Master of Science Thesis

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Potential of Real-Time Use of Dynamic Drilling Models

Trondheim, 10.06.2011

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TITLE (ENGLISH):	**Potential of Real-Time Use of Dynamic Drilling Models**
TITLE (NORWEGIAN):	**Potensiale ved Sanntids Bruk av Dynamiske Bore Modeller**
FIELD OF STUDY:	**Earth Sciences and Petroleum Engineering**
SPECIALIZATION:	**Drilling Engineering**
DEGREE:	**Master of Science**
TIME PERIOD:	**17 January – 14 June 2011**
SUPERVISOR:	**John-Morten Godhavn**

Abstract

The history of drilling engineering applications has revealed that the frequent operation problems are still common in oil well practice. Blowouts, stuck pipes, and well leakages are examples of repeated problems in the petroleum industry. The main reason why these unwanted problems are unavoidable can be the complexity and uncertainties of drilling processes. Unforeseen problems happen again and again because they are not fully predictable, which could be due to lack of sufficient data or improper modeling to simulate the real conditions in the process. Traditional mathematical models have not been able to totally eliminate unwanted drilling problems because of the many involved simplifications, uncertainties, and incomplete information. Drilling models have however developed from simplified steady-state models to more advanced models having increasing complexity with regards to process details in real-time. The main objective of this study is to evaluate the potential of real-time use of dynamic drilling models.

eDrilling is providing the technology elements to realize real-time modeling and simulation of drilling processes. By integrating available real-time drilling data with advanced mathematical drilling models, a throughout analysis of the drilling operation is possible. A case study is conducted, in which the system is run in replay-mode with actual drilling data. Results are evaluated carefully with respect to user-friendliness and efficiency potential.

The study has shown that successful utilization of real-time use of dynamic drilling models is challenging due to five reasons:

1. Manual control is required to configure and tune models properly
2. Access to needed input data is demanding due to complex data routes crossing multiple actors and vendors
3. Lack of communication across departments, disciplines, and companies
4. Differences in company culture, internal policies, work procedures, etc.
5. Lack of support and faith in new technologies

Case study results have demonstrated that the technology elements and modules integrated in eDrilling are well-developed and ready for commercialization. The applied drilling models have proven to give a correct representation of the drilling process with reproducible results. More case studies should however be conducted with playback data from different wells in order to agree upon the findings presented in this study. In order to realize the full potential of eDrilling, an imminent challenge is to create field pilots where both management and drilling teams involved are more deeply committed to a successful outcome.

Acknowledgements

This master thesis has been prepared in partial fulfillment of the requirements for the degree Master of Science in Earth Sciences and Petroleum Engineering at the Norwegian University of Science and Technology.

There are several people without whom this thesis would not have been possible. First of all, I would like to thank my advisor, Professor John-Morten Godhavn at NTNU/Statoil, for helpful guidance throughout this work. His encouragement has been much appreciated and his feedback has been very motivating in the fulfillment of this thesis.

I am in great debt to eDrilling Solutions AS and Managing Director Rolv Rommetveit for giving me the opportunity of writing this thesis. Their very welcoming atmosphere and enthusiasm has been vital when first presenting the objective of this work. I would like to thank them for facilitating this research in terms of giving me access to the eDrilling tool with subsequent models and real-time data. The evaluation of the system has been very exciting and interesting.

I cannot emphasize enough how grateful I am to Doctor Svein Hovland at SINTEF Petroleum Research and Mr. Morten Svendsen at eDrilling Solutions AS for their eagerness to help and guide me through this work. They have always been available for discussion and questions, and they have always allocated time and resources to assist my inquiries whenever needed. This has been inspiring and highly appreciated. I would also like to thank for the financial and technical support given by SINTEF Petroleum Research in Stavanger, as they have paid my travel expenses and given me access to relevant literature research work.

Thanks to my fellow colleagues and friends at NTNU. Their ability to make a good and cheerful atmosphere during five years of studying has given me the strength and encouragement to earn my degree with style.

Not at least, special thanks go to my parents, Marian and Jim, for a lifetime of unlimited love, understanding, and support.

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Live as if you were to die tomorrow. Learn as if you were to live forever.

Mahatma Gandhi (1869-1948)

1. Introduction

1.1 Background

As far as drilling engineering is concerned, there are many problems that are difficult to solve purely by traditional analytical or numerical approaches due to many uncertainties as well as numerous simplifications and assumptions. In spite of remarkable advances in computing technology, many businesses are still struggling with the problem of modeling and accessing data. Particularly, problems related to drilling and oil well technologies are not fully solved in spite of long-term activity and a fairly large amount of data and experience. Catastrophic blowouts have not been eliminated in drilling practice. Less dramatic and more common events like stuck pipes, drillstring wash-outs, or mud losses are still common drilling problems. Average non-productive-time (NPT) for wells drilled in Europe is 20-25% (Godhavn 2009), but drilling has survived with such numbers as long as the well potentials have been so great. Now, however, the trend is going towards marginal drilling for smaller volumes, which motivates for more efficient, more accurate, more robust, and less expensive solutions.

Real-time connectivity from the rig to the office is becoming the norm for many operations today. The real-time Operation Support Center (OSC) is the hub of these activities in town where domain experts, data interpretation experts, and drilling experts can be involved directly in collaboration and critical decision-making. Having the ability to move the point of decision-making from the rigsite to the OSC intuitively provides the capability for more effective drilling optimization and the direct saving of NPT through risk mitigation. However, one of the major challenges drilling engineers face is to make good and timely use of the large amounts of data that are continuously produced from the well. The latter goes to the fact that this challenge is related to integration across departments, disciplines, and companies, to knowledge sharing and experience transfer, to the decision-making process in operation and planning, and to the quality, management, and modeling of data.

With the advent of dynamic drilling models, a more detailed analysis of the drilling operation is achievable in real-time. This is utilized by integrating real-time drilling data with advanced modeling technology, also often just referred to as *real-time drilling*. It’s main goal is to provide the technology elements and functionality required to meet the challenges mentioned above.

Developments are ongoing to realize the full potential of real-time drilling as such tools now have reached the commercialization phase.

1.2 Methodology

Real-time drilling is a methodology that considers real-time drilling data and predicts drilling trends for advising optimum drilling parameters to improve drilling efficiency and to reduce the probability of encountering drilling problems. Within the application, certain engineering models are available using real-time data. These models are designed for hydraulic analysis versus real-time data, which in turn enables real-time simulation, visualization, and decision support. In addition to having integral complex models within the application, the presence of graphical-user interface (GUI) functionality provides additional enhancement when monitoring drilling information in real-time. By allowing the creation of information from user defined model calculations, the user is able to make quick, informed decisions based on the timely information.

1.3 Scope of Thesis

This thesis presents research work focusing on real-time use of mathematical descriptions of the well combined with real-time data. The idea is to apply and evaluate a developed tool named eDrilling to address the potential of real-time drilling. A case study is conducted by applying the system in replay-mode.

1.3.1 Objectives

The goal here is to evaluate eDrilling in terms of efficiency potential, field application, and user-friendliness. Based on case study results, pros and cons are investigated rigorously to address capabilities and challenges. The case study covers the drilling process of a previously drilled well with realistic real-time data acquired at the time of drilling. A central effort is to evaluate how tools like eDrilling can be utilized successfully in the drilling industry. With this in mind, the major focus of this study is dedicated to the obtained results when running the system in replay-mode, and based on these whether or not eDrilling has the features needed to optimize and enhance drilling operations. If this is not the case, what will it take to accomplish this task? The thesis sets out to answer some of these important questions.

The author will however emphasize that the findings and conclusions obtained herein are mainly based on the case study presented in this work. Due to the complexity of eDrilling and its subsequent modules, model results will ultimately differ depending on manual configuration, availability and quality of input data, and allocated resources in terms of manpower and time.

These conditions will change from well to well and from operation to operation. An illustrative example is when the case study shows that eDrilling is unable to detect drilling problems concerning pack-off tendencies, even though deteriorating trends are observed for some drilling parameters. This issue might lead to a disappointing conclusion stating that the system is not completely able to detect unwanted events as promised. However, with sufficient tuning of model sensitivity parameters, this behavior could possibly be detected and thus give eDrilling valuable recognition. As a consequence, the reader should have the complexity of the system in mind when going through the judgments presented in this thesis.

1.3.2 Content

The thesis is divided into 8 chapters and 3 appendices:

Chapter 1 mentions some of the current challenges present in the drilling industry, and gives an overview of the motivation and objectives of writing this thesis.

Chapter 2 discusses the concepts of real-time drilling in general terms, including applications and limitations of dynamic models. This chapter also addresses the criticality of sensors, the requirements on data quality and proper data handling, and the possible changes related to work processes and organization.

Chapter 3 describes the technology and functionality elements implemented in eDrilling, where the modules utilized in the case study are identified in particular.

Chapter 4 explains how the case study is performed, involving analysis of the provided input data and description of system setup.

Chapter 5 presents case study results, putting emphasize on output calculated by the models. Some results are analyzed mathematically to show relationships to engineering principles presented in the literature.

Chapter 6 gives discussions about the utilization of eDrilling and real-time systems in general, and how to successfully implement these in future operations in the drilling industry. Today’s overview is presented in a rational manner as well as directions for future improvements.

Chapter 7 sums up the conclusions drawn based on the work presented in this thesis.

Chapter 8 suggests possible recommendations for future work.

2. Real-Time Drilling

In this chapter, a general description of real-time drilling is presented.

2.1 History

Drilling modeling and optimization, with the objective to maximize footage drilled in time, minimize drilling costs, and to mitigate unexpected problems, have been described in numerous research studies. In most of the early studies, the drilling parameters were required to be investigated off-site due to lacking the opportunity of transferring data in real-time. Recent enhancements in computer technology, handling of large data sets, and high-speed communication systems enabling deployment of faster, more efficient networks to the fields, have made drilling optimization possible in real-time.

Simmons (1986) performed one of the first ever real-time drilling optimization studies. His findings offered a viable technique for optimizing bit hydraulics to the supervisor at the rigsite, where he suggested two approaches for improving on drilling efficiency while on-bottom drilling. He concluded that the combination of current technology and engineering, coupled with "real-time" drilling optimization, would nearly always save on rotating hours, improve drilling efficiency, reduce possible formation damaging effects and ultimately save on overall drilling costs.

Ursem et al. (2003) demonstrated how an operator and a service company implemented the use of latest technology within the scope of Real Time Operations Centers (RTOC). Their work revealed that communication between the involved parties improved interventions and made the advices much clearer, resulting in limited downtimes. They concluded that it was possible to influence unexpected outcomes in real-time instead of relying on an expensive lesson to be learned.

Rommetveit et al. (2004) developed a new and innovative drilling automation and monitoring system named Drilltronics. All available surface and sub-surface drilling data were utilized to optimize the drilling process in real-time. The system included a broad set of advanced dynamic models which would calculate missing parameters if needed. Several optimization modules were introduced and linked together by an integrated drilling simulator to enable a comprehensive assessment of the entire drilling operation.

Dupriest and Koederitz (2005) evaluated drilling efficiency of bits in real-time by effectively using the Mechanical Specific Energy (MSE) concept. They developed a system allowing the driller to continuously monitor MSE calculated through surface measurements alongside with normal mechanical drilling logs. Bit balling type occurrences were easily identifiable with the analysis.

Milter et al. (2006) showed how real-time data transfer from offshore to land enabled support of drilling, well intervention, and production operations in an efficient manner. Their work revealed that remote support resulted in a much better utilization of engineering resources, enhanced a common understanding, and made the work process integrated. Drilling optimization was conducted based on the judgment of experts involved in the process based on their experience. They concluded that by implementing automatic surveillance by means of real-time data transmission, the number of unforeseen events was reduced. The number of well shut-ins was decreased, thus increasing the regularity in operations.

Monden and Chia (2007) established that the decision-making point could be moved from the data acquisition point to the OSC. It was mentioned that real-time connectivity from the rigs to the offices was becoming the norm for many operations being performed recently. They concluded that significant value could be achieved by maximizing the effectiveness of the OSC by fully integrating real-time quality and decision-making procedures into all drilling operations.

Rommetveit et al. (2007) presented eDrilling, a new generation real-time simulation and visualization system designed to integrate all actors involved. The concept used all available surface and downhole real-time drilling data in combination with real-time analysis to monitor and optimize the drilling process. An advanced integrated drilling simulator was introduced, capable to model different sub-processes dynamically, and also the interaction between these sub-processes in real-time. This enabled forward-looking, real-time supervision, diagnosis of the drilling state, advisory technology for more optimal drilling, and a 3D visualization of the wellbore. The technology was successfully tested and verified in several drilling operations in the North Sea (NS) (Rommetveit et al. 2008a; 2008b; 2010a; 2010b; 2010c).

Iversen et al. (2008) adapted the Drilltronics system into the rig control mechanisms in order to transfer signals from both surface and downhole sensors in real-time. The introduced system worked dynamically for well flow, drillstring mechanics, thermo-physical properties, solids transport, and torque and drag models. Their test study proved that it was possible to achieve a system which could calculate parameters and verify the quality of safeguard calculations. Using the torque and drag model, they showed that wellbore stability could be diagnosed through trend analysis of friction between the wellbore and the drillstring. They concluded that the system could alleviate challenges like fluid loss, stuck pipe, and pack-off tendencies, and come up with suggestions to avoid such behavior. However, they addressed that challenges with real-time data were related to both accuracy and validity, and that the system functionality was a function of data quality as well as correct system setup.

Gandelman et al. (2009) introduced a methodology to interpret pressure-while-drilling (PWD) measurements and mud-logging data for vertical wells. Real-time data were received during drilling to predict equivalent circulating density (ECD), pump pressure, and solids concentration. Measured data were then compared to predicted parameters to identify and diagnose potential problems. The methodology represented a step further in real-time drilling data interpretation, and was implemented for use as a software tool at rigsites and OSCs.

Cayeux (2011) developed a new software tool designed to ensure safer and more effective drilling operations. DrillScene is a computer system for real-time monitoring of downhole conditions during drilling operations, in which its main objective is to detect and warn, in real-time, when drilling operations are getting critical. It uses advanced real-time models to calculate hydraulic and mechanical forces, and by calibrating the models and handling the real-time signals, this has yielded very good results. He demonstrated that the system has given give warnings about deteriorating downhole conditions during tests on several wells in the NS.

2.2 Dynamic Models

As real-time monitoring of drilling operations gave way to trending, trending is now yielding the stage to dynamic modeling. While static models are generally accepted, the use of dynamic models is emerging. Drilling models have developed from simplified steady-state models, used primarily for planning and decision-making purposes, to more advanced models having increasing complexity with regards to process details in real-time. They typically address drilling dynamics such as drillstring mechanics and vibrations, temperature modeling, and multiphase flow including high-accuracy multiple fluid and cuttings transport calculations (Bjørkevoll et al. 2006; Petersen et al. 2008b; Bjørkevoll et al. 2010). New types of model-enabled control functionalities, e.g., advanced managed pressure drilling (MPD), dual-gradient applications, rate of penetration (ROP) optimization, or automatic safeguarding of the drilling process, are in turn enabled through these dynamic drilling models. Florence and Iversen (2010) showed that controlling machines for drilling operations using outputs from models has been successfully achieved in the oil business.

As outlined by Bjørkevoll et al. (2006), some of the key points of advanced dynamic models are:

- Models are directly linked to real-time data
- Models are integrated with intelligent algorithms that automatically interpret deviations between measured data and model predictions
- Models and diagnosis algorithms are integrated with data acquisition systems and run in real-time driven by real-time data
- Models do not require the presence of model experts

2.2.1 Concept

A software representation of the model consists of: (1) Numerical software implementation of physical relations or correlations based on the mathematical model, and (2) a software solver for solving the implemented equations. To apply such dynamic equations in a computer model, they must be discretized and implemented in a computer program. The methods selected for discretizing and solving the equations will affect both speed of solution and dynamic response. Methods such as 2D or 3D finite element or finite volume discretization might be applied for time consuming and resource demanding calculations. However, Petersen et al. (2008b) reported that such methods might not be applicable to achieve high enough calculation speeds for real-time purposes.

As more effects are taken into account, the complexity of the model equations increases. The number and complexity of required sub-models and correlations are increasing to achieve the level of complexity required as the model results are linked closer and closer to diagnosis and control of the drilling process. Moreover, the demand for detailed information of process parameters is increasing with increasing model complexity. Examples of such parameters are typically mechanical descriptions of drillstring and casing, wellbore geometries, detailed properties of drilling fluids, formation characteristics, and process dynamics. This information is required for setting up and updating model parameters, for providing boundary conditions related to real-time calculations, and for correctly interpreting the state of the process so that the right model or right model-state is applied. These requirements for multiple measurements and increased data flow lead to increased demand on availability and quality of data, processing capacity, and efficiency in communication and teamwork. Not to mention that the input data play a significant role in order for the equations to be solved correctly and for the models to give reliable results. For use in real-time applications, the drilling models generally depend on the following information (Florence and Iversen 2010):

- Geometry of the system:
    - Providing pipe properties, wellbore inclination, length of string, etc.
- Pre-determined relations:
    - Providing base ρ and μ tables/relations
- Manually or automatically measureable variables of the system:
    - Pump strokes providing volumetric flowrate, density and temperature, and mud rheology properties
- Methods for deriving variables not directly measureable
- Relations for process effects influencing pressure such as:
    - Effect of flow area changes
    - Relations for pressure drop in bottom-hole assembly (BHA)
    - Applications of other tools (e.g., flow subs)
- Means of determining state of process (circulating, surge/swab, drilling etc.) for applicability of models and application of other models and sub-models

2.2.2 Shortcomings

With the previous section in mind, it is not only a question of whether a model is accurate enough for its purpose, but also to what extent the requirements for its application could be met, and how to solve them if not. The quality of the model must be related to the application being considered, and whether it is appropriate or right for the specific application. Generally, the model is of high quality if it is appropriate for its purpose. However, there is much more to applying real-time drilling models than just implementing and running them. When a measurement is needed as an input to a drilling model, there are potential shortcomings related to data inconsistency. These should be addressed either by means of the models being built to accommodate lack of data, or development of enhanced sensors that gives appropriate response when sensor readings are missing. Another problem might stem from the need of manual configuration pertinent to the sizes of the wellbore, tubulars, liners and other fixed components. To update this information, a model expert or well-trained drilling crew is usually necessary.

Based on the above, there must be well-functioning means for providing sufficient input to the models. This appropriate input must be provided through:

- Input from rig and downhole sensors
- Manual input
- Detection of the state of process
- Pre-processing of data through application of:
    - Relations used to derive model parameters
    - Statistical methods for filtering input data

A model needs to be tuned to ensure adequate accuracy in real-time calculations, and this is accomplished by model calibration or updating model parameters. The calibration of the model is achieved through tuning model parameters such that the model results fit the real-time measurements. Calibration will be poor if sensors are unable to provide high enough accuracy in the measurements. Due to the fact that the different models and sub-models are linked closely together, miscalibrated parameters will ultimately also affect the output calculated by other models. For example, recorded real-time signals for block position, hook load, axial velocity, and rotational speed are used when calculating torque and drag. Consequently, these calculations might be flawed if the recorded measurements are not calibrated correctly. The accuracy of the process data therefore affects the reliability of the system, in which uncalibrated models potentially could generate misleading output and confusing results (Gravdal et al. 2005; Bjørkevoll et al. 2006).

It is essential that the state of the process is correctly diagnosed and that the appropriate model configuration is applied at all times. Different parts of the model might be applicable to different stages in the drilling process. For example, detecting the drilling state might be achieved by monitoring string revolutions per minute (RPM) and circulation rate together with hook load and weight-on-bit (WOB) signals from surface sensors. However, low accuracy in weight measurements could make such diagnostics challenging, and such uncertainties will become even more of a challenge in real-time applications of more advanced drilling mechanics models. Measurements must therefore meet the requirements on accuracy and validity requested by the models.

2.3 Sensors

The introduction of real-time drilling requires an analysis of the criticality of the sensors providing the needed real-time data. Better understanding of how the different sensors are functioning will most likely improve the interpretation of the acquired data and the fidelity[1] of the models for use in future improvements. To understand their capabilities and limitations, the most common sensors used in drilling operations today are discussed in the following. Unless otherwise stated, the next sections build on work presented by Schafer et al. (1992), Schooley (2008) and Florence and Iversen (2010).

2.3.1 Design and Limitations

Diaphragm Weight Indicator

Commonly used measurements are WOB and hook load, and these measurements are usually made with a load indicator. In 1926, the first ever diaphragm[2]-type weight indicator was developed, which also remains as one of the most common weight sensors used today. Diaphragm-type weight indicators are closed, sealed hydraulic systems consisting of an indicating pressure gauge, hose and diaphragm. They provide remarkably consistent indications of load on the hook by sensing changes in the deadline tension. Because deadline tension is part of the tackle system, there is a proportional relationship to the total hook load. The diaphragm sensor creates a deflection when it is clamped onto the deadline. As the load in the deadline increases, a resultant force acts against the diaphragm as the deadline attempts to straighten. This deadline force is converted into a pressure signal that is displayed as a load on the indicator, which is a specially built hydraulic gauge. In spite of its longevity, the design has limitations and weaknesses that should be understood by those real-time systems that are using WOB and hook load as inputs to their respective models. The line tension measurement depends on several factors such as proper maintenance and changes in ambient temperature. In addition, worn contact points and excessive wear increases friction, which in turn can alter the degree of accuracy. As the diaphragm ages, it also stretches, which significantly is offsetting the factory calibration. Adding all these effects together, an estimated error in accuracy of 10 to 13% is not unusual.

The Clamp-On Sensor

The development of electronic weight indicator systems has accelerated in recent years to overcome some of the issues related to hydraulic sensors, while retaining the ease of installation present in earlier designs. The clamp-on sensor measures the side force created by the line

[1] *Fidelity* of the simulator refers to how closely the simulator emulates the mechanisms, inputs, and outputs of a given system or process (Millheim 1986).

[2] In mechanics, a *diaphragm* is a sheet of a semi-flexible material anchored at its periphery (Schooley 2008).

deflection by a strain gauge within the block assembly. This sensor is more prevalent in the colder climates since its readings are less affected by temperature. However, the contact point between the line and the sensor might vary, which can affect the deflection measurement by as much as 1%. Improper installation can also cause significant error, e.g., all readings will be affected if the clamp is overtorqued. Knowing that few rig crews re-calibrate the sensor after slip and cut, even more erroneous measurements are not uncommon. Estimated environmental and application errors range from 2 to 3.5%.

Compression Load Cell

Instead of reading line displacement, a measure of the forces at the deadline anchor itself is another technique for reading hook load. Caged within the anchor to prevent lateral movement, the compression load cell's sensor could be either hydraulic or electrical, where increase in line tension increases the pressure inside the load cell. Some sensors make use of multiple bridges with an internal processor that uses voting logic to compare readings to compensate for temperature variations. Even though compression load cells eliminate some of the issues with the clamp-on and diaphragm sensors, they are still measuring the load at the wrong end of the drill line. It remains subject to the environmental effects on the drill line, such as wear and tear, and friction at the sheaves of the tackle. The error rate is in the range of 1 to 2%.

Load Pins

Strain gauges are used routinely to instrument pins to measure shear forces in the connecting pins between components in the traveling equipment. This configuration eliminates external effects on the drill line and sheaves, and a common location is the becket pins beneath the traveling block. Different clearances between the pins and the holes in the becket can cause error, and wear can enlarge the holes. Temperature effects can introduce a small shift in the output signal, but the total application error is still lower than for the other systems. The combination of these effects results in an estimated error of 2.5 to 3%.

Torque

Due to the fact that it is difficult to measure torque in a rotating machine, rotary torque is often obtained from an electrical measurement in the powered portion of the rotary or the top drive. A toroidal magnetic field surrounding one of the power leads to the motor on direct current (DC) rigs is commonly used for torque measurement. A voltage is induced in the sensor as current is passing through the magnetic field. Rotary torque is taken as an output from the variable frequency drive on alternating current (AC) rigs. Readings are then compared to a performance curve provided by the manufacturer, in which motor current is converted to torque. The curve applies to an average motor, so it does not account for wear or degradation, like changing impedance in the windings. Likewise, the variation of the field strength, an adjustable setting on the rig, is often not accounted for.

The sensor is calibrated at the low end of operation where the output is zero. Measurements are generally considered accurate at this zero output, also known as normal offset. The data system uses the amperage reading at the rig floor to calibrate at the high operational end. Calibration is rarely performed against a true torque measurement, and field installation can cause considerable error. If calibration however is undertaken, the torque sensor is usually not re-calibrated during the remaining life of the rig. Moreover, torque measurement requires the pipe to be turning or the motor to be stalled. If the drillstring is wound up and the top drive or rotary brake is set when the throttle goes to zero, the motor speed also goes to zero, and so does the torque, even though the mechanical energy is being held by the brake. Thus the torque sensor is subject to issues which might result in less accurate torque measurements.

Pump Pressure

Pressure readings might be measured at the standpipe or elsewhere on the rig. A diaphragm is used to isolate mud from a gauge's hydraulic fluid, or separating the mud from an electronic strain gauge package for electrical readouts. Some manufacturers provide a chip located inside the sensor to compensate through a wide temperature range. Shortcomings of mud pumps include slow response due to the relatively long time period (typically 1-2 seconds) between strokes, and inaccuracies due to uncertainties in pump efficiency, which changes with pump pressure and piston seal wear.

