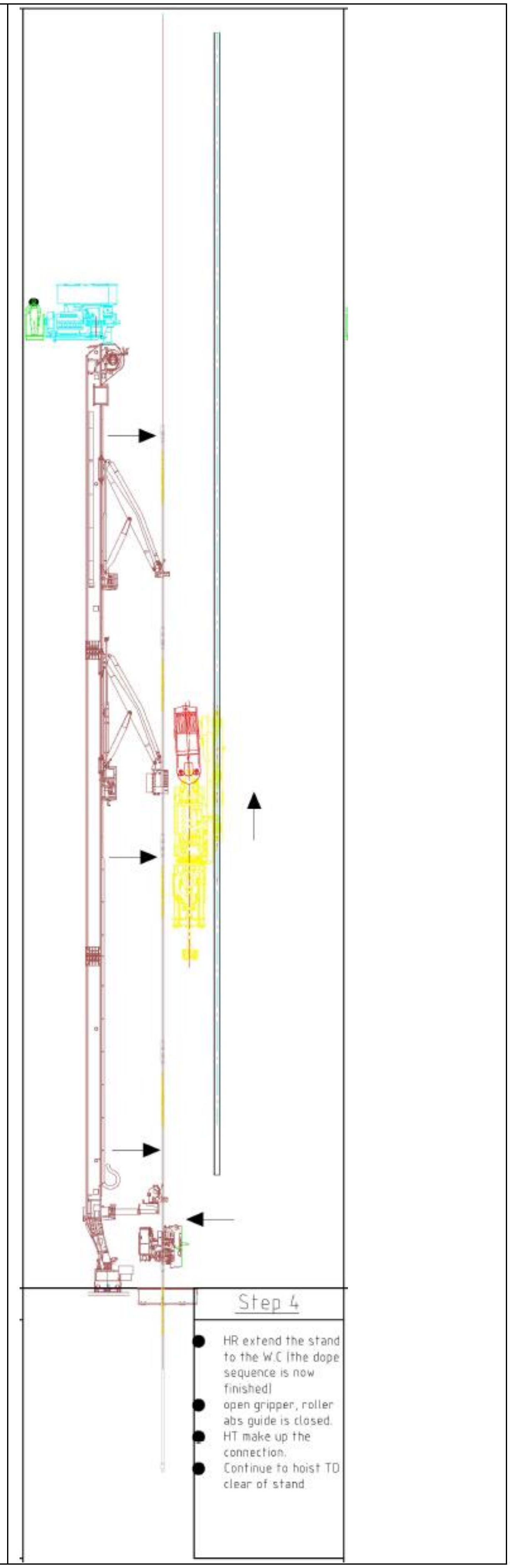
3.1.2 Sequence of operations – tripping in [2]

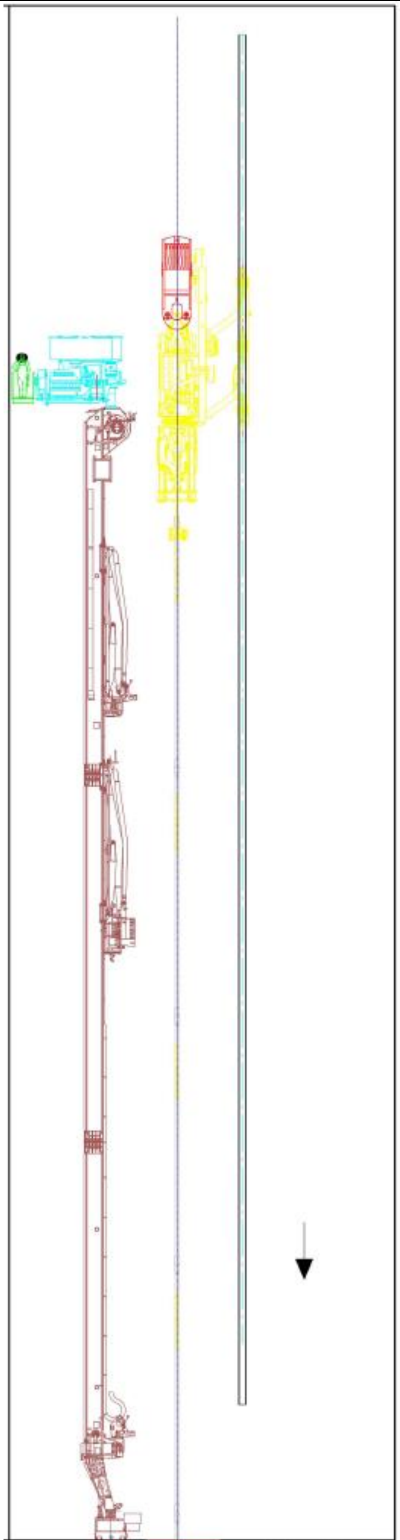
The sequence of operations for tripping in for a conventional drilling rig is illustrated below with figures and description of how this is performed. The conventional way of tripping is to hoist or lower one stand length of the drillstring, then suspend it in the slips, connect a new stand and the cycle goes on until target depth is reached.


Step 1
HR drive to pick up position.
HR extends arms
TD lowers string


Step 2
HR pick up a stand.
TopDrive lowers string, and stops clear of drillfloor (normal stickup)
Set slips
TD latch off box end
retract TD


Step 3
HR rotate.
Select pin doper.
Pin doper elevates on to the pipe, wash and apply dope whiles HR rotates and goes to W.C.
Hoist TD


Step 4
HR extend the stand to the W.C (the dope sequence is now finished)
open gripper, roller abs guide is closed.
HT make up the connection.
Continue to hoist TD clear of stand



Step 5

- TD elevator latches onto string.
- HR retracts the arms
- TD transfer the weight from the slips
- slips open
- TD lower the string into the well.
- Continue with step 1

Equipment used:

1. Hydraracker IV-ER
2. Catwalk Shuttle
3. Mousehole Racking System
4. ARN-200 HydraTong
5. TDX-1000 TopDrive
6. Fingerboard

Symbols:

→ ← ↑ ↓	Indicates movement direction of object.
⟲	Indicates rotation of object.

Abbreviations:

1. HR: Hydraracker
2. MH: Mouse Hole
3. HT: HydraTong
4. FB: Finger Board
5. PUE: Pick up elevator

Notes:

Some objects are simplified for clarity.

3.2 Efficiency of tripping

Tripping constitutes:

- Tripping in
- Tripping out

The goal for tripping out is hoisting of drillstring. The goal for tripping in is lowering of drillstring. Summarized the goal for these activities is vertical movement of drillstring at Well Center (WC). The duration of getting one stand in or out of the well will be a measure of the efficiency. Thereby the efficiency is measured in $\frac{[sec.]}{[Stand]}$.

Tripping in and tripping out is a way of measuring the available efficiency of machinery on a drilling rig that will be delivered by a vendor. This is since tripping represents activities less restricted by well parameters. While ROP while drilling is strongly dependent to the hardness of the formation being penetrated, tripping speed is not dependent of this parameter.

Hoisting and lowering of the drillstring are operations which are part of the activities tripping out and tripping in, respectively. When hoisting or lowering the drillstring in the well, you need to evaluate pressure fluctuations, since this can cause undesired incidences as drilling mud entering the formation/lost circulation, fracture of formation, formation fluid entering the well, kick and well collapse.

An obvious point of view for the operator in charge of the drilling operation is to reduce the number of trips. This will not be evaluated in this thesis. On the other hand, the duration of tripping one stand will be evaluated.

Vertical movement of drillstring at Well Center (WC)

Duration for tripping is hereby divided into:

- Vertical movement
- Prepare (Non-vertical movement)

See Figure 3-5 below which illustrate time for Vertical movement vs Prepare.

	Machine	Name	Duration
1	TD	Dolly extend	6 mins
2	HR	HR guide open	3 mins
3	TD	Open slips	3 mins
4	DW	Elevate to take string weight	3 mins
5	DW	Lower to stickup	24 mins
6	DW	Lowering last section	3 mins
7	TD	Close slips	3 mins
8	DW	Transfere weight to slips	3 mins
9	TD	Open elevator	3 mins
10	TD	Retract TD clear of stickup	6 mins
11	DW	Elevate till pipehandler above new stand	18 mins
12	ARN	Travel forward	8 mins
13	ARN	Travel back	11 mins
14	ARN	Travel forward and elevate	5 mins
15	ARN	Spin clamp close	3 mins
16	ARN	TW lower clamp close	3 mins
17	HR	Move to FB	18 mins
18	HR	Lift stand, open FB and move out of FB.	3 mins
19	HR	To standby positons	15 mins
20	HR	To WC	4 mins
21	HR	Lower	5 mins
22	HR	Stab	3 mins
23	HR	HR guide close	3 mins
24	HR	HR gripper open	3 mins
25	ARN	Spin in	10 mins
26	ARN	Make up connection	10 mins

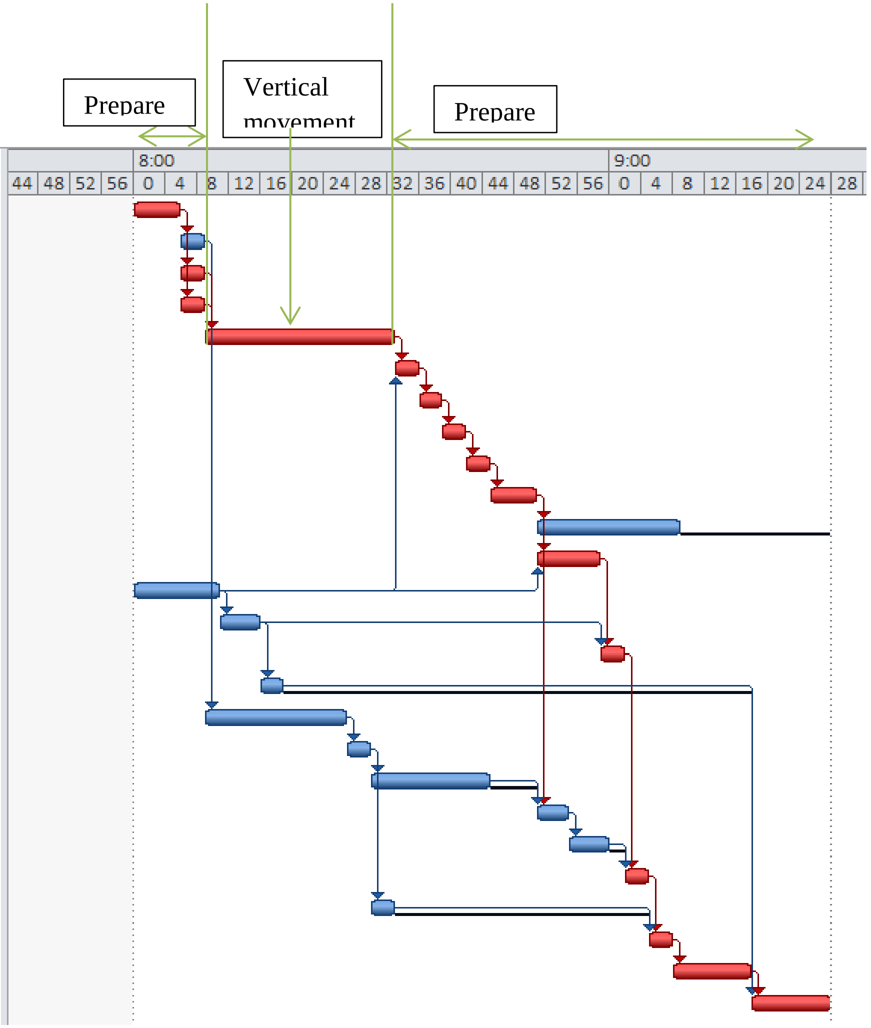


Figure 3-5: Tripping in, time for Vertical movement vs. Prepare in MicrosoftSoft project (MS project).

Figure 3-5 show an estimate to illustrate the time for vertical movement. The values for duration is not possible to be given as seconds in MS project, thereby the values typed in as mins are actually seconds. These values for duration are not Quality Analyzed (QA) and are estimates of duration for each operation. The values give an estimate and show the logic of how to evaluate the relative time used to actually lower the drillstring, "lower to stickup". The time which is not used for vertical movement in this figure, illustrates the time to prepare for vertical movement.

Ratio of Vertical movement and Prepare

What would be of interest is to study the time of vertical movement and time to prepare. To actually take time from time to prepare and replace these operations in parallel to vertical movement would be of great interest to increase the efficiency of tripping. There is a study ongoing where they try to make a machine configuration which is able to have vertical movement through the whole tripping activity. To check this out, see reference [11] which is a video presentation of a new concept named "Continous Motion Rig". The conventional way of tripping is to hoist or lower one stand length of the drillstring, then suspend it in the slips, connect a new stand and the cycle goes on until target depth is reached. The project of "Continuous Motion Rig" try to develop machines and a configuration which is able to do the connection while continuously perform vertical movement of the drillstring.

A measure of the relative Vertical movement is:

$$\boldsymbol{rVm = \frac{Vm}{T}} \quad (1)$$

A measure of the relative Prepare is:

$$\boldsymbol{rP = \frac{P}{T}} \quad (2)$$

A measure of the relative Vertical movement to the Prepare will be:

$$\boldsymbol{rVmP = \frac{Vm}{P}} \quad (3)$$

Vm: duration for Vertical movement, T: Total duration of sequence, P: duration for Prepare, rVM: relative Vertical movement, rP: relative Prepare, rVmP: relative Vertical movement to Prepare.

In Figure 3-5 rVm = 9/28 ≈ 1/3 = 30% of the time while tripping in is used to actually lower the drillstring, while 70% is used to prepare and be able to lower the drillstring.

4 Hydraulics

A lot of the machines on a drilling rig are driven by hydraulic pressure. The department Drilling Systems has been asked to evaluate the requirements for the Hydraulic Power Unit (HPU). They need to evaluate the total flow required [l/min] of hydraulic oil at the time of highest consumption. For how this can be evaluated, see chapter 9. Here is an introduction to the hydraulic ringline system and its components, referring to NOV documentation, [2].

4.1 Functional description and abbreviations

4.1.1 Hydraulic ringline system

The hydraulic ringline system consists of the Hydraulic Power Unit (HPU) and motors driven by the hydraulic pressure from the HPU. The energy from the pressurized oil is consumed by various motors and then returned to the HPU to be pressurized for the next roundtrip or loop. The HPU consist of pumps increasing the pressure from inlet to outlet. The energy is consumed by various motors and cylinders which convert the hydraulic pressure into torque (angular displacement) and linear force.

The consumers in a ringline system are connected in parallel to each other. This makes the available pressure from the HPU (e.g. 207 bars) more or less the same for every consumer. If a new consumer is added to the ringline system in parallel to the other consumers this lead to a higher flow needed from the HPU. This refers to the same logic as for the electrical design in a house where every consumer of the electricity is connected in parallel to each other. Pressure [Pa] refers to the voltage [V] and hydraulic flow [l/min] to electric current [A].

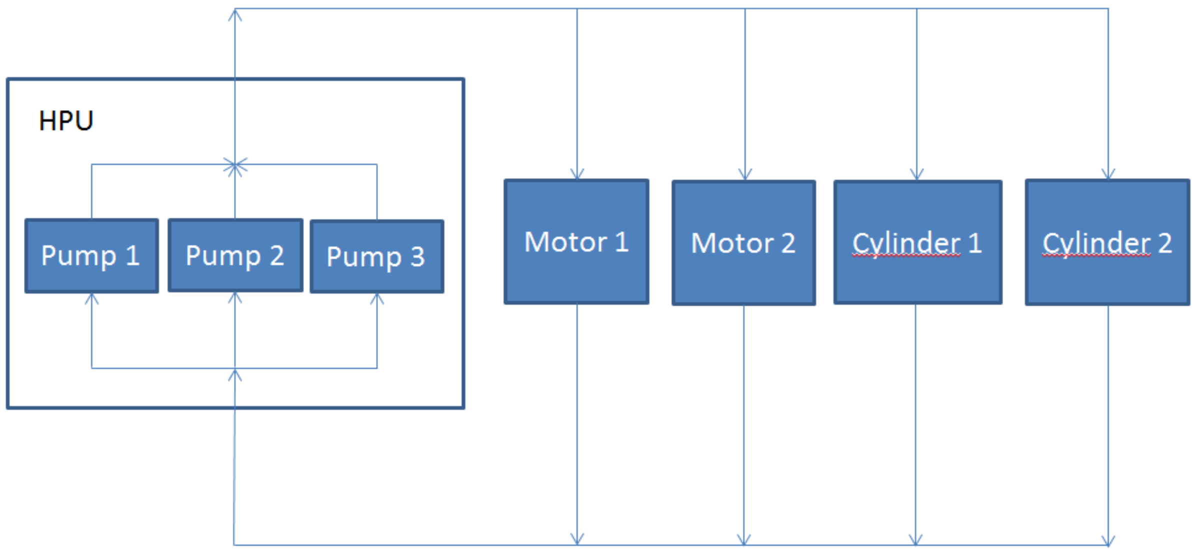


Figure 4-1: Hydraulic ringline system

Hydraulic Power Unit (HPU)

The Hydraulic Power Unit (HPU) is designed to supply hydraulic oil with sufficient flow and pressure to ensure safe, reliable and efficient operation of the hydraulic ringline system.

The main hydraulic pump is an axial pressure compensated piston pump for use in open circuits with closed center valve delivering necessary flow to maintain the set pressure. The HPU is equipped with pressure relief valves and pressure regulator valve. The pressure regulator is set to the required working pressure of 207 bars, and the pressure relief valves are set to design pressure of 227 bar.

One pump is designed to be able to deliver the required working pressure of 207 bars. One pump is able to deliver a specific flow. The HPU is made up by several pumps connected in parallel to increase the capable flow from the HPU. If a new consumer is added to the ringline system and the flow needed from the HPU is increased, another pump is added in parallel to the other pumps.

Figure 4-2: HPU

Hydraulic cylinder

A cylinder is used to give a linear force through a stroke.

Hydraulic motor

Hydraulic motor converts hydraulic pressure into torque and angular displacement (rotation).

Pump

A pump consumes energy and converts it to hydraulic pressure. The pump may be driven by an electromotor.

Axial piston pump: Bosch RexRoth A10 pump

Bosch RexRoth A10 axial piston pump delivers a variable amount of oil with a constant pressure. The pump is usually driven by an electro motor running on a fixed rotational speed. The drum contains hollow cylinders for a series of axial pistons. Each piston has a shoe that slides on a swash plate during rotation. This swash plate is angled and gives the correct oil amount. The angle of the swash plate causes a piston movement, which produces a suction side and a pressure side. The swash plate is spring loaded to a maximum angle, or full delivery. The regulator in the pump controls the delivery amount and thus reduces the delivery. The regulator maintains the system full of oil with the correct pressure, typically 207 bar. When a component consumes oil, it results in lower pressure. The regulator will notice this and angle the swash plate for more delivery until correct pressure is obtained. The balance between the spring and the piston is controlled by the regulator and gives a constantly fixed pressure, while variable amount of oil [l/min] is needed and dependent of which consumers that are active in that moment.