Flow-In and Flow-Out

Due to the high operating pressures and flowrates present while drilling, the quantity of flow of the mud pump is difficult to measure. Debris in the mud could render inoperative any sensor that has a rotating device inside the line. The most common method of measuring flow through a positive displacement pump is to count the strokes over time and calculate the volume of each stroke. Fluid compressibility, mechanical efficiencies, or pump valve maintenance are not taken into account in the measurement. New techniques using high frequency sensors on the fluid ends allow a complex calculation of efficiency, leading to a more accurate flow-in measurement. While flow-in is based on pump parameters and is fairly consistent for most field applications, the flow-out sensor is typically a simple paddle meter and is subject to significant variations. The paddle itself is subject to accumulations of cuttings, gumbo, etc., requiring regular cleaning. The reading assumes a linear relationship such that the higher the flowrate, the greater deflection on the paddle. A mechanical linkage to a potentiometer can be converted into an electrical signal. After installation, the calibration procedure assumes that the potentiometers are within 3 or 4% of the standard resistance, and that the resistance is linear over the full range of values. The full range goes from when the paddle is down at no flow, to when it is fully extended at what should be the maximum flowrate. The J-meter is another flow-out device which is an instrumented U-tube in the flow line. A strain gauge is measuring a spreading force caused when flowrates are increased. This type of flow meter is more accurate, but it is sometimes difficult to install because more headroom is required between the flow line and the drill floor.

Rotating Speed

The speed of a rotating part or a mud pump in RPM or in strokes per minute (SPM), respectively, are routinely measured with either an inductive proximity switch, a magnetic proximity switch, or a limit switch. The target should be at least the size of the face of the switch, and the alignment requires that the target should be flat and positioned parallel with the switch's face. Depending on the size and model of the machine, the calibration differs widely because the debounce rate must be properly adjusted. The limit switch has a whisker that makes contact with the piston assembly at each stroke in the mud pump. To ensure high enough degree of accuracy, it should make contact with the pump only once per cycle. Some sensors are, however, allowing multiple counts per cycle, leading to measurement errors.

Additional Sensors

Some drilling models require additional information, such as the physical parameters of the mud. The most common measurements are taken by mud engineers at the rigsite, although there are in-line sensors available. These measurements are usually made only a few times daily or after significant changes are made to the mud system. Typical readings include measurements of viscosity/rheometer, mud weight and pit volume, and temperatures. Developments are underway to make automatic real-time sensors available for drilling fluid properties at the rigsite (Bern et al. 2007; Saasen et al. 2009), which will benefit greatly in real-time applications. In addition, heave sensors, gas indicators, and many other specialty devices are available on rigs today. Efforts are ongoing to make downhole measurements and their analyses more prevalent in real-time implementing applications such as wired drill pipe (WDP) (Jellison et al. 2003; Johnson and Hernandez 2009), improved LWD[3] (Radtke et al. 2009), and real-time analysis of measurements (Rommetveit et al. 2007; Iversen et al. 2008; Luthje et al. 2009). A steady progress is being made towards a fully instrumented rig, in which all relevant information will be available for application of real-time dynamic models in order to improve drilling processes.

2.3.2 Quality and Reliability

In real-time model applications, it has been found that rig equipment analysis is necessary to assess the applicability or upgrading requirements. Mathematical models used with the drilling control must communicate regularly with the drilling process to extract information from sensors and provide updated control commands for the drilling operation. Sensor failure could potentially jeopardize the safety of the entire operation if the applied models are fed with invalid or erroneous measurement readings. Another potential hazard might originate from the positioning of the sensor. A measurement which has become more critical with the introduction of new drilling technologies is the drilling fluid temperature measurement. This measurement is required for estimating the temperature gradient of the fluid in the drillstring and annulus. The temperature

[3] *Logging While Drilling (LWD)* is a technique of conveying well logging tools into the wellbore downhole as part of the bottom-hole assembly (BHA) (Radtke et al. 2009).

has a large effect on the density and the viscosity of the drilling fluid, and consequently on the effective ECD. In real-time drilling, the calculated downhole pressure is a key control parameter in calculating process safeguards and providing valuable diagnostics of the drilling operation. Erroneous readings might often be due to a low mud level in the pit with a higher placing of the temperature sensor. To avoid these problems, Cayeux et al. (2009) suggested that the measurement should be made directly on the flow line to the top drive to make sure that the temperature of the fluid actually injected is measured.

Traditionally, the drilling fluid rheology is used to track possible deviations and for reporting, rather than used directly for computations during drilling operations. Changing between mud types during operations constitutes an added challenge. When a new fluid is displaced in the hole, there exists no standard real-time signal informing about the change in mud rheology. Consequently, models will not be aware of the changes in drilling conditions without manual configuration. For example, the selection of the active pit is sometimes done using manual valves, and it would therefore be necessary to trust that someone is manually changing the configuration in the computerized drilling control system.

With this background, the criticality of sensors with respect to quality of measurements is substantial. Sensor reliability is a prerequisite that *must* be present in order for real-time drilling systems to be implemented successfully in the industry in near future. Existing design limitations should be addressed carefully, and additional efforts from operational units, manufacturers, rig personnel, and system developers should be promoted to meet the challenges. Some of these issues are discussed further in Chapter 6.

2.4 Data Flow and Management

There is a clear need for data to be validated, calibrated, and normalized before being sent to an application. Bad points need to be removed without destroying vital information. The issue of data quality and its influence on workflows and decision-making is not a new one. Kyllingstad et al. (1993) described how errors and poor quality of mud-logging data restricted their quantitative use in drill bit optimization and modeling work. They addressed that common sources of error were related to sensor quality, calibration procedures, and sampling rates. Data flow and proper handling of data will become even more crucial with the introduction of real-time drilling, and these challenges must therefore be taken very seriously by the drilling industry.

2.4.1 Data Quality Control

Mathis and Thonhauser (2007) state that data quality control consists of the following steps:

- Range check
- Gap filling
- Outlier removal
- Noise reduction
- Logical checks

Range Check

A very simple, highly effective approach to improve the data quality is the range check. This approach removes unrealistic spikes from the data set by using upper and lower limits to check if the recorded measurement lies within a predefined range. Holland et al. (2004) showed that about 80% of the wrong data could be identified with this technique.

Gap Filling

The general problem with measurement data are that the data points are never equally spaced. Although measurements are recorded at a specified frequency, missing data points always occur due to outliers, sensor failures, etc. Gaps are identified as missing data points as well as points with null values. Figure 2.1 shows gap filling of a data set with 91% of missing data. A gap filling technique is therefore needed to prevent missing data points. Mathis and Thonhauser (2007) presented an algorithm including a defined gap time to mitigate this problem.

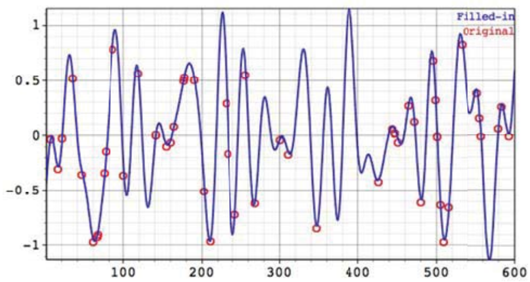

Figure 2.1: **Gap filling of missing data points.**

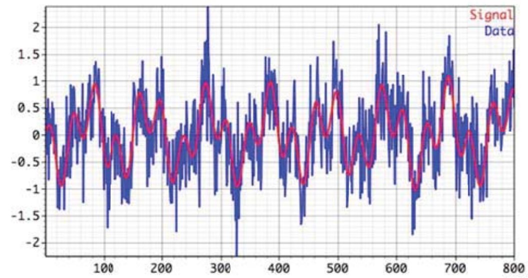

Figure 2.2: **Signal (red curve) after noise reduction.**

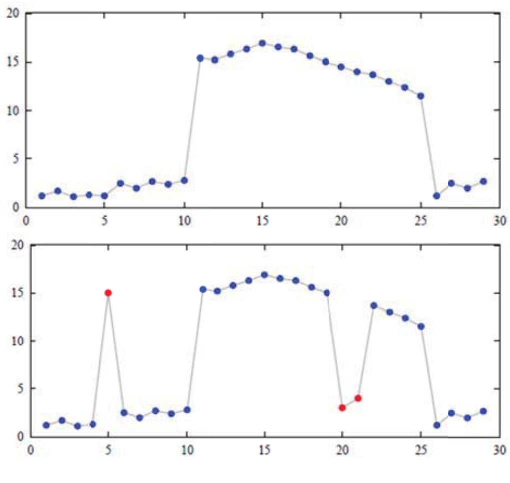

Figure 2.3a,b: **(a) Clean data set without any outliers.**
(b) Data set with outliers (red dots).

Copyright Mathis and Thonhauser (2007) and Spectraworks (2011).

Outlier Removal

"Outliers" are the data points lying away from the general data trend. After the range check and the gap filling, data might still contain outliers that are within the plausible range. Figure 2.3a shows a clean sample data set, while Figure 2.3b shows the same set with outliers represented as red dots. The plausible data range check could be from 0 to 20 units on these data, so the range check does not take effect on the introduced outliers. Mathis and Thonhauser (2007) reported that while outliers do not have any big influence on the total duration of recognized operations, they influence tremendously the results where the duration of events is important. For example, an outlier in the hook load could prevent the correct detection of the connection duration. Their findings concluded that a mean filter method, which is broadly used in the drilling industry nowadays, is not suited to remove outliers at all. Filtering of erroneous data will become more important with the introduction of real-time drilling models, and a detailed discussion of different filtering techniques could be found in their work.

Noise Reduction

Noise usually exists in data recorded by sensors and downhole gauges, and denoising is thus an important step in data processing. In order to denoise the data, the data noise level must be estimated beforehand, as depicted in Figure 2.2. One appropriate approach to estimate the noise level is to first best fit the data, subtract predicted pressure response from recorded values, and then calculate the noise level based on the difference. Ouyang and Kikani (2002) applied a nonlinear regression method for best fitting downhole gauge data to determine the noise level. They found that this method was superior to the least square error linear regression method more commonly used for fitting purposes. Olsen and Nordtvedt (2005) investigated filtering and compression of real-time production data by means of wavelets. They demonstrated that wavelet noise estimators combined with a median filter were suited for removal of outliers. Depending on the application and the type of noise, the most appropriate method should be incorporated in the design of the real-time system.

Logical Checks

Logical checks give information about relations between different data channels as well as physical boundaries that exist. The primary function of these checks is not to automatically correct the data, but to automatically provide alarms if something is not working as it is supposed to. Hole depth check, relation between flow and pressure, and correspondence between bit depth and block position are just a few examples of logical checks which allow removal of possible errors. Such functionality will be needed in order for real-time applications to prove to the user that they are reliable and trustworthy.

2.4.2 How to Measure Data Quality?

The previous section explains how quality control of data can be managed by utilizing the listed steps mentioned above. However, what is needed in order for the models to achieve this challenging task? As outlined by Sawaryn et al. (2009), actual values must be compared against clearly stated requirements to make meaningful and objective assessments of the data quality. Actual values can then be compared to requirements for each of the following categories:

Data Identification

Data are usually identified using some well name, hole section, depth or time marker, and name tags. It is very important to apply proper naming conventions since standards like WITS[4] or WITSML[5] have catalogs to name measurements properly. It is favored that these catalogs are used by all actors to control the data quality more easily.

Presence

Presence tells whether or not the parameter or data channel is to be provided. By distinguishing between a null value and zero, diagnostic procedures and locating the source are made easier. A null value is a value used to signify that a specific value does not have a valid measurement. Normally -999.25 for floating numbers and -999.00 for integer numbers are used (Mathis and Thonhauser 2007). However, different numbers are broadly used in the industry, and the null value should therefore be standardized to prevent misinterpretation.

Measurement Depth and Frequency

The depth at which measurements are taken and the number of samples that is required per unit time are also important. Data from different channels might be provided at different rates and the ability to provide these data depends on several factors, including sensor capability, processing power, and bandwidth. Dropouts of data might result if these resources are insufficient.

Accuracy

Accuracy can be defined as the degree to which the numerical value of the data represents the physical parameter being measured, including the number of digits of precision. Accuracy is also a function of datum offsets, including time, location, elevation and distance from drill floor to sea level, and details of the map projection that is to be used. In oil well drilling, the rotary kelly bushing (RKB) is widely used as the standard reference for any depth measurement. However, it is seldom reported or specified when measurements are exchanged, and problems could occur if the data do not provide the possibility to define multiple depth references over time.

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[4] *Wellsite Information Transfer Specification (WITS)* is an industry standard from the mid 1980s that uses a binary file format for transferring wellsite drilling data (Energistics 2011).

[5] *Wellsite Information Transfer Standard Markup Language (WITSML)* is web-based and builds on XML technology, which is both platform and language independent (Energistics 2011).

Continuity

Continuity is by means the number of gaps in the data set and the percentage of the required data that is actually provided over some time period. Data continuity should always be above an acceptable level to ensure sufficient input to the models at all times.

Units

In order to use data, the unit of a measurement needs to be known. Recorded and presented units might differ, and it is still common to find that the unit's translation is incorrectly set. To prevent such errors, it is necessary that the first step in any data management process is to define the units of the measurements.

Metadata

Metadata are information that might help to interpret the data and their quality, e.g., notes on any re-calibration or changes that have been made. Implementation of such information could potentially ease the quality control of the input data.

2.4.3 Data Recording, Transmission and Communication

In addition to sensor related issues, data quality also depends on data recording, transmission, and communication. Today, information is sent from the near bit area of the drillstring via mud pulse telemetry. The signal rate for this form of telemetry is quite low, nominally 5 to 20 bits/second (Halsey and Rafdal 2009). In addition, communication is essentially going only one way from downhole to surface, which makes it difficult to send signals down to the bit. Circulation must also be present, and mechanical vibration adds a significant amount of noise to the data, which in turn reduce the sampling rate. Low telemetry rates mean that important data are stored in the memory of the downhole tools, which can be downloaded only once the tool is retrieved to surface. This way of gathering valuable data would be too late for use in real-time applications, and also in many cases contain lower data resolution than required.

Due to limitations on signal rate, the number of sensors in the drillstring is also limited, and processing of the measurements has to be done downhole. Advanced electronic components are consequently subjected to high temperatures and severe vibrations etc., which might affect the overall data quality. Moreover, measurements are often recorded electronically, in which the resolution of an analog-to-digital conversion affects the accuracy of any retrieved data. Some data systems filter the measured data, but only a few record the amount of filtering applied. The data might not have sufficient resolution for a detailed analysis, and the sample rate often varies by the supplier. While sample rate refers to the number of samples per second, the resolution corresponds to the length of each sample. Most measurements are made at 1 Hz[6] or more, while some manufacturers use 10 Hz sampling for critical values, such as hook position. There are no

[6] Hz = 1/second

industry standards in this area, but most recorded data are stored at 30-, 10-, or 1-second intervals (Florence and Iversen 2010).

The number of data channels has grown significantly as rigs and downhole tools have become increasingly instrumented (Sawaryn et al. 2009). These data could be recognized as surface engineering parameters, such as hook load, rotary speed, standpipe pressure (SSP), and petrophysical downhole parameters, e.g., gamma ray and resistivity. Both sets of data are measured in time and depth, and both sets are required for successful real-time drilling. The increase in channels has been propelled by growth in computing power, and sampling rates have been increased ten folds with the introduction of WDP. According to Ølberg et al. (2008), this technology allows data to flow approximately 10,000 times the rate of fast mud pulse telemetry. Likewise, Hovda et al. (2008) reported that this drillstring telemetry technology has been utilized on two separate offshore locations in the Norwegian NS (NNS), allowing reliable data transmission at speeds up to 57,600 bits/second. The results from these deployments prove that a reliable technology exists for high-bandwidth, two-directional communication between downhole sensors and surface. This by means demonstrates that the existing industry challenge related to low bandwidth and time lag associated with mud pulse telemetry is possible to overcome.

Data volumes vary according to hole section and sub-surface tool requirements. Up to 60-70 data channels are used on average, both in time and depth, for 17 ½ in. holes. Some of 30-40 of these channels are normally populated (Sawaryn et al. 2009). For 12 ¼ in. holes and down, up to 90-100 channels are used, where an average of 60-70 channels are populated. The data volumes therefore vary from rig to rig due to changes in operational phases and tool requirements. These volumes sum up to approximately 1 gigabit (Gb) per well per day, meaning a 50 day well typically generates 50 Gb of data. Bandwidth for drilling and completions ranges from 256 kilobits/second to 4 megabits/second (Mb/s), and is increasing steadily to keep pace with the required applications. NS platforms are now connected by fibre optics, in which the bandwidth available for each has been increased to minimum 34 Mb/s. Rommetveit et al. (2008b) reported that the lowest bandwidth available to shore from any ConocoPhillips (CoP) platform in the NNS is 155 Mb/s.

2.4.4 Aggregation of Data

Issues regarding data quality and transmission have already been mentioned. Another challenge just as crucial is the responsibility of gathering and sharing the required real-time data. From the operator's perspective, there are three other parties involved in the data provision: the rig-sensor systems companies, the service providers, and the rig contractor. Their roles and responsibilities are deliberated more tediously in the discussions of Section 6.2. Pickering et al. (2007) presented two information architectures for real-time operations and aggregation and delivery of rigsite data, which ultimately affect the utilization of real-time systems. These are described as follows:

Service Company Managed

In this architecture model, the rigsite mud-logging or MWD[7]/LWD company is contracted to aggregate the data produced at the rig and transmit them to their own data centre. The data are housed on the service company's server, and in order to pull the data into the operator environment, access is provided to the operator either with client tools or with the operators own server. Visualization of the data is generally provided via a web-enabled data viewer.

The major advantage of a service company managed information architecture is that the data aggregation is consistent with historical approaches to sourcing real-time data. Continuity is provided because the service is incorporated into the contracted rigsite service, e.g., MWD/LWD or mud-logging. However, additional hops are required before the data arrives back inside the operator's environment as it goes via a service company data centre first. In addition, the multiple service providers transmits and displays the data in several ways, thus standardization is not promoted. Historically, less attention has been paid to service level requirements for data (Sawaryn et al. 2009), which in turn makes it more difficult to ensure sufficient data quality for real-time measurements.

Operator Managed

In this model, the operator contracts either the rigsite mud-logging company or a specialist data aggregation provider to aggregate the rigsite data and transmit the data directly to the operator's office-based server. Hence in this, case most of the data architecture is deployed, owned, and supported directly by the operator. Data transmission, storage, and visualization are under direct control of the operator, and it will therefore have greater influence over design, security, resilience, and support levels from end to end.

It is advantageous that the core data flow stays within the operator's environment by means of reducing the number of hops and potential failure points. Standardization, consistency, and sharing of data between teams are also promoted. On the contrary, internal requirements not previously considered are needed in order to ensure high availability and quality of the data. The operator might have neither the experience nor the organizational capability to provide 24/7 support as routinely provided by service companies.

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[7] *Measurement While Drilling (MWD)* is a system developed to perform drilling related measurements downhole and transmit information to the surface while drilling a well (Navarro et al. 2006).

2.5 Work Processes and Organization

Implementation of real-time drilling is going to put additional constraints on work processes and real-time workflows within the organization. Roles of the people involved will change dramatically as new support functions are needed. New work procedures must be established and awareness must be increased by training all the team members for their new roles and responsibilities. Not to mention that successful implementation also depends on a wide understanding of the functioning of the system in order to build necessary confidence in the new technology. A throughout assessment on how real-time drilling technology will affect work processes and organization are evaluated in detail in Section 6.3.

3. eDrilling

A general description of eDrilling with subsequent modules and models are given in this chapter.

3.1 Description

eDrilling is providing the technology elements to realize real-time modeling, supervision, optimization, diagnostics, visualization, and control of the drilling process. The system consists of software tools that make advanced dynamic models more accessible for all kinds of operations in real-time. Rommetveit et al. (2007) demonstrated that by integrating available real-time drilling data with real-time dynamic modeling, a throughout analysis of operations is possible.

3.1.1 System Infrastructure

eDrilling has a modular structure, in which individual clients collect and process the data, see Figure 3.1. It is based on an open system architecture where the Data Distribution System (DSS) server is the kernel for data distribution; it is the hub through which all data are sent. Equipment suppliers, service companies, contractors, and operators can connect via standard interfaces to the DDS server such that all actors involved are integrated in the ongoing operation. Unless otherwise stated, the following section builds on efforts described by Rommetveit et al. (2007; 2008b; 2010c) and Kolnes et al. (2008)

Individual modules (clients) are connected to the system to provide different functions, as shown in Figure 3.2. Each client has a list of variables which it receives from other clients through the server, which are called the *subscribed* variables. The clients perform operations making use of its subscribed variables, and they can generate new variables and pass them on to the other clients through the server. These variables are then the client's *provided* variables. A list of the clients' subscribed and provided variables are readily available to the user. Functional descriptions of the individual clients are given below.

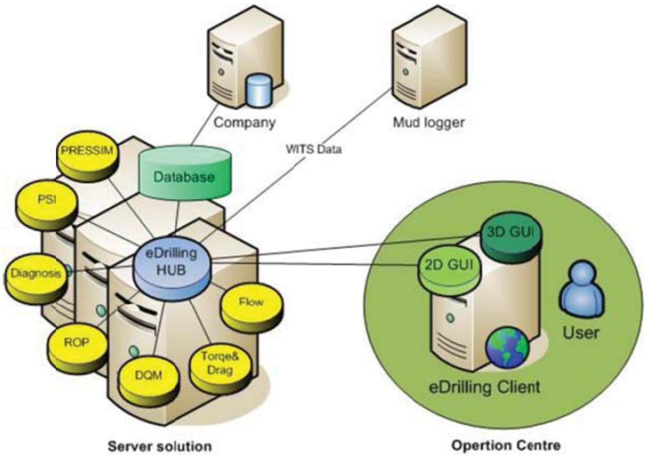

Figure 3.1: **Data flow and system infrastructure (Rommetveit et al. 2010c).**

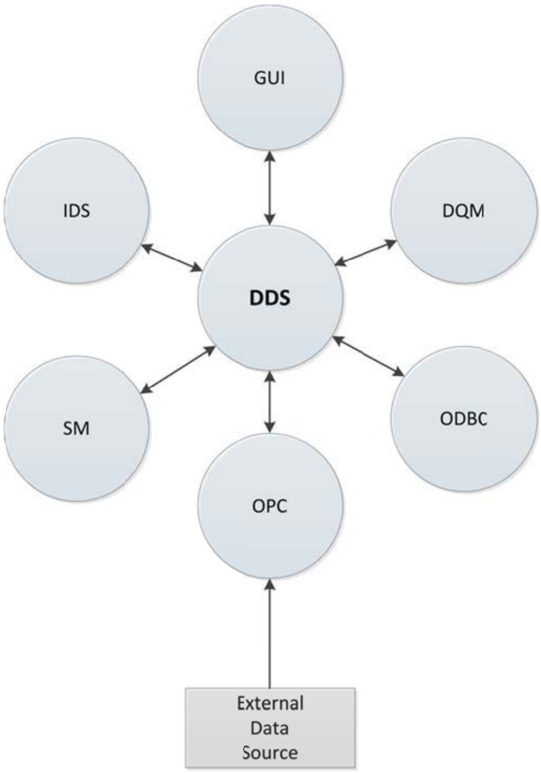

Figure 3.2: **Schematic of the clients integrated in eDrilling. Adapted from Kolnes et al. (2008).**

External Data Sources

eDrilling allows for integration of standard interface protocols like *WITS, WITSML, PROFIBUS*[8] *OPC*[9], etc. Real-time data combined with well configuration data are fed to the system via real-time interfaces from reporting tools, e.g., mud logging systems, MWD logging tools, and well planning database interfaces.

OPC

The OPC client was originally designed to provide a common bridge for Windows-based software applications and process control hardware (Burke 1999). Standards define consistent methods of accessing field data from control devices. This method remains the same regardless of the type and source of data. All real-time signals are distributed through the OPC client, which in turn allows access to any hardware data.

ODBC

Configuration data are stored in a database where an ODBC[10] link and an ODBC client are used to access these data. The client uses the link to make the data accessible to the other clients through the server. Recorded real-time signals are also stored here during replays. Particularly, the difference between the OPC client and the ODBC client is that they are connected to a real-time interface and a database interface, respectively.

Session Manager

It is the session manager's (SM) job to control the running of the other clients, and it acts as a real-time data provider when running the system in replay-mode. It subscribes to the real-time data table from the ODBC client and provides input data for one time step at a time, waiting for the clients to finish calculation of the previous time step before it provides the next. The SM therefore synchronizes the calculation from the various modules, where the system time is normally set to 1.0 second or to the interval of the signals if the signal exceeds this value.

Data Quality Module

The data that are used as input to the models must be of sufficient quality to ensure efficient and reliable interpretation of the drilling process. A full description of the Data Quality Module (DQM) is presented in Section 3.2.1.

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8 *PROFIBUS (Process Field Bus)* is a standard for field bus communication in automation technology. It allows communication between devices of different manufacturers without any special interface adjustment (Profibus 2010).

9 *OLE for Process Control (OPC),* which stands for Object Linking and Embedding (OLE) for Process Control, is the original name for an industry-standard mechanism to communicate and exchange data between clients and servers from different manufacturers (Burke 1999).

10 *Open Database Connectivity (ODBC)* is an application program interface to access information from numerous types of databases. The design of ODBC aims to make it independent of programming languages, database systems, and operating systems (Idehen 1993).

Integrated Drilling Simulator

The models that enable real-time analysis of the drilling process are assembled in an Integrated Drilling Simulator (IDS). The IDS is capable to model the different sub-processes dynamically, and also the interaction between these sub-processes in real-time. Strictly speaking, the IDS functions as the “heart” of the eDrilling system; it is a synthesis of multiple transient and steady-state coupled models that calculate the well conditions based on all available data from the drilling process. The IDS consists of a dynamic flow and temperature model, a torque and drag model, a ROP model, a drilling vibration model, a wellbore stability model, and a pore pressure model. Figure 3.3 shows the different dynamic models that are a part of the simulator. Some of these models interact with the mechanical earth model[11] (MEM), and they are also closely linked to a diagnostic module. The novel modules are discussed further in the Section 3.2.