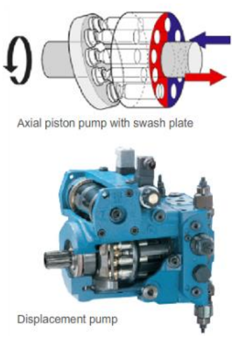


Figure 4-3: Axial piston pump, BoschRexRoth A10 pump.

Oil reservoir

The hydraulic oil tank serves as storage reservoir for the hydraulic fluid.

Return oil system

Return oil from various consumers enters the return manifold before it flows back to the reservoir via the return filter(s). There are installed return check valves in order to maintain a constant backpressure of 1 bar in the return system.

Drain oil system

Drain oil form various consumers enters the drain manifold before it flows back to the reservoir via the drain filter(s).

4.2 Power

Power is the pressure multiplied by the flow:

$$\boldsymbol{W}[\boldsymbol{J}/\boldsymbol{sec}.] = \boldsymbol{P}[\boldsymbol{Pa}] * \boldsymbol{Q}[\boldsymbol{m}^3/\boldsymbol{sec}.] \quad (4)$$

The power needed from the HPU is dependent on which activities, machines and operations that will be run, as well as pressure drops between the HPU and the consumers. The machine with the highest pressure needed to be operated, result in the pressure needed from the HPU. The highest flow needed to the consumers, including simultaneous operations and activities, will give the highest flow needed from the HPU. This will have to be evaluated by the department Drilling Systems, referring to chapter 9.

4.2.1 Flow in a Cylinder

The hydraulic consumption of a cylinder is calculated according to:

$$\boldsymbol{Q}\left[\frac{\boldsymbol{m}^3}{\boldsymbol{sec}.}\right] = \boldsymbol{A}[\boldsymbol{m}^2] * \boldsymbol{v}[\frac{\boldsymbol{m}}{\boldsymbol{s}}] \quad (5)$$

Where *A* is the cross-sectional area of the piston at the piston side or rod side, *v* is the needed velocity to stroke and *Q* is the hydraulic flow for the cylinder as a result of the cross-sectional area and desired velocity of cylinder.

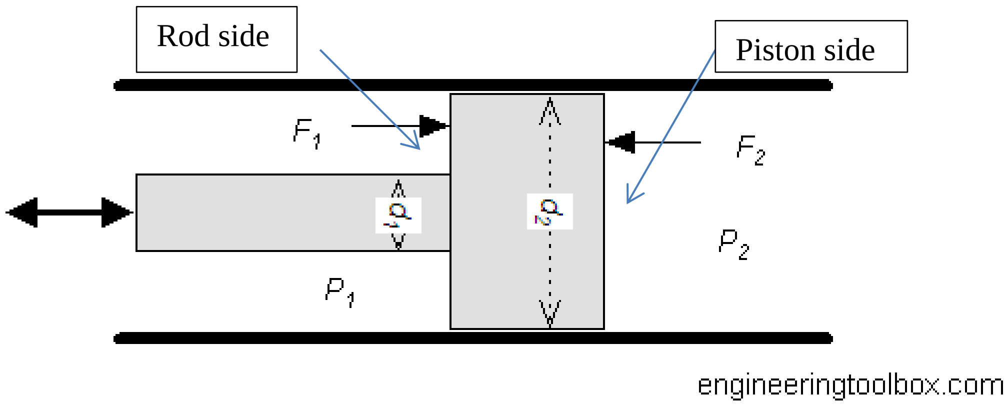


Figure 4-4: Cylinder [12]

Methods evaluated to be useful for Drilling Systems

The goal is to make the machine configuration as efficient as possible. The methods and evaluations needed are discussed in cooperation with Jan Morten Haavik.

5 Gantt chart

It is possible to use Microsoft Project (MS project) to build the sequence of operations constituting one activity, e.g. the activity tripping in. A Gantt chart gives a nice impression of the dependencies, sequence of operations, simultaneous operations, duration of each operation and duration of the activity. The Gantt chart show the duration for the activity and where to improve, i.e. decrease the duration of the activity.

5.1 Sequence of operations in Microsoft Project 2010

To illustrate the functionality of MS project, the trip in sequence is rebuilt in this program and displayed in a Gantt chart.

Operations

Write up the operations in MS project.

Machines and operator

It is of interest to type in the associated machine and chair (IOC) for each operation to indicate which machine and which operator that will execute or be responsible for the operation. The machines chosen for the trip in sequence in Figure 5-1 are:

- Vertical pipehandler: Hydraracker (HR)
- Roughneck: (ARN)
- Topdrive: (TD)
- Drawwork: (DW)

Chair A represent the driller and Chair B represent the assistant driller.

Durations and dependencies

The next step is to evaluate and type in the duration of each operation. The operations are dependent of each other, these dependencies need to be evaluated and typed in. The sequence of operations will be a result of these dependencies. The Gantt chart will know show the sequence of operations and the total duration of this activity is given by what is called the “Critical path”. The red color indicates the critical path for the activity, arrows indicates the dependencies between the operations and the black horizontal lines indicate the slack for operations. Operations which are part of the critical path will not have any slack. See Figure 5-1 below.

NB! In MS project the lowest level of time unit is minutes, but this will actually refer to seconds.

	Machine	Name	Duration		Task Mode	IOC	Predecessor
1	TD	Dolly extend	6 mins			1	
2	HR	HR guide open	3 mins			2	1
3	TD	Open slips	3 mins			1	1
4	DW	Elevate to take string weight	3 mins			1	1
5	DW	Lower to stickup	24 mins			1	4;3
6	DW	Lowering last section	3 mins			1	5;13
7	TD	Close slips	3 mins			1	6
8	DW	Transfere weight to slips	3 mins			1	7
9	TD	Open elevator	3 mins			1	8
10	TD	Retract TD clear of stickup	6 mins			1	9
11	DW	Elevate till pipehandler above new stand	18 mins			1	10
12	ARN	Travel forward	8 mins			2	10;13
13	ARN	Travel back	11 mins			2	
14	ARN	Travel forward and elevate	5 mins			2	13
15	ARN	Spin clamp close	3 mins			2	14;12
16	ARN	TW lower clamp close	3 mins			2	14
17	HR	Move to FB	18 mins			2	2
18	HR	Lift stand, open FB and move out of FB.	3 mins			2	17
19	HR	To standby positons	15 mins			2	18
20	HR	To WC	4 mins			2	10;19
21	HR	Lower	5 mins			2	20
22	HR	Stab	3 mins			2	15;21
23	HR	HR guide close	3 mins			2	18
24	HR	HR gripper open	3 mins			2	22;23
25	ARN	Spin in	10 mins			2	24
26	ARN	Make up connection	10 mins			2	25;16

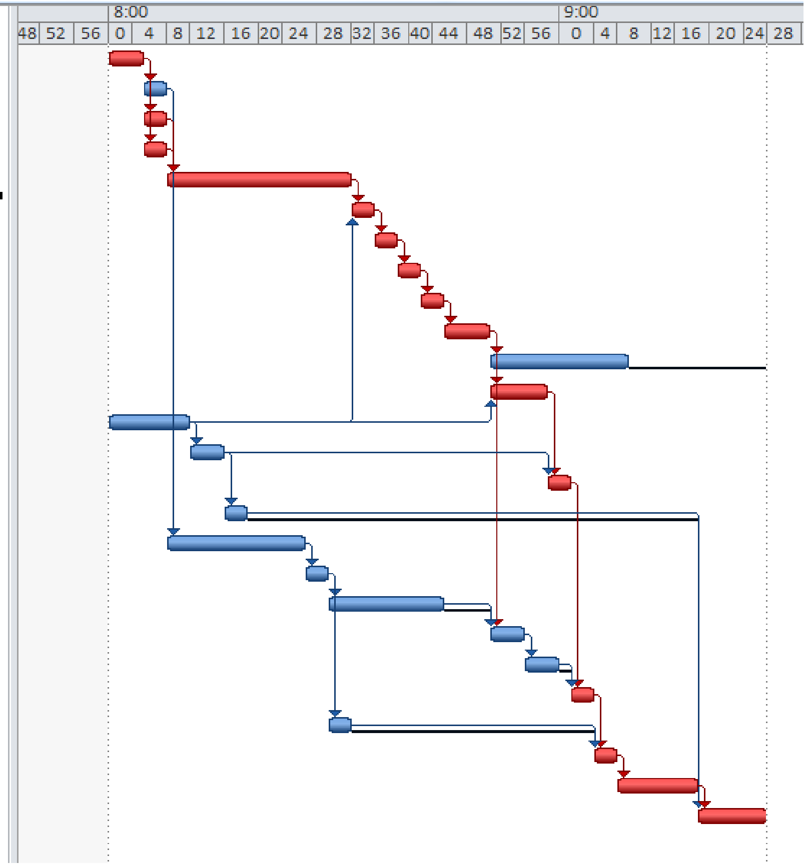


Figure 5-1: Tripping in illustrated by Gantt diagram in MS project. This figure refers to the same setup as Figure 3-5. The duration is represented with mins, but this actually refers to seconds, as it is not possible to present the duration in seconds in MS project!

Operator input/verification

The driller need to have time to confirm and choose operations when operating from the driller's cabin/chairs. This duration needs to be added to the Gantt chart to illustrate a realistic duration of tripping one stand.

Dependencies

The dependencies between the operations show the procedure of how to perform the specified activity. You may drive a machine faster or decrease the travelling distance to decrease the duration of an activity, but the dependencies are set according to restrictions. The restrictions which define a dependency are:

- Passive object present, e.g. the stand or the drillstring.
- Executing machine present at desired/needed coordinate (x,y,z)
- Passive object free to move on
- Interlock: Always one gripping "hand" holding the passive object, i.e. no falling objects.
- Collision: Free trajectory for executing machine and passive object

I.e. the dependencies rely on which machines and the configuration (layout).

Critical path

In an activity represented in MS project, the critical path will illustrate the operations that are critical for the activity. If one of these operations is made in less time, the duration of the activity will decrease. The goal is to set up the correct dependencies and duration for each operation in the activity and find the critical operations which will be the bottlenecks and therefore the operations to improve. MS project have the functionality to show the critical operations as illustrated in Figure 5-1 by red color.

6 Evaluation of Duration

Duration of an activity is a measure of the efficiency for the activity. To achieve the duration and decrease the duration of an operation, it would be of interest to study the following.

6.1 Operation level

From General Arrangement (GA) drawings it is possible to get information about the velocity and the distance to travel (trajectory) of an operation. Dividing distance by velocity you obtain the duration for the operation, referring to:

$$\boldsymbol{t}[\boldsymbol{sec.}] = \frac{\boldsymbol{d}(\boldsymbol{p},\boldsymbol{q})[\boldsymbol{m}]}{\boldsymbol{v}[\frac{\boldsymbol{m}}{\boldsymbol{s}}]} \qquad (6)$$

In formula (6) *d(p,q)* represent the travelling distance from standby position *p* to standby position q for the operation, *v* is the constant(average) velocity and *t* is the duration.

6.2 Cylinder level

For operations missing information about velocity and distance at operation level, it is possible to break down to a level of cylinders which fulfill the operation. By combining information of velocity and stroke (distance), duration for a cylinder is given. This information is given both for extension and retraction of a cylinder in drawings. Dividing stroke (distance) by the velocity you obtain the duration to one cylinder:

In formula (6) *d(p,q)* represent the travelling distance to the stroke, *v* is the average velocity and *t* is the duration.

Assemble durations of each cylinder – discrete movement

If the trajectory for the operation is made up by discrete movement of cylinders which constitutes a discrete movement of the operation, the duration for the operation can be calculated summarizing the durations for each cylinder.

$$\boldsymbol{t_{op}} = \boldsymbol{t_{cy1}} + \boldsymbol{t_{cy2}} + \cdots + \boldsymbol{t_{cyn}} \qquad (7)$$

Where t_{op} = duration for operation, t_{cy1}, t_{cy2},….t_{cyn} is duration for each cylinder.

Assemble durations of each cylinder – continuous movement

If the trajectory for the operation is made up by overlapping and simultaneous movement of cylinders which constitute a continuous (smooth) movement of operation, the duration has to take cylinders operating simultaneously into account. Information about cylinders operating simultaneously need to be given from employees which have programmed the trajectory of the operation.

In this case, the duration (t_{op}) for the operation will not be the sum of the duration for each cylinder as in formula (7). The duration for the operation will be lower than if calculated based on formula (7). The velocity needed for each cylinder is the same. What make the duration of an operation less is the overlapping durations for movement of cylinders or from another point of view, the shorter trajectory for the operation.

The overlapping movement of cylinders and hydraulic motors, which constitute the operation, fits to be set up in a Gantt chart. This will now give you the correct duration of the operation.

6.3 Logged duration

It is possible to use data from logged duration from simulator, real data from tests onshore or offshore to obtain the duration of an operation.

6.4 Decreasing the distance and trajectory

To decrease the duration of an operation you can decrease the travelling distance of an operation which is part of the critical path, refers to formula (6).

Three dimensional coordinates

It would be of great value to incorporate a three dimensional Cartesian coordinate system referring to the Well Center (WC) where the machines standby positions are set, but can be changed. The travelling distance, *d(p,q)*, of a straight line between two standby positions is calculated according to the formula for the length of a three dimensional vector:

$$\boldsymbol{d(p,q) = \sqrt{(p_1 - q_1)^2 + (p_2 - q_2)^2 + (p_2 - q_2)^2}} \qquad (8)$$

Where $p = [p_1, p_2, p_3]$ and $q = [q_1, q_2, q_3]$ is the two standby positions with reference to WC.

Changing coordinates

By introducing coordinates for standby positions, it would be of interest to be able to change these coordinates and see the consequence regarding duration.

By changing the coordinates of a standby position, it is possible to calculate the new travelling distance to the operation, formula (8), and the corresponding new duration to the operation, formula (6).

Visualization

There is a need to visualize the machine configuration. Coordinates for standby positions and trajectories should be possible to see in 3D to be able to maneuver the standby positions in order to minimize the duration of an activity. 3D pictures will help you visualize the coordinates to the standby positions and trajectories.

6.5 Increasing the velocity

To decrease the duration of an operation you can increase the velocity of an operation which is part of the critical path, refer to formula (6). This will demand a higher hydraulic consumption or electric current to the operation/machine.

6.5.1 Velocity of hoisting and lowering the drillstring

The operation to hoist or lower the drillstring has restrictions as:

- Pore pressure
- Fracture pressure
- Friction in the well
- Drawwork machinery

Drawwork machinery

The velocity of hoisting and lowering of the drillstring is dependent on the hook load. The hook load is a result of the weight of drillstring and friction. Eliminating friction and specifying dimension of drill pipe, the weight is a product of how long the drillstring is. As more stands is disconnected from the drillstring while tripping out, the hook load decreases. As more stands are added to the drillstring while tripping in, the hook load increases. Less hook load give higher speed of drawwork as shown when comparing Figure 6-1 and Figure 6-2 or Figure 6-3 and Figure 6-4.

By comparing Figure 6-1 and Figure 6-5, hoisting with 12 lines will have a higher speed, but 12 lines will demand less maximum weight compared to 14 lines. This is the logic behind block and tackle.

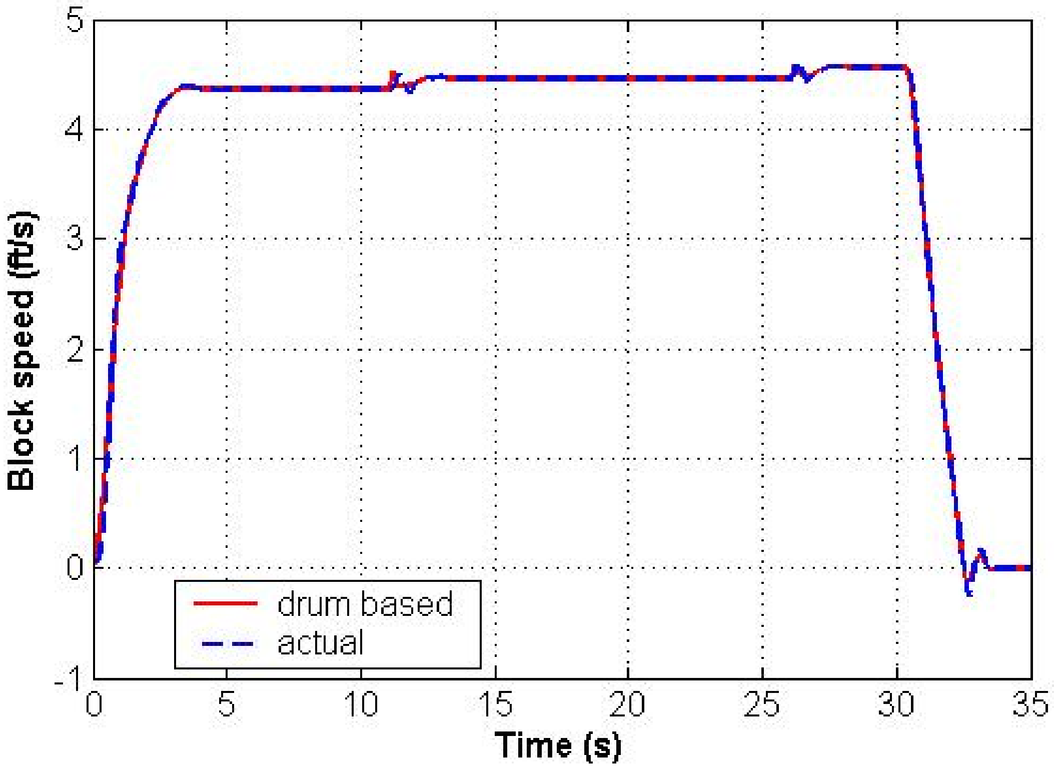


Figure 6-1: Hoisting 400 sT (363 mT) with 12 lines. [2]

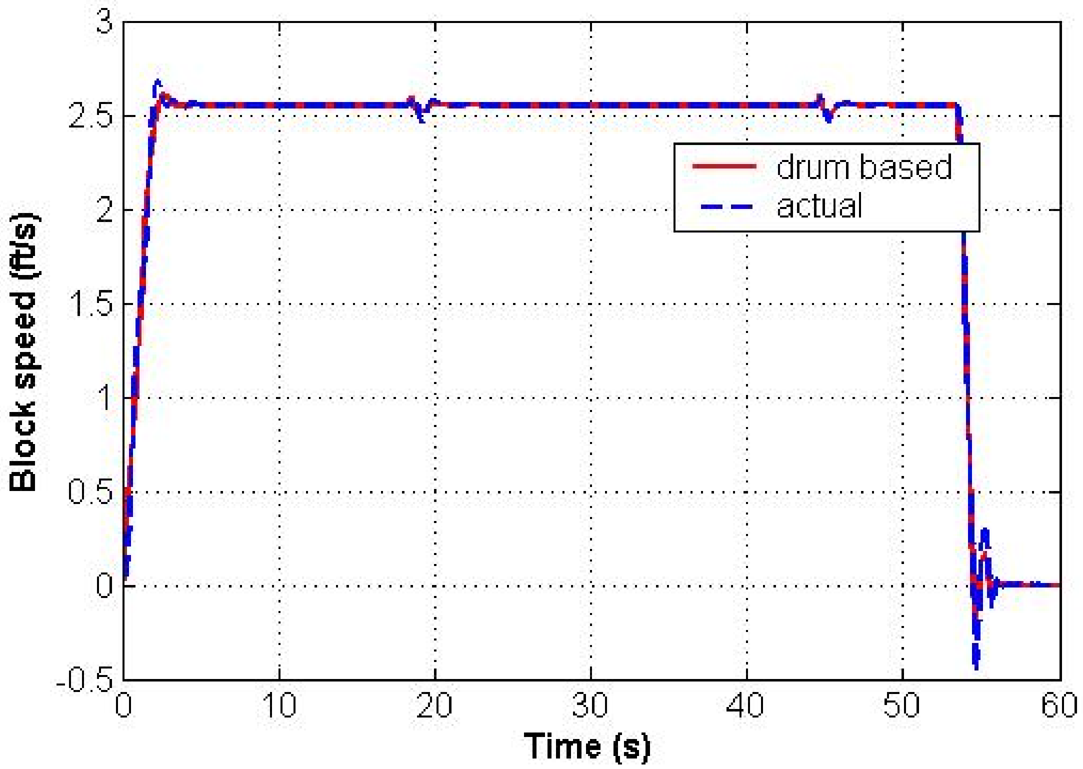


Figure 6-2: Hoisting 750 sT (680 mT) with 12 lines. [2]

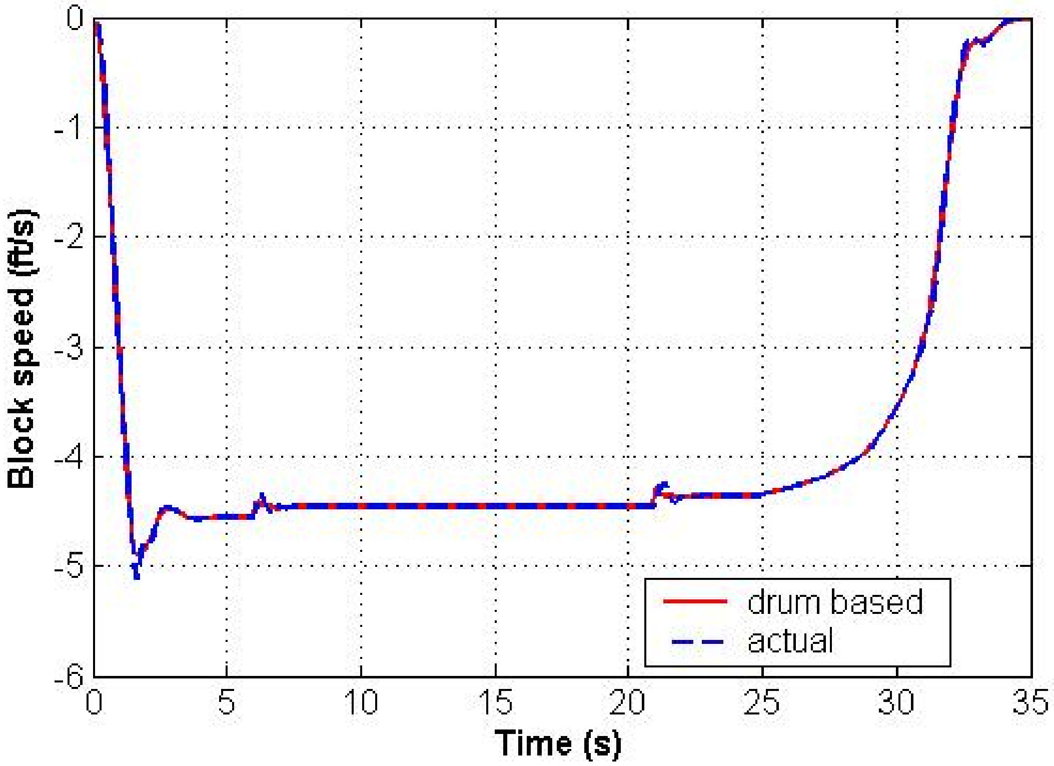


Figure 6-3: Lowering 400 sT (363 mT) with 12 lines. [2]

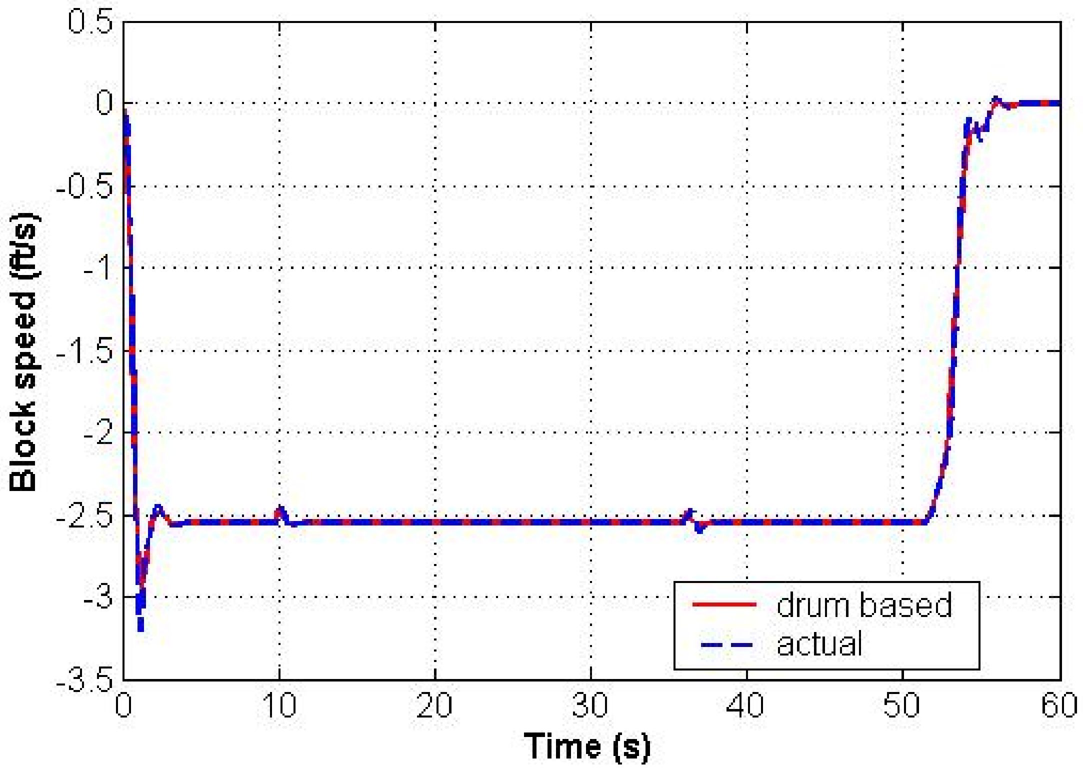


Figure 6-4: Lowering 750 sT (680 mT) with 12 lines. [2]

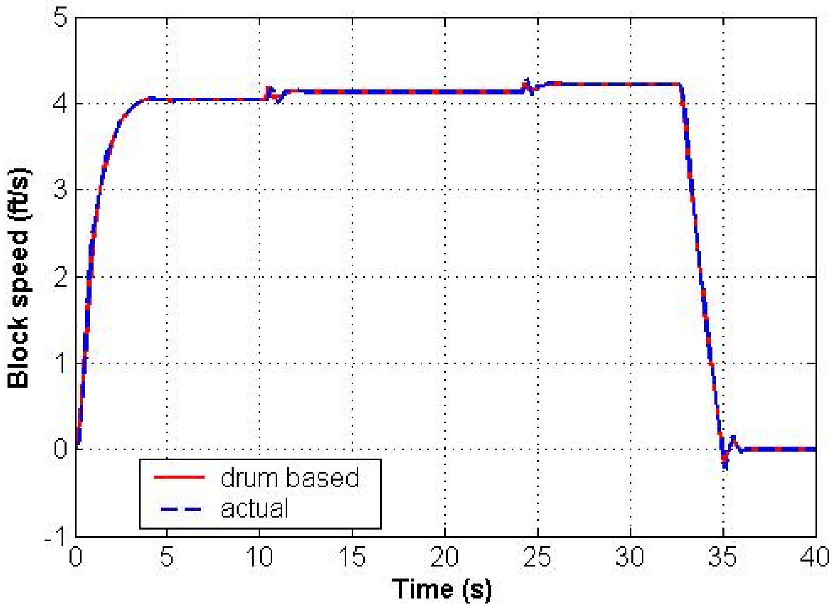


Figure 6-5: Hoisting 400 sT (363 mT) with 14 lines. [2]

Frictional forces

Frictional forces as drillstring in contact with the wall of the well increase the hook load. The hook load is also affected by the hydrodynamic force caused by flow rate, density and rheology of drilling fluid. These scenarios are not evaluated in this thesis.

Swab and Surge

By pulling the drillstring you produce a swab pressure which is negative and will reduce the pressure at a given point in the well.

By lowering the drillstring you produce a surge pressure which is positive and will increase the pressure at a given point in the well.

In conventional drilling you have to stay between the pore and fracture pressure in the open-hole section, thus swab and surge pressures need to be evaluated regarding the velocity of lowering or hoisting the drillstring.

See chapter 7 for more information regarding this topic.

6.6 Simultaneous operations

It is desirable to perform operations simultaneously as long as the dependencies between the operations are maintained. A machine configuration with few dependencies needed, will be illustrated in MS project with many simultaneous operations, which result in an efficient activity.

6.7 Summary

To increase the speed of tripping:

- Organize possible operations in the activity to operate simultaneously.
- Increase the velocity of an operation which is part of the critical path.
- Decrease the travelling distance which is part of the critical path.

7 Surge/Swab pressures and ECDs

By pulling the drillstring out of the well you produce swab pressures and by lowering the drillstring into the well you produce surge pressures [13]. In a trip out activity the goal is to hoist the drillstring out of the well. In a trip in activity the goal is to lower the drillstring into the well. Swab pressures are negative and will reduce the pressure. Surge pressures are positive and will increase the pressure.

The conventional way to drill a well is in overbalance, i.e. mud pressure above pore pressure. At the same time you do not want to exceed the fracture pressure, which would fracture the formation (open-hole section, rock). These well parameters restrict the velocity of hoisting and lowering the drillstring, thus well parameters as pore pressure gradient and fracture gradient are needed.

By assuming that the DW is strong enough to hoist or lower the drillstring at desired velocities, the pore pressure and fracture pressure is the restrictions. The effect of swab or surge becomes higher when you increase the velocity of hoisting or lowering the drillstring.

The undesired incidences are:

- If well pressure < pore pressure => Inflow of formation fluid, collapse and kick.
- If mud pressure > fracture pressure => Fracture of formation and lost circulation.

The surge and swab pressures are dependent on the cross-sectional area of the annulus, the viscosity of the mud, the velocity of pipe movement and the length of drillstring inside the well. See chapter 7.4 and formula (10).

7.1 Swab

As pipe is pulled out of the well, there constantly occurs a new volume in the well. As a result the pressure decreases and frictional forces limit the flow of fluid downwards to this location in the well. This establishes a frictional pressure drop in the direction of flow downwards and a lower pressure in the well. Thus swab pressure is negative and will reduce the pressure at a given point in the well. This pushes the well pressure towards the pore pressure limit. [14]

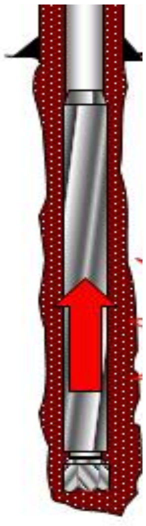


Figure 7-1: Swabbing, an effect of hoisting the drillstring. [13]

If the swabbing effect results in a well pressure beneath the pore pressure, there will be inflow of formation fluid into the well. A critical situation is that if low density formation fluid flow into the well as the well pressure deceede the pore pressure. The low density formation fluid mixes with the mud so that the mixed mud system density will be reduced. This will reduce the Bottom Hole Pressure (BHP) to a lower static mud weight. The static mud weight is now the mixed mud system density. [13]

7.2 Surge

As pipe is lowered into the well, the fluid is displaced by the drillstring and the pressure increases in the well. The frictional forces limit the flow of fluid upwards. This establishes a frictional pressure drop in the direction of flow upwards and a higher pressure in the well. Thus surge pressure is positive and will increase the pressure at a given point in the well. This pushes the well pressure towards the fracture pressure limit. [14]

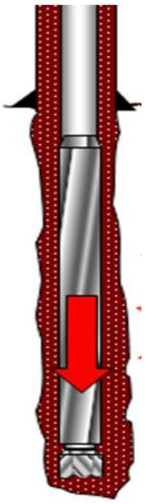


Figure 7-2: Surge, an effect of lowering the drillstring. [13]

7.3 The effect of flow rate on ECD

The Equivalent Circulating Density (ECD) of drilling fluid is the sum of the hydrostatic and dynamic effect/friction.

ECD = Static + Friction

$$ECD = \rho_{static} + \frac{\Delta P_{friction}}{g * TVD} \tag{9}$$

Where $\Delta P_{friction}$ = annular and choke pressure loss, ρ_{static} = static mud density, g = acceleration.

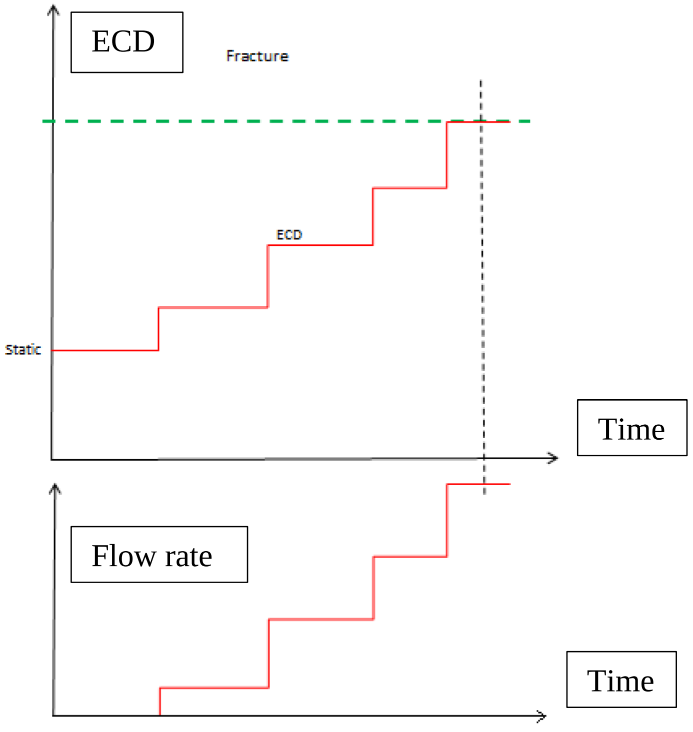


Figure 7-3: The effect of flow rate on ECD [13]. At critical flow rate the ECD crosses the fracture pressure.

7.4 Swabbing effect and flow rate

Hoisting of the drillstring reduce the well pressure.

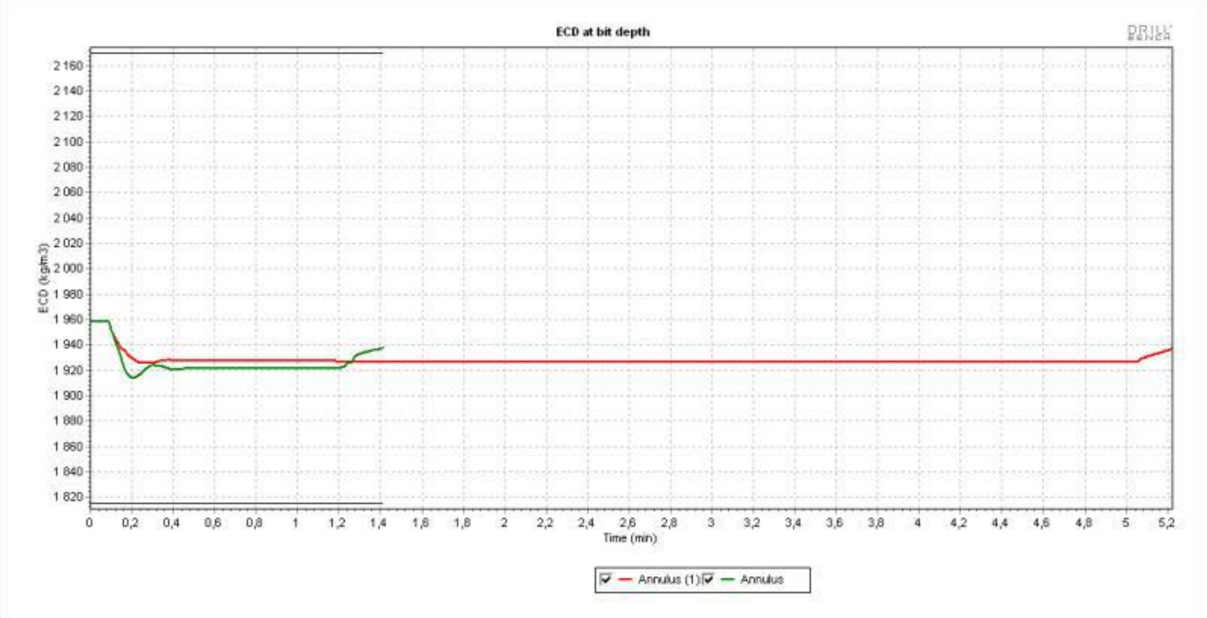


Figure 7-4: ECD when swabbing, no circulation [15]. Red curve for pulling slow, green curve for pulling fast.

Figure 7-4 show simulated values calculated with the use of Drillbench simulator.

In order to compensate for the swabbing effect you can increase the flow rate of mud during hoisting of drillstring, tripping out. While hoisting the drillstring, the correct flow of drilling fluid needs to be evaluated to maintain overbalanced. Higher velocity of hoisting the drillstring will decrease the pressure in the well and a higher flow rate is needed to stay overbalanced. [13]

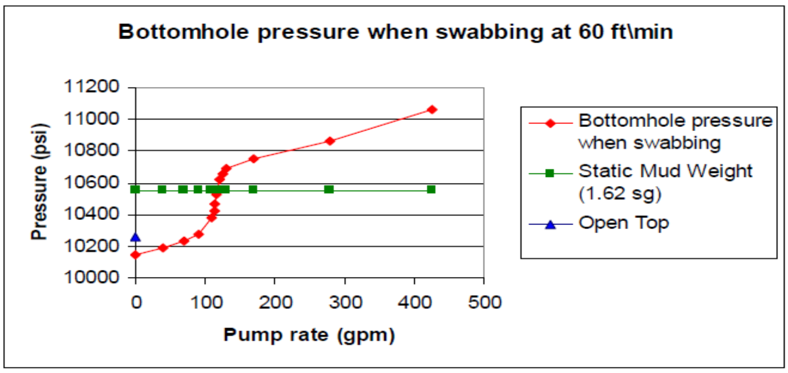


Figure 7-5: To maintain the Bottom Hole Pressure (BHP), the flow rate need to be approx. 120 gpm during hoisting 60 ft/min. [16]

Figure 7-5 show simulated values calculated with the use of Drillbench simulator.