Graphical User Interface

The GUI includes a 2D-client and a 3D-client. The 2D-client is an engineering and administration tool, which is used for operation monitoring and drilling analysis. Measured and calculated values are compared and plotted against each other in order to investigate developing trends and potential unwanted drilling conditions. The real-time 3D-client is a new generation advanced visualization tool where the user has a 3D visual view of the entire drilling process through an easy-to-use interface. The client runs on a personal computer (PC) based platform, and is more than powerful enough to visualize structural data, equipment at topside, seafloor, and downhole, together with real-time data sources.

The 2D and 3D-client can be used as an advanced information cockpit in a single PC setup, in a multi-screen control room environment, or in a collaborative setting where multiple users, sitting at different locations, are able to connect to the clients via the Internet. Diagnostic messages and advisory functionalities are incorporated in both clients as well, giving real-time insight into the ongoing drilling operation.

[11] *The mechanical earth model (MEM)* is a numerical representation of the state of stress and rock mechanical properties for a specific stratigraphic section in a field or basin (Schlumberger 2011).

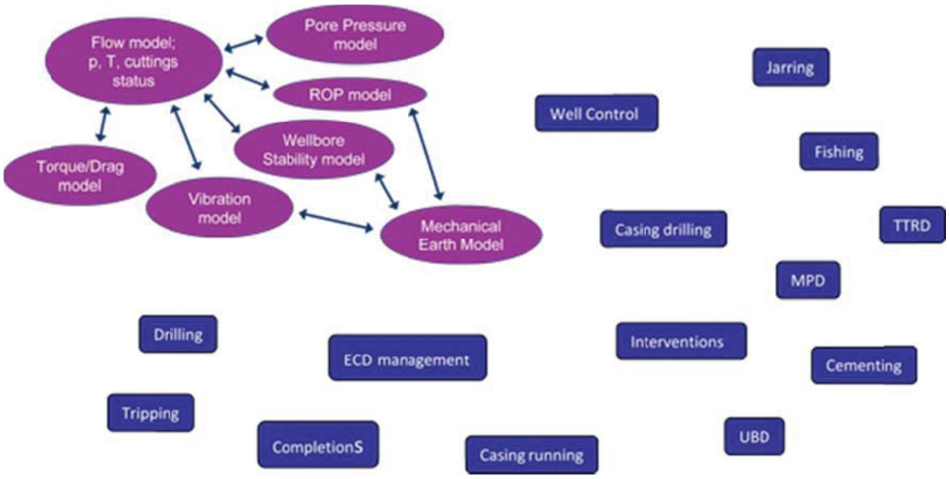

Figure 3.3: **Dynamic models and different drilling sub-processes integrated in the IDS (Kolnes et al. 2008).**

3.1.2 Data Requirements

Even though the integrated models and sub-models follow a novel and robust design, a considerable large amount of input data must be available in order for them to function as specified. Well configuration data as well as real-time sensor signals are of essential value in order for the system to be useful and contributive at all. Table 3.1 and Table 3.2 sum up the most important input parameters.

Table 3.1: **Configuration data required by eDrilling.**

Parameter	Description
Drillstring Characteristics	Inner and outer diameter of pipe body and tool joint, weight per length, E-modulus, yield strength
Well Trajectory	Inclination and azimuth vs. measured depth (MD)
Completion Data	Wellbore friction factor and inner diameter vs. MD
Temperature Profiles	Temperature vs. true vertical depth (TVD) or MD

Table 3.2: **Real-time signals required by eDrilling.**

Date	SSP
Time	Mud flowrate-in
Bit position	Mud density in
Well depth	Rotary off-bottom
Block position	Lift/stack
Block speed	Slips
ROP	Axial speed
WOB	Rotational speed
Rotary torque	Hook load

This list of input requirements surely adds up to the fact that real-time drilling systems are completely dependent on input data no matter what level of novelty and robustness.

3.2 Modules

The novel modules integrated in eDrilling are described in this section, particularly with most emphasis on those utilized in the case study.

3.2.1 Data Quality Module

It is essential that interpretation and processing of the acquired data from the drilling process for use in the real-time models are correct and suitable. The DQM provides a software tool for quality assurance and improvements of the data relevant in drilling operations. By systematic modeling of physical effects that influence the measured values, acquired real-time data can be improved for crucial drilling parameters (Rommetveit et al. 2007; Kluge and Frøyen 2010a). Sensor failure is detected by utilizing data quality checks performed by the DQM, which in turn are used to inform when a signal is corrupt. Systematic errors and noise are corrected, and erroneous or misleading data can be flagged so that calculations performed by other modules do no react to bad data. The DQM has a modular and flexible design for easy integration in existing systems. It is designed to function on a minimum of available input data and should be able to handle large variations in data quality with respect to measurement precision and sampling rate. Basically, the module has three main functions:

Data Validity

Changes in the drillstring are automatically tracked such that nominal bit depth is updated. Configuration data, such as tubular components and station surveys, are also checked. Some input data to the system comes from humans entering information manually, in which errors might occur if this is done under stressful conditions. The DQM checks these manual input values against the acceptable range for the parameter being read in, and asks for confirmation for suspicious values. The bulk of the data coming into the system is dynamic signals acquired from rig sensors. Such data could be sampled once per second to perhaps once per minute or even less often. Due to the fact that sensors have different physical form, different forms of communication, use different analog and digital filtering techniques, and sample at different rates, signals will vary from rig to rig. The DQM is responsible for checking the validity of the provided real-time signals.

Data Corrections

If the data is lacking the quality required, the DQM can perform corrections and deliver these immediately. Examples are typically correction of bit depth due to a number of physical effects, such as ballooning effects, thermal effects, tensional stretch and residual drag, or just errors measured in bit depth recorded by the sensors. By a combination of theoretical modeling and automatic calibration during rotation on-bottom, the WOB might also be improved. It is usually measured at the surface by observing the reduction in hook load when the bit is pressed into the formation. Developments in bit technology with the combination of more complex wells drilled give a less predictable communication of axial forces from the bit up to the surface. The DQM takes these effects into account, as relative errors in estimated WOB could be as much as 100%.

Status Detection

Drilling a well consists of many other activities, not just making the well deeper. It is the DQM's responsibility to identify the activity and communicate this to the other modules. Algorithms are developed for identification of the proper state of the drilling process, e.g., drilling, tripping, circulation, making connection, drillstring in slips, and so forth.

3.2.2 Torque and Drag Module

Knowledge of string forces and string torque is essential for supervision and diagnosis of the drilling process, and the Torque and Drag Module (TDM) is able to calculate these during operations. The module is based on the standard soft-string model originally developed by Johancsik et al. (1984), put in standard form by Sheppard et al. (1987), and later evaluated by Mitchell and Samuel (2007). Interaction between torque, drag, and buckling is taken into account based on models described by He and Kyllingstad (1995) and He et al. (1995).

The objective of the TDM is to calculate the axial force, contact forces, torque and drag, drill pipe stresses, and friction coefficients. This kind of information is necessary for calculations of the stress state of the string, in which observed deviations between model predictions and real-time measurements are evaluated. Consequently, the results are used for string integrity assessment and wellbore condition monitoring, e.g., sudden fluctuations in torque might indicate poor hole-cleaning or impending stuck pipe. Calculated results are also used by the DQM to aid in calculating improved values for WOB. In addition, several extensions are implemented in the TDM to enable friction factor back-calculation and calculation of effective stresses along the well trajectory.

It is to be mentioned that torque and drag calculations are rather sensitive to bends in the wellbore. Survey values, i.e., well inclination and azimuth direction, acquired during drilling are often poor in quality and recorded at larger depth intervals. The latter is particularly evident when drilling from floating rigs, in which it is not unusual that heave signals are recorded wrongly. This means that the TDM may underestimate the torque, drag, and stresses acting on the string. However, the module is not very sensitive to small errors in wellbore data (Kluge and Frøyen 2010b).

3.2.3 Flow Module

The Flow Module (FM) is a dynamic thermo-hydraulic model based on fundamental physical principles, such as conservation of mass and momentum. The module consists of a combined dynamic flow, pressure, and temperature model. It takes into consideration fundamental physical effects that are present in the wellbore, e.g., slip between different fluid phases, rheology effects, gelling, frictional pressure losses, etc. Figure 3.4 demonstrates how complex the physics of a well flow model is. The FM handles a large amount of real scenarios and possible situations that might exist in the wellbore during drilling operations, some of them addressed in Table 3.3. Hence the module is universal and does not need to be changed for different scenarios. The current version of eDrilling uses the conventional drilling part of the model, but additional features might be activated as the system is extending. The following section is based on research work described by Petersen et al. (2008a; 2008b) and Bjørkevoll (2010) unless otherwise stated. A more rigid discussion of the application of the FM, including detailed steps for solving governing equations, could be found in their work.

Table 3.3: Scenarios and situations handled by the FM.

Tripping, circulation, drilling, and running of casing and liner	Transient well pressure and flow vs. time during surge and swab
Well pressure/ECD, temperature, and pit volume vs. time including flow of cuttings	Transient well pressure vs. time during running and cementing of casing/liner and when pumping or displacing drilling fluids
Effect of connection breaks on well pressure and temperature vs. time	Equivalent Static Density (ESD) and temperature vs. time during static periods

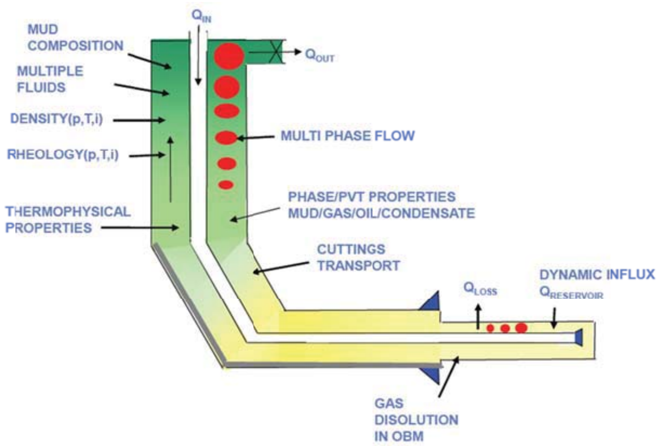

Figure 3.4: The physics of a well and flow model (Gulsrud 2011).

Mathematical Representation

To give insight in how complex the FM is, a mathematical representation with included governing equations is presented. A simplified set of these equations are derived based on the following assumptions:

- All variables depend on only one spatial dimension[12], i.e., the flow along the flow line
- Temperature is known and depends only on the spatial coordinate
- Gas can be dissolved in oil but not in water
- A fluid is composed of up to five different components and might include: drilling fluid, formation gas, formation oil, formation water, and formation cuttings
- Frictional pressure loss computations are based on the Herschel-Bulkley nonlinear three parameter representation of the fluid rheology

Governing Equations

The governing equations comprise conservation of mass of each fluid component and conservation of the total momentum for the system.

Conservation of mass of drilling fluid:

$$\frac{\partial}{\partial t}(A\alpha_m \rho_m) = -\frac{\partial}{\partial s}(A\alpha_m v_m \rho_m) + A\dot{m}_{g,m} \qquad \textbf{(3.1)}$$

Conservation of mass of produced gas:

$$\frac{\partial}{\partial t}(A\alpha_g \rho_g) = -\frac{\partial}{\partial s}(A\alpha_g v_g \rho_g) - A\dot{m}_g + q_{fg} \qquad \textbf{(3.2)}$$

Conservation of mass of gas dissolved in mud:

$$\frac{\partial}{\partial t}(A\alpha_m x_{dg,m} \rho_m) = -\frac{\partial}{\partial s}(A\alpha_m v_m x_{dg,m} \rho_m) - A\dot{m}_{g,m} \qquad \textbf{(3.3)}$$

Conservation of mass of formation oil:

$$\frac{\partial}{\partial t}(A\alpha_{fo} \rho_{fo}) = -\frac{\partial}{\partial s}(A\alpha_{fo} v_{fo} \rho_{fo}) + A\dot{m}_{g,fo} + q_{dg} + q_{fo} \qquad \textbf{(3.4)}$$

[12] A *spatial dimension* begins at one point and moves onward in an orderly fashion (Petersen et al. 2008b).

Conservation of mass of gas dissolved in formation oil:

$$\frac{\partial}{\partial t}(A\alpha_{fo}x_{dg,fo}\rho_{fo}) = -\frac{\partial}{\partial s}(A\alpha_{fo}v_{fo}x_{dg,fo}\rho_{fo}) + A\dot{m}_{g,fo} + q_{dg} \tag{3.5}$$

Conservation of mass of formation water:

$$\frac{\partial}{\partial t}(A\alpha_{fw}\rho_{fw}) = -\frac{\partial}{\partial s}(A\alpha_{fw}v_{fw}\rho_{fw}) + q_{fw} \tag{3.6}$$

Conservation of mass of cuttings:

$$\frac{\partial}{\partial t}(A\alpha_{c}\rho_{c}) = -\frac{\partial}{\partial s}(A\alpha_{c}v_{c}\rho_{c}) + q_{c} \tag{3.7}$$

Conservation of total momentum:

$$\begin{aligned}
&\frac{\partial}{\partial t}\left[A(\alpha_m\rho_m v_m + \alpha_g\rho_g v_g + \alpha_{fo}\rho_{fo}v_{fo} + \alpha_{fw}\rho_{fw}v_{fw} + \alpha_c\rho_c v_c)\right] + \\
&\frac{\partial}{\partial s}\left[A(\alpha_m\rho_m v_m^2 + \alpha_g\rho_g v_g^2 + \alpha_{fo}\rho_{fo}v_{fo}^2 + \alpha_{fw}\rho_{fw}v_{fw}^2 + \alpha_c\rho_c v_c^2)\right] \\
&= -\frac{\partial(Ap)}{\partial s} - A\left(\frac{\partial p}{\partial s}\right)_{fric} + A\left[\alpha_m\rho_m + \alpha_g\rho_g + \alpha_{fo}\rho_{fo} + \alpha_{fw}\rho_{fw} + \alpha_c\rho_c\right]g\cos\theta
\end{aligned} \tag{3.8}$$

t	-	time
s	-	spatial variable along the flow lines
A	-	cross-sectional area of flow line
α_z	-	volume fraction of component “z”
$x_{a,b}$	-	mass fraction of “a” in “b”
$fric$	-	frictional pressure loss
m	-	drilling fluid
g	-	gas
fo	-	formation oil
fw	-	formation water
c	-	formation cuttings
$\dot{m}_{g,m}$	-	rate of gas dissolution in drilling fluid

$\dot{m}_{g,fo}$ - rate of gas dissolution in formation oil

It is assumed that the fluid components fill the system:

$$\alpha_m + \alpha_g + \alpha_{fo} + \alpha_{fw} + \alpha_c = 1 \tag{3.9}$$

$$\dot{m}_g = \dot{m}_{g,m} + \dot{m}_{g,fo} \tag{3.10}$$

Sub-Models

The system is closed by adding additional equations, also referred to as sub-models.

Drilling fluid density:

$$\rho_m = P_m(p, T, x_{dg,m}) \tag{3.11}$$

Gas density:

$$\rho_g = P_g(p, T) \tag{3.12}$$

Formation oil density:

$$\rho_{fo} = P_{fo}(p, T, x_{dg,fo}) \tag{3.13}$$

Formation water density:

$$\rho_{fw} = P_{fw}(p, T) \tag{3.14}$$

Cuttings density is constant:

$$\rho_c = C \tag{3.15}$$

Rate of gas dissolution in oil:

$$\dot{m}_{g,l} = \dot{M}_{g,l}(p, T, x_{dg,l}) \tag{3.16}$$

l - liquid, i.e., drilling fluid, m and formation oil, fo

The flow consists of different fluid components, which generally will be transported at different velocities.

Gas velocity:

$$v_g = V_g(p, T, V_{mix}, \alpha_{g,} \rho_g, \rho_{fo}, \rho_m, \sigma) \tag{3.17}$$

V_{mix} - average flow velocity, i.e., volume flux divided by cross-sectional area

σ - surface tension between gas and mud

A numerical representation is utilized for solving the equations, in which the flow path is divided into several segments. The numerical methods solve conservation of mass and momentum (and energy) with actual boundary conditions and fluid models imposed. Each segment contains a number of numerical boxes, which can be treated independently, as shown in Figure 3.5. The flow in each well segment is computed separately, and solved for the appropriate flow in the junctions. A segment could be the drillstring, the choke line, a part of the annular region, etc. The segments are connected such that it represents the actual physical system to be modeled in such a way that requirements on calculation speed and accuracy are met. For use in real-time drilling, it is crucial that the model is able to deliver results faster than real-time, and it might have to run several times faster than real-time when it is calibrated. The FM has been used for automatic choke control in different MPD operations (Bjørkevoll et al. 2008; Syltoy et al. 2008), where stability is found to be very good.

Figure 3.5: Segment structure with numerical boxes.

A dynamic two-dimensional temperature model is closely linked to the mass transport model integrated in the FM. Temperature profiles inside the running string and in the annulus are updated in every time step, and dynamic effects due to pump rate changes and string movements (axial and rotational) are taken into account. The pressure computations and the heat/thermal computations are offset from each other, i.e., they are not computed simultaneously. This simplifies the computation greatly, because a set of difficult non-linear equations is not required as shown in the equations below. In order to solve them, the domains needed for the temperature model are discretized and divided into numerical grids, as depicted in Figure 3.6.

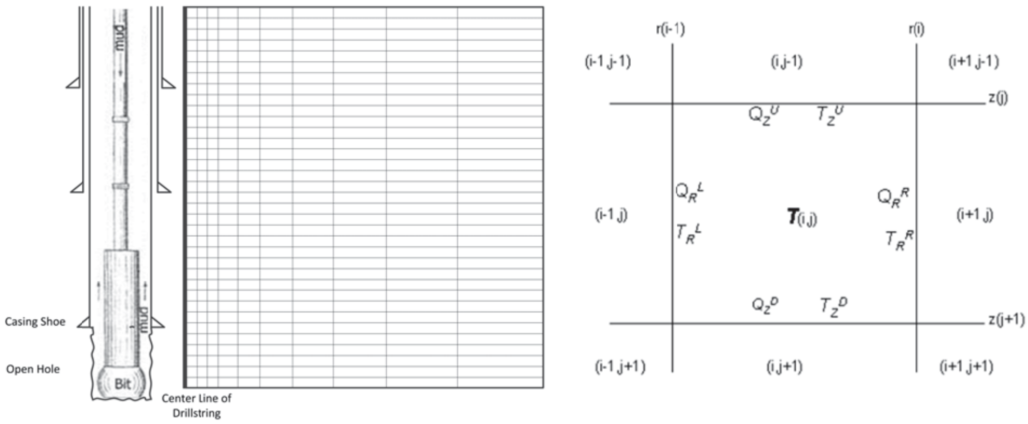

Figure 3.6: **Computational domain, discretized domain, and schematic diagram of numerical grid. Illustration adapted from Petersen et al. (2008b).**

Heat and Thermal Equations

The equation for conservation of energy could be written as

$$\frac{\partial \rho H}{\partial t} - \nabla \cdot (\vec{Q}_f + \vec{Q}_c) = 0 \qquad \textbf{(3.18)}$$

ρ	-	density
H	-	enthalpy per unit mass, J/kg
Q_f	-	forced-convective heat flow, J/sec
Q_c	-	conductive and natural-convective heat flow, J/sec

Q_f ,which represents the forced-convective term, is given by

$$\vec{Q}_f = \rho H \vec{V} \qquad \textbf{(3.19)}$$

$\vec{V}$	-	velocity vector
T	-	temperature field

The conductive and natural-convective term does not have a general expression. In the particular case of a purely conductive isotropic material, Q_c is expressed by

$$\vec{Q}_c = \lambda \nabla T \tag{3.20}$$

λ - thermal conductivity

Using cylindrical symmetry, the differential operator could be written as

$$\nabla = \frac{\partial}{\partial r}\hat{r} + \frac{\partial}{\partial z}\hat{z} \quad \text{and} \quad \nabla \cdot \vec{A} = \frac{1}{r}\frac{\partial}{\partial r}(rA_r) + \frac{\partial A_z}{\partial z} \tag{3.21}$$

The distribution is assumed linear between two nearby points in the axial direction. In radial direction, it is assumed that the radial temperature distribution follows the general trend of the steady state solution, described by Corre et al. (1984)

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = 0 \quad \Rightarrow \quad T(r) = T_1 + \frac{T_1 - T_2}{\ln(r_1 / r_2)} \ln\left(\frac{r}{r_1}\right) \tag{3.22}$$

T_1 - $T(r_1)$

T_2 - $T(r_2)$

The discretized heat equation could then be written as:

$$E_T^{new}(i,j) - E_T^{old}(i,j) = \Delta t \cdot \left(Q_R^L(i,j) + Q_R^R(i,j) + Q_Z^U(i,j) + Q_Z^D(i,j)\right) + E_{other}(i,j) \tag{3.23}$$

$E_T^{new}(i,j)$	-	new thermal energy in box with radial position i, and axial position j
Δt	-	time step size
$Q_R^L, Q_R^R, Q_Z^U, Q_Z^D$	-	heat flux through the left radial boundary, right radial boundary, axial upper boundary, and axial lower boundary, respectively, see Figure 3.6
$E_{other}(i,j)$	-	large “bag” of different contributions. It is possible to put the forced-convection contribution, the heat generated in the drillstring by the bit, and thermo-chemical reactions into this “bag”

The numerical system is solved using a semi-staggered grid. Heat flux parameters are computed in order by using the various grid boundary positions. By evaluating all parameters that are varying with temperature, e.g., density, heat capacity, thermal conductivity, etc., and using the previous time step temperature, the heat equation listed in Eq. 3.23 becomes linear with temperature for the new step.

3.2.4 Diagnosis and Advisory Module

Undesired and potential hazardous well conditions during drilling operations should be diagnosed and detected as early as possible. Based on real-time drilling parameters and calculated values from other modules, the Diagnosis and Advisory module (DAM) gives out diagnostic messages which support the drilling operation. A key feature is to paint a clear picture of what is going on in the well. This is achieved by providing the user appropriate warnings that are issued with easy visualization techniques in both the 2D and 3D-client. More rigid descriptions of the module is found in the work of Kristoffersen (2010). By any means, the DAM is designed to detect the following situations:

Abnormal Well Pressures

There are two different situations involving calculated well pressure for diagnostic messages; *real-time* and *forward-looking*. The FM is used both for real-time simulations and for prediction of future problems to potentially happen in the wellbore. In real-time, the calculated well pressure is continuously compared to pore and fracture pressures. If the well pressure is close to or outside the pressure window, a warning from the DAM is given as output. The forward-looking feature is able to continuously compute expected well pressure profiles vs. depth for the next section or drilling period. It is typically started every five minutes and calculates 30 m ahead (both are configurable). Thus it can generate important information which will assist in controlling the well pressure to stay within the boundaries as drilling goes along. If the forward-looking instance predicts that the opposite behavior is developing, then the DAM will give out a warning together with expected time to occurrence of the problem.

Too High Cuttings Concentration

As for well pressure, the FM calculates cuttings concentration and cuttings transport ratio vs. depth on a grid. The DAM performs two checks involving the cuttings concentration and cuttings transport ratio. In the first check, the module analyzes whether or not the concentration or transport ratio is above or below predefined limits. A warning is raised if this is the case. The second check is if the cuttings concentration is very high compared to a predefined limit, then again a warning is given.

Volume Changes in Active Tank

A loss/gain situation is detected by comparing calculated changes in active tank volume (pit gain) from the FM with measured active tank volume. If the difference between the pit gain and the active volume measurement is larger or smaller than the initial value, a warning is given.

Excessive Tripping Speeds

If a maximum tripping speed is given to the DAM, a simple comparison of calculated bit velocity and maximum tripping speed is performed. The module raises a warning if calculated tripping speed exceeds maximum tripping speed.

Deteriorating Trends Developing

Both real-time and modeled parameters are analyzed by the DAM to detect developing trends during drilling. For example, loss/gain detection uses measurements of mud flow-in and mud flow-out to determine current status, while wash-out detection evaluate calculated vs. measured SPP to detect discrepancies between the two. These unwanted events as well as other common drilling problems are detected as follows:

Wash-Out

Measured SPP and calculated SPP are used for detecting possible drillstring wash-out. Basically, a wash-out is an enlargement of the wellbore, causing the pressure to drop due to an increase in hole size. Because the model is not taking this increase in hole volume into account, the calculated pressure will not be affected by a wash-out situation. A wash-out could therefore be detected by analyzing the difference between the measured and calculated values, and comparing the deviation to a detection threshold.

Loss/Gain

By monitoring mud flow-in and mud flow-out, proportional changes between the two are detected. Depending on data quality for mud flowrate measurements, relatively small differences might be discovered and loss/gain situations are then identified at an early stage.

Critical Bottom-hole Temperature

The purpose of time series analysis of measured or estimated BHA temperature is to give a warning if the temperature is close to critical equipment operational temperature.

Poor Hole-Cleaning

Two methods are implemented for detection of poor hole-cleaning using trend analysis. The first is early warning of poor hole-cleaning, which uses a multivariate statistical analysis approach. Simple trending of back-calculated friction factors resulting from drill tests is the second method.