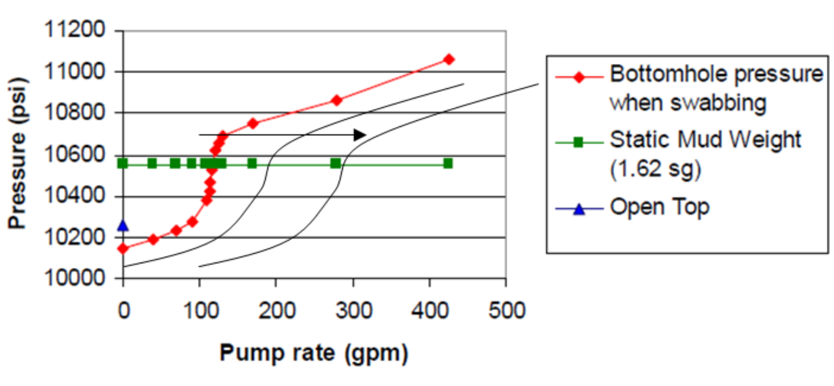


Figure 7-6: As the hoisting speed increase, a higher flow rate is required to maintain BHP.

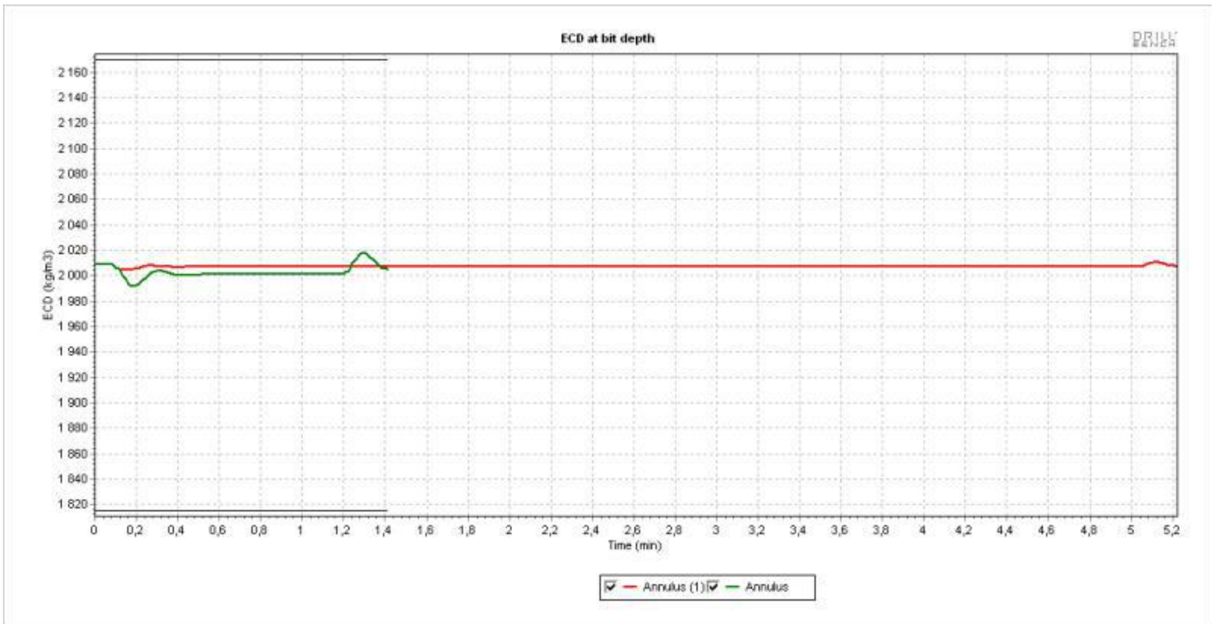


Figure 7-7: ECD when swabbing, circulation rate 1500 litre per minute (l/min) [15]. Red curve is for pulling slow, green curve is for pulling fast.

Figure 7-7 show simulated values calculated with the use of Drillbench simulator.

Interpretation of Figure 7-4 and Figure 7-7: Figure 7-4 with no circulation show 1960 kg/m^3 at time=0min, while Figure 7-7 show 2010 kg/m^3 at time=0min. ECD is higher on Figure 7-7 due to circulation at t=0min. For Figure 7-4 the ECD for the green line drops to 1915 kg/min corresponding to 45 kg/ m^3 drop, while Figure 7-7 green line drops to 1990 kg/min corresponding to 20 kg/m^3 drop. *The frictional pressure drop according to Figure 7-7, circulating 1500 l/min, gives a lower swab pressure than Figure 7-4, no circulation.*

7.5 Surge effect and flow rate

Lowering the drillstring increase the well pressure.

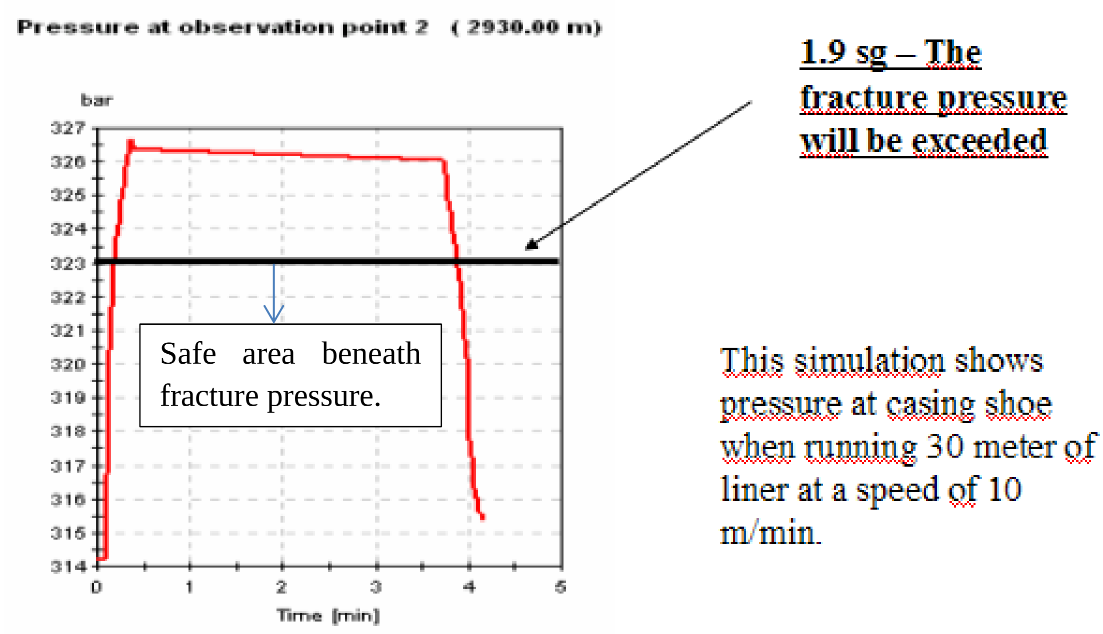


Figure 7-8: As the velocity of lowering the drillstring increases, the well pressure also increases, red line. [17]

Figure 7-8 show simulated values calculated with the use of Drillbench simulator.

In order to compensate for the surge effect you can decrease the flow rate of mud during lowering the drillstring, tripping in. While lowering the drillstring, the correct flow of drilling fluid needs to be evaluated to avoid fracturing the formation. Higher velocity of lowering the drillstring will increase the pressure in the well and a lower flow rate is needed to maintain the BHP beneath the fracture pressure. [13]

7.6 Summary

To stay above pore pressure while hoisting the drillstring, a higher flow rate is required.

To stay beneath fracture pressure while lowering the drillstring, a lower flow rate is required.

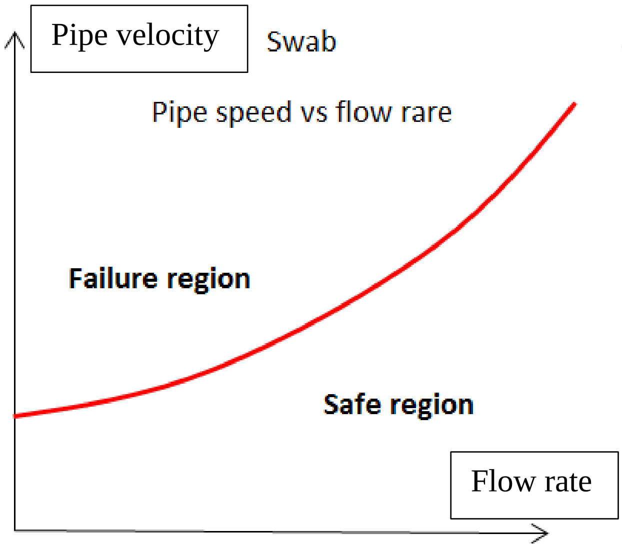


Figure 7-9: Swab-Pipe speed vs. flow rate. [13]

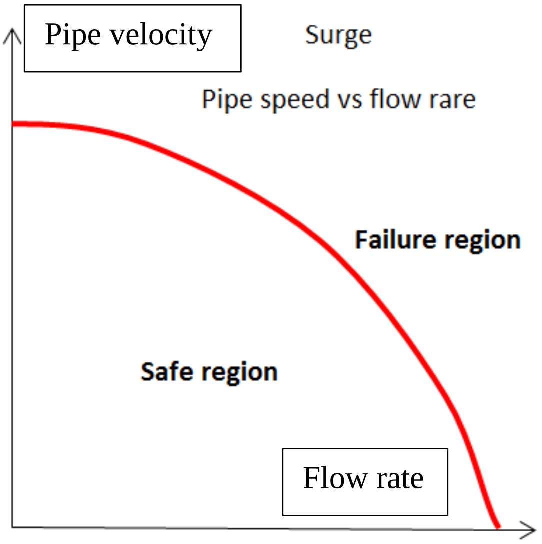


Figure 7-10: Surge-Pipe speed vs. flow rate. [13]

7.7 Swab and surge calculation – frictional pressure drop due to vertical pipe movement.

From known procedures, the driller is able to hoist or lower the drillstring faster when the drillstring is in the riser and upper part of the casing compared to deeper down in the well. Thus the hoisting system and machine configuration may be the limiting factor in the riser and upper part of the casing. [18]

To explain how the driller is able to lower or hoist the drillstring fast in the riser or upper part of the casing, a model and expression need to presented. According to reference [14], for steady state, annulus represented as a narrow slot, laminar flow and a newtonian fluid, the pressure gradient is:

$$\frac{dp_f}{dL} = \frac{12\mu(v_a + \frac{v_p}{2})}{(r_2 - r_1)^2} \tag{10}$$

Where μ is the viscosity, v_a is the annular flow due to vertical pipe movement, v_p is the velocity of vertical pipe movement, r_2 is the inner radius of well and r_1 is the outer radius of the drillstring.

For closed ended pipe v_a is a function of v_p, r_r and r_2, see chapter 8.3, formula (14).

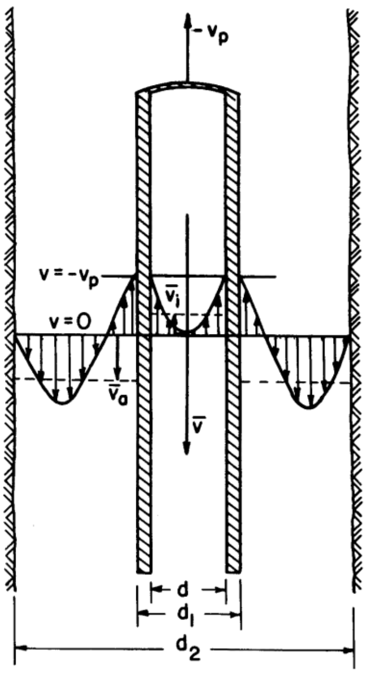


Figure 7-11: Velocity profiles for laminar flow pattern when pipe is pulled out of hole. [14]

In formula (14), V_a decreases when r_2 increases. According to equation (10), the swab or surge pressure decreases when r_2 increases and v_a decreases. Equation (10) and (14) illustrates the fact that by increased cross-sectional area of the annulus, the pressure loss or gain due to vertical pipe movement is decreased. This explains that the driller can run the drillstring faster when the drillstring is in the riser and casing, while if the drillstring reaches the liner deeper down, r_2 decrease, thus the annular cross-sectional area decrease, thus the pressure gradient due to vertical pipe movement will increase and affect the Bottom Hole Pressure (BHP) more.

The BHP is also affected by the length of drillstring that are inside the well while performing vertical pipe movement. E.g. if the drillstring at one moment is 300ft inside the riser, lowered into the well at a specified velocity and the pressure gradient due to surge is calculated to 0,04 psi/ft, the BHP will be increased due to surge by 0,04psi/ft * 300ft = 12 psi. If the pressure gradient due to surge stays 0,04 psi/ft, but the drillstring is 600ft into the riser, the BHP will be increased due to surge by 0,04psi/ft * 600ft = 24 psi. This show that as the drillstring is deeper down in the well, the impact on the BHP due to vertical pipe movement increases.

Summarized, when the drillstring is at shallow depth, as in the riser and upper part of the casing, the annular cross-sectional area is bigger and the length of drillstring in the hole is less. This makes it possible for the driller to run fast in the riser and the upper part of the casing, as the impact of surge or swab is smaller in this section of the well.

In chapter 8.3, a simplified calculation of surge pressure is done.

8 Evaluation of efficiency for a specified rig – tripping in

The information needed to evaluate the efficiency on a specified rig is available from NOV, but the thesis is restricted to not point out which drilling rig and operator the rig is made for. Thus the rig is named without its real name and the operator not mentioned. The sequence of operations has been set up in MS Project by Kjell Rhode working for NOV. The duration of each operation is based on NOV documentation.

The goal for this chapter is to show the logic for how to evaluate the efficiency of an activity for a specified rig. A specific rig has specified machines and configuration (layout). The machines and the configuration give:

- Dependencies between operations
- Distance and velocity of the operations which gives the duration of each operation.

Based on the dependencies between the operations and the durations for each operation, MS Project will show the critical path(s), referring to chapter 5. One critical path defines the duration of an activity. If there is only one critical path, i.e. no parallel critical paths, decreasing the critical operations will decrease the duration of an activity.

Questions that need to be answered to increase the efficiency of an activity are:

- Which operations are critical (bottlenecks) for the activity on the specified rig?
- Is there only one critical path or do there exist parallel critical paths?
- How much is it possible to reduce the duration of each critical operation until further reduction will not reduce the duration for the activity?
- Which critical operations reduce the duration of tripping in the most?
- Which of these critical operations are easy and possible to reduce?
- What can be done to decrease the duration of these critical operations?

NB! The duration in MS project is represented with mins, but this actually refers to seconds, as it is not possible to present the duration in in seconds in MS project.

8.1 Rig 1

Rig 1 is in the design phase and the customer has asked for the duration for tripping in one stand. See figures 8-2, where Figure 8-2 shows the whole activity, Figure 8-2-a, Figure 8-2-b and Figure 8-2-c together constitute Figure 8-2.

The duration of operation ID 6, “Lower to stickup”, is set to 49 sec. One stand on this rig is 41 m long. I.e. the average speed lowering the drillstring is 41m/49sec = 0,84 m/sec.

The duration of operation ID 15, “Elevate till pipehandler above new stand”, is set to 36 sec. I.e. the average speed hoisting the TopDrive (TD) is 41m/36sec = 1,14 m/sec.

Tripping in is evaluated to take 124 sec/stand, i.e. 29 stands/hr.

8.1.1 Critical operations

First question is: Which operations are critical (bottlenecks) for the activity?

The critical operations for Rig 1 while tripping in are marked red in figures 8-2, filtered out in Figure 8-3 and listed in Figure 8-4.

Second question is: Is there only one critical path or do there exist parallel critical paths?

As can be seen in Figure 8-4, there is only one critical path. This means that by reducing the duration of one of the critical operations, the duration of tripping in will decrease.

Evaluation of critical operations

Third question is: How much is it possible to reduce the duration of each critical operation until further reduction will not reduce the duration of tripping in?

The answer to the second question is easy to obtain by testing each critical operation in MS project. The test is executed by decreasing the duration of a critical operation until the critical path changes or the duration of the critical operation reaches 0 seconds. After one critical operation has been tested and given the value of how many seconds it is helpful to reduce until further reduction will not reduce the duration of tripping in, the duration of the critical operation is set back to its original value, and the next critical operation is tested. These values of how many seconds it is helpful to reduce the duration of a critical operation, is listed in column *Reduced duration each operation* in Figure 8-4.

Fourth and fifth question are: Which critical operations reduce the duration of tripping in the most? Which of these critical operations are easy and possible to reduce?

The operation with the highest value in column *Reduced duration each operation* in Figure 8-4 shows the operation with biggest impact to decrease the duration of tripping in. The answer to which critical operations that are evaluated to be easy and possible to reduce is evaluated below.

The critical operations are listed in Figure 8-4. Beneath is a description of the different columns used in Figure 8-4.

Operation ID: is the ID-number given in MS project for each operation.

Operation description: describe the operation.

Duration: is the original duration for each operation.

Machine: lists the machines executing the operation.

Reduced duration each operation: One operation has a specified amount of seconds to be reduced before the critical path changes or the duration of the operation is reached. This value is obtained by decreasing the duration of one of the critical operations until the critical path changes or the duration reaches 0 seconds.

E.g. Rig 1: The *Duration* of *Operation ID* 7 is 3 seconds and can be reduced by 3 seconds. The *Duration* of *Operation ID* 6 is 49 seconds and can be reduced by 20 seconds before the critical path changes. The reason why the critical path changes for *Opertaional ID* 6 is that there is another parallel branch of operations which restricts to decrease the *Duration* of tripping in more than 20 seconds.

<u>*Group*</u>: It is evaluated to be useful to define groups for the critical operations according to operations that make one branch of operations in the Gantt chart, see figures 8-2. One group will not have any branching in the Gantt chart. Where there is branching in the Gantt chart, this will define a new group. Grouping is made to illustrate the different branches of operations and how they affect the duration of an activity.

<u>*Reduced duration each group*</u>: One group of operations has a specified amount of seconds to be reduced before the critical path changes or total amount of duration in the group is reached.

E.g. Rig 1: The operations in *Group* 1 can in total be reduced by 20 seconds before the critical path changes. If the *Duration* of operations which is part of *Group* 1 is decreased more than 20 seconds, the operations in *Group* 1 will not be part of the critical path. There is another parallel branch of operations which restrict to decrease the duration of tripping in more than 20 seconds.

<u>*Changed duration*</u>: Lists only the new durations of the operations which have been evaluated to decrease.

E.g. Rig 1: Intuitive choice is to start to decrease an operation which belongs to the *Group* with the highest value of *Reduced duration each group*, but this need to be evaluated. *Group* 1 has highest value, 20 seconds, which can be reduced before the critical path changes. *Operation ID* 6 is part of *Group* 1 and has 20 seconds for *Reduced duration each operation*. Thus this will be the intuitive operation to decrease in *Group* 1, as this will exploit the available *Reduced duration each group* for *Group* 1. Decreasing the duration of *Operation ID* 6, "Lower to stickup", is of interest, but may be restricted to well parameters, referring to chapter 7 and 8.3. On the other hand, *Operation ID* 15 is not restricted by well parameters and constitute the group with the second largest value of *Reduced duration each group*. The drillstring is not connected to the TD while *Operation ID* 15 is executed, "Elevate till pipehandler above new stand". The only restriction to *Operation ID* 15 is how fast the DW is able to hoisting an empty block. Thus the primary operation to evaluate if it is possible to decrease the *Duration* is *Operation ID* 15 and the secondary operation is *Operation ID* 6.

Evaluation of solution to decrease the duration of tripping in

Operation ID 15 is a critical operation which is possible to reduce by 10 seconds before the critical path changes. There is no need to reduce this operation more than 10 seconds since that will change the critical path. *Operation ID* 15 is named “Elevate till pipehandler above new stand”. In other words, the drillstring has been lowered and is suspended in the slips, while the Top Drive (TD) is hoisted from drill floor to top of new stand. This means that *Operation ID* 15 is not restricted by well parameters, but only by the hoisting system and its velocity to pull an empty block.

Sixth question is: What can be done to decrease the duration of these critical operations?

As already indicated, a solution to this is to increase the velocity to *Operation ID* 15 and 6.

In parallel and while TD elevates to reach top of new stand, the new stand is connected to the drillstring by the ARN machine. The ARN machine connects a new stand faster than the TD reach top of new stand. The goal is to eliminate to wait for the TD to be hoisted above new stand. To see the effect of reducing the *Duration* of *Operation ID* 15, see Figure 8-5. This can be obtained by hoisting the TD faster. The average velocity needed for this is: 41 m / (36-10) sec. = 1,58 m/s. This average velocity considers acceleration, maximum constant velocity and deceleration.

A cylinder hoisting system will fulfill the average speed of 1,58 m/s. A specified cylinder hoisting system delivered by NOV has a maximum speed for operational ID 15 of 2,4 m/s [2]. If possible, a less extensive modification will be a faster DW, able to hoist the empty block with an average velocity of 1,58 m/s.

A cylinder hoisting system demands an expensive modification for Rig 1. Therefor Rig 1 is evaluated to be given a faster DW for hoisting an empty block. NOV documentation show that there exist a DW that hoist an empty block with a maximum constant velocity of 6,3 ft/sec = 1,92 m/s. See figure below, Figure 8-1.

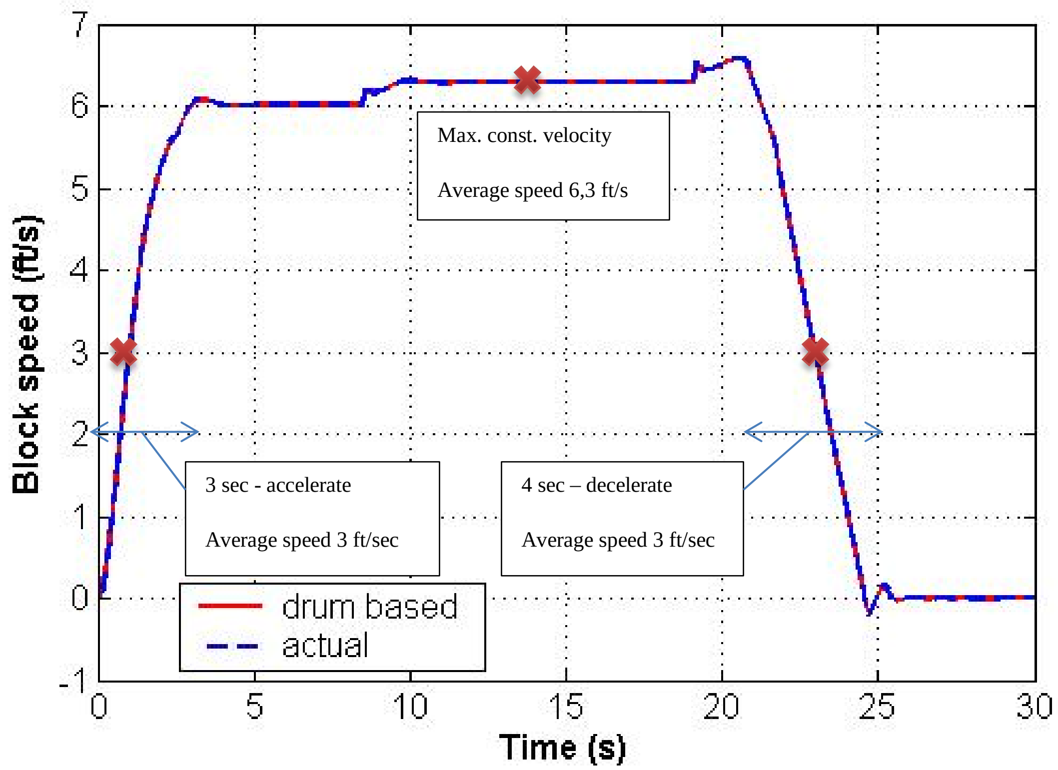


Figure 8-1: DW hoisting an empty block with 12 lines. [2]

The average velocity related to Figure 8-1 and hoisting for 26 seconds is then approximately:

(3ft/sec * 3sec + 3ft/sec * 4sec + 6,3ft/sec * (26-3-4)sec) / 26sec = 5,41ft/sec = 1,65m/sec

Operation ID 6 is the secondary operation to evaluate if it is possible to decrease the duration.

If *Operation ID* 15 first is reduced by 10 seconds, then *Operation ID* 6 can be reduced by 10 seconds, to see the effect, see figures 8-6. This value is obtained by decreasing the *Duration* of *Operation ID* 6 until the critical path changes, when the *Duration* of *Operation ID* 15 is already reduced by 10 seconds.

The *Duration* of *Operation ID* 6 can be decreased by lowering one stand length of the drillstring faster. I.e. the average velocity needed to decrease the duration of tripping in is: 41m/(49-10)sec = 1,05 m/s. The average velocity considers acceleration, maximum constant velocity and deceleration.

As can be seen from Figure 6-3 representing the same DW as represented in Figure 8-1, the average velocity of lowering the the drillstring can be approximated to:

(2,5ft/sec * 3sec + 2ft/sec * 6sec + 4,5ft/sec * (39-3-6)sec) / 39sec = 4,96ft/sec = 1,21m/sec.

Thus there is a Drawwork (DW) delivered by NOV that hoist an empty block with an average velocity above 1,58 m/sec and lower the drillstring with an average velocity above 1,05 m/s. The velocity of lowering is based on a hook load of 400 sT (363 mT) as in Figure 6-3. If the hook load exceed this, further evaluation need to be done to ensure an average velocity above 1,05 m/s for lowering the drillstring.

By decreasing *Operation ID* 15 by 10 sec and *Operation* ID 6 by 10 sec, the duration of tripping in is reduced by 20 sec. I.e. tripping in is reduced to 104 sec/stand, corresponding to 34,6 stands/hr. See Figure 8-4 and figures 8-6.

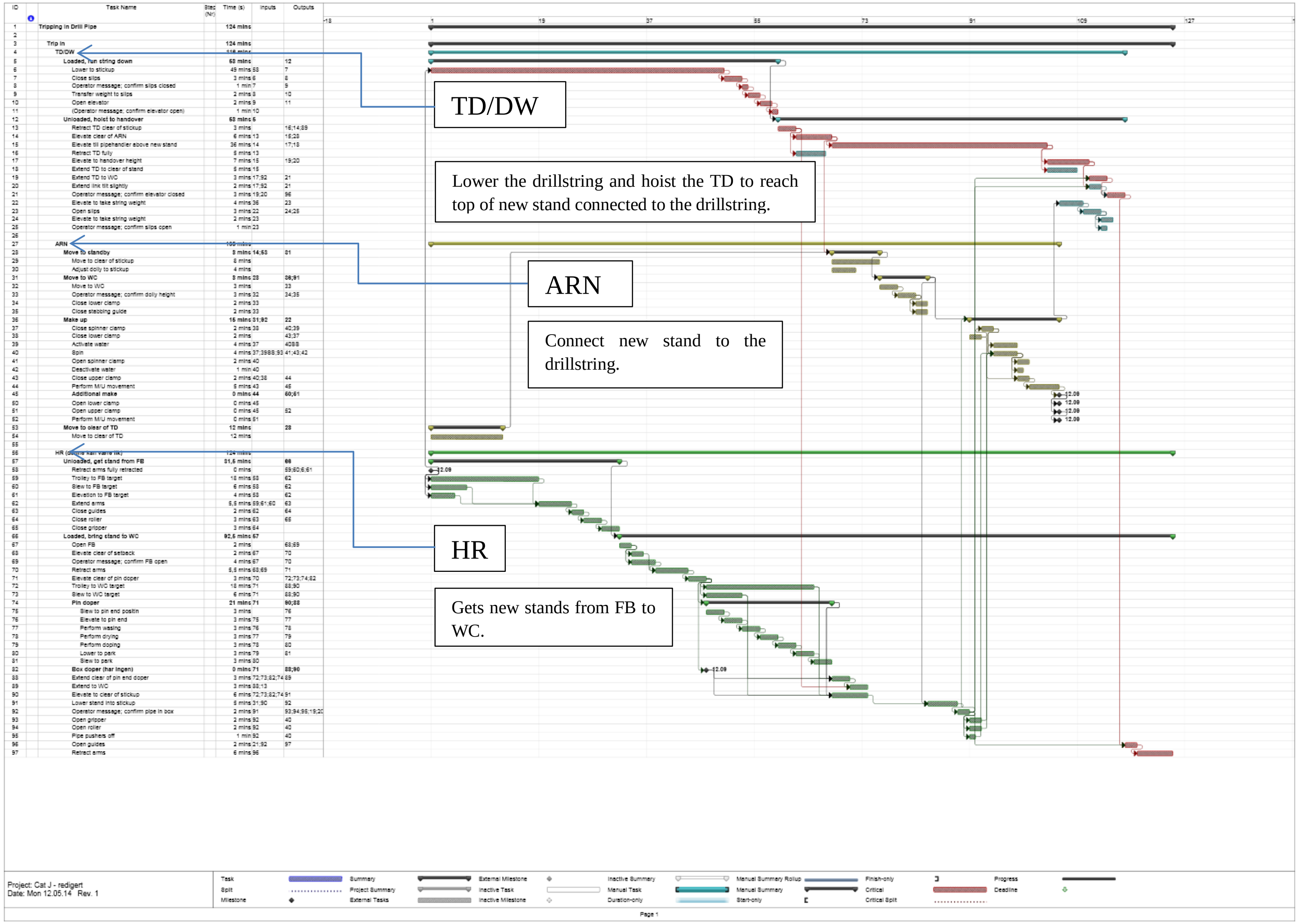
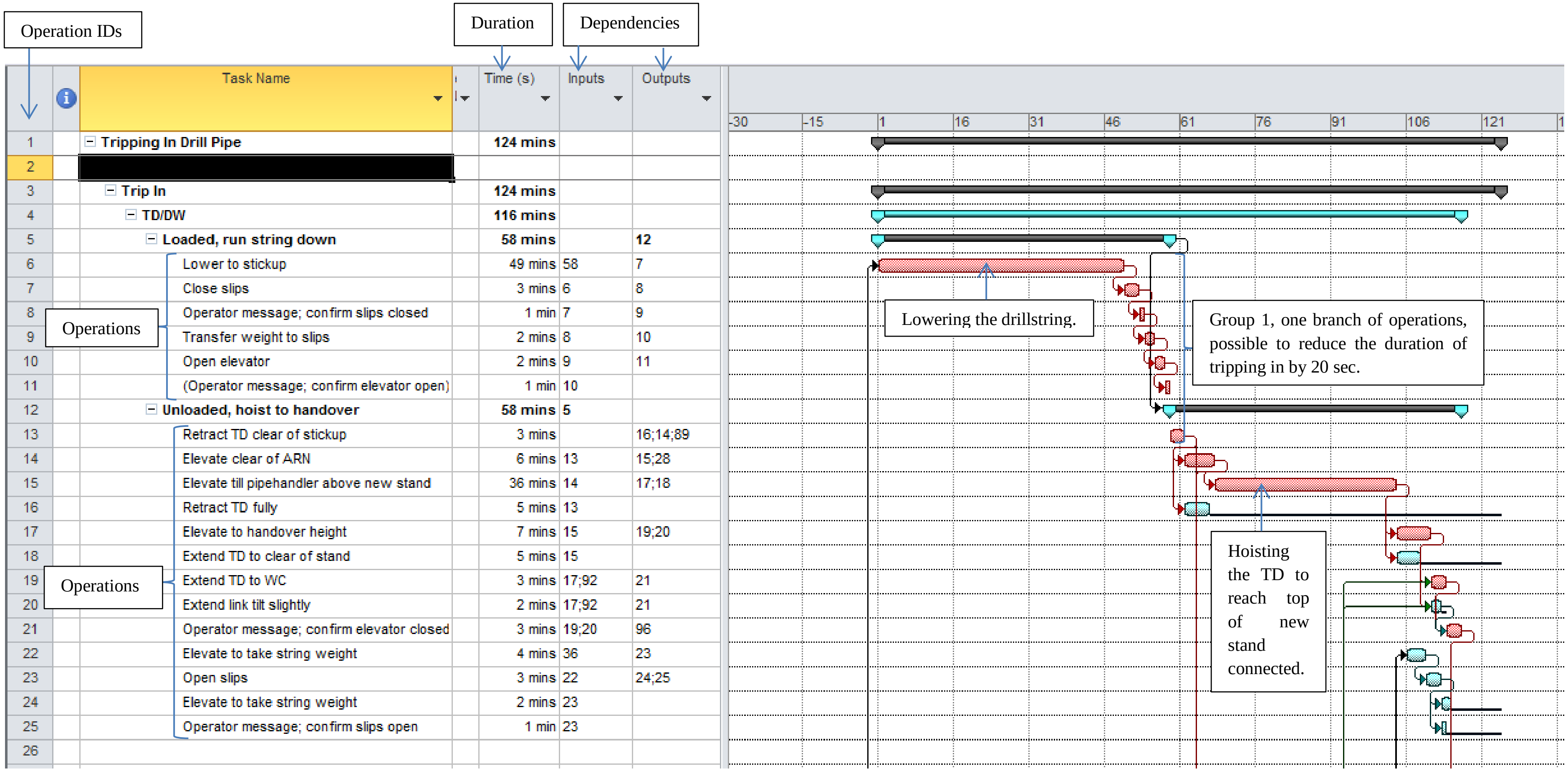


Figure 8-2: Rig 1, Critical path marked red [2]. See Figure 8-2-a, 8-2-b and 8-2-c for better resolution.



	Task Name	Time (s)	Inputs	Outputs
1	**Tripping In Drill Pipe**	**124 mins**		
2	[redacted]			
3	**Trip In**	**124 mins**		
4	**TD/DW**	**116 mins**		
5	**Loaded, run string down**	**58 mins**		**12**
6	Lower to stickup	49 mins	58	7
7	Close slips	3 mins	6	8
8	Operator message; confirm slips closed	1 min	7	9
9	Transfer weight to slips	2 mins	8	10
10	Open elevator	2 mins	9	11
11	(Operator message; confirm elevator open)	1 min	10	
12	**Unloaded, hoist to handover**	**58 mins**	**5**	
13	Retract TD clear of stickup	3 mins		16;14;89
14	Elevate clear of ARN	6 mins	13	15;28
15	Elevate till pipehandler above new stand	36 mins	14	17;18
16	Retract TD fully	5 mins	13	
17	Elevate to handover height	7 mins	15	19;20
18	Extend TD to clear of stand	5 mins	15	
19	Extend TD to WC	3 mins	17;92	21
20	Extend link tilt slightly	2 mins	17;92	21
21	Operator message; confirm elevator closed	3 mins	19;20	96
22	Elevate to take string weight	4 mins	36	23
23	Open slips	3 mins	22	24;25
24	Elevate to take string weight	2 mins	23	
25	Operator message; confirm slips open	1 min	23	
26				

Figure 8-2-a: Rig 1, Critical path marked red. [2]

	Task Name	Time (s)	Inputs	Outputs
27	**ARN**	**105 mins**		
28	**Move to standby**	**8 mins**	**14;53**	**31**
29	Move to clear of stickup	8 mins		
30	Adjust dolly to stickup	4 mins		
31	**Move to WC**	**8 mins**	**28**	**36;91**
32	Move to WC	3 mins		33
33	Operator message; confirm dolly height	3 mins	32	34;35
34	Close lower clamp	2 mins	33	
35	Close stabbing guide	2 mins	33	
36	**Make up**	**15 mins**	**31;92**	**22**
37	Close spinner clamp	2 mins	38	40;39
38	Close lower clamp	2 mins		43;37
39	Activate water	4 mins	37	40SS
40	Spin	4 mins	37;39SS;9	41;43;42
41	Open spinner clamp	2 mins	40	
42	Deactivate water	1 min	40	
43	Close upper clamp	2 mins	40;38	44
44	Perform M/U movement	5 mins	43	45
45	**Additional make**	**0 mins**	**44**	**50;51**
50	Open lower clamp	0 mins	45	
51	Open upper clamp	0 mins	45	52
52	Perform M/U movement	0 mins	51	
53	**Move to clear of TD**	**12 mins**		**28**
54	Move to clear of TD	12 mins		
55				