In the first method, a statistical analysis of SSP and topside torque is included in the poor hole-cleaning methodology. The main principle is that in the case of cuttings build-up (pack-off) in a part of the well, there will be a small rise in SSP and some larger fluctuations in torque. This could happen for a variety of reasons, the most common being that either the drilling fluid is not properly transporting cuttings and cavings out of the annulus, or portions of the wellbore wall collapse around the drillstring. If prompt remedial action is not successful, an expensive episode of stuck pipe could result. An early warning of poor hole-cleaning can be issued by extracting higher order statistical moments (skew or normalized standard deviation) from the SSP and torque, and combining them in a feature. The combined feature is used in comparison with a detection threshold, where the proportion of positive indications over a limited time period should be above the threshold in order to give a warning.

The second method analyzes calculated friction factors from lift/slack and rotating-off-bottom tests in relation to connections to detect build-up of cuttings. By comparing current values of calculated friction factors with a running minimum of the preceding friction factors, a warning is given if the deviation is sufficiently large. The calculations of friction factors are done by the DQM and TDM.

3.2.5 Additional Modules

The modules described below are not used during the conduction of the case study, but still important technology elements of eDrilling.

ROP

The ROP will vary while drilling a well due to variations in formation and drilling parameters. Important formation parameters are compressive strength and formation pressures, while critical drilling parameters include a description of the bit, WOB, rotary speed, well pressure, mud flowrate, and so forth. More information on conditions downhole is obtainable by analyzing variations in these parameters. eDrilling enables such analyses simultaneously by evaluating torque on bit/WOB relationships, analyzing torque and drag, monitoring hole cleaning conditions, and controlling well pressures. Analysis of these data have revealed that drilling time can be reduced by as much as 15% (Rommetveit et al. 2007) by adjusting the WOB such that maximum ROP is achieved.

Drilling Vibrations

Drillstring vibrational problems can be detected by algorithms implemented in eDrilling. If severe vibrations occur, solutions are suggested by the module, including active-damping algorithms to cure stick-slip motion of the drillstring or adjustments to drilling parameters, such as WOB or rotary speed. The algorithms concentrate on the detection and cure of vibrations, not on the prediction of vibrations.

Wellbore Stability

Wellbore stability problems are related to mechanical instabilities of the rock around the hole. By transforming mathematical models to borehole geometry, expected behavior of shales around the wellbore can be estimated. In order to perform such an integrated rock mechanics analysis, a number of effects and a corresponding number of parameters have to be accounted for. These parameters are related to formation properties, drilling conditions, and wellbore data. Fjær et al. (2002) developed a *Predicting Shale Instability (PSI)* software, which is a numerical model that accounts for a variety of such parameters, including chemical effects, mechanical plasticity, strength anisotropy, and pressure and temperature. The PSI model takes into account a rich amount of rock and fluid properties affecting the wellbore stability over time.

For real-time stability analysis, the PSI features have been adapted by eDrilling to accept input from its modules in real-time. The wellbore stability module (WSM) checks whether the criteria for shear or tensile failure are fulfilled or not at a series of points around the hole during drilling. It might be used to test the impact of variations in different drilling parameters, and to give an overview of which of the parameters that are most important for the stability of the wellbore. Examples might be the impact of chemical additives in the mud or the effect of different hole orientations. The stability of the holes as a function of mud weight and time since drilling might then be estimated, and conditions around the borehole might also be analyzed more in detail. The WSM is described more extensively in the work of Fjær et al. (2002) and Nes et al. (2005).

Pore Pressure

In sedimentary rocks, pore pressures could vary from hydrostatic (normal) pressures to very high (abnormal) overpressures. Thus pore pressures are important constraints that will influence the drilling strategy, casing programs, mud weights, etc. both in well planning and during operations. A model for pore pressure predictions is integrated in eDrilling for real-time purposes. Pre-drill pore pressure predictions from basin modeling using Monte-Carlo simulation[13] works as a base for the real-time update, but as drilling and log-data become available during drilling, fast calculations of pore pressures along the well can be performed (Luthje et al. 2009). The calculated pressures along the well are used to weight the pre-drill Monte-Carlo results to update the pore pressure prediction ahead of the bit. Updated pore pressure predictions in real-time are of vital importance for further decision-making. Early warnings are given if abnormal overpressures are to be expected ahead of the bit or if the well pressure tends to drop below the predicted pore pressures. The updated pore pressure prediction is used as input to the FM, WSM, and the DAM providing diagnostic warnings and decision support.

[13] *Monte Carlo simulation* is a method for iteratively evaluating a deterministic model using sets of random numbers as inputs (Anderson 1986).

4. Case Study: eDrilling Replay

In this chapter, information concerning the conducted case study is explained.

4.1 Drilling in "Real-Time"

A case study is conducted where the drilling process of the Ekofisk X-16A Well is replayed in eDrilling. The study covers initial setup, software testing, and evaluation of overall user-potential. A real-time assessment of the drilling process is achieved by running the system in replay-mode with actual real-time data, which were acquired when drilling the well back in 2009.

The following modules are implemented and used during the case study:

- Data Quality Module (DQM)
- Torque and Drag Module (TDM)
- Flow Module (FM)
- Diagnostics and Advisory Module (DAM)

4.1.1 Ekofisk

The Ekofisk field, which is operated by CoP, is the first and main discovery located in the southwestern part of the Norwegian Continental Shelf (NCS). Discovered in 1969 and put on production in 1971, it remains one of the most important oil fields in the NS. Today, the operative parts of the Ekofisk Centre consist of the accommodation facilities Ekofisk H and Ekofisk Q, the production facility Ekofisk C, the drilling and production facility Ekofisk X, the processing facility Ekofisk J, and the production and processing facility Ekofisk M. From the wellhead facility Ekofisk A, located in the southern part of the field, production goes to the riser facility Ekofisk FTP for processing at the Ekofisk Centre. Figure 4.1 shows a schematic of the existing infrastructure.

The field produces from naturally fractured chalk of the Ekofisk and Tor Formations of Early Paleocene and Late Cretaceous ages. Reservoir rocks have high porosity, but low permeability, and lies at a depth of 2,900 to 3,250 m. With an oil column of more than 300 m, the reservoir is just as thick as the height of the Eiffel Tower. Figure 4.2a illustrates this where the orange colored section represent oil. A 3D cut of the reservoir is depicted in Figure 4.2b. Reserves per December 2009 were estimated to be 1,105 million Sm3 oil and 293 billion Sm3 gas. Oil production is planned to continue until at least 2050 (Conocophillips 2010; Npd 2011). Ekofisk was originally developed by pressure depletion, but limited gas injection and comprehensive water injection have contributed to a substantial increase in oil recovery. There have been drilled over 300 wells, and new wells are being drilled as injectors and for production. Much of this drilling is supported from an OSC located onshore about 300 km from the field.

4.1.2 Well X-16A

Well X16-A is planned as a horizontal producer with a 1,030 m horizontal reservoir section in Block 2/4, which is included in production license 018. In the main wellbore, a cement plug has been set into the conductor casing at 364 m, and the well has been sidetracked from here. The 13 $^{5}/_{8}$ in. casing has already been run and cemented, and drilling is resumed from 2,186 m MD when the replay is initiated. From this point forward, the drilling operation carries on until a MD of 2,560 m is reached. A schematic of the wellbore showing the replay interval of interest is depicted in Figure 4.3. As listed in Table 4.1, eDrilling is run continuously for two days while drilling the 12 ¼ in. section of the well. A rotary steerable BHA with a rollercone insert bit and roller reamer is used to drill this section. The MWD package consists of resistivity, gamma, PWD, and vibration. In the drillstring, a 5 ½ in. drill pipe with grade S135 and nominal weight 21.90 lb/ft is used. A full description of the wellbore configuration is found in Appendix A.

Table 4.1: Date and time duration of the replay.

02.03.2009 00:00 → 03.03.2009 23:59

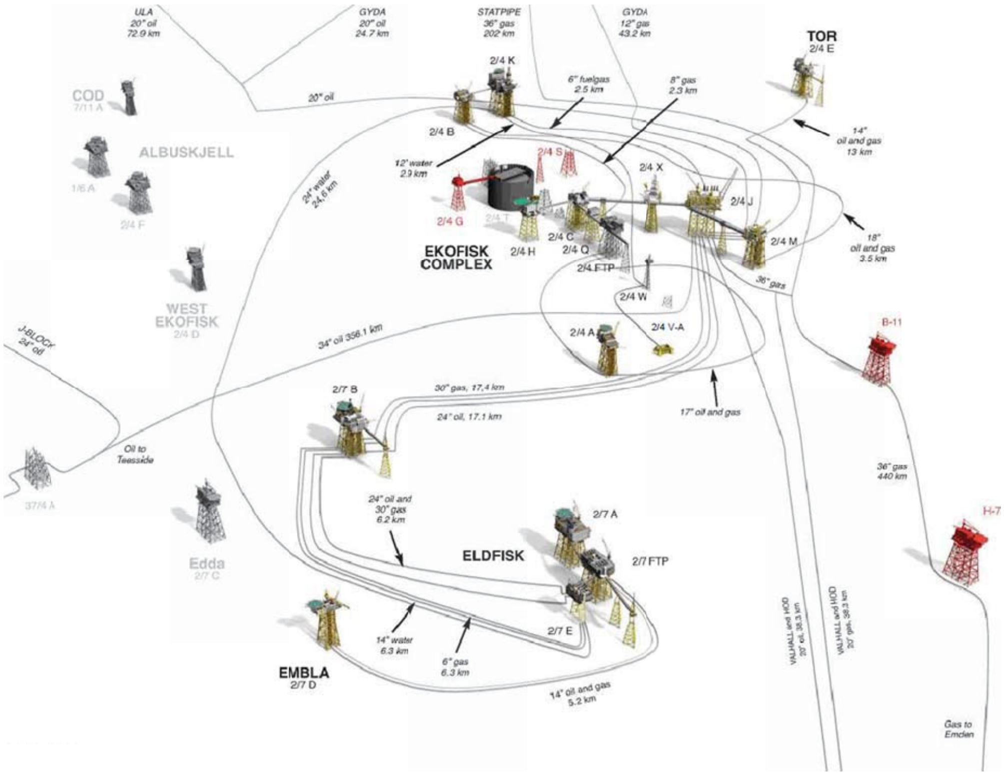

Figure 4.1: Schematic showing existing infrastructure in the Ekofisk field. Grey platforms indicate facilities which have been closed down. Red platforms are owned by 3rd part companies (Conocophillips 2010).

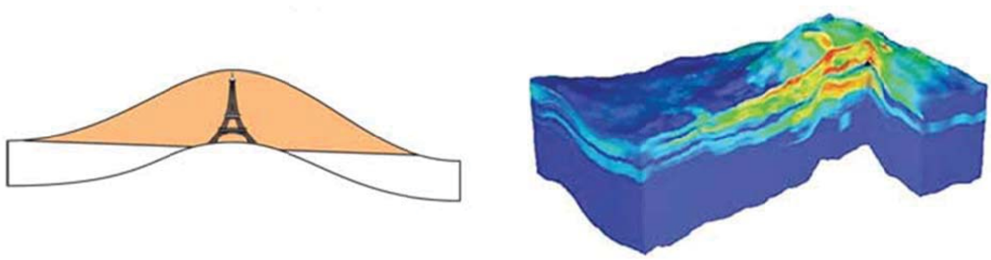

Figure 4.2a,b: (a) The Ekofisk reservoir is as thick as the height of the Eiffel Tower.
(b) 3D view of the Ekofisk reservoir. Blue colors represent water, while oil layers are pictured in red, green, and yellow.

Copyright Rommetveit et al. (2008b).

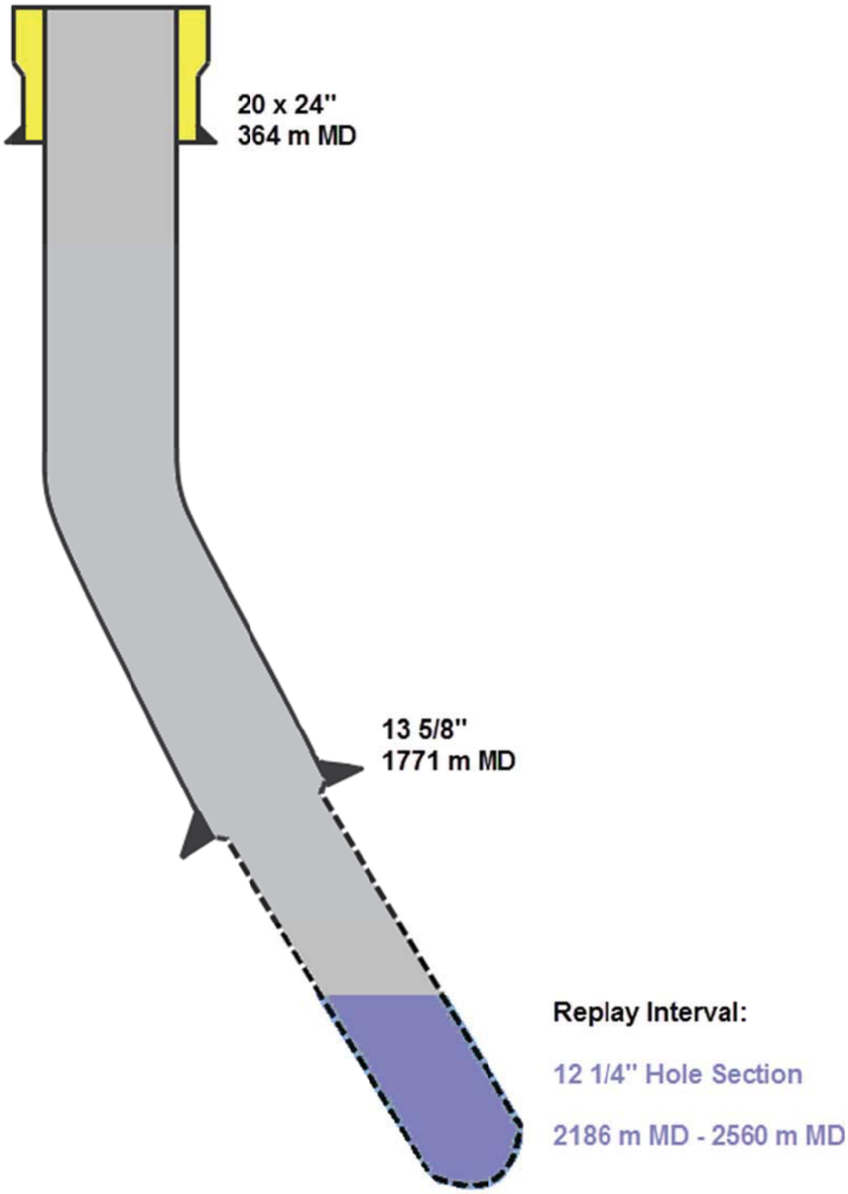

Figure 4.3: **Wellbore schematic showing replay interval.**

4.1.3 Drilling Data

As previously described in Section 3.1.2, eDrilling depends on large sets of data to be used as input to the models. Description of the geometry of the system, e.g., wellbore properties, casing programs, drillstring, well trajectory, drilling fluids etc., is provided by CoP. A nominal description of the lithology and formation pressures is given based on offset wells and gathered logging data. Automatic measurable variables, such as hook load, torque, flowrate, pump pressure, and so forth, are provided from rig and downhole sensors, in which the data are stored as LAS[14] data. An LAS file is a structured ASCII[15] file containing log curve data and header information located at the beginning of the file. Well configuration data are collected from *WellView*, which is a reporting tool used by CoP. The real-time sensor data are stored

Figure 4.5 illustrates the different real-time data utilized by eDrilling. It is worth mentioning that not all of the listed data are used as input to the model calculations, but instead for comparison and identification of relationships between the measured and calculated values (Hovland and Svendsen 2011). In this context, the measured SPP is for example not used as input when modeling this parameter, but rather for trending purposes between the two. Initially, the recorded data were stored at 5-second intervals, i.e., a new measurement value was recorded only every 5th second. This is explained in the lower left part of the figure, in which the data points listed in the table could be looked at as typical measurement values acquired by a rig sensor. Data resolution of the time signal has then been corrected to 1 second such that a sampling rate of 1 Hz is used as input. This is achieved by using the same measurement value for each time step until a new value is recorded. Such an assumption is suitable as long as the magnitude of the recorded value between two subsequent measurements not differs too much. However, in drilling operations where the bottom-hole pressure (BHP) must be accurately reproduced at all times, e.g., in MPD operations, interpolation algorithms are often required to find acceptable values (Godhavn 2011). The difference between the simplified method used by eDrilling and two well-known interpolation techniques are depicted in Figure 4.4a,b,c. The green-colored parameters in Figure 4.5 are found to be of sufficient quality. The red ones, however, are data that either are missing or are recorded wrongly, i.e., they cannot be used as inputs to the models without corrections. These wrong data are identified as follows:

[14] *Log ASCII Standard (LAS)* is a standard file format common in the oil and gas industry to store wellbore log information (Struyk and Karst 2009).

[15] The *American Standard Code for Information Interchange (ASCII)* is a character-encoding scheme used to represent text in computers, communications equipment, and other devices that use text (Cerf 1969).

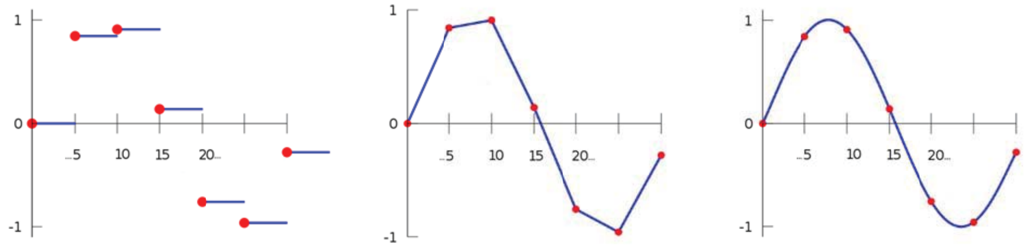

Figure 4.4a,b,c: (a) No interpolation, as used by eDrilling.
(b) Linear interpolation.
(c) Polynominal interpolation.

Mud Flowrate

There is no data for mud flow-out in the data set. This means that discrepancies between flow-in and flow-out cannot be evaluated, and detection of kick or loss situations will therefore give no meaning.

Mud Temperature

Measured temperature of mud flow-in and mud flow-out is recorded to be 6 °C and 7657 °C, respectively, which is totally flawed. These temperatures cannot be used by the models. A measured annulus temperature of 90 °C is recorded, which seems to be correct.

Mud Density

The mud weight in and out is set manually to 1.76 specific gravity (SG[16]) based on information given by the mud engineer (Conocophillips 2009). This is sufficient as long as the mud is kept at a stable mud weight, but in order to catch fluctuations, it would be much better to have automatic mud density measurements, as discussed in Section 2.3.1.

Survey Data

Depth of survey and wellbore inclination and azimuth sensor data are recorded as null values (-999.25), i.e., these specific values do not have valid measurements. Given the fact that some modules, e.g., the DQM and TDM, are dependent on such data, lack of these measurements might have a bad influence on model calculations.

Due to the fact that there are some data inconsistencies with respect to the acquired real-time data, manual configuration is necessary to avoid that these data cause misleading results or system failure. How some of these issues are solved is discussed in Chapter 6.

[16] $SG = \frac{\rho}{\rho_{water}}$

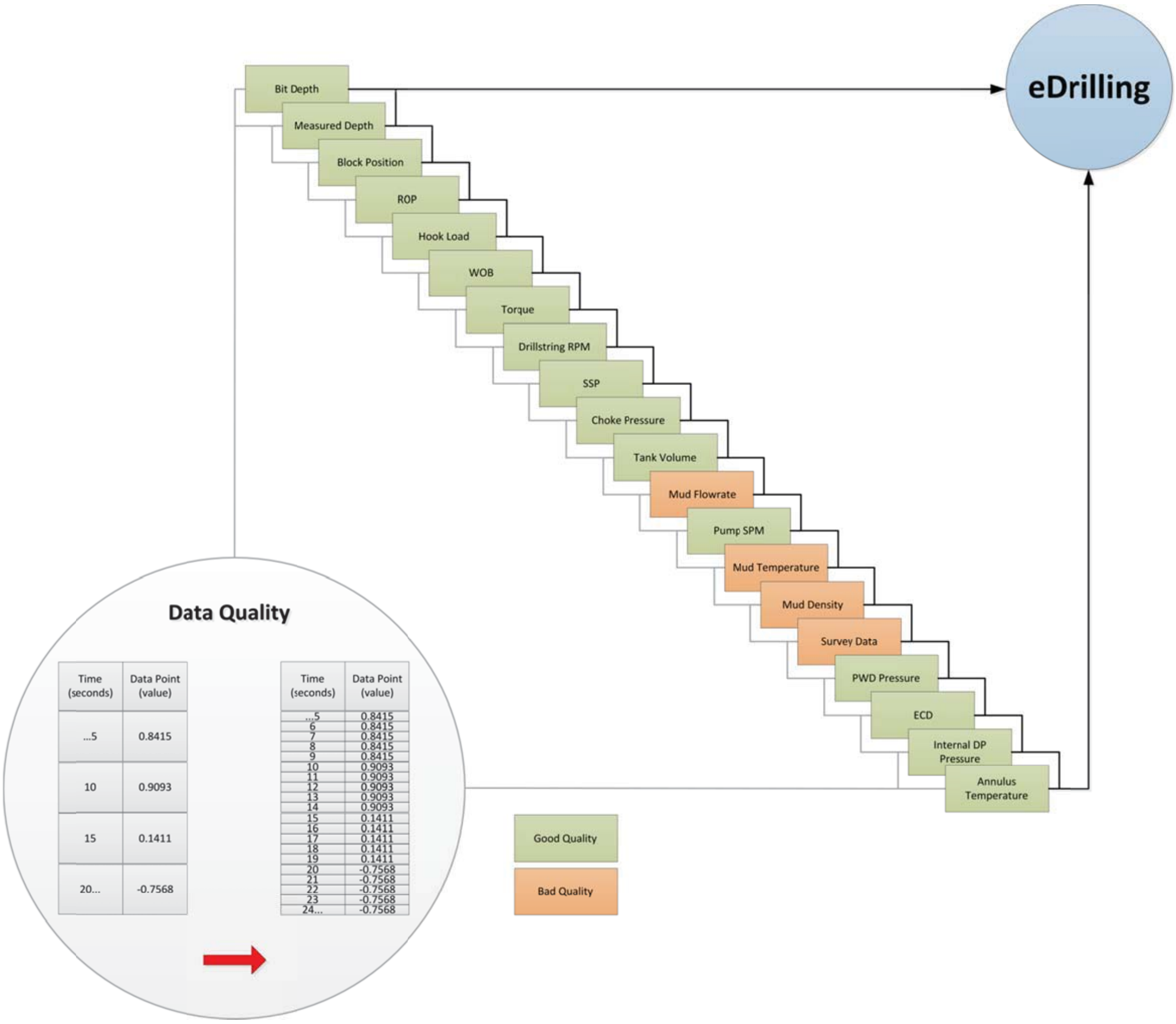

Figure 4.5: **Schematic of different real-time data used by eDrilling. The figure illustrates how data resolution and sampling rate are corrected before being sent to the application.**

4.1.4 System Setup

eDrilling is installed on a dedicated Windows server which supports remote access through sockets via ordinary TCP/IP[17]. The modules utilized by the system are administrated and configured whenever needed by using a software tool named *APIS*. This tool is also installed on the server and gives easy access to model parameters and system configuration data. In order to run eDrilling in replay-mode, the following simplified user guide is used for start-up:

1. **Server Login**
   Access to the server is given by connecting to the server's IP-address using Internet. APIS will pop up when server connection is established.

2. **Retrieve Data**
   Before starting any replay, data must be retrieved from the external databases and initialized into the data tables that will be used by eDrilling. This is achieved by toggling a trigger that is created for this particular purpose.

3. **Start Replay**
   The next step is to start the replay, where start and end time of the operation can be set optionally. This means that a certain time interval of interest can be replayed again and again without the need of playing the entire drilling operation all over again.

4. **Start Modules**
   The modules utilized by eDrilling during the replay are then started separately. All time-logs are also reset before each replay sequence.

5. **Open GUIs**
   The results generated by eDrilling are displayed using a 2D and/or 3D-client. Both of them are installed on the user's computer desktop as for typical computer programs. In order to link the GUIs to the running replay, they must be connected to the server using the same server IP-address as mentioned above.

[17] *Transmission Control Protocol/Internet Protocol (TCP/IP)* is a software-implemented protocol for connecting different networks to each other (Cerf and Kahn 1974).

5. Results

The results obtained during the case study are discussed and analyzed in this chapter. The system's user-friendliness, model output, and decision support capabilities are evaluated in particular. To some extent, mathematic representations are addressed for some of the calculated parameters in order to give understanding of how the models work and what principles they build on. All numbers, figures, and screenshots given in herein are generated during the conduction of the case study and genuine in this respect.

5.1 User Friendliness

5.1.1 Supervision and 3D Visualization

The replay of the drilling process is monitored continuously in real-time using the 2D and 3D-client. The 2D GUI works as a supervision tool where measured and calculated values are monitored and compared, see Figure 5.1. Essential real-time measurements and calculated results are listed together on the left hand side to give a quick and easy overview of the most important parameters. Measured and modeled values are plotted against each other to easily identify developing trends and possible deteriorating conditions. A warnings-table is initiated at start-up, which gives out messages when potential problems are likely to occur. For example, a significant drop in measured SPP compared to calculated SPP might indicate possible wash-out, as listed in this table in the upper part Figure 5.1. ECD and temperature can also be monitored in a 2D tunnel view of the wellbore if desired, which is depicted on the right hand side of the figure. Remark that different drilling states are monitored in various tabs located below the warnings-table.