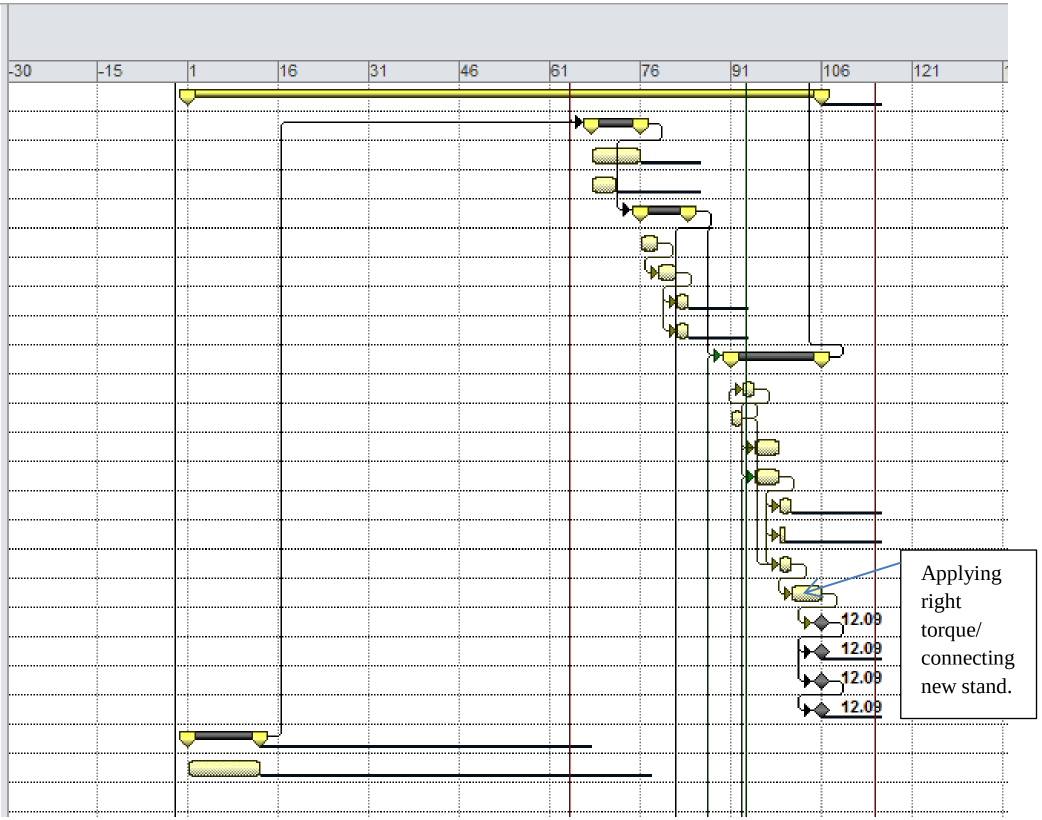


Figure 8-2-b: Rig 1, Critical path marked red. [2]

	Task Name	Time (s)	Inputs	Outputs
56	HR	**124 mins**		
57	**Unloaded, get stand from FB**	**31,5 mins**		**66**
58	Retract arms fully retracted	0 mins		59;60;6;61
59	Trolley to FB target	18 mins	58	62
60	Slew to FB target	6 mins	58	62
61	Elevation to FB target	4 mins	58	62
62	Extend arms	5,5 mins	59;61;60	63
63	Close guides	2 mins	62	64
64	Close roller	3 mins	63	65
65	Close gripper	3 mins	64	
66	**Loaded, bring stand to WC**	**92,5 mins**	**57**	
67	Open FB	2 mins		68;69
68	Elevate clear of setback	2 mins	67	70
69	Operator message; confirm FB open	4 mins	67	70
70	Retract arms	5,5 mins	68;69	71
71	Elevate clear of pin doper	3 mins	70	72;73;74;82
72	Trolley to WC target	18 mins	71	88;90
73	Slew to WC target	6 mins	71	88;90
74	**Pin doper**	**21 mins**	**71**	**90;88**
75	Slew to pin end positin	3 mins		76
76	Elevate to pin end	3 mins	75	77
77	Perform wasing	3 mins	76	78
78	Perform drying	3 mins	77	79
79	Perform doping	3 mins	78	80
80	Lower to park	3 mins	79	81
81	Slew to park	3 mins	80	
82	**Box doper**	**0 mins**	**71**	**88;90**
88	Extend clear of pin end doper	3 mins	72;73;82;7	89
89	Extend to WC	3 mins	88;13	
90	Elevate to clear of stickup	6 mins	72;73;82;7	91
91	Lower stand into stickup	5 mins	31;90	92
92	Operator message; confirm pipe in box	2 mins	91	93;94;95;19;2
93	Open gripper	2 mins	92	40
94	Open roller	2 mins	92	40
95	Pipe pushers off	1 min	92	40
96	Open guides	2 mins	21;92	97
97	Retract arms	6 mins	96	

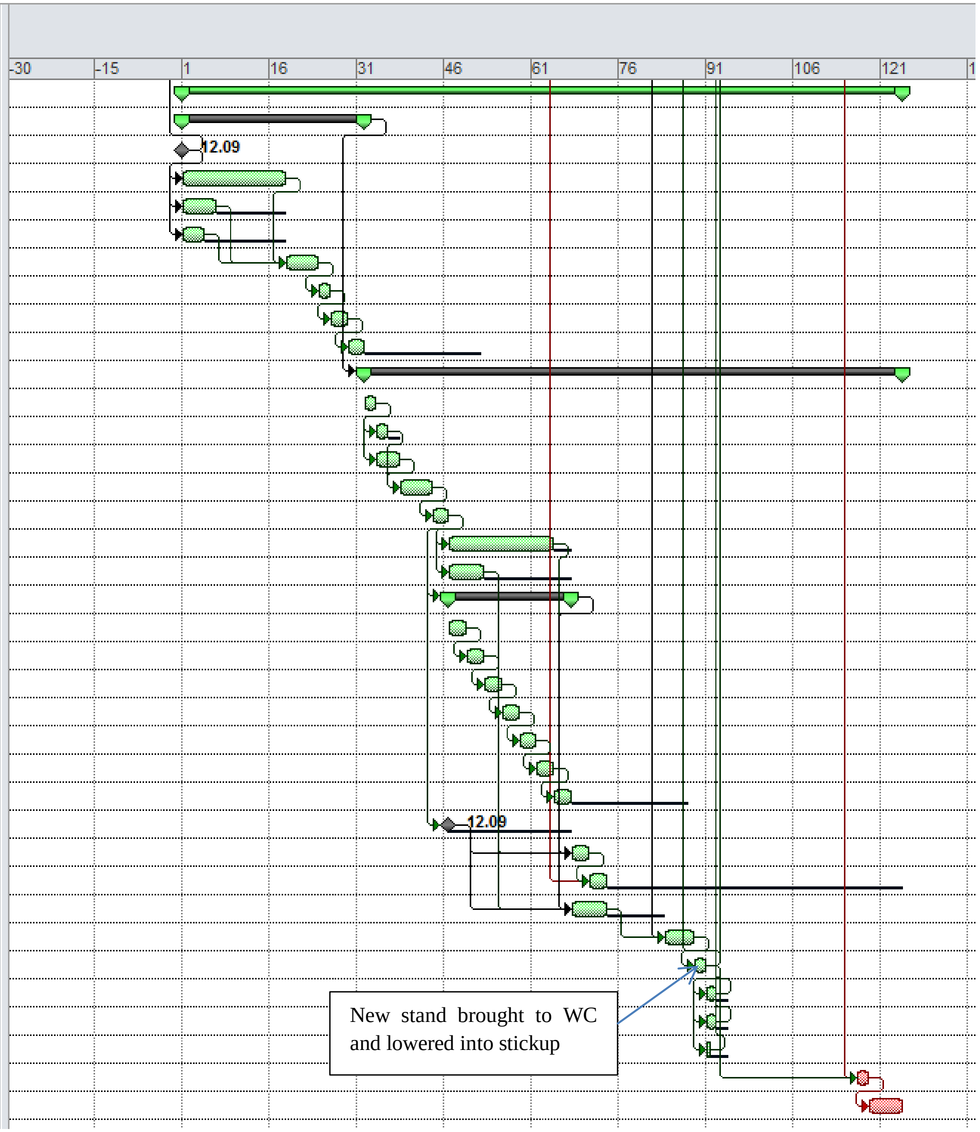


Figure 8-2-c: Rig 1, Critical path marked red. [2]

	Task Name	Time (s)	Inputs	Outputs
1	Tripping In Drill Pipe	124 mins		
3	Trip In	124 mins		
4	TD/DW (her er det en tx1250, vi har en tdx 1000. regner med et blir likt - nytt drawwork)	116 mins		
5	Loaded, run string down	58 mins		12
6	Lower to stickup	49 mins	58	7
7	Close slips	3 mins	6	8
8	Operator message; confirm slips closed	1 min	7	9
9	Transfer weight to slips	2 mins	8	10
10	Open elevator	2 mins	9	11
11	(Operator message; confirm elevator open)	1 min	10	
12	Unloaded, hoist to handover	58 mins	5	
13	Retract TD clear of stickup	3 mins		16;14;89
14	Elevate clear of ARN	6 mins	13	15;28
15	Elevate till pipehandler above new stand	36 mins	14	17;18
17	Elevate to handover height	7 mins	15	19;20
19	Extend TD to WC	3 mins	17;92	21
21	Operator message; confirm elevator closed	3 mins	19;20	96
56	HR (denne kan være lik)	124 mins		
57	Unloaded, get stand from FB	31,5 mins		66
58	Retract arms fully retracted	0 mins		59;60;6;61
66	Loaded, bring stand to WC	92,5 mins	57	
96	Open guides	2 mins	21;92	97
97	Retract arms	6 mins	96	

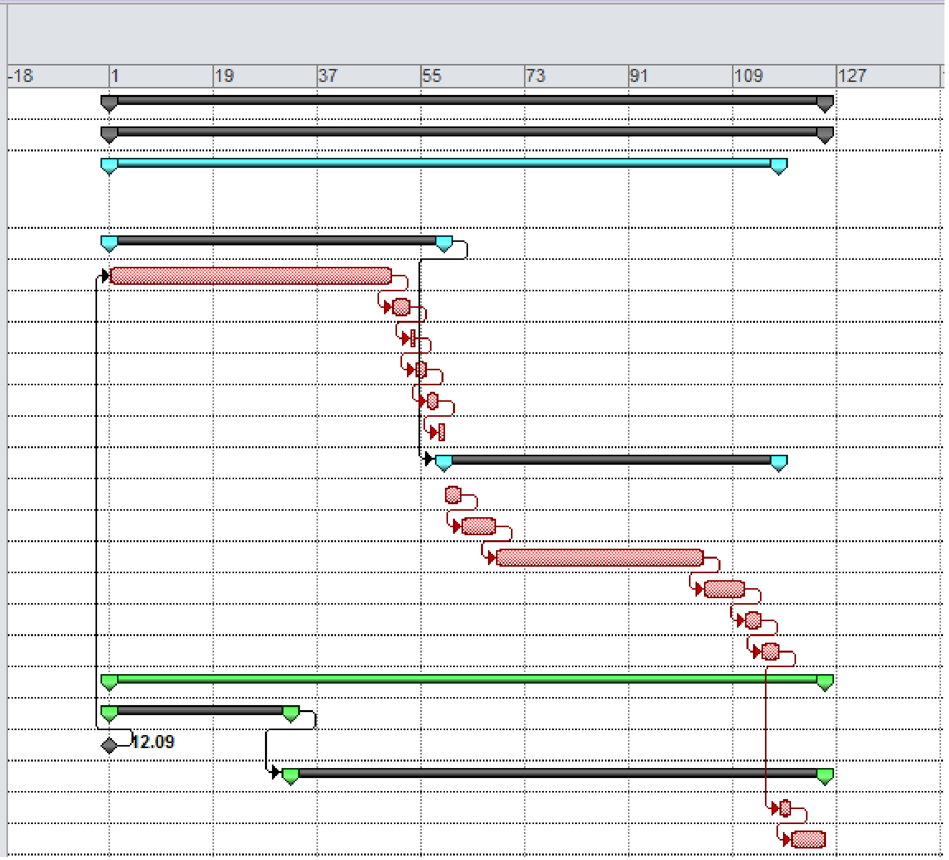


Figure 8-3: Critical operations for tripping in, Rig 1. [2]

Operation ID	Operation description	Duration [sec.]	Machine	Reduced duration each operation [sec]	Group	Reduced duration each group [sec.]	Changed duration [sec.]
6	Lower to stickup	49	TD/DW	20	1	20	39
7	Close slips	3	TD/DW	3			
8	Operator message; confirm slips closed	1	TD/DW	1			
9	Transfer weight to slips	2	TD/DW	2			
10	Open elevator	2	TD/DW	2			
11	(Operator message; confirm elevator open)	1	TD/DW	1			
13	Retract TD clear of stickup	3	TD/DW	3			
14	Elevate clear of ARN	6	TD/DW	6	2	6	
15	Elevate till pipehandler above new stand	36	TD/DW	10	3	10	26
17	Elevate to handover height	7	TD/DW	7	4	7	
19	Extend TD to WC	3	TD/DW	1	5	1	
21	Operator message; confirm elevator closed	3	TD/DW	3	6	3	
96	Open guides	2	HR	2	7	8	
97	Retract arms	6	HR	6			
		TOTAL DURATION				**MAXIMUM**	**TOTAL DURATION**
		124				**20**	**104**
		STANDS PER HOUR					**STANDS PER HOUR**
		29,03					**34,62**

Figure 8-4: Critical operations for tripping in, Rig 1. [2]

Summary

Primary: It is faster to connect a new stand with the ARN machine than to hoist the TD to reach the drillstring with the new stand. Hoisting of the TD shall be done 10 seconds faster to make these machines synchronized. The new critical operations as a result of reducing *Operational ID* 15 by 10 seconds are filtered out and illustrated in Figure 8-5. New critical operations are marked by blue ellipses in Figure 8-5.

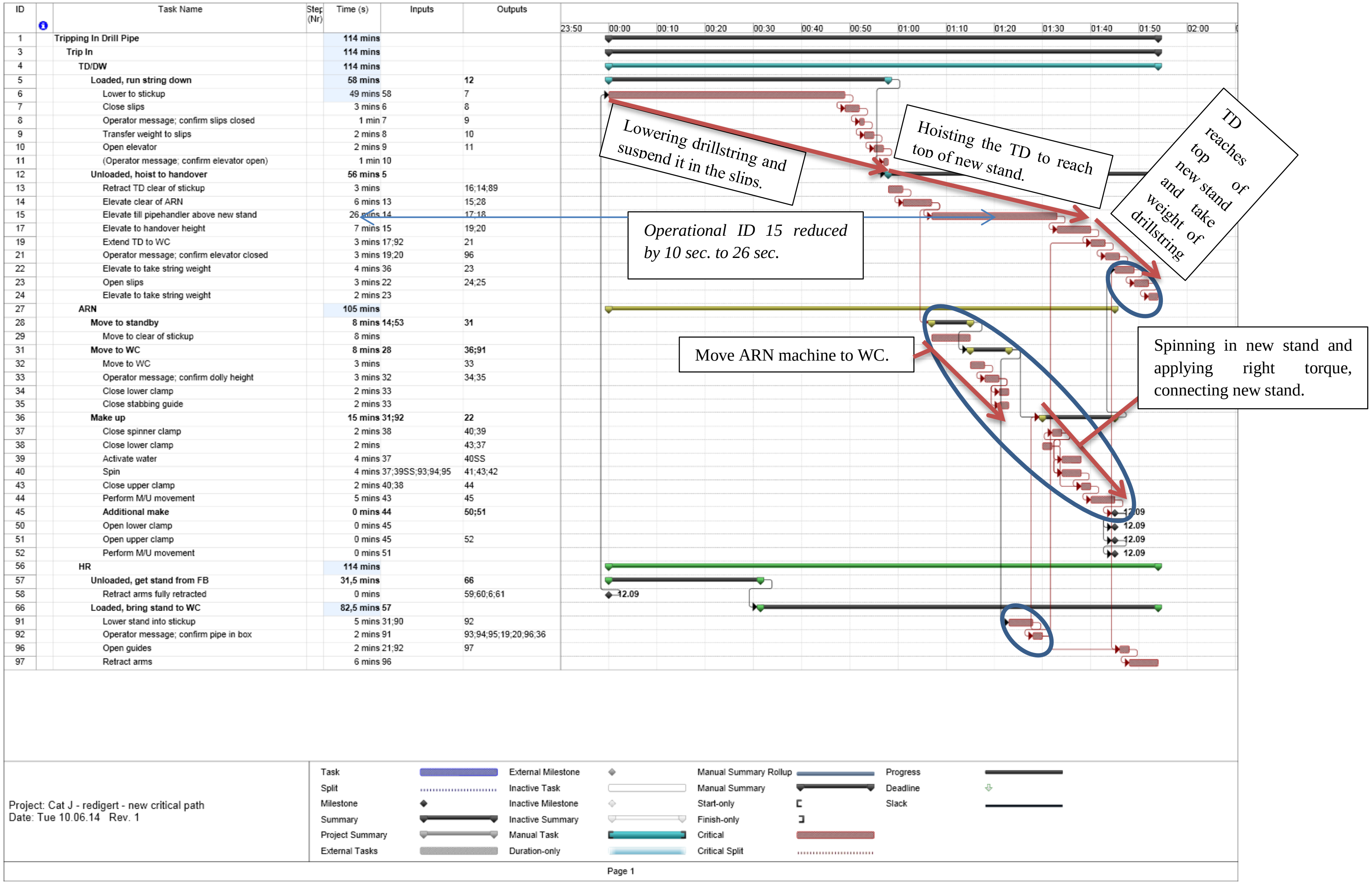
Secondary: *Operational ID* 6 is reduced by 10 seconds.

The new critical operations as a result of reducing *Operational ID* 15 by 10 seconds and *Operational ID* 6 by 10 seconds are illustrated and filtered out in figures 8-6. New critical operations are marked by blue ellipses in figures 8-6.

The total duration of tripping one stand would in total be reduced by 20 seconds and make Rig 1 able to trip in 34,6 stands per hour instead of originally 29 stands per hour.

The solution demands a DW which is strong and fast enough to lower the drillstring and hoist the TD at desired velocities. This DW has been evaluated to be available from NOV.

The surge effect related to *Operation ID* 6 is evaluated in chapter 8.3 and show that this will not be the limiting factor to the well presented in chapter 8.3.



ID	Task Name	Step (Nr)	Time (s)	Inputs	Outputs
1	**Tripping In Drill Pipe**		**114 mins**		
3	**Trip In**		**114 mins**		
4	**TD/DW**		**114 mins**		
5	**Loaded, run string down**		**58 mins**		**12**
6	Lower to stickup		49 mins	58	7
7	Close slips		3 mins	6	8
8	Operator message; confirm slips closed		1 min	7	9
9	Transfer weight to slips		2 mins	8	10
10	Open elevator		2 mins	9	11
11	(Operator message; confirm elevator open)		1 min	10	
12	**Unloaded, hoist to handover**		**56 mins**	**5**	
13	Retract TD clear of stickup		3 mins		16;14;89
14	Elevate clear of ARN		6 mins	13	15;28
15	Elevate till pipehandler above new stand		26 mins	14	17;18
17	Elevate to handover height		7 mins	15	19;20
19	Extend TD to WC		3 mins	17;92	21
21	Operator message; confirm elevator closed		3 mins	19;20	96
22	Elevate to take string weight		4 mins	36	23
23	Open slips		3 mins	22	24;25
24	Elevate to take string weight		2 mins	23	
27	**ARN**		**105 mins**		
28	**Move to standby**		**8 mins**	**14;53**	**31**
29	Move to clear of stickup		8 mins		
31	**Move to WC**		**8 mins**	**28**	**36;91**
32	Move to WC		3 mins		33
33	Operator message; confirm dolly height		3 mins	32	34;35
34	Close lower clamp		2 mins	33	
35	Close stabbing guide		2 mins	33	
36	**Make up**		**15 mins**	**31;92**	**22**
37	Close spinner clamp		2 mins	38	40;39
38	Close lower clamp		2 mins		43;37
39	Activate water		4 mins	37	40SS
40	Spin		4 mins	37;39SS;93;94;95	41;43;42
43	Close upper clamp		2 mins	40;38	44
44	Perform M/U movement		5 mins	43	45
45	**Additional make**		**0 mins**	**44**	**50;51**
50	Open lower clamp		0 mins	45	
51	Open upper clamp		0 mins	45	52
52	Perform M/U movement		0 mins	51	
56	**HR**		**114 mins**		
57	**Unloaded, get stand from FB**		**31,5 mins**		**66**
58	Retract arms fully retracted		0 mins		59;60;6;61
66	**Loaded, bring stand to WC**		**82,5 mins**	**57**	
91	Lower stand into stickup		5 mins	31;90	92
92	Operator message; confirm pipe in box		2 mins	91	93;94;95;19;20;96;36
96	Open guides		2 mins	21;92	97
97	Retract arms		6 mins	96	

Figure 8-5: New critical operations because of *Changed duration* for *Operational ID 15*, Rig 1 [2].

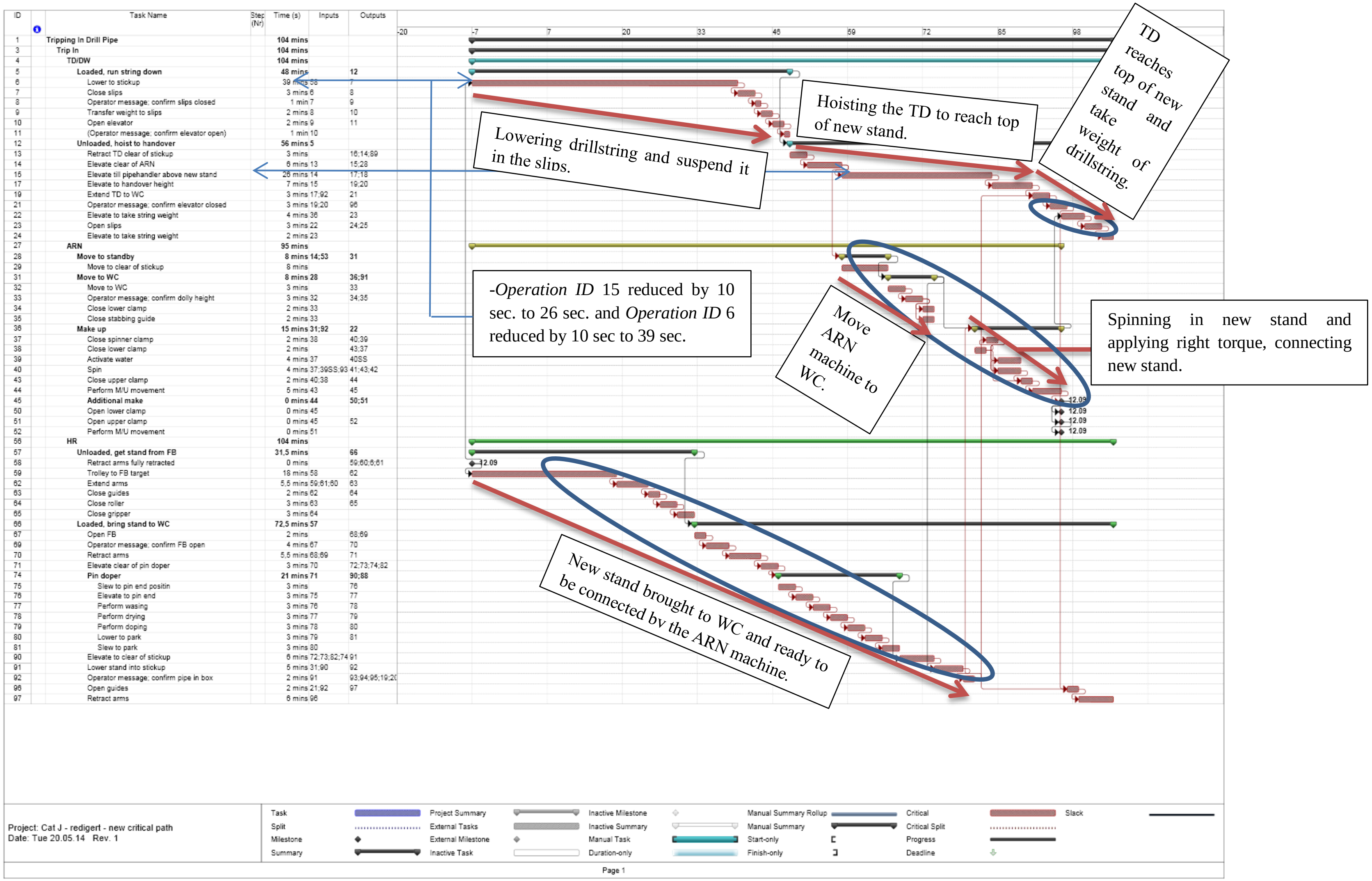
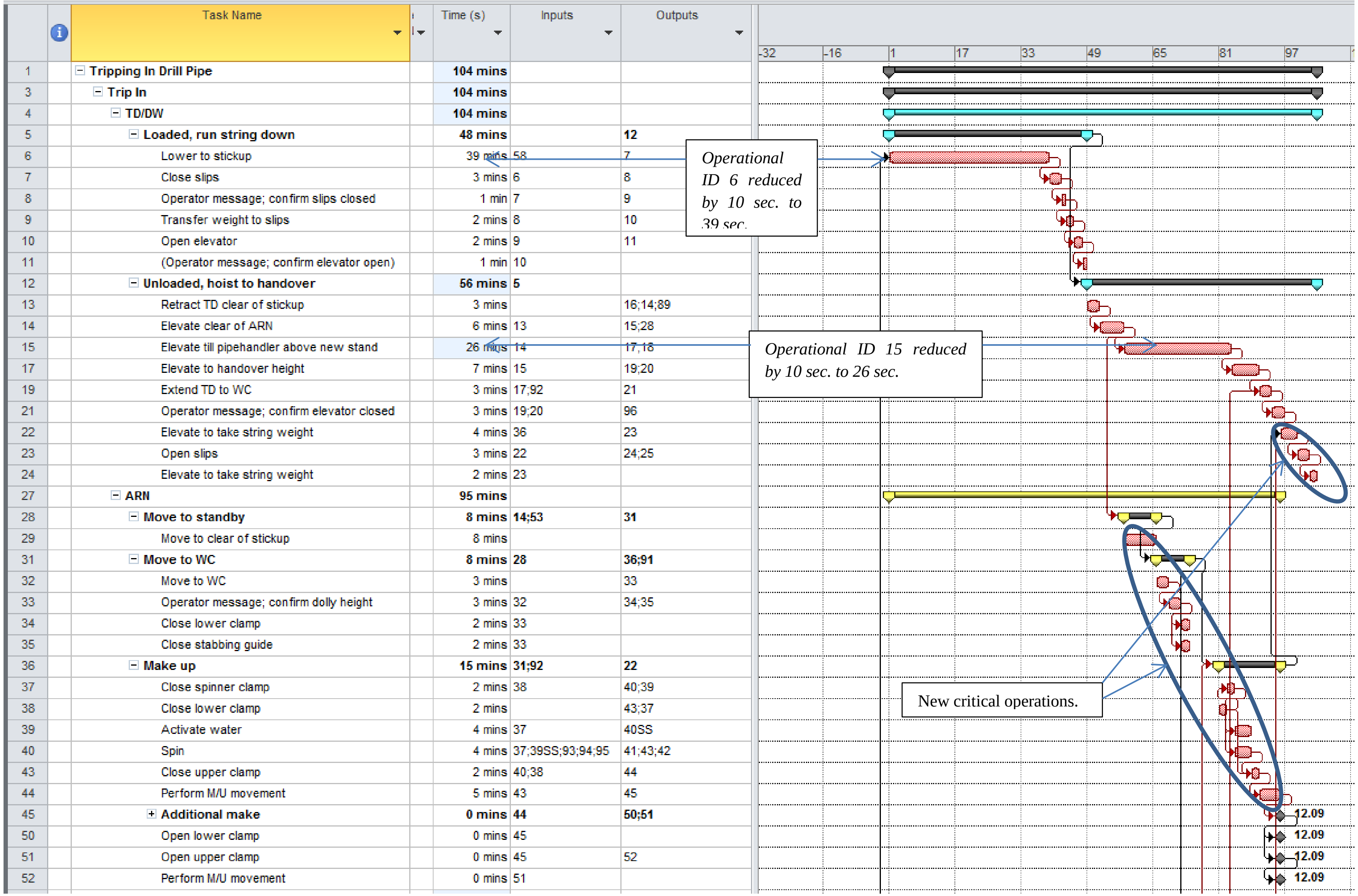
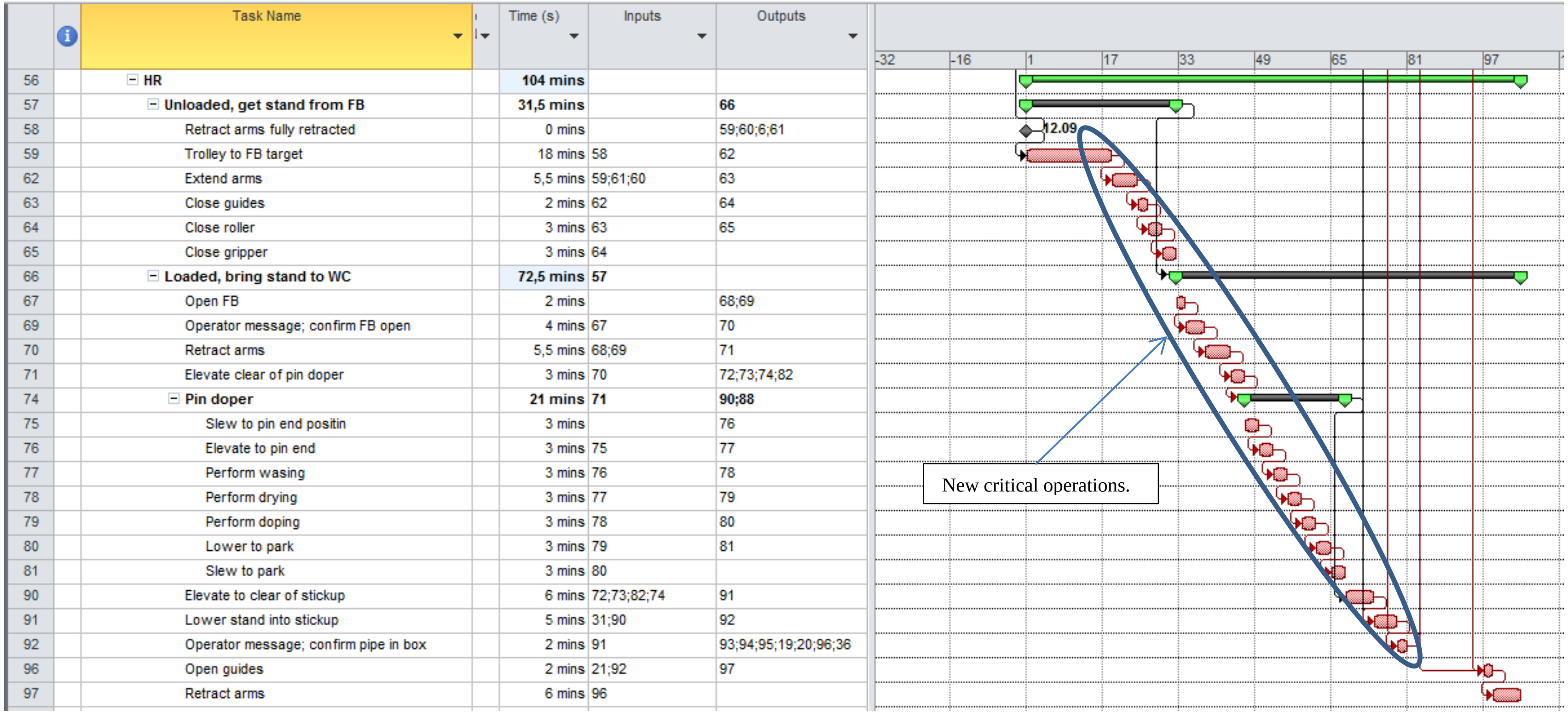


Figure 8-6: New critical operations because of *Changed durations* for *Operational ID* 15 and 6, Rig 1 [2]. See Figure 8-6-a and 8-6-b for better resolution**.**



	Task Name	Time (s)	Inputs	Outputs
1	**Tripping In Drill Pipe**	**104 mins**		
3	**Trip In**	**104 mins**		
4	TD/DW	**104 mins**		
5	**Loaded, run string down**	**48 mins**		**12**
6	Lower to stickup	39 mins	58	7
7	Close slips	3 mins	6	8
8	Operator message; confirm slips closed	1 min	7	9
9	Transfer weight to slips	2 mins	8	10
10	Open elevator	2 mins	9	11
11	(Operator message; confirm elevator open)	1 min	10	
12	**Unloaded, hoist to handover**	**56 mins**	**5**	
13	Retract TD clear of stickup	3 mins		16;14;89
14	Elevate clear of ARN	6 mins	13	15;28
15	Elevate till pipehandler above new stand	26 mins	14	17;18
17	Elevate to handover height	7 mins	15	19;20
19	Extend TD to WC	3 mins	17;92	21
21	Operator message; confirm elevator closed	3 mins	19;20	96
22	Elevate to take string weight	4 mins	36	23
23	Open slips	3 mins	22	24;25
24	Elevate to take string weight	2 mins	23	
27	**ARN**	**95 mins**		
28	**Move to standby**	**8 mins**	**14;53**	**31**
29	Move to clear of stickup	8 mins		
31	**Move to WC**	**8 mins**	**28**	**36;91**
32	Move to WC	3 mins		33
33	Operator message; confirm dolly height	3 mins	32	34;35
34	Close lower clamp	2 mins	33	
35	Close stabbing guide	2 mins	33	
36	**Make up**	**15 mins**	**31;92**	**22**
37	Close spinner clamp	2 mins	38	40;39
38	Close lower clamp	2 mins		43;37
39	Activate water	4 mins	37	40SS
40	Spin	4 mins	37;39SS;93;94;95	41;43;42
43	Close upper clamp	2 mins	40;38	44
44	Perform M/U movement	5 mins	43	45
45	**Additional make**	**0 mins**	**44**	**50;51**
50	Open lower clamp	0 mins	45	
51	Open upper clamp	0 mins	45	52
52	Perform M/U movement	0 mins	51	

Figure 8-6-a: New critical operations because of *Changed durations* for *Operational ID 15 and 6*, Rig 1. [2]



	Task Name	Time (s)	Inputs	Outputs
56	**HR**	**104 mins**		
57	**Unloaded, get stand from FB**	**31,5 mins**		**66**
58	Retract arms fully retracted	0 mins		59;60;6;61
59	Trolley to FB target	18 mins	58	62
62	Extend arms	5,5 mins	59;61;60	63
63	Close guides	2 mins	62	64
64	Close roller	3 mins	63	65
65	Close gripper	3 mins	64	
66	**Loaded, bring stand to WC**	**72,5 mins**	**57**	
67	Open FB	2 mins		68;69
69	Operator message; confirm FB open	4 mins	67	70
70	Retract arms	5,5 mins	68;69	71
71	Elevate clear of pin doper	3 mins	70	72;73;74;82
74	**Pin doper**	**21 mins**	**71**	**90;88**
75	Slew to pin end positin	3 mins		76
76	Elevate to pin end	3 mins	75	77
77	Perform wasing	3 mins	76	78
78	Perform drying	3 mins	77	79
79	Perform doping	3 mins	78	80
80	Lower to park	3 mins	79	81
81	Slew to park	3 mins	80	
90	Elevate to clear of stickup	6 mins	72;73;82;74	91
91	Lower stand into stickup	5 mins	31;90	92
92	Operator message; confirm pipe in box	2 mins	91	93;94;95;19;20;96;36
96	Open guides	2 mins	21;92	97
97	Retract arms	6 mins	96	

Figure 8-6-b: New critical operations because of *Changed durations*, Rig 1. [2]

8.1.2 Machines and their configuration as the limiting factor

It is not necessary to hoist the TD faster than an average speed of:

- Rig 1: 1,58 m/s (**)

This is due to the fact that the duration of tripping one stand will be restricted to the parallel operations by the ARN machine, even though the TD is hoisted faster.

It is not necessary to lower the drillstring faster than an average speed of:

- Rig 1: 1,05 m/sec (*)

This is due to the fact that the duration of tripping one stand will be restricted to the parallel operations by the HR machine, even though the drillstring is lowered faster.

Related to the machine configuration of Rig 1 and the average speed of lowering the drillstring at 1,05 m/s, the maximum constant speed during lowering one stand is calculated in chapter 8.3 to 1,17 m/s. As long as this velocity does not produce a BHP that exceed the fracture pressure, the velocity of lowering the drillstring is “limited” by the parallel branch of operations which brings new stand to WC. I.e. The duration of tripping one stand will not decrease even though the driller lower faster than an average speed of 1,05 m/s. This example illustrates the fact that even though well parameters may allow lowering the drillstring faster, the machine configuration restrict to decrease the duration of tripping one stand.

If the velocities presented above, marked (*) and (**), are used, the different machines are synchronized. I.e. TD/DW lower the drillstring and hoist the TD to reach new stand, while HR machine gets new stand to WC and ARN machine connect new stand to the drillsting, are operating in parallel and for the same duration. This is illustrated for Rig 1 in figures 8-6. By comparing Figure 8-3 with figures 8-6, the numbers of critical operations increases from 14 to 47. Figure 8-6 is an example of machines working synchronized and that they do not wait on one another.

8.1.3 Well parameters as the limiting factor for lowering the drillstring

A simplified example follows beneath to illustrate how to calculate and evaluate the effect of surge pressure which may limit how fast you can lower the drillstring.

For Rig 1: The maximum constant velocity while lowering one stand with an average speed of 1,05 m/sec = 3,445 ft/sec, can be approximated to:

(2,5ft/sec*3sec + 2ft/sec*6sec + X*(39-3-6)sec) / 39 sec = 3,445 ft/sec

(7,5+12+30X) / 39 =3,445

X = 3,83 ft/sec = 1,17 m/sec

The calculation above is related to the acceleration and declaration presented in Figure 6-3. The maximum constant velocity of 1,17 m/sec should be evaluated regarding surge pressure. The important part, presented in chapter 8.1, is that the machines and the configuration show that there is nothing to gain in respect to the duration of tripping one stand, by lowering the drillstring faster than an average speed of 1,05m/s.