The author finds the user-friendliness of the 2D-client to be simple and straightforward. It is easy to operate and very informal as the most vital drilling information is continuously updated and displayed. User options are limited, which are believed to be beneficial in order to keep the GUI as user-friendly as possible. Based on the fact that potential users might have little knowledge in computers and vice versa, this will remain important in future improvements of eDrilling. However, the author has experienced that the optional 2D tunnel view of the wellbore is found to be superfluous given that it was not used a single moment when monitoring the drilling operation during replays. A question whether or not this functionality is necessary might therefore be raised.

The 3D visualization tool enables the user to get a true overview of the well by displaying all relevant information in real-time 3D. Typical views are for example visualization of the casing shoe, the bit when rotating off-bottom, or generated cuttings when drilling. These examples are illustrated in Figure 5.2a,b,c. Cuttings are visualized at the bit only when drilling new formation, which makes it is easy to identify whether the bit is on-bottom drilling or not. Configuration data are imported into the 3D-client automatically. For example, formation layers and stratigraphy settings can be loaded to give a visual understanding of formation characteristics, such as hard stringers, reservoir sections, etc. If these data are readily available, the drillstring is visualized inside the various hole section of the wellbore. In this case study, unfortunately, such information was not available for Well X-16A. The different BHA tubular components, such as bit, drill collars, accelerators, float subs, stabilizers, and MWD tools are displayed in detail as separate parts of the drillstring, e.g., a stabilizer is located behind the bit in Figure 5.2c.

The diagnostics features of eDrilling are also incorporated in the 3D-client, i.e., if unwanted conditions are likely to occur, early warnings with relevant information are given in the GUI. These warnings are the same as those given in the warnings-table displayed in the 2D-client. Probability of kicks, losses, stuck pipes, wash-outs, tight spots, tripping velocity limits, and so forth, is then provided as instant "pop-ups" if detected by the DAM. This functionality was however not installed at the time being due to limitations on time and resources for the eDrilling development team. Additionally, the graphs plotted in the 2D-client are possible to link and integrate directly to the 3D-client such that trend analysis and supervision of the drilling process is achievable from one single GUI.

The contribution of all these visual effects might give the user a better understanding of what is going on in the wellbore at all times. A total and more shared view of the drilling process might then be achievable for all actors involved. However, the author states that necessary visualization data should be available and utilized in order for the 3D GUI to feel realistic and vivid. Without correct visualizations of the different formation layers, the various cased hole sections, and the many drillstring components, the author claims that the 3D view functionality is limited as you only see a bit drilling in the middle of "nowhere". A display like this is not found useful or productive at all. On the contrary, Rommetveit et al. (2008b) has shown that the 3D tool has the capability to visualize the drilling process accurately if loaded with adequate amounts of visualization data. Screenshots illustrating such displays could be found in their work.

Figure 5.1: The 2D-client monitors the drilling process continuously in real-time.

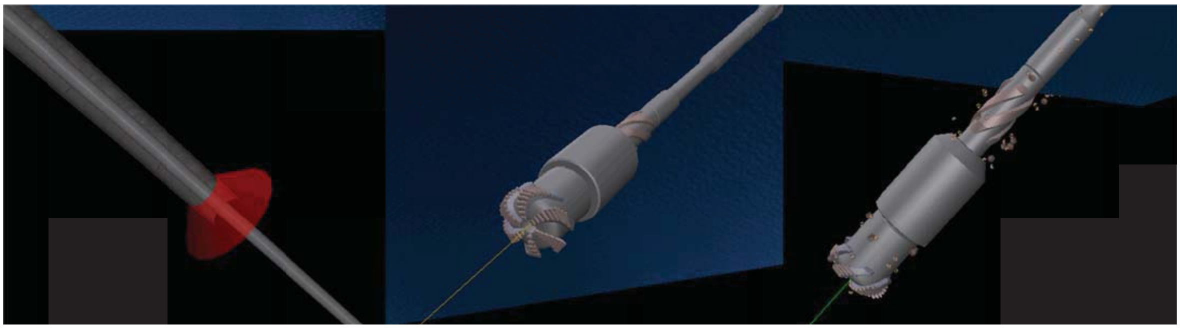

Figure 5.2a,b,c: (a) Casing shoe.
(b) Rotating off-bottom.
(c) Drilling formation.

5.1.2 System Configuration

The software tool *APIS* is used to administer and configure system settings and model parameters, e.g., when configuration data must be updated manually or when models need to be tuned. Mud temperatures and friction factors are set manually by adjusting certain coefficients, as depicted in Figure 5.3a,b, respectively. Proper system configuration might support that future differences observed between calculated and measured values are most likely due to non-expected occurrences and not due to model uncertainties. For use in the case study, suitable values are found from well reports or by trial-and-error. For example, appropriate mud temperatures are found from mud sample summaries provided by CoP, whereas friction factors are obtained by adjusting the friction coefficients shown in Figure 5.3b. The used values are set such that no discrepancy is observed between measured and calculated SPP at replay start-up. Table 5.1 shows the model friction factors that were found most suitable for the drillstring and annulus. The effect of improper adjustments of model parameters, i.e., temperature and friction coefficients in this particular case, are analyzed mathematically for SPP and ECD in later sections.

Table 5.1: Friction factors used by the models in the case study.

Parameter	Model Friction Factor
Drillstring	1.34
Annulus	0.60

Basically, APIS could be looked at as the system kernel, which works as a bridge between the software applications and the actual data processing done at the hardware level. The kernel's responsibilities include managing the system's resources, and each calculated time step is also shown for all model parameters. Figure 5.4 shows how this is displayed for a set of real-time data used in the replay. In other words, this tool enables the opportunities to utilize and control eDrilling as desired when implemented in the drilling process. APIS is not considered very user-friendly, though, and it is subject to human errors in terms of the chance of human “typos[18]”. Hence it is recommended that a very limited amount of people have access to this system tool, which is further discussed in Section 6.3.

[18] A *typographical error* (often shortened to *typo*) is a mistake made in a manual type-setting process often due to mechanical failure or slips of the hand or finger (Princeton 2011).

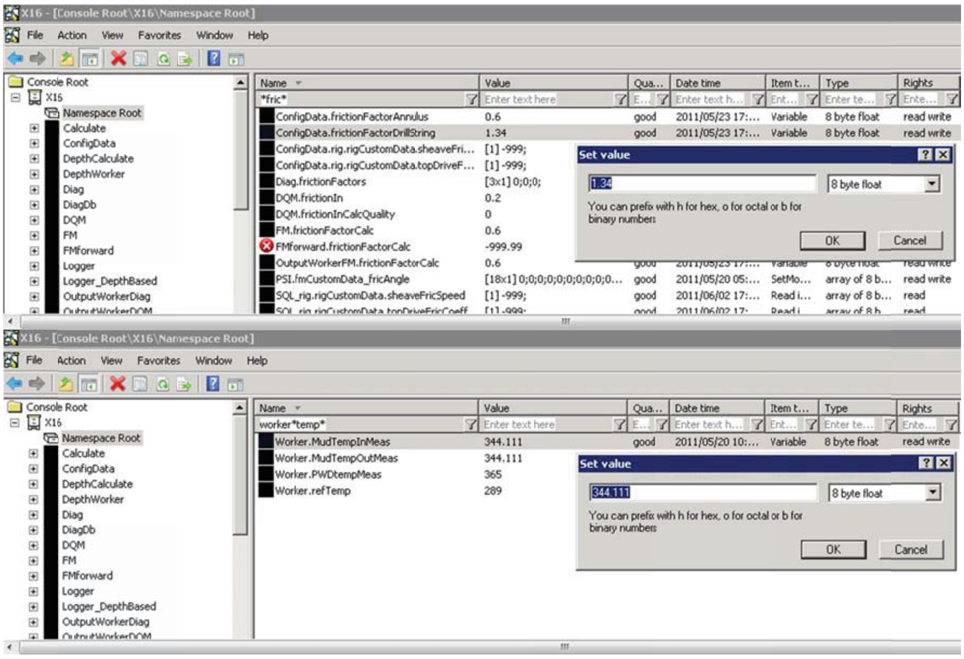

Figure 5.3a,b: (a) Calibration of drillstring model friction factor.
(b) Mud temperatures are set manually based on mud sample reports.

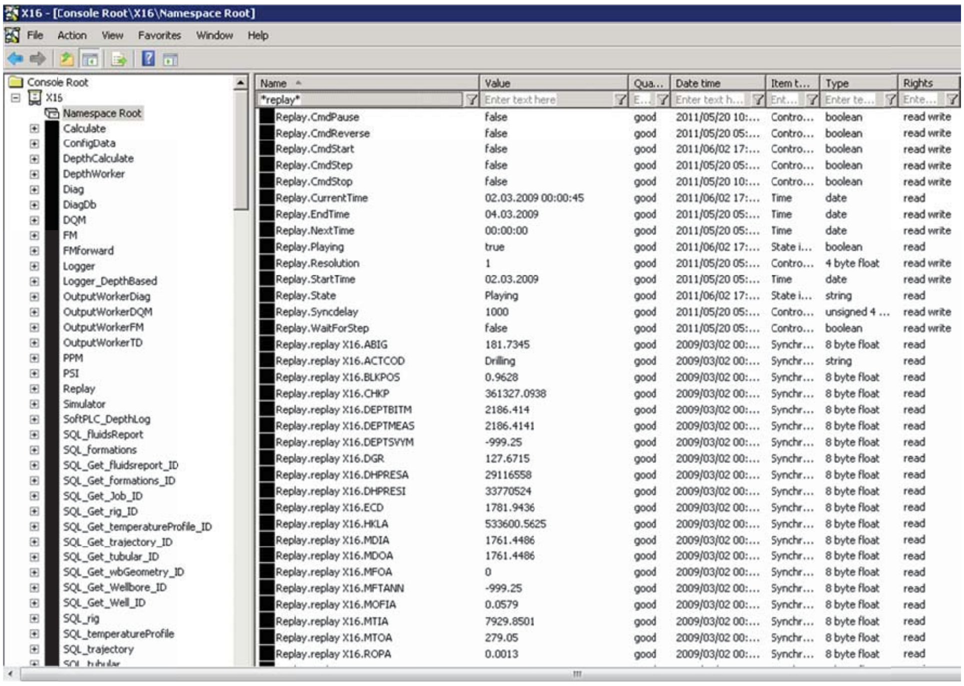

Figure 5.4: APIS is used to configure system settings and parameters, in which each time step is shown.

5.2 Interpretation of Results

The output generated by the models is stored in large LAS files. Substantial time and effort are spent to create MATLAB-scripts that read the results properly and plot them in a fashionable manner. Program language code and an example of a generated output file could be found in Appendix B. The figures presented in this section display generated results when replaying the drilling process for 48 hours. They show that model calculated values match the measured real-time data very accurately. However, even though they show similar trends, some deviations exist for certain parameters. Attempts are made to address some of these mathematically.

It is mentioned in Section 4.1.2 that drilling is initiated from 2,186 m MD to 2,560 m in the 12 ¼ in. section of the well. In order to get an overview, the most important aspects of the drilling operation are listed in Table 5.2. Figure 5.5 tells when the bit is drilling or lifted off-bottom, and might therefore give an operational overview. For example, the reaming sequences performed at 24.0 hours and 34.2 hours are identified in the figure by observing that the bit position is going up and down.

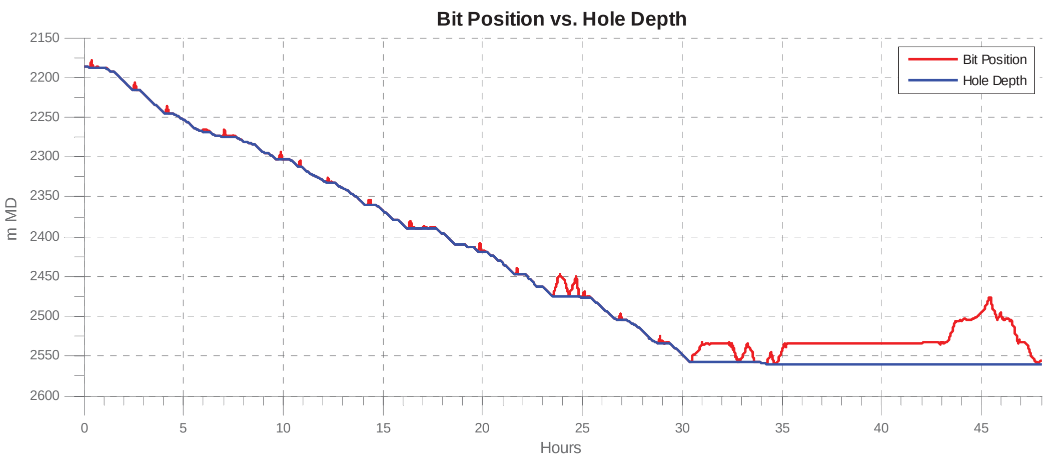

Figure 5.5: Bit position vs. hole depth.

Table 5.2: Operational overview of Well X-16A. Adapted from Conocophillips (2009).

Time (hours)	Operation
0	Drilling resumed from 2,186 m MD
23.5	Pick off-bottom to circulate due to ECD falling
24.0	Ream while circulating bottoms-up
24.5	Resume drilling from 2,474 m MD to 2,558 m MD
30.4	Pack-off tendencies detected. Circulate out cavings
31.4	Washing/reaming from 2,533 m MD to 2,558 m MD.
33.7	Resumed drilling from 2,558 m MD to 2,560 m MD Tendencies of hole packing-off at times
34.2	Back-reaming and bottoms-up out from 2,560 m MD to 2,534 m MD
35.2	Circulating
37.0	Shut in well for to observe for possible pressure build-up
37.8	Displacing well to heavier mud, i.e, from 1.76 SG to 1.78 SG
42.0	Flow-check
43.0	Back-reaming to 2,475 m MD
45.2	Washing/reaming down to 2,559 m MD

5.2.1 Flowrate

Figure 5.6 shows measured and calculated values for flowrate in and out of the well, respectively. Since the FM does not “see” deteriorating conditions that might occur in the well, the calculated flow works more like a reference point when everything is going smoothly. The mud circulation system could be looked at as a closed system, and if deviations between measured in and out values are observed, a kick or loss situation would probably be the case. If such trends are developing, warnings indicating this deteriorating behavior should be generated by the DAM. Keep in mind that there is no available real-time data for mud flow-out. Hence a direct relationship between measured flow-in and measured flow-out cannot be evaluated. A comparison between measured and calculated values will neither give any meaning as they are equal. Detection of kick or loss situations is therefore hard to identify by analyzing the flowrate only, but sudden discrepancies in BHPs might potentially help to address these incidents if they occur.

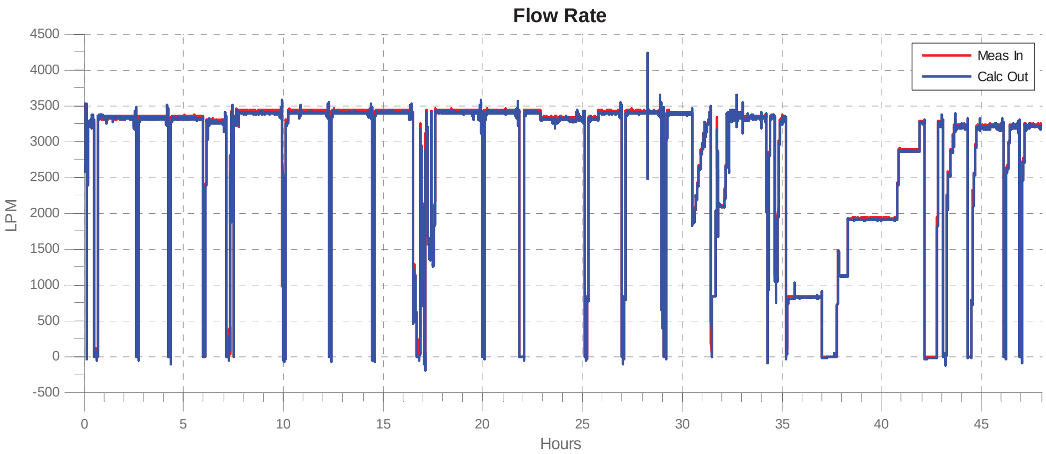

Figure 5.6: Measured vs. calculated flowrate.

5.2.2 SPP

Figure 5.7 shows that SPP is accurately reproduced, which indicates that both input data and models are representative for this parameter. Initially, no offset is observed between the measured and calculated pressure in the beginning of the drilling operation. Variations seen in pressure magnitudes, such as those observed from 6.2 hours to 7.1 hours and from 22.9 hours to 25.7 hours, are due to changes in measured pump rate. Some small positive spikes in measured SPP are observed at 22.8 hours, 30.4 hours, 32.9 hours, and 34.6 hours, which might look suspicious. However, Figure 5.8 shows that measured ECD and torque are not fluctuating at these times, indicating that there are no obstructions in the annular space or no solids accumulation at the bit. A closer analysis of the peak seen at 22.8 hours reveals that the measured SPP at the mentioned time points tends to increase by 10-20 bar just before pumps are ramped down. The scaling of the axes in Figure 5.7 therefore appears to be misleading at first glance.

An interesting observation in Figure 5.7 is that after the displacement of 1.78 SG mud at 37.8 hours, the calculated SPP now lies below the measured one. Recall that the mud weight has been set manually to 1.76 SG in eDrilling at replay start-up. This means that the mud weight must be configured accordingly for the system when changes in drilling conditions are made, i.e., 1.78 SG in this particular case. Today's density sensors do not provide sufficient data quality of measurements in order to be used directly by the models, and these parameters must therefore be updated manually. If they are not, the models might generate false results and the DAM might in turn raise possible false alarms, which jeopardizes operational safety and overall drilling efficiency. Typically in offshore operations, manual measurements of density and temperature of the mud are gathered every 30 minutes. This procedure has proven to give good and reliable results (Hovland and Svendsen 2011). Consequently, a qualified person is required to provide up-to-date input data for certain measurements and to configure the models accordingly.

Larger spikes are observed for the SPP differential shown in Figure 5.9, where magnitudes of as much as 100 bar are present, e.g., at 6.0 hours. These are solely caused when ramping the pumps quickly up or down, e.g., during connections or when circulating. Further investigation confirms that the data resolution of the measured SPP real-time signal is lower than the calculated one, as depicted in Figure 5.10. Thus the measured pressure is changing in incremental steps depending on sampling rate and resolution of the data, whereas the calculated ones are fully smoothed as high-resolution output is calculated. The overall result is therefore large deviations between the two when looking at the differential for each single time step. Application of appropriate filtering techniques is believed to possibly mitigate some of these problems. It is suggested that extensions should be implemented in the DQM to accommodate this behavior when ramping pumps quickly up and down.

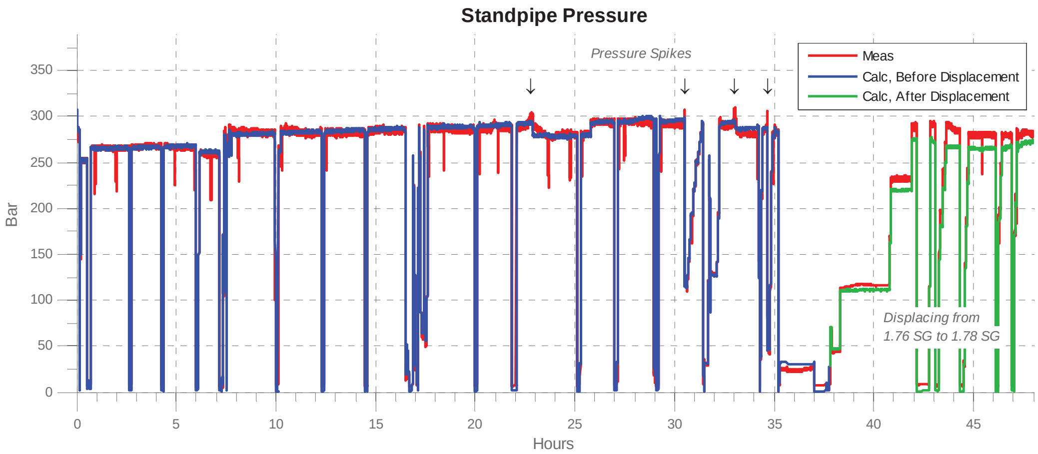

Figure 5.7: Measured vs. calculated SPP.

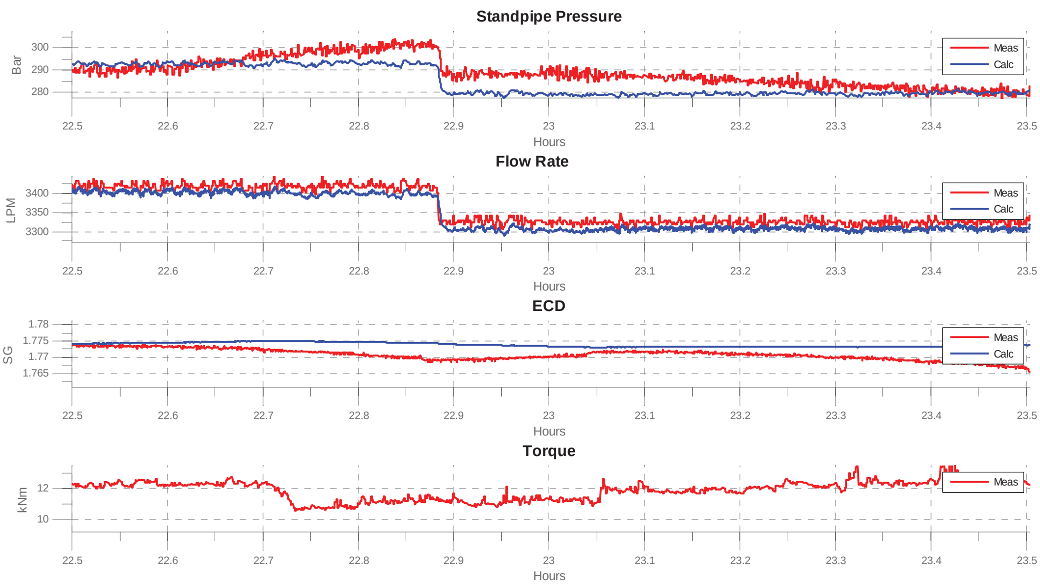

Figure 5.8: Analysis of the pressure spike observed for SPP at 22.8 hours.

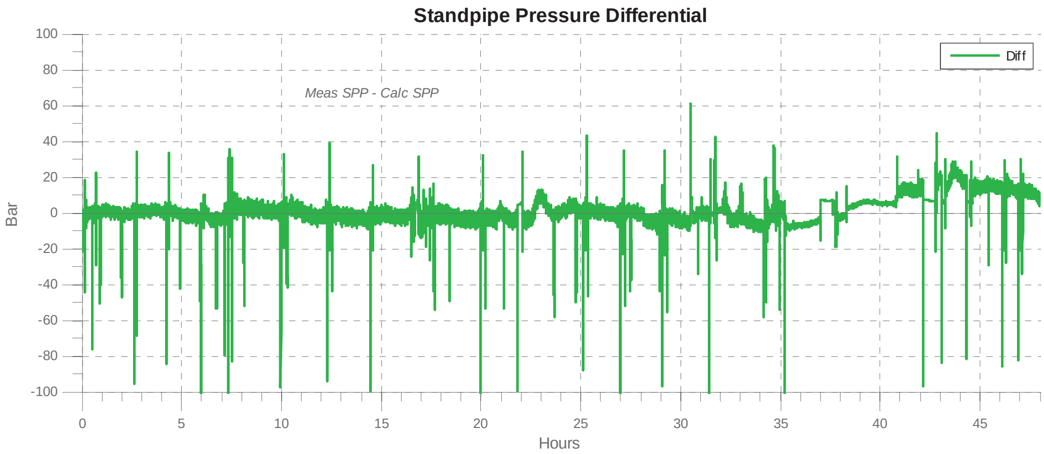

Figure 5.9: SPP differential.

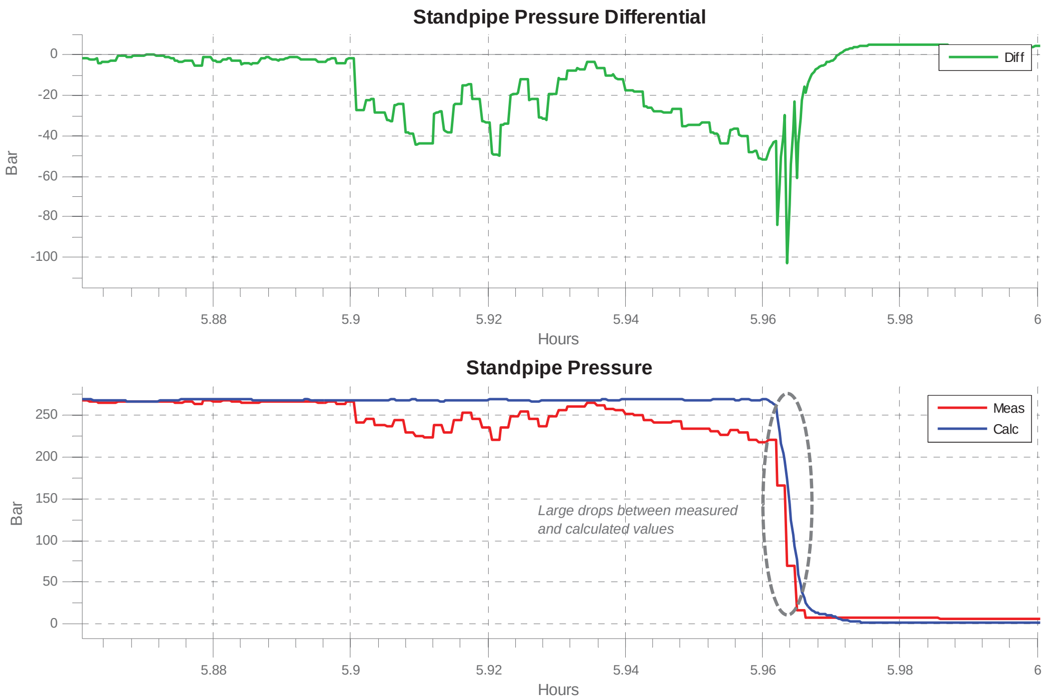

Figure 5.10: Analysis of SPP differential at 6.0 hours.