A simplified calculation to calculate the surge pressure assumes:

- Steady-state
- Isothermal
- Annulus represented as a narrow slot, restriction: $d_1/d_2 > 0,3$
- Closed ended pipe
- Laminar flow
    - Assumed flow in the annulus mostly behaves laminar flow pattern
- Fluid: mud, non-compressible liquid
- Bingham plastic model
- Non-newtonian fluid and the use of Burkhardt's technique
- Vertical well
- Annulus cross-sectional area as a product of constant hole size and drill pipe diameter.
    - This simplification makes the annulus cross-sectional area constant from rig to end of drillstring. Which make it easy to illustrate how to calculate the surge effect and does not demand to break into sections for each different annulus cross-sectional area.

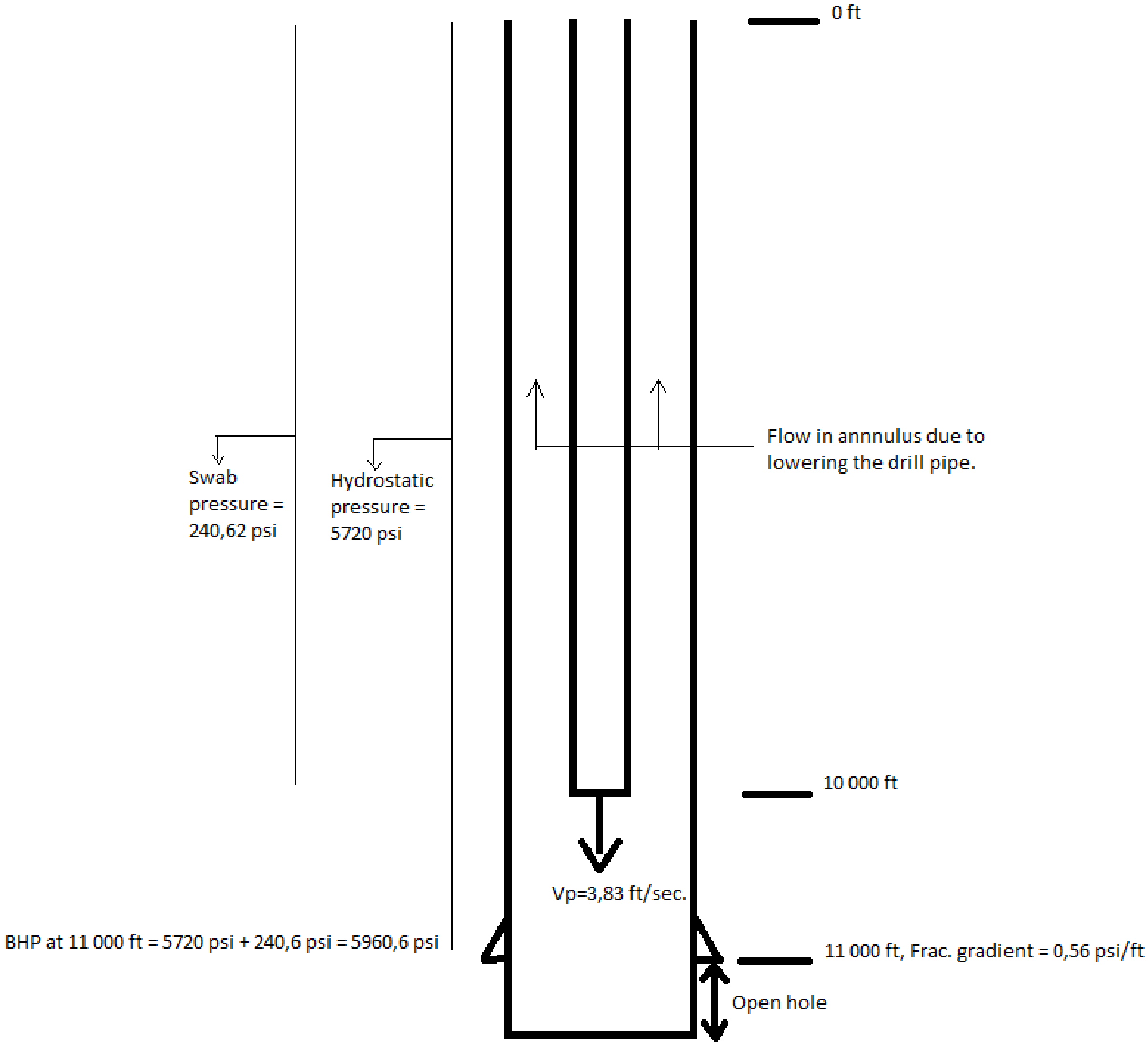


Figure 8-7: Sketch of simplified well and the effect of surge pressure.

Drillstring at	10000	ft	Hydrostatic BHP	5720	psi
Casing shoe, BHP	11000	ft	Hydrostatic gradient	0,52	psi/ft
Casing inner diameter	7,875	in	d1/d2	0,63	
Drill pipe outer diameter	5	in	K_lam	0,43	
Mud density, ρ_mud	10	ppg	Va	2,59	ft/sec
ϴ600	65	Pa	Vae_lam	4,22	ft/sec
ϴ300	40	Pa	µp	25	cP
Pore pressure gradient	0,5	psi/ft	Ty	15	lbf/100 ft^2
Frac gradient	0,56	psi/ft	dPf/dL	0,0388	psi/ft
Vp lowering	3,83	ft/sec	Surge pressure, ΔPf	388,38	psi
			BHP	6108,38	psi
			Max BHP	6160	psi

Figure 88-8: Information and calculated surge pressure.

The formulas used to calculate what is listed in Figure 8-8 are presented beneath, formula (11-18).

The BHP is restricted by the fracture pressure. Since the BHP does not exceed the Max BHP, which is the fracture pressure, it is safe to lower the drillstring at 3,83 ft/sec = 1,17 m/sec.

Referring to reference [14] and [19], the frictional pressure loss for laminar flow in the annulus according to the Bingham plastic model and in field units is:

$$\frac{dp_f}{dL} = \frac{\mu_p v_{ae}}{1000(d_2 - d_1)^2} + \frac{\mathrm{T}_y}{200(d_2 - d_1)} \quad (11)$$

The effective mean annular velocity is defined by Burkardt as:

$$v_{ae} = v_a + K v_p \quad (12)$$

K is called the *mud clinging constant* and is used for non-newtonian fluids. For laminar flow, K_{lam} is:

$$K_{lam} = \frac{\alpha^2 - 2\alpha^2 ln\alpha - 1}{2(1 - \alpha^2) ln\alpha} \quad (13)$$

Where $\alpha = \frac{d_1}{d_2}$, d_1 is the outside diameter of pipe in the well (drillpipe/drillstring) and d_2 is the inside diameter of the well (hole size/casing).

The annular flow is a result of the pipe displacing the mud and can be expressed as:

$$v_a = \frac{d_1^2 v_p}{(d_2^2 - d_1^2)} \quad (14)$$

The plastic viscosity is:

$$\mu_p = \Theta 600 - \Theta 300 \quad (15)$$

The yield point is:

$$\mathrm{T}_y = 2\Theta_{300} - \Theta_{600} \quad (16)$$

The hydrostatic BHP is:

$$BHP_{hyd} = 0{,}052 \rho_{mud} D \quad (17)$$

The BHP is increased due to surge effect:

$$BHP = BHP_{hyd} + \Delta P_f \quad (18)$$

Fracture pressure, max BHP, defines the limit for surge. The maximum velocity lowering the drillstring, max v_p, can be calculated. Max v_p is calculated by rearranging formulas above. The maximum constant velocity lowering the drillstring shall stay beneath max v_p in order to stay beneath the fracture pressure. Calculated value, max v_p, is presented in Figure 8-9 and marked bolded. As can be seen, the BHP reaches the max BHP at max v_p.

Information	**Value**	**Units**
Drillstring at	10000	ft
Casing shoe, BHP	11000	ft
Casing inner diameter	7,875	in
Drill pipe outer diameter	5	in
Mud density, ρ_mud	10	ppg
Θ600	65	Pa
Θ300	40	Pa
Pore pressure gradient	0,5	psi/ft
Frac gradient	0,56	psi/ft
Max Vp lowering	**5,381**	**ft/sec**

Calculated	**Value**	**Units**
Hydrostatic BHP	5720	psi
Hydrostatic gradient	0,52	psi/ft
d1/d2	0,63	
K_lam	0,43	
Va	3,63	ft/sec
Vae_lam	5,92	ft/sec
µp	25	cP
Ty	15	lbf/100 ft^2
dPf/dL	0,0440	psi/ft
Surge pressure, ΔPf	440,00	psi
BHP	6160,00	psi
Max BHP	6160	psi

Figure 8-9: Max v_p, restricted by the fracture pressure (max BHP).

Summary

Related to the well, illustrated in Figure 8-7 and the information given in Figure 8-8 and 8-9, the duration of tripping one stand for Rig 1 is not limited by well parameters, but by the machines and their configuration.

9 Hydraulic consumption

The functionalities recommended in this chapter are evaluated in collaboration with Jan Morten Haavik.

As described in chapter 4 it is essential to evaluate the hydraulic consumption of the machinery on a drilling rig and conclude with the total fluid requirement.

9.1 Hydraulic motor or cylinder level - consumers

Hydraulic motors and cylinders are consumers of the hydraulic ringline system. They consumes energy from the flow they are given. The velocity is given by the flow they are given. If the flow to a consumer is increased, the velocity of the movement will increase, for a cylinder, see formula (5). A consumer is set up with a given flow needed to operate with the desired velocity. The flow to a consumer will consist of three phases through time; acceleration, maximum constant flow, deceleration. To present the consumption in an easy way, the consumption is regarded as the maximum constant flow for a consumer. The flow needed for each consumer is given from hydraulic drawings.

9.2 Operation level

An operation may consist of several hydraulic motors and cylinders. These consumers have dependencies between each other and durations to fulfill the movement of the operation. This can be illustrated using a Gantt chart and show the sequence of consumers (hydraulic motors and cylinders) through the operation. This will illustrate which consumers that are running through the operation. Each consumer has a given flow needed to operate as intended, referring to chapter 9.1. The total hydraulic flow at operational level is given by summing the hydraulic flow to consumers that are run simultaneously, which results in a specific hydraulic flow through the operation. The hydraulic flow through the operation can be seen by a graph which displays hydraulic consumption [l/min] along the y-axis and time along the x-axis.

9.3 Activity level

At activity level the operations in the activity have dependencies between each other and durations, which can be set up in a Gantt chart illustrating the sequence of operations, referring to chapter 5 and Figure 5-1. This illustrates which operations that are running through the activity. Each operation has a given hydraulic flow through the operation, referring to chapter 9.2. The total hydraulic flow at activity level is given by summing the hydraulic flow to operations that are run simultaneously, which results in a specific hydraulic flow through the activity. The hydraulic flow through the activity can be seen by a graph which displays hydraulic consumption [l/min] along the y-axis and time along the x-axis.

Sequence of consumers defining the hydraulic flow through the activity

Hydraulic flow needed for consumers, together with sequence of consumers and sequence of operations give the hydraulic flow through the activity. In other words, after the sequence of operations is optimized and illustrated in a Gantt chart, it can be broken down to a level which illustrates the sequence of consumers through the activity. The sequence of consumers through the activity and the flow needed to each consumer results in the hydraulic flow through the activity.

A graph which displays hydraulic consumption [l/min] along the y-axis and time along the x-axis will indicate the total flow through the activity, see the blue graph in Figure 9-1 below. In Figure 9-1, machines 1 to 4 have one graph each, represented by its own color. Each machine consists of hydraulic motors and cylinders (consumers). By following one of these graphs, there are certain levels of consumption, indicating consumers demanding this level of hydraulic flow to operate as intended. The hydraulic flow for a machine through the activity is given by summing the hydraulic flow to consumers operating simultaneously for that machine. The total hydraulic flow through the activity is given by summing the hydraulic flow for each machine through the activity.

Because of confidentiality the machine types are not specifically mentioned in Figure 9-1. The important part is to show how to calculate the hydraulic consumption of the hydraulic ringline system.

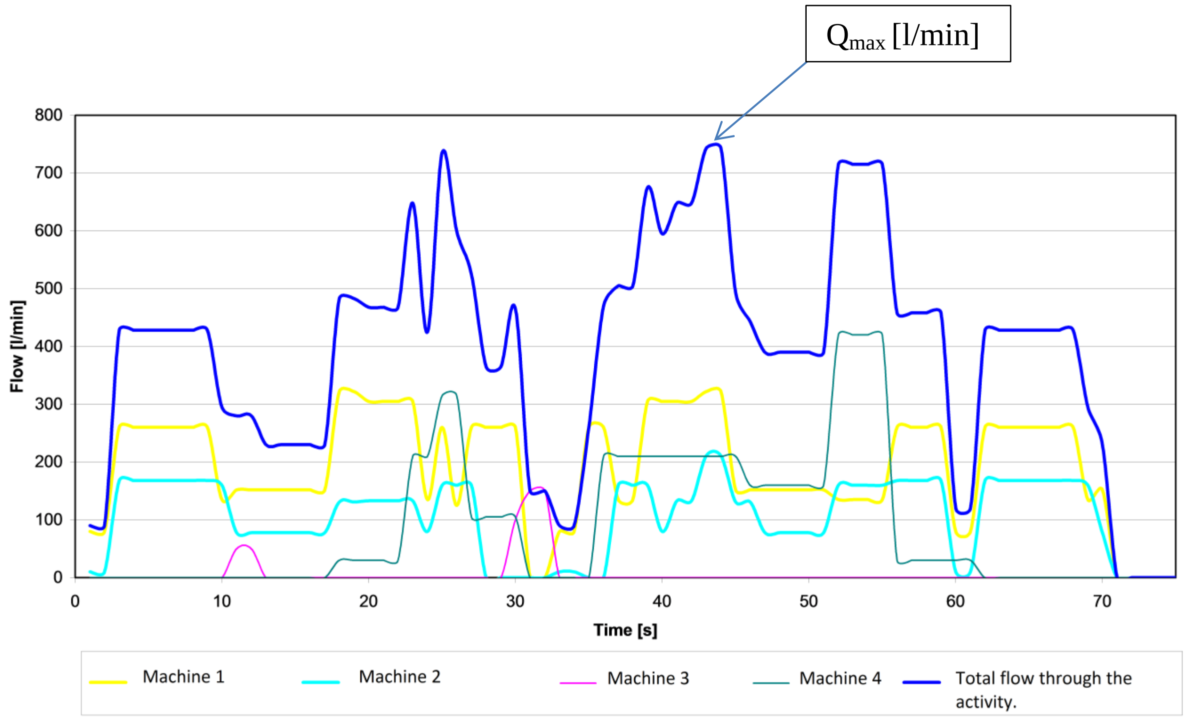


Figure 9-1: Display of hydraulic consumption for an activity.

It is of interest to display the hydraulic consumption beneath the Gantt chart for an activity. This will make it easy to relate the hydraulic consumption to the sequence of operations. The maximum value of hydraulic consumption represents the worst case.

It should be considered to choose a local maximum value, since a maximum value operating for less than 3 seconds may be regarded as an extreme value because of its short duration and thus not be taken into account to decide the total fluid requirement for the HPU.

9.4 Rig level

At rig level the sequence of activities are fairly random and all outcomes of chosen activities must be regarded as possible, i.e. what is of interest is the worst case scenario when maximum consumption of possible simultaneous running activities coincides.

It should be evaluated which activities that may be run simultaneously. The sum of maximum values of consumption for each of these activities represents the value of total hydraulic fluid requirement [l/min]. This number defines the flow required from the HPU.

9.5 Summary

The goal is to conclude with the worst case scenario for hydraulic consumption, defining the flow needed from the HPU.

The Hydraulic flow through the activity is a result of:

- The flow needed to each consumer to operate as intended
- The sequence of consumers through the activity set up in a Gantt chart.

The total hydraulic fluid requirement is the sum of the maximum value of hydraulic consumption for each activity possible to be run simultaneously.

10 Conclusion

MicroSoft Project (MS Project) is evaluated to be a program with functionalities of great value to evaluate and decrease the duration of an activity, e.g. tripping in. Several operations constitute an activity and the goal is to make the sequence of operations as efficient as possible.

To decrease the duration of an activity, machines and their operations should aim to be executed simultaneously, with short trajectories/distances to travel and high, but safe velocities. The sequence of operations in an activity is restricted by dependencies between the operations that define which operations that can be run simultaneously.

The critical path in MS Project consists of the critical operations with no slack, and defines the duration of an activity. The goal is to set up the correct dependencies and the duration for each operation in an activity to find the critical operations. These critical operations will be the bottlenecks and therefore the operations and machines to improve.

For Rig 1 it is evaluated to be possible to decrease the duration of tripping in one stand from 124 seconds to 104 seconds. Instead of tripping 29 stands per hour it should be equipped with a faster hoisting system which make it possible to trip 34,6 stands per hour.

Even though well parameters allow high velocities lowering the drillstring into the well, the machine configuration may restrict to decrease the duration of tripping in one stand by increasing the velocity of the operation “Lower to stickup”. In that case the machine configuration is the limiting factor.

A lot of the machines on a drilling rig are driven by hydraulic pressure. The department Drilling Systems has been asked to evaluate the requirements for the Hydraulic Power Unit (HPU). They need to evaluate the total flow required [l/min] of hydraulic oil at the time of highest consumption. Each consumer of the hydraulic oil as hydraulic motor(s) and/or cylinder(s) demand a flow [l/min] to operate as intended. The sequence of consumers is a result of the sequence of operations. After the sequence of operations is optimized and illustrated in a Gantt chart, it can be broken down to a level which illustrates the sequence of consumers through the activity. The sequence of consumers through the activity and the flow needed to each consumer results in the hydraulic flow through the activity. The activities evaluated to take place at the same time may coincide such that the maximum flow in each activity must be added to determine the flow required from the HPU.

11 Future work

The following listed below are proposed for further work:

- The efficiency for a specified rig for other activities than tripping in shall be evaluated.
- The efficiency for other rigs with other machine configurations shall be evaluated.
- The efficiency of a drilling rig for tripping in on Rig 1 was evaluated to be restricted to its machine configuration and the solution represented was to increase the velocity to two of the critical operations. A new concept of the machine configuration is an interesting point of view to decrease the duration of tripping in.
- Calculation of hydraulic consumption for a specified rig shall be done to illustrate this by an example.
- The swab and surge effect have been evaluated by assumptions simplifying the calculations. Further evaluation and calculations should be done for swab and surge. This should include different geometries, different fluid rheology and hydraulic models, turbulent flow, open ended pipe, thermal effects and transient model.

12 List of figures

14 References

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