Mathematical Analysis of Friction Effects

When changes in drilling conditions are made, the models might also need to be re-calibrated in order to give accurate and reliable results. Figure 5.11 shows the difference in SPP between a calibrated and uncalibrated model in terms wrongly adjusted model friction factors. These are listed in Table 5.3 and configured as shown in Figure 5.3a. It is observed that the uncalibrated model gives misleading output in the presence of a too low SPP. A significant discrepancy like this will be detected by the DAM and in turn probably raise false alarms indicating possible poor hole-cleaning. This could make a lot of confusion as the user is not aware that improper calibration is the cause behind this behavior.

A closer mathematical analysis of the model behavior for the calculated SPP with different friction factors are evaluated in this section to show that the advanced drilling models build on fundamental engineering principles. This section is based on work presented by Dodge and Metzner (1959) and Bourgoyne et al. (1986), where equations are given in field units[19].

Table 5.3: Model friction factors used for the calibrated and uncalibrated model.

Parameter	Calibrated Model	Uncalibrated Model	|Δ%|
Drillstring	1.34	1.00	25.4
Annulus	0.60	1.00	66.7

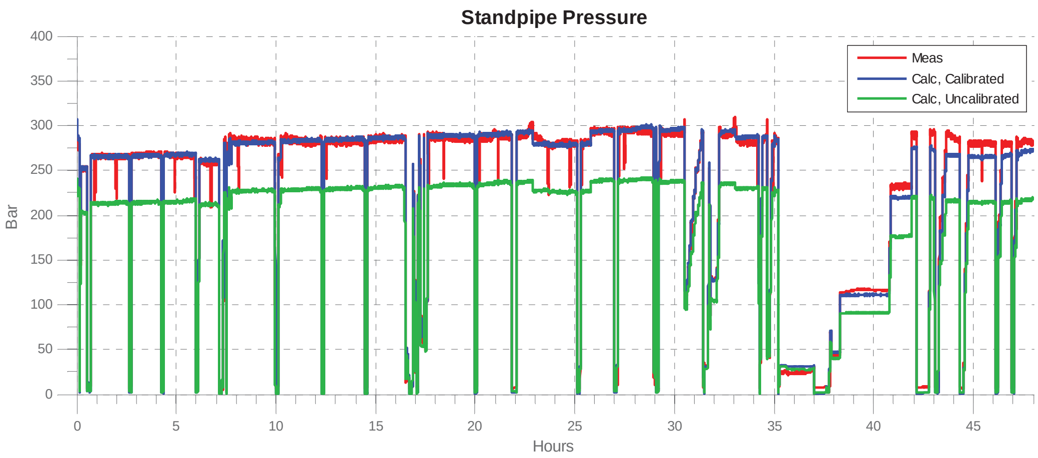

Figure 5.11: Calibrated vs. uncalibrated model for SSP.

[19] *Field units* are units commonly used in the oil and gas industry.

Section 3.2.3 shows that the equations used by eDrilling comprise conservation of mass of each fluid component and conservation of the total momentum for the system. The governing equation of conservation of total momentum is expressed as

$$\begin{aligned}
&\frac{\partial}{\partial t}\left[A(\alpha_m\rho_m v_m+\alpha_g\rho_g v_g+\alpha_{fo}\rho_{fo}v_{fo}+\alpha_{fw}\rho_{fw}v_{fw}+\alpha_c\rho_c v_c)\right]+\\
&\frac{\partial}{\partial s}\left[A(\alpha_m\rho_m v_m^2+\alpha_g\rho_g v_g^2+\alpha_{fo}\rho_{fo}v_{fo}^2+\alpha_{fw}\rho_{fw}v_{fw}^2+\alpha_c\rho_c v_c^2)\right]\\
&=-\frac{\partial(Ap)}{\partial s}-A\left(\frac{\partial p}{\partial s}\right)_{fric}+A\left[\alpha_m\rho_m+\alpha_g\rho_g+\alpha_{fo}\rho_{fo}+\alpha_{fw}\rho_{fw}+\alpha_c\rho_c\right]g\cos\theta
\end{aligned} \quad \textbf{(5.1)}$$

where each variable is described in Section 3.2.3.

Hence one easily identify that the calculated output depends on several parameters, not to mention fluid densities and frictional losses. The dependency on friction factors for SPP should be possible to explain mathematically since SPP equates to the summation of the total pressure loss of the whole system under dynamic conditions. The equation for SPP is then given by

$$SPP=\Delta p_b+\Delta p_{dc}+\Delta p_{dp}+\Delta p_{ann} \quad \textbf{(5.2)}$$

Δp_b - pressure loss at bit

Δp_{dc} - pressure loss in drill collars

Δp_{dp} - pressure loss in drill pipe

Δp_{ann} - pressure loss in annulus

The appropriate model representing a drilling fluid must be determined before any pressure calculations can be done. A rheological model describes the relationship between shear stress and shear rate when a fluid flows through a circular section or an annulus. Fluids that do not exhibit a direct proportionality between shear stress and shear rate are classified as non-Newtonian. A graphical representation of the four rheological models is presented in Figure 5.12. The FM is based on the Herschel-Bulkley nonlinear three parameter representation of the fluid rheology, which is found to represent the flow behavior of drilling fluids very accurately. It is to be noted that this model can yield mathematical expressions that are not readily solved analytically, but can be solved using numerical methods on computers.

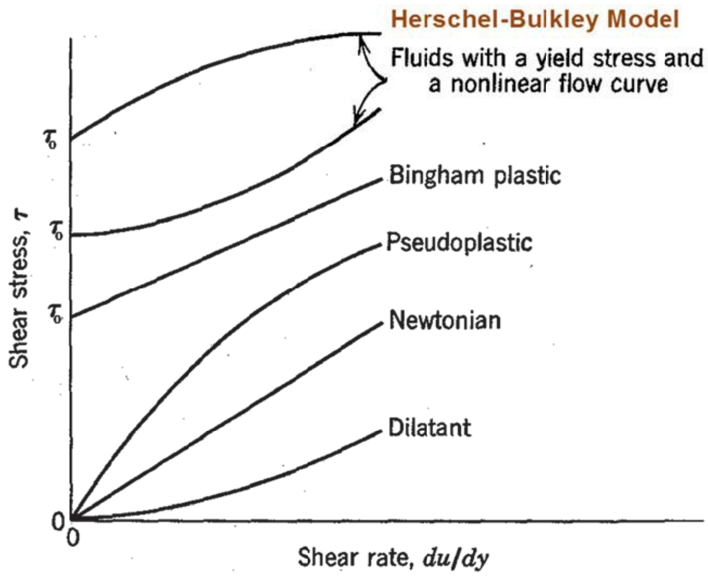

Figure 5.12: **Schematic of different rheological models.**

The Herschel-Bulkley model is defined as

$$\tau = \tau_y + K\gamma^m \tag{5.3}$$

τ	-	shear stress
γ	-	shear rate
τ_y	-	yield shear stress
K	-	consistency index
n	-	flow behavior index

In order to find frictional pressure losses, the type of flow in each well section must be established. As listed in Appendix A, the well geometry consists of different drillstring components, such as drill pipe, crossover subs, collars, stabilizers, MWD motors, etc. Some simplifications are however made for use in this mathematical analysis. For example, the different BHA components are looked at as one single drill collar component with the same inner and outer diameter. Suitable size and length of this drill collar section are chosen based on the BHA configuration listed in Appendix A. The simplified well schematic is shown in Figure 5.17.

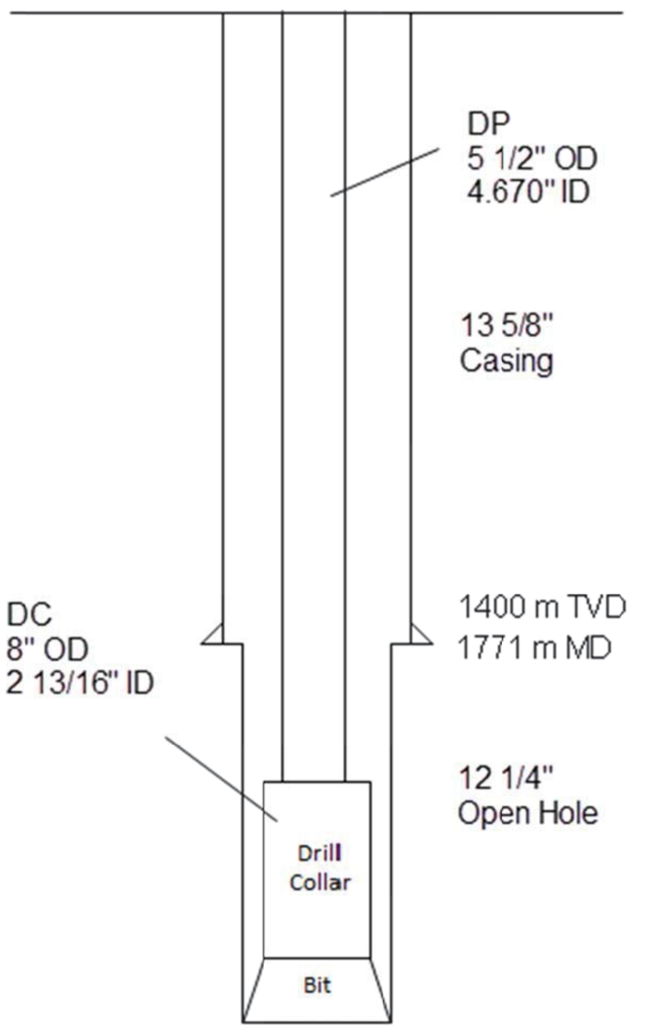

Figure 5.13: Simplified wellbore schematic of Well X-16A.

Depending on the various geometries in the wellbore, different types of flow might exist. Determination of flow patterns depend on the calculated Reynolds number, N_{Re}, which for a Newtonian fluid inside a pipe is expressed as

$$N_{\mathrm{Re}} = \frac{\rho \bar{v} d}{\mu} \tag{5.4}$$

ρ - fluid density
$\bar{v}$ - mean fluid velocity
d - pipe diameter
μ - fluid viscosity

For engineering purposes, flow of fluid in pipes is usually considered to be laminar if the Reynolds number is less than 2,100 and turbulent if the Reynolds number is greater than 2,100. However, for Reynolds numbers of about 2,000 to 4,000, the flow is actually in a transition region between laminar and fully developed turbulent flow. Figure 5.14 illustrates the difference between the different flow patterns.

Figure 5.14a,b,c:(a) Laminar flow.
(b) Transition between laminar and turbulent flow.
(c) Turbulent flow.

Adapted from Bourgoyne et al. (1986).

A correlation of the Reynolds number for the Herschel-Bulkley rheological model is given as

Pipe:

$$N_{\mathrm{Re}} = \frac{89{,}100 \rho \bar{v}^{2-n}}{K} \left[\frac{0.0416 d}{3 + 1/n} \right]^n \tag{5.5}$$

Annulus:

$$N_{\mathrm{Re}} = \frac{109,000\rho\bar{v}^{2-n}}{K}\left[\frac{0.0208(d_2 - d_1)}{2+1/n}\right]^n \tag{5.6}$$

where K and n values are obtained from viscometer readings when taking mud samples. These are listed in Appendix A.

Mean fluid velocity, $\bar{v}$, is found by dividing the flowrate with cross-sectional area for pipe or annulus. In field units, it is given by

Pipe:

$$\bar{v} = \frac{q}{2.448d^2} \tag{5.7}$$

Annulus:

$$\bar{v} = \frac{q}{2.448(d_2^2 - d_1^2)} \tag{5.8}$$

q	-	flowrate, gal/min
d	-	diameters, in.

When flow patterns are determined for each section, the frictional pressure losses can be found by using the following expressions:

<u>Laminar flow:</u>

Pipe:

$$\frac{dp_f}{dL} = \frac{K\bar{v}^n\left[\frac{3+1/n}{0.0416}\right]^n}{144,000d^{1+n}} \tag{5.9}$$

Annulus:

$$\frac{dp_f}{dL} = \frac{K\bar{v}^n\left[\frac{2+1/n}{0.0208}\right]^n}{144,000(d_2 - d_1)^{1+n}} \tag{5.10}$$

Turbulent flow:

Pipe:

$$\frac{dp_f}{dL} = \frac{f \rho \bar{v}^2}{25.8d} \tag{5.11}$$

Annulus:

$$\frac{dp_f}{dL} = \frac{f \rho \bar{v}^2}{21.1(d_2 - d_1)} \tag{5.12}$$

Hence one can observe from Eq. (5.11) and Eq. (5.12) that the pressure loss in the drillstring and annulus is dependent on the fanning friction factor, f. However, this friction factor is *not* the same as the friction factors used by the models. The empirical friction factor correlation developed by Dodge and Metzner (1959) is used to find the fanning friction factors in each section of the wellbore. The correlation is given by

$$\sqrt{\frac{1}{f}} = \frac{4.0}{n^{0.75}} \log(N_{\mathrm{Re}} f^{1-n/2}) - \frac{0.395}{n^{1.2}} \tag{5.13}$$

Rearranging Eq. 5.13 one get

$$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}} \log(N_{\mathrm{Re}} f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0 \tag{5.14}$$

which can be solved by iterative techniques.

Even though model friction factors and fanning friction factors are not the same coefficients, they are assumed proportional in magnitudes. In other words, a percentage change in model friction factors can therefore be directly translated to fanning friction factors. Figure 5.15 might make this relationship more clear

$$f_{MODEL} \xrightarrow{|\Delta\%|} f_{MODEL}$$

$$\Updownarrow$$

$$f_{FANNING} \xrightarrow{|\Delta\%|} f_{FANNING}$$

Figure 5.15: Changes in friction factors are assumed proportional.

In other words, the $|\Delta\%|$ listed in Table 5.3 are used when determining the uncalibrated values for the fanning friction factors.

The only term left to evaluate in Eq. 5.2 is the pressure loss at the bit, Δp_b.

The pump pressure is expended by

$$p_p = \Delta p_s + \Delta p_{dp} + \Delta p_{dc} + \Delta p_{bit} + \Delta p_{dc,ann} + \Delta p_{dp,ann} \tag{5.15}$$

Δp_s	-	frictional pressure loss in surface equipment
Δp_{dp}	-	frictional pressure loss in drill pipe
Δp_{dc}	-	frictional pressure loss in drill collars
Δp_{bit}	-	pressure loss at bit nozzles
$\Delta p_{dc,ann}$	-	frictional pressure loss in drill collar annulus
$\Delta p_{dp,ann}$	-	frictional pressure loss in drill pipe annulus

If the total frictional pressure loss to and from the bit is called the *parasitic pressure loss*, Δp_d, then

$$\Delta p_d = \Delta p_s + \Delta p_{dp} + \Delta p_{dc} + \Delta p_{dc,ann} + \Delta p_{dp,ann} \tag{5.16}$$

Eq. 5.15 can now be expressed as

$$p_p = \Delta p_b + \Delta p_d \tag{5.17}$$

A commonly used correlation for the total parasitic pressure loss is represented by

$$\Delta p_d \propto q^m = cq^m \tag{5.18}$$

m	-	constant that theoretically has a value near 1.75
c	-	constant that depends on mud properties and wellbore geometry

Substitution of Eq. 5.18 into Eq. 5.17 and solving for Δp_b yields

$$\Delta p_b = p_p - cq^m \tag{5.19}$$

Hence the pressure loss at the bit is given by Eq. 5.19 .

Based on the previous, the difference in SPP between the calibrated and uncalibrated model is derived as

$$\Delta SPP = SPP_{Calibrated} - SPP_{Uncalibrated} \tag{5.20}$$

Or in terms of Eq. 5.2 given by

$$\Delta SPP = (\Delta p_b + \Delta p_{dc} + \Delta p_{dp} + \Delta p_{ann})_{Calibrated} - (\Delta p_b + \Delta p_{dc} + \Delta p_{dp} + \Delta p_{ann})_{Uncalibrated} \tag{5.21}$$

Given that Eq. 5.19 is unaffected by friction factors, the bit pressure loss term, Δp_b , cancels out in Eq. 5.21 and gives

$$\Delta SPP = (\Delta p_{dc} + \Delta p_{dp} + \Delta p_{ann})_{Calibrated} - (\Delta p_{dc} + \Delta p_{dp} + \Delta p_{ann})_{Uncalibrated} \tag{5.22}$$

Final steps for each section of the wellbore are then to:

1. Calculate N_{Re} to determine flow patterns

2. Find f by iteration

3. Calculate $\frac{dp_f}{dL}$ by using:

    a. Calibrated friction factors
    b. Uncalibrated friction factors

Steps 1-3 are conducted by programming the above equations in Excel, see Appendix C for further details. In this example, ΔSPP is evaluated at 11.0 hours, with the most important calculated results summarized in Table 5.4.

Table 5.4: Calculated change in SPP with calibrated and uncalibrated friction factors.

Section	$\bar{v}$ (ft/s)	N_{Re}	f Calibrated	f Uncalibrated	Δp (bar) Calibrated	Δp (bar) Uncalibrated
Innside Drill Pipe	16.9	1 451,198	0.00098	0.00073	157.4	117.5
Inside Drill Collar	46.5	6 677,317	0.00073	0.00054	184.0	137.3
Drill Collar vs. Open Hole	4.3	146,823	0.00165	0.00275	2.9	4.8
Drill Pipe vs. Open Hole	3.1	98,432	0.00183	0.00305	1.2	1.9
Drill Pipe vs. Casing Section	3.0	94,922	0.00185	0.00308	6.7	11.2

$\Delta SSP_{Equations}$ **= 79.5 bar**

ΔSSP_{Model} **= 53.0 bar**

The calculations show that the change in SSP based on the equations is higher than the modeled one obtained from Figure 5.11 at 11.0 hours, i.e., 79.5 bar vs. 53.0 bar. However, having in mind that several simplifications and assumptions are made when deriving the equations, the calculated result actually seems to be fairly correct. For example, the estimation of the drill collar section size and length surely affect calculations because Table 5.4 tells that the pressure loss inside the collars is found to be most prevalent. There is often laminar flow where cross-sectional flow areas are large, i.e., between annulus and drillstring. However, Eq. 5.6 shows how the Reynolds number is inverse proportional to the consistency index, K. Hence a low index number will result in turbulent flow no matter how low fluid velocities are. In addition, due to the fact that the turbulent pressure loss is proportional to the velocity in the power of two, see Eq. 5.12 , low velocities ultimately result in smaller frictional losses. This does by far explain the low pressure losses obtained for the annulus sections in the table. Moreover, the iterated friction factors for the calibrated model match the friction factor chart presented by Bourgoyne et al. (1986) in Figure 5.16 very accurately, concluding that the iterative calculations of fanning friction factors are correct.

The mathematical representation outlined herein demonstrates that the advanced dynamic drilling models follow the same fundamental engineering principles presented in the literature. Nevertheless, the author is absolutely aware that the derived equations cannot be related directly to the advanced models, as they take several more effects into account.

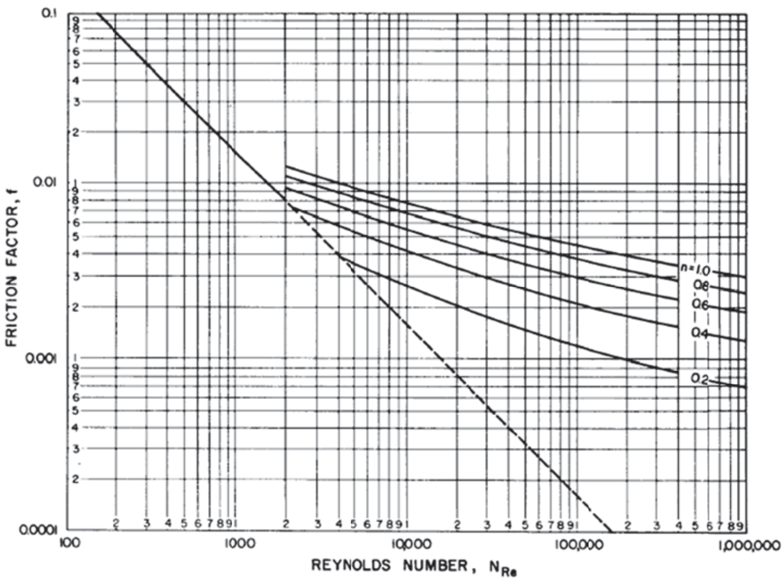

Figure 5.16: Friction factor chart for Herschel-Bulkley fluid (Bourgoyne et al. 1986).

5.2.3 ECD

Figure 5.17 shows that measured and calculated ECD follow the similar trend, even though some deviations are observed. Measured densities are fluctuating slightly between 1.77 SG and 1.78 SG until a drop down to 1.76 SG occurs at 23.5 hours. According to the operational overview listed in Table 5.2, more mud is added to the active system and reaming while circulating bottoms-up is performed the next hour. After this, the measured ECD is increasing to 1.78 SG again, as observed for the red curve at 25.0 hours. Sudden peaks in measured ECD is observed between 30.4 hours and 34.8 hours, which might indicate possible pack-off because poor hole-cleaning might increase density as cuttings are accumulating at the bit. It is also shown that back-reaming results in a larger drop in ECD at 35.2 hours before circulation is continued and the well is being displaced with heavier mud. The rise in ECD is clearly identified after the displacement.

Mathematical Analysis of Temperature Effects

The measurement of drilling fluid temperature is critical in order to calculate a correct ECD since temperature has a large effect on mud rheology, e.g., density and viscosity. When analyzing the input data in Section 4.1.3, totally wrong values are recorded for the temperature of mud flow-in and mud flow-out, i.e., 6 °C and 7657 °C, respectively. However, the measured ECD at the rigsite was of course not recorded under the influence of such extreme temperatures, but still it remains unclear which temperatures that were actually present when drilling the well. With this in mind, manual input pertinent to temperatures is required if these sensor readings are recorded wrongly.

Figure 5.18 demonstrates the effect of temperature on ECD. Initially, a replay was run with a mud temperature of 6 °C and an annulus temperature of 0 °C, which are set as initial default values by eDrilling. As a consequence, the calculated ECD turned out to be much higher than the measured one, as illustrated by the green curve in the figure. This will generate misleading output telling that calculated ECD might exceed fracture gradients. In this context, false alarms indicating circulation losses might also be raised, which in turn will make confusion in the drilling team. As a worst case scenario, decisions involving detrimental remedial actions might be taken, leaving the operation in danger. After troubleshooting and conferring with the development team of eDrilling (Hovland and Svendsen 2011), the problem was detected and new temperatures were be chosen. Based on available mud summaries and fluid reports provided by CoP, a new replay with mud and annulus temperatures of 71 °C and 92 °C, respectively, was found to be more correct and therefore used (Conocophillips 2009). The configuration of the temperatures is depicted in Figure 5.3b, in which the temperatures are given in Kelvin.

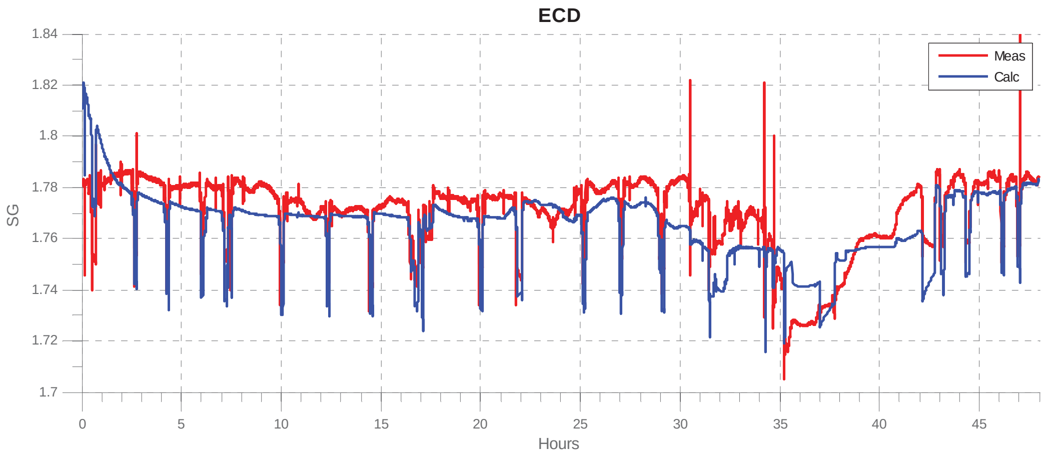

Figure 5.17: Measured vs. calculated ECD.

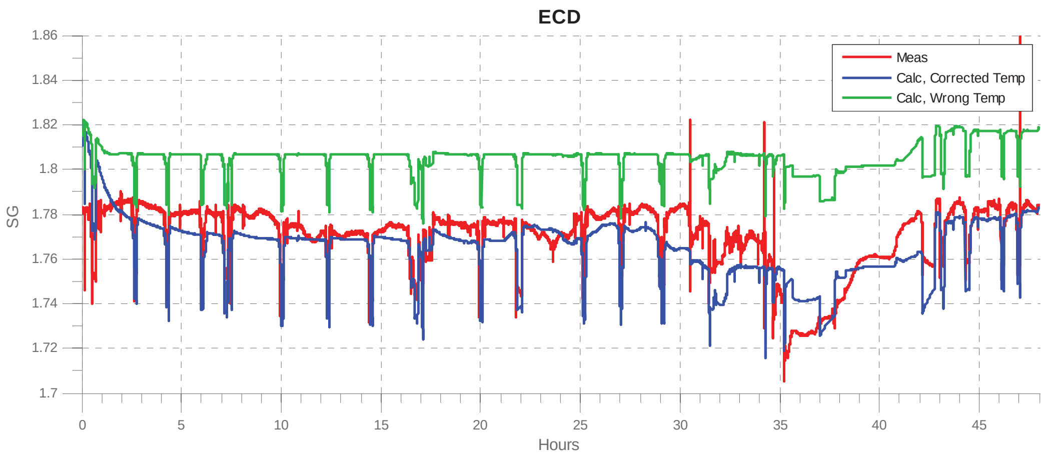

Figure 5.18: Wrong mud temperatures alter model results, i.e., wrong ECD is calculated.

ECD could be explained as the increase in BHP that results from the annular friction pressure created when drilling fluids are circulated along the wellbore. Mathematically it is given by

$$ECD = \rho_m + \frac{\Delta p_{ann}}{gh} \tag{5.23}$$

g - gravity, 9.81 m/s^2
h - vertical height, i.e., TVD

In field units, Eq. 5.23 becomes

$$ECD = \rho_m + \frac{\Delta p_{ann}}{0.052TVD} \tag{5.24}$$

The drilling fluid density is a function of several parameters as shown by Eq. 3.11 as

$$\rho_m = P_m(p, T, x_{dg,m}) \tag{5.25}$$

where each variable is described in Section 3.2.3.

In this mathematical analysis, however, the drilling fluid is treated as one single fluid with mud properties given by ConocoPhillips (2009). It is reported that an oil-based mud (OBM) is used, see Appendix A. The oil-density correlation developed by Sorelle et al. (1982) can thus be used to estimate densities at different temperatures and pressures. It is expended by

$$\rho_{OBM} = A_0 + A_1T + A_2\,p \tag{5.26}$$

ρ_{OBM} - density for OBM, lbm/gal
A_0 - 7.24032
A_1 - -2.84383 x 10^{-3}
A_2 - 2.75660 x 10^{-5}
T - mud temperature in Fahrenheit, °F
p - downhole pressure, psia

Assuming that the annulus frictional loss term, Δp_{ann}, in Eq. 5.23 remains constant, the discrepancy in ECD is possible to explain mathematically as

$$\Delta ECD \propto \Delta\rho_m = \rho_m(T,p)_1 - \rho_m(T,p)_2 \tag{5.27}$$

Or in terms of Eq. 5.26 as

$$\Delta ECD \propto \Delta\rho_m = A_1(T_1 - T_2) + A_2(p_1 - p_2) \tag{5.28}$$

where “1” and “2” refers to two different drilling conditions.

Downhole pressures, p_1 and p_2, are here equal to the calculated BHP during circulation, which is given by

$$BHP = \rho gh + \Delta p_b + \Delta p_{dc} + \Delta p_{dp} \tag{5.29}$$

Again, making the simplified assumption that pressure losses remain constant even though temperatures are changing, Eq. (5.29) becomes

$$BHP = \rho gh \tag{5.30}$$

Hence downhole pressures in field units could be expressed as

$$\begin{aligned} p_1 &= 0.052\rho_1 TVD \\ p_2 &= 0.052\rho_2 TVD \end{aligned} \tag{5.31}$$

Combining Eq. 5.31 with Eq. 5.28 , the change in density becomes

$$\Delta\rho_m = A_1(T_1 - T_2) + A_2 0.052TVD(\Delta\rho_m) \tag{5.32}$$

where $\Delta\rho_m = \rho_1 - \rho_2$

Solving Eq. 5.32 for $\Delta\rho_m$ yields

$$\Delta\rho_m = \frac{A_1(T_1 - T_2)}{1 - A_2 0.052TVD} \tag{5.33}$$

Or in terms of Eq. 5.27 as

$$\Delta ECD = \frac{A_1(T_1 - T_2)}{1 - A_2 0.052TVD} \tag{5.34}$$

Putting in values for A_1 and A_2 one get

$$\Delta ECD = \frac{-2.84383 \text{ x } 10^{-3}(T_1 - T_2)}{1 - 2.75660 \text{ x } 10^{-5} \text{ x } 0.052TVD} \tag{5.35}$$

The magnitude of the right term in the denominator is significantly small, i.e., 1.43x10^{-6}xTVD, which allows Eq. 5.35 to be approximated as

$$\Delta ECD = -2.84383 \text{ x } 10^{-3}(T_1 - T_2) \tag{5.36}$$

Based on the simplifications and assumptions made above, Eq. 5.36 shows that the change in ECD is certainly related to mud temperature. However, the author would like to emphasize that he is aware that the mathematical analysis carried out herein is done with very simplified assumptions. By any means, the analysis shows that presented correlations in the literature can be utilized to explain the behavior of ECD in terms of temperature effects on mud density. Table 5.5 summarizes the calculated result when programming Eq. 5.36 in Excel with the wrong and corrected temperatures mentioned in the beginning of this section. It is interesting to see that the calculated drop in ECD is consistent with the deviations observed in Figure 5.18.

Table 5.5: Calculated change in ECD due to temperature effects.

Data				Comment
T1	=	0	°C	*Wrong mud temperature initially set by eDrilling*
		42	°F	
T2	=	71	°C	*Corrected mud temperature*
		160	°F	
	=	0.3347	ppg	*Divide by 8.33 to find answer in SG*
ΔECD	=	**0.0402**	**SG**	*Consistent with observed deviations in Figure 5.18*

5.2.4 Other Parameters

PWD Pressure

The PWD pressure is recorded by means of annular fluid being ported through a drill collar to a downhole recording pressure gauge that is connected to the MWD tool. Figure 5.19 and Figure 5.20 show that measured and modeled PWD pressure is very coincident and that the calculated differential is more accurate here compared to SPP. An interesting observation is that the blue curve is dropping just a few moments after the operation has begun. This goes to the fact that the models are "cold" at replay start-up. As a consequence, models should be run for some time prior to start-up to ensure that the system is "warmed up and ready". These issues must be taken into account when initializing eDrilling.

Tank Volume

Figure 5.21 shows how active tank volume changes when pumps are stopped or pump rate is changed. As observed at 0.6 hours, 4.4 hours, 6.1 hours, etc., a certain volume increase due to emptying of surface lines is expected when the pump rate is reduced. Large gaps in the tank volume are observed when additional mudpits are assembled to the active system, e.g., at 2.7 hours, 4.1 hours, 9.7 hours, etc.

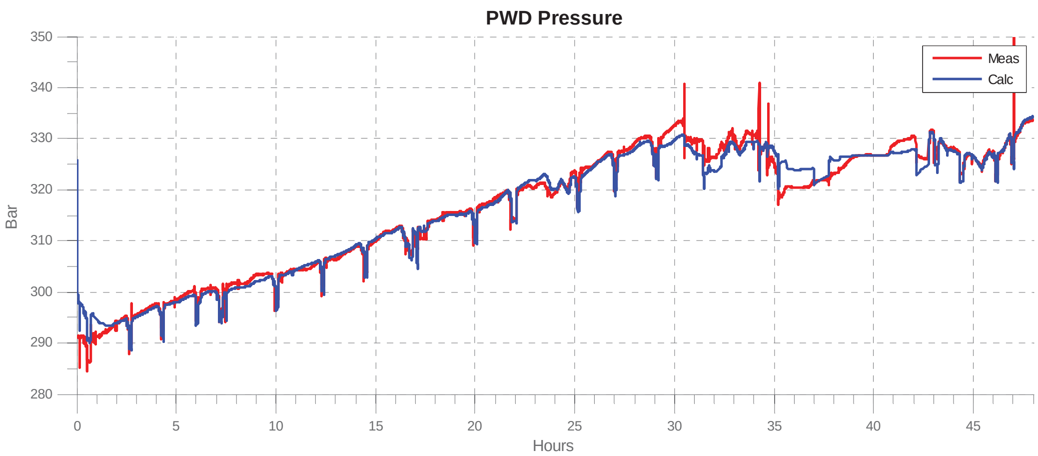

Figure 5.19: Measured vs. calculated PWD pressure.

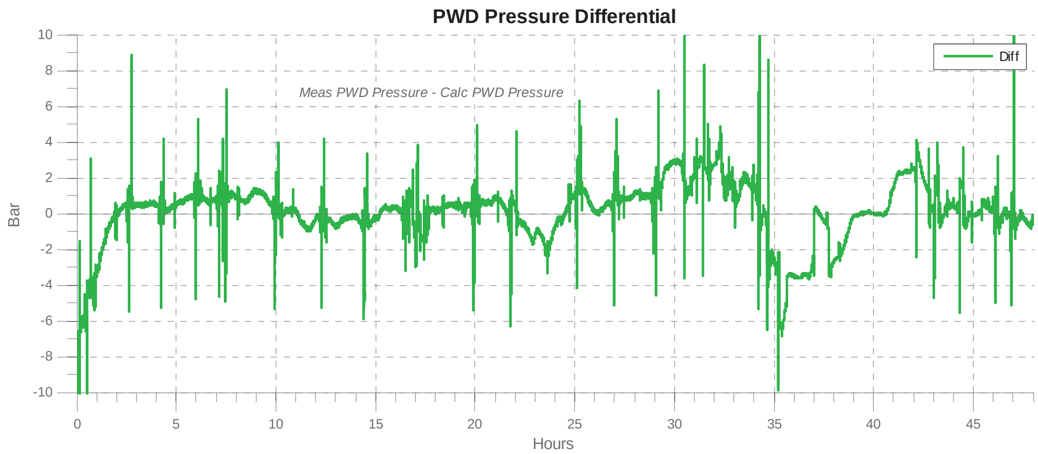

Figure 5.20: **PWD pressure differential.**

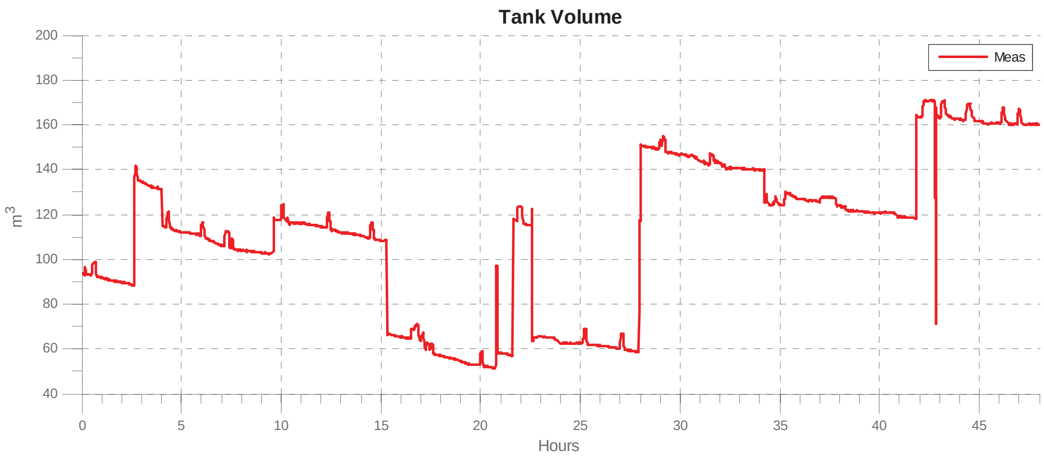

Figure 5.21: **Changes in measured tank volume.**

Torque

Figure 5.22 tells that topside rotary torque is fairly constant and coincident until some excessive readings are observed at 30.4 hours and after this time. Pack-off tendencies actually occurred at this time (Conocophillips 2009), so an increase in torque makes sense here. There are also some very rapid peaks occurring already at 0.6 hours, 2.7 hours and 12.4 hours, but these are caused by over-torqued connections. It could also be seen that the torque readings are increasing as expected when performing washing and reaming sequences, such as shown in the last six hours of the operation.

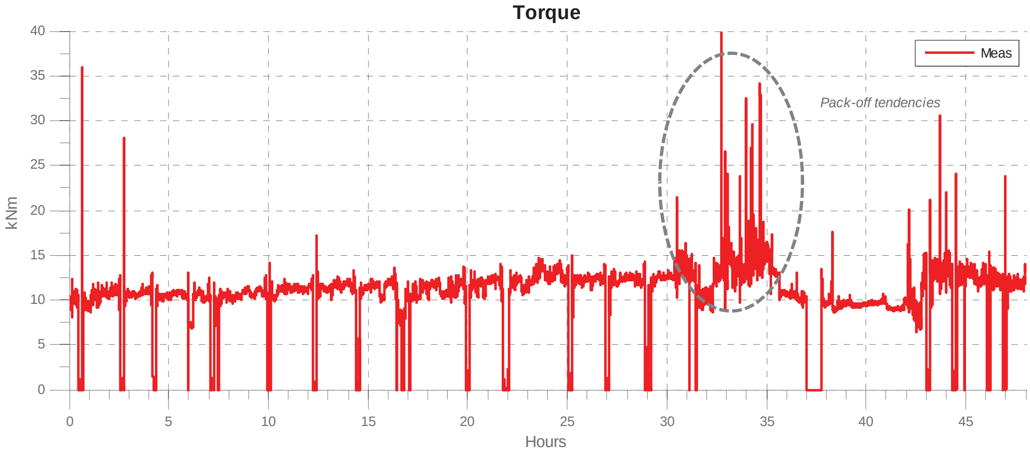

Figure 5.22: Measured topside torque.

ROP

The ROP is fairly constant during drilling, but with a maximum of approximately 27.5 m/h, see Figure 5.23. This figure could be used to easily identify the drilling state of the operation, since one knows that ROP values are only generated when drilling on-bottom.

Figure 5.24 demonstrates how the DQM analyzes the time based data to generate improved values for WOB. A measurement error of a few tons might represent a 100% error in WOB and alter ROP considerably. Such systematic errors are very often seen during connections due to drillstring stretching or deadline elongation, as mentioned in Section 2.3.1. As could be observed, the most significant peaks are reduced by the DQM by combining theoretical modeling and automatic calibration,. Whilst on-bottom, the driller can control only three parameters: WOB, RPM, and mud flowrate. With no mud motor in the drillstring, flowrate has a limited effect on ROP, so the optimization is two dimensional in WOB and RPM (Dunlop et al. 2011). In this particular drilling operation, however, a potential increase in ROP based on WOB is not obtainable due to the fact that improved values for this parameter are only generated when making connections.

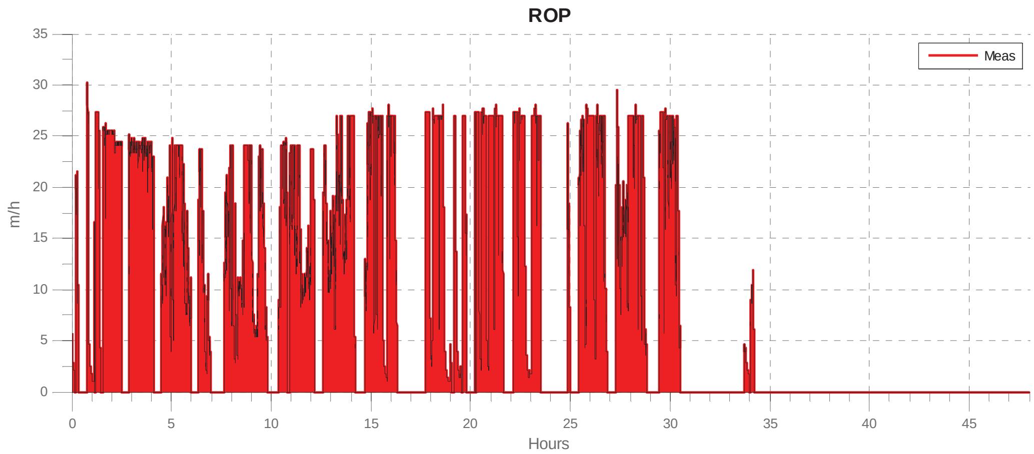

Figure 5.23: Measured ROP.

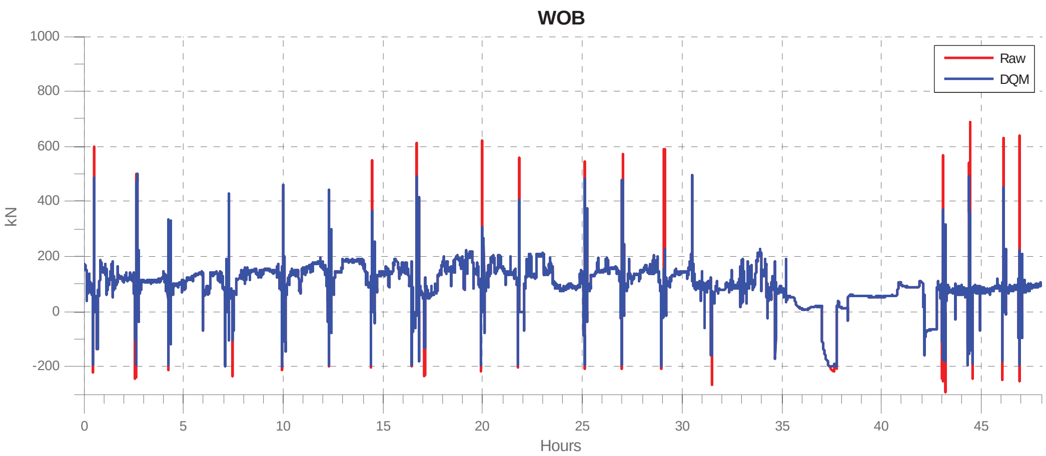

Figure 5.24: Raw data vs. DQM corrected data for WOB.

5.3 Decision Support

Table 5.6 shows a complete list of all the warnings generated by the DAM during the case study. According to ConocoPhillips (2009), pack-off tendencies occurred frequently at 30.4 hours and after. However, no warnings or alarms indicating poor hole-cleaning or possible pack-off are raised. This deteriorating behavior should be possible to address by analyzing the trends observed in ECD and torque at this time interval. Sensitivity limits must then be adjusted properly, where appropriate values could be found using trial-and-error. Knowledge about the detection thresholds for events like poor hole-cleaning is also required, in which necessary user-experience and understanding of how the models work is favorable. Unfortunately, due to constraints on time and travel distance between the author and the developers, detection of the mentioned pack-off tendencies by configuring sensitivity limits have not been obtainable at this time.

On several occasions, however, eDrilling has raised false alarms indicating possible wash-out due to rapid drops in SPP, e.g., as those observed at 0.1 hours, 0.9 hours, 5.0 hours, 5.9 hours, etc. in Figure 5.7. The reason why these are considered as false alarms is because the observed pressure drops are caused by downlinks being sent to the MWD tool from surface. This can be done manually by varying the throttle of existing drilling machines or via a valve connected to the standpipe. Most of the valves used today are semi-automated with computer controlled pre-programmed sequences (Wang and Finke 2003). False alarms related to downlinks could possibly be removed by widening the size of threshold parameters and length of the sign detection period. Then the rapid drops in SPP must occur over a larger time period in order for the DAM to raise a warning. In contrast, a change of sensitivity limits might accidentally lead to ignorance of other problems yielding similar trends, so modification of detection thresholds might probably not be the best solution to this problem. Due to the fact that MWD downlinks are sent using computers signals, the author wonders whether it is possible for the DAM to utilize these signals in such a way that downlinking activity is detected automatically, and thus no false alarms are given.

Another important aspect is how the DAM is able to distinguish between problems caused by improper tuning and configuration of the models, and problems caused by deteriorating behavior actually occurring in the well. Methods correlating statistical features calculated from various real-time signals might be useful in this context, in which the correlated diagnostic signal is used as input to a warning generation scheme. This scheme should be based on detecting the sign of the correlated signal samples within a moving time window rather than only on isolated diagnostic signals given by each modeled parameter. By this means that an observed deviation caused by insufficient re-calibration for a certain parameter might not affect the correlated diagnostic signal sample in such a manner that detection thresholds are exceeded, as illustrated for SPP in Figure 5.25a,b. Gulsrud et al. (2009) have demonstrated that a statistical approach by analyzing the third order moment of bottom-hole or standpipe pressure time series and normalized standard deviation of torque time signals can provide early detection of poor hole-cleaning and stuck pipe.

Table 5.6: Warnings generated by eDrilling during the case study.

Id	Hours	Warning
1		Initiating warningTable
2	0.1	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
3	0.9	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
4	4.9	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
5	5.9	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
6	6.7	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
7	8.1	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
8	10.3	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
9	12.5	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
10	17.7	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
11	18.4	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
12	21.2	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
13	25.4	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
14	27.2	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
15	27.5	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
16	29.3	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
17	34.1	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
18	46.3	Measured SPP decreased compared to calculated SPP indicates possible wash-out.
19	47.1	Measured SPP decreased compared to calculated SPP indicates possible wash-out.

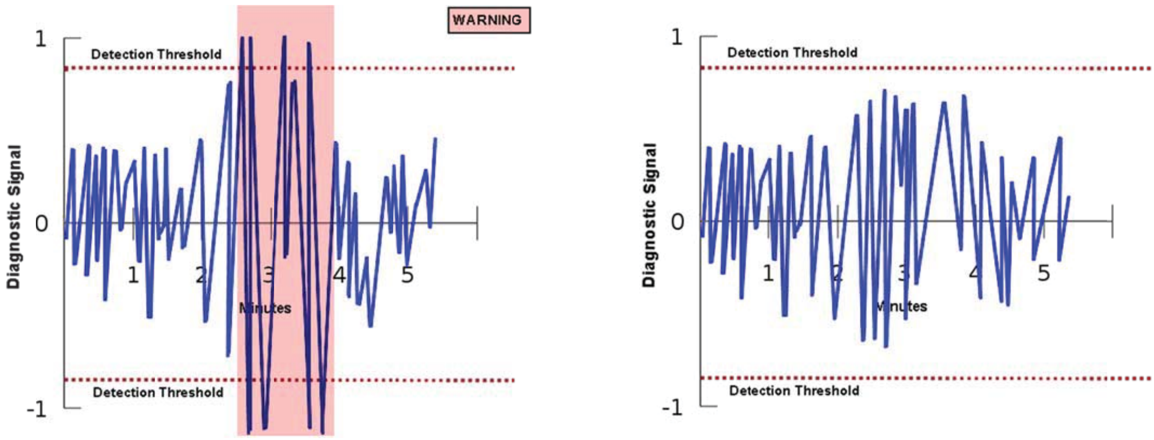

Figure 5.25a,b: (a) Diagnostic signal for SPP exceeds the detection threshold due to improper calibration and warnings are raised.
(b) Correlated diagnostic signal based on statistical features for several parameters during the downlink results in no warning.

Just as important is how quickly the diagnostic signal is fluctuating. A sudden change in the signal will be more frequent when unwanted events are likely to occur compared to when it is caused by miscalibrated models. For example, poor hole-cleaning could result in an increase in ECD and torque almost right away as cuttings are accumulating at the bit, while changes in these parameters probably will take more time to develop when tuning is found insufficient. Figure 5.26 illustrates the methodology, and the DAM should be possible to distinguish between these behaviors.

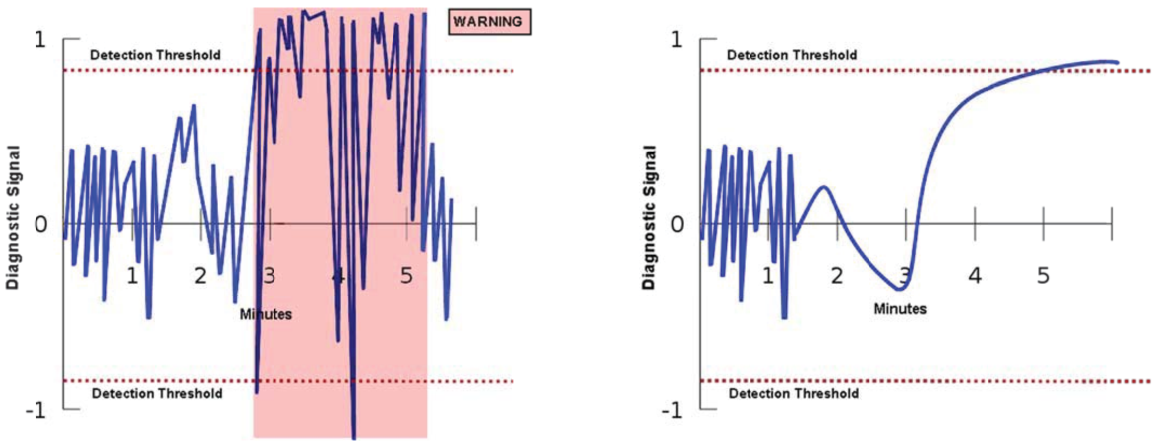

Figure 5.26a,b: (a) A sudden change in the diagnostic signal possibly indicates deteriorating events occurring, and a warning is therefore given.
(b) Changes related to improper calibration take some time to develop, which should be possible to be analyzed by the DAM.

As the DAM is a module that is dependent on several other modules, care must be taken to ensure that the warnings do not show up to late. The cause of late warnings must not be to latency of the system, i.e., the complete route of diagnostic signals should be faster than the reaction time of the driller. This has not turned out to be a problem when generating warnings in the 2D-client. However, given the fact that the decision support feature was disabled in the 3D-client when running the case study, potential warnings delays in this view cannot be evaluated. Another probably cause of problems might occur when signal trends are examined by comparing signals at different time since some signals change more quickly than others. Slow changing signals, e.g., bottom-hole temperature, are not so critical to receive and calculate on a time step or two out of sync, while a fast signal, such as drilling state (drilling, tripping, in slips, etc.), could cause complications if compared with other fast changing signals. Requirements on fast data processing and transmission between modules must therefore be met to avoid these potential problems. Issues related to *data flow and management* are discussed in Section 6.2.

6. Discussion

A general discussion of real-time use of dynamic drilling models is presented in this chapter. In this manner, eDrilling is evaluated in particular with emphasis on the obtained case study results.

6.1 Case Study

As mentioned in Section 2.1, real-time drilling technologies have been successfully tested and verified by the drilling industry in several field pilots. The case study of Well X-16A does by far support that the technology elements and modules integrated in eDrilling are well-developed and ready for commercialization. The applied models used in the replay have proven to give a correct representation of the drilling process with reproducible results and no system errors. With this background, accuracy, robustness, and calculation speed and processing requirements are believed to be promising. However, the need for human system configuration is identified as a possible setback that might affect overall efficiency and reliability.

6.1.1 Potential

Accuracy can be considered in two different types when related to models (Florence and Iversen 2010): The *short-term accuracy*, which might be achieved through application of continuously calibrated models, and *long-term accuracy*, which requires more complete models with possible additional calibration for key parameters/coefficients. Ideally, the models with short-term accuracy should be highly accurate over a short time period until re-calibration is utilized, while long-term accuracy should not deviate too far from the behavior of the process over time. Real-time drilling applications require both types of accuracy.

Cases study results demonstrate that the applied models are very accurate in the short run when they are properly calibrated. In order for eDrilling to give reliable results over time, accuracy in the long run is also a prerequisite. This means that the models need to have adequate accuracy so their qualitative behavior corresponds to changes in drilling conditions or drilling state. For example, when pumps are stopped during connections, or when the bit is rotated off-bottom, such behavior must be accurately reproduced and displayed. Results show that these changes are identified at all times, showing that a very acceptable long-term accuracy is achieved for the system.

On the other hand, Figure 5.7 shows how the calculated SPP is inaccurate after the well is displaced to heavier mud. Models might need re-calibration when major changes are undertaken in order to be accurate. In order to accomplish this task, either manual input or automatic self-calibration is required. The DQM is built to calibrate itself and the models when the opportunities to tune are sufficiently good. However, the case study shows that normal operations do not produce sufficient tuning opportunities, which raises the question whether continuous calibration only can be performed manually. If so, it is recommended that a qualified person with experience and knowledge in real-time applications and drilling procedures is physically monitoring the drilling process. Data management and communication remains one of the biggest challenges for oil and gas operators (Peytchev et al. 2011), so the author finds it beneficial that this expert is located at the rigsite. He will then be as close to the drilling operation as possible, which should secure that up-to-date information is provided regularly with no time delays. However, increased manning costs and reduced bed capacity on already overpopulated rigs will then be the scenario.

Florence and Iversen (2010) explain that the robustness of a model is understood as the ability to provide adequate accuracy and calculation stability in spite of challenges such as inaccurate input data, data noise, low sampling rate, and poor data resolution. This ability is important for instantaneous control and real-time supervision where crashing of the models is critical. Since they are run in real-time, there is limited time available to correct the data, restart the model, debug system errors, etc. Given the fact that real-time applications consist of complex models covering all dynamics and physical aspects of the drilling process, they generally are more prone to error than simpler models requiring fewer inputs and calculations. Data crash or system failure is not observed under the conduction of the case study, which implies that robustness is believed to be promising. However, given that eDrilling is run only in replay-mode, the used input data have been modified and quality checked before being fed to the system. Initially, some data points were recorded wrongly or missing for certain parameters, but later corrected using manual input, see Section 4.1.3. In real-time, though, such corrections might not be possible to administer manually since time is very limited. Thus robustness of the model is closely linked to pre-processing of the measured data, where erroneous data causing possible errors must be flagged and removed before they are utilized. The application itself must therefore be a part of a design which is robust no matter what. A good start in this direction is the integration of the DQM, which enables handling of lack of information due to poor input data. The author however believes that this capability has not been able to demonstrate its true potential given that corrected playback data are used. Eventually, several more case studies should be investigated before system robustness is accredited.

Calculation speed and processing requirements go hand in hand, and the individual models need to be fast enough for predictive and accurate calculations. The complexity of the real-time models and interacting sub-models demand processing capacity, and there must therefore be enough processing power available to run multiple model-instances simultaneously. Because the system kernel of eDrilling is installed on an up-to-date server, the demand for increased processing capability should not be an ambiguous challenge. The two GUI-clients, which are installed locally on the author's PC, also run smoothly without any system lag etc. One might therefore conclude that requirements on calculation speed and processing capacity are undoubtedly fulfilled. Nevertheless, the 3D-client requires a considerable amount of CPU[20] capacity, which must be taken into careful judgment when choosing which computers to install the clients on. What will be the scenario then when not only a single person, but an entire drilling organization is supposed to use eDrilling in everyday work processes? Is the system still going to be fast enough to provide the necessary information in real-time? When choosing how many computers to be included in the system, *latency* must be taken into consideration. For each new computer a signal has to go through, more latency is added. Note that an additional GUI-computer will not add more latency to the system, as the signal does not go through it, but ends in the GUI (Kolnes et al. 2007). The author therefore suggests that the system is installed and setup in the same way as for the case study when implementing eDrilling into organizations. This should ensure sufficient calculation speed and the processing capabilities required.

6.1.2 Manual Requirements

Based on lessons learned and the discussions made above, the author comes to an end that a responsible person is necessary to guarantee that model parameters are continuously tuned and that manual input always is updated. At least four times during the conduction of the case study, human input is needed:

1. When calibration and configuration are necessary due to changes in drilling conditions
2. When data are missing or of insufficient quality
3. When measurements are performed manually due to limitations on sensors
4. When sensitivity limits need adjustments to enable proper detection of unwanted incidents

As a drilling operation might be initiated at any time, including night, weekend, etc., the verification of the provided data should be performed on a 24/7 basis. The person verifying the data should have broad knowledge about the drilling process as he will need to quality control data from many different suppliers. Potentially, the on-site drilling supervisor could possibly be seen as a good candidate for this function since he is available 24/7 and should have the necessary qualifications. However, based on experience gained during the conduction of the case study, the author claims that at least basic understanding of how the different modules with their subsequent models work is essential. In future perspectives, proper training of personnel might possibly reduce the need for a dedicated expert present on-site since the drilling supervisor hopefully will be ready to take over his job. As discussed in Section 6.3, important changes in *work processes and organization* are then necessary such that people's roles and responsibilities are more clearly defined.

[20] The *Central Processing Unit (CPU)* is the portion of a computer system that carries out the instructions of a computer program (Hennessy and Goldberg 1996).

6.2 Data Flow and Management

Currently, information related to drilling operations is normally spread over several systems, none of which have a complete description of the well configuration or the real-time data. For example, the daily drilling reporting (DDR) system holds a relatively complete description of the wellbore and its constituents, while the sensor measurements are typically stored in a WITSML-server. However, the multiple service providers transmit and display the data in several ways, and standardization is thus not promoted. In addition, each operator company typically has different procedures for gathering, storing, and sharing the measured data, making it impossible to automate the interface between the database and eDrilling to ensure full system integration. Additional efforts in time and resources, both from the customer and the developer, are therefore needed when setting up and installing the system.

Experiences from pilots (Janssen et al. 2008; Rommetveit et al. 2008b) have opposed several challenges due to data gathering and integration. eDrilling needs detailed input values to work properly, but this information might have varying reference values and units. Errors are not uncommon, and quality inspection of the data is often required before they are fed to the database. Integration of data shared by multiple parties has also turned out to be more challenging than anticipated. The 3rd parties, i.e., the service companies, have different procedures on when and how they choose to fill in data. This provides a real risk of data inconsistency and does not allow the system to be updated with the latest data. Janssen et al. (2008) stated that the wellbore data they received from 3rd parties during pilots often arrived late, causing eDrilling to run with the wrong configuration data for quite some time. One example of this was when the drilling crew used a different drillstring than what was specified in the data sheets they received. The result was a significant unexpected WOB. Another example was when formation pore pressures were not updated correctly, causing the system to raise warnings that were not representative for the particular well situation. Drillstring description requires a lot of work, both with regards to entering the data and subsequent validation when changes are made. Sampaio et al. (1998) reported that Radio Frequency Identification (RFID) technology has the potential of making this process simpler and more reliable, but this technology is still under development. In an effort to tackle these problems related to data inconsistencies, thus far developers have been present on-site working closely together with the drilling team (Hovland and Svendsen 2011).

The author believes that it will be of great benefit if all the needed information is made accessible from one central place. A remaining question is whether the central repository should be constructed around a WITSML-server or a DDR system. One solution could be to expand the DDR system with real-time log management; a solution which will need more system maintenance, better access control, and higher requirements in terms of data handling and communication bandwidth. It is suggested that industry standards should be introduced and agreed upon by the entire drilling industry in order to lead the way to better quality and reliability of measurements. Proper naming conventions, specification of invalid sensor readings, sufficient data resolution, and consistent sampling rates should be organized in a standardized framework. Typical reference values, such as when the RKB is used as reference for depth measurements, should be more clearly defined to avoid measurement uncertainties. Not at least, measurements are recorded with different units, where field units are most broadly used. However, SI[21] units are becoming more common, particularly for some companies operating on the NCS. Thus the unit of a measurement needs to be identified and properly distinguished in order for eDrilling to be reliable and trustworthy.

Another potential problem might stem from limitations on the amount and quality of the real-time data acquired from rig and downhole sensors. Section 2.3.2 and 2.4.1 discuss the importance of reliable sensors and how to control the quality of data, respectively. Sufficient data quality control is required and should: (1) check if the data lies within a predefined acceptable range, (2) auto-fill gaps with missing data points, (3) filter out possible outliers, (4) reduce signal noise, and (5) provide alarms if something is not working as it is supposed to, e.g., if a sensor fails or a module is malfunctioning. The DQM is designed to meet these requirements, but this module is also sensitive to errors in input data. On initialization, eDrilling needs a complete description of the drilling process, including data describing rig, well, drilling fluid, bit, formations, etc. The DQM will read some of these data from 3rd part to initialize at start-up, but sometimes the needed data are missing. This might accidentally lead to flawed results or data crash. The DQM is also sensitive to errors in calibration. For example, even though the module can detect when a drill pipe is added to the drillstring and estimate its length and weight, it is dependent on the calibration of the hook position signal to obtain the correct bit depth. Again, as discussed in Section 6.1, the dependency of proper calibration manifests itself here.

Additionally, time offsets in the sampling and processing of certain parameters, e.g., for the hook load and hook position signal, might consequently produce a systematically wrong estimate of certain parameters, e.g., pipe length. As a result, the error in estimated bit depth will grow as more pipes are added to the drillstring. It is crucial that the data flow is arranged in a structured and efficient way such that unnecessary signal latency is avoided. The real-time hook load signal is calculated from the force at the dead line anchor and sent through the OPC server and the OPC client to the DDS server, see Figure 3.2. The server distributes this value to the ODBC client for storing and to the DQM for improvement. In the DQM, the value is calibrated with comparison to earlier values, and also adjusted with respect to friction. The corrected hook load value is then sent via the server to the GUI, because the user wants it in his output window, and to the TDM client for calculation of stresses on the pipe. The stress state of the string is then sent, again via the server, to the GUI for visualization and to the DAM. The DAM checks the stresses against allowed values, and if necessary, sends a warning to the GUI. In this way, the hook load signal, or a derivation of this, is sent through the system up to four times. This parameter journey is sketched in Figure 6.1. The result is that the GUI receives up to three signals that are dependent

[21] *The International System of Units* (abbreviated *SI* from French: Système international d'unités) is the modern form of the metric system (International and Mesures 2006).

on the hook load. If the lag time in the system is too large, it could happen that a signal on the last of its three tours through the system arrives at a client after the same signal from the next time step on its first tour. Thus the possibility of calculations using signals coming from two different time steps must be addressed if latency is experienced. However, these issues are not experienced during the case study.

In addition, as described in Section 2.4.3, there are setbacks and limitations on today's methods of data transmission between downhole and surface, in which mud pulse telemetry is recognized as the "industry standard". The need for not only good quality input data, but also better data resolution and higher sampling rates, has already been emphasized. If these requirements are not fulfilled, misleading output might be the results as discussed for the SPP differential in Figure 5.9. More importantly, real-time models must perform "here and now" in order to be useful at all. Lags in data handling and transmission are therefore unacceptable. For future perspectives, the author strongly considers WDP technology to have the potential to eliminate or greatly reduce these problems as it can give access to larger amounts of high-resolution data in real-time. Increased communication bandwidth and network infrastructure between offshore and OSCs will then be required.

With the mentioned data problems in mind, what could be done to reduce the vulnerability of eDrilling related to data flow and management? A solution is to use default values when needed information is not available or to use preceding measurements to estimate current values. The user should then be asked to verify and accept these choices. The author recommends that backup of the data should be performed routinely in order to be able to reconstruct the course of events in case of incidents, e.g., after data crash, system reboot etc. In that way, it might be possible to estimate conditions at the time of failure and to analyze what has happened up to present time. If a particular signal begins to vary wildly when other signals are stable, it is a reasonable indication that something is wrong with that signal. Suspicious data is difficult to handle, but warnings indicating this problem should be issued. However, algorithms enabling such functionality will probably take time to develop.

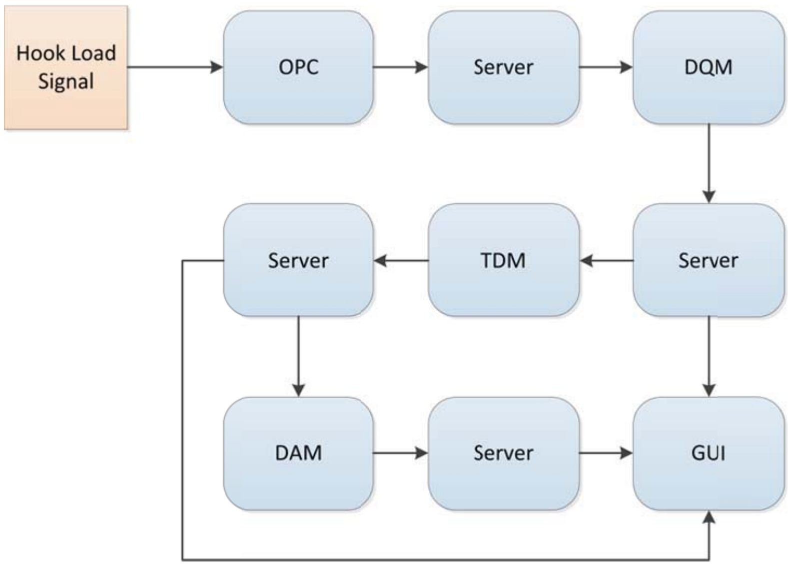

Figure 6.1: A parameter's journey through the system. Adapted from Kolnes et al. (2007).

6.3 Work Processes and Organization

The introduction of real-time systems using dynamic drilling models does not only put additional constraints on sensors and data handling capabilities, but also on work processes and the organization of people involved with the needed support functions. Full utilization of real-time drilling spans multiple disciplines and parties, making communication and cooperation a challenge. Not to mention that many of these systems have not yet been extensively tested in real operations and therefore it will take some time to learn completely how these systems affect work processes and organizational culture. This section will attempt to address some of the requirements and recommendations related to the changes in work procedures and people's roles and responsibilities when implementing real-time technologies such as eDrilling in the industry.

As discussed in previous sections, it is important that sensors are of acceptable quality and reliability. Work procedures should be defined to check the quality and reliability of critical sensors prior to the installation of eDrilling. The author speculates whether lack of understanding around the criticality of rig hardware or real-time technology in general, is the reason why these checks often are overlooked. One must also keep in mind that there will always be dissimilarities between rig equipment and sensors depending on type and age of the drilling rig. The equipment is also provided from different manufacturers and sensors are often installed at different locations on the rigs. Differences like these must always be addressed by the involved parties during setup such that eDrilling is configured and tuned accordingly. In addition, failure of downhole sensors or faulty data transmission is fairly common, which might result in system malfunctioning. Proper work procedures accommodating the management of data crash, system reboots, etc., are then required.

Issues regarding changes in mud rheology are already mentioned, in which some of the gathered data are provided from analysis of mud samples. In general, a mud logging company is responsible for collecting data from mud returns and shakers. It is necessary to establish work procedures to make sure that the needed drilling fluid measurements manually performed by the mud engineer are taken at a regular basis. This is vital in order for the expert, which is responsible for configuring eDrilling, to have access to the latest information. These procedures should include handling of possible changes in the well configuration data as well. The responsibility of the company responsible for aggregation and delivery of real-time rigsite data should also be clearly stated by contract. Additional assurance around work procedures must be established in order to certify the quality and reliability of the provided signals. The author asserts that provision of required real-time data is a major challenge that must be sorted out in order for real-time drilling to take-off in the years to come.

The following possible scenario might illustrate the challenge related to inadequate communication of information: The driller decides to use a secondary mud pit due to problems with the main mud pit. Thus the main mud pit is emptied and the temperature sensor subsequently measures the ambient air temperature. Without system re-configuration, real-time systems might apply this temperature as the drilling fluid temperature, and as a consequence the downhole mud density will increase rapidly. To avoid losses to the formation, the system will generate warnings advising to reduce pump rate based on the observed deviation between measured and calculated values. This misleading decision support might create confusion for the drilling team as this will not be understandable to them.

As just illustrated, the severity of incomplete or faulty input of well configuration data is huge. These data typically include the planned trajectory, geological prognosis, formation gradients forecast, casing programs, and detailed drilling operation procedures. Different persons representing different disciplines take part in preparing this information during the well planning process. It is usually made available in different computer systems and sometimes also in non-structured documents, such as spreadsheets etc. Work procedures that make sure that each discipline representative enters the correct and relevant planned information in a single data repository will greatly simplify the cumbersome and time-consuming process of finding the needed configuration data. Likewise when drilling is initiated, proper work procedures are needed to ensure cooperation between the involved parties such that potential changes in the configuration data are given to the person in charge of updating the input data, i.e., the on-site expert.

To ease the work load and responsibility of the expert, one might argue that some of the manual input data could be entered directly by the persons who are responsible for giving him these data in the first place. Due to the complexity of eDrilling, the author finds it necessary, however, to restrict the access to system configuration to a limited amount of people. These persons should be aware of their responsibilities and the consequences of their actions if they make changes. Being able to track manual changes made to the system is found necessary in order to diagnose potential unexpected behavior due to human changes. Too many "contributors" might possibly make this task impossible. It is therefore recommended that the on-site expert should have the overall responsibility of updating system parameters and configuring input data. Close dialogue with actors involved are then vital since the system will be more prone to human errors implied by the single expert in charge. The dependency of this person is schematized in Figure 6.2, where the dotted lines illustrate communication between the many different roles. Having too strong limitations might also result in lack of flexibility, so accessibility allowing quality control of the data entered by the expert should be addressed for the individual rig and work organization.

eDrilling is based on an open system architecture where all parties involved can connect via standard interfaces, see Section 3.1.1. However, Janssen et al. (2008) reported that unforeseen waiting time was encountered in some pilots when connecting the databases to the system. They experienced that internal policies established by the customer prohibited access by 3rd parties, so they had to travel a long administrative path to achieve the desired solution in mind. In order to foresee this in the future, it might be necessary to revise the standard work procedures in order to manage firewall configurations and to establish safe communication channels with the many data acquisition systems used by the different parties. In addition, it will be beneficial if the data are made available using industry standard formats with consistent data resolution, sampling rate, and clock synchronization. The author suggests that official cooperation between the customer and the hired 3rd party in the project should be clearly identified and agreed upon when signing the contract.

A weakness of current work processes in drilling is the decision-making process, in which many different departments and disciplines are involved. The latter is particularly evident when multiple problems arise, showing that the process often is seen as slow and lacks a holistic approach[22]. When implementing eDrilling, the author assumes that this will remain a challenge until work procedures providing the needed decision support functions are established and promoted. These procedures should clearly identify the different roles and responsibilities for each member of the team, e.g., who is responsible for communicating the selected decision to the driller. Sure, real-time drilling systems can increase the integration across departments and disciplines, remove communication barriers, and speed up the decision-making process, but teamwork must then be raised to new levels, and trust must lie in bottom for the whole team. As a consequence, it is recommended to increase the awareness by training the team members for their new roles and responsibilities, which is discussed further in the next section.

[22] A *holistic approach* looks at the whole picture.

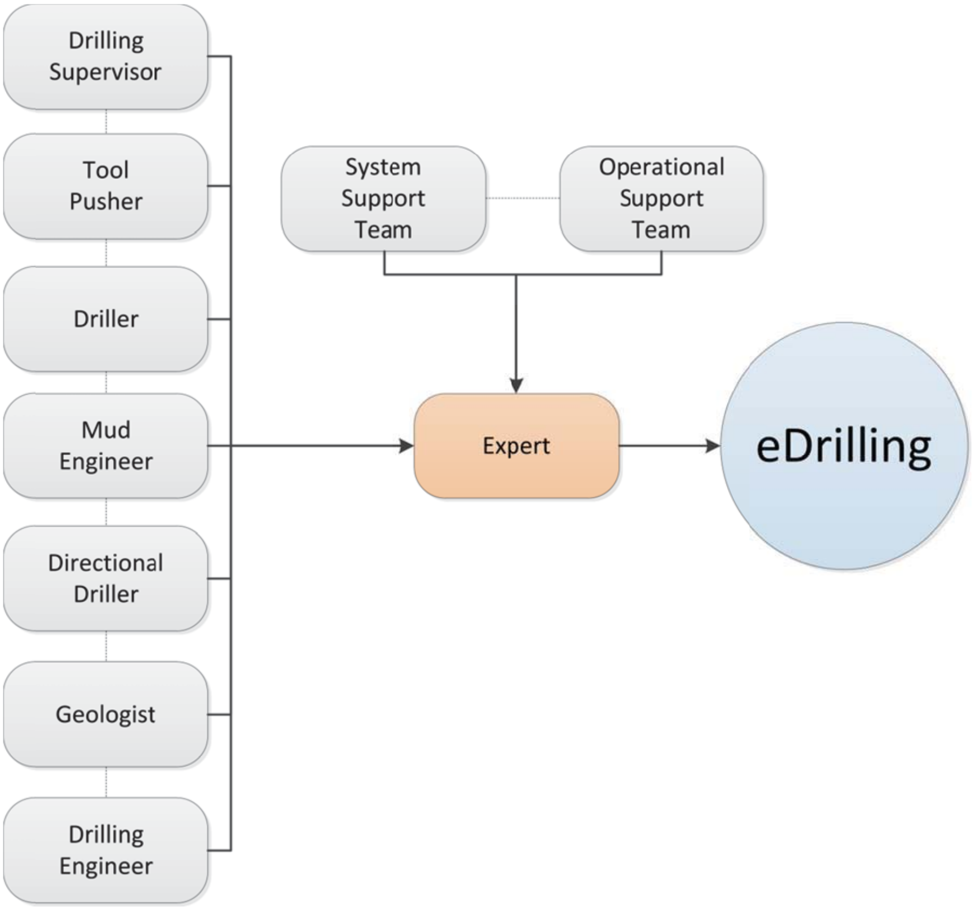

Figure 6.2: **Flow of information showing the dependency on the model expert.**

With the previous discussions in mind, some of the following changes in roles and responsibilities, both onshore and offshore, are expected by the author and summarized as follows:

Offshore roles:

- *Driller*: Access to more data will change the driller's role from being a supervisor for the drilling crew to become more of a drilling process operator. However, as already stated, the author sees the need for an on-site expert having the overall responsibility of controlling the real-time system until needed work procedures and skill levels are adapted.

- *Suppliers/contractors*: The situation today is that different 3^{rd} parties are located in separate containers, looking at different data. This gives each involved actor access to a fragmented view of the overall picture. With better and more integrated access to data, a total and more shared view of the drilling process is possible for all parties. However, challenges related to data availability are going to put additional work load and responsibility on existing work processes for 3^{rd} part suppliers.

- *Operative roles*: There will still be need for operative roles that are responsible for the actual carrying-out of the drilling process. The expert in particular will carry a lot of burden in this respect to make sure that the real-time system is configured with the latest input data and is running correctly.

Onshore roles:

- *Operation support functions*: OSCs are still needed to carefully support the drilling operation, but the involved parties must communicate more regularly across departments and disciplines to provide the most up-to-date information to the real-time system. Moreover, a total understanding of how the system works is needed to understand its capabilities. It will take time to gain the required knowledge and to incorporate these new work procedures.

- *Technical support*: There will be need for a role that is responsible for the quality assurance of data going into and coming out of the real-time system. It is believed that this task by far could be performed by the on-site expert. However, also support from development teams regarding modeling results and diagnosis will be needed, particularly in a transition period until the technology is verified and acknowledged by the users.

In summary, the changes related to work processes and organization could be carried out in multidisciplinary steps. Korsvold et al. (2009) explain how changes in work procedures are assumed to take place in two change-steps referred to as the first generation (G1) work processes and the second generation (G2), as illustrated in Figure 6.3. The G1 work processes focus on integrating onshore and offshore organizations, while the G2 processes focus more on tearing down organizational borders between operators and vendors, fields and units as well as suppliers. Consequently, the G2 will imply a profound change in roles and responsibilities towards operating with more shared responsibility between the actual companies involved. The author concludes that in order for real-time technologies to be implemented successfully in future drilling operations, all parties must work towards the G2 level.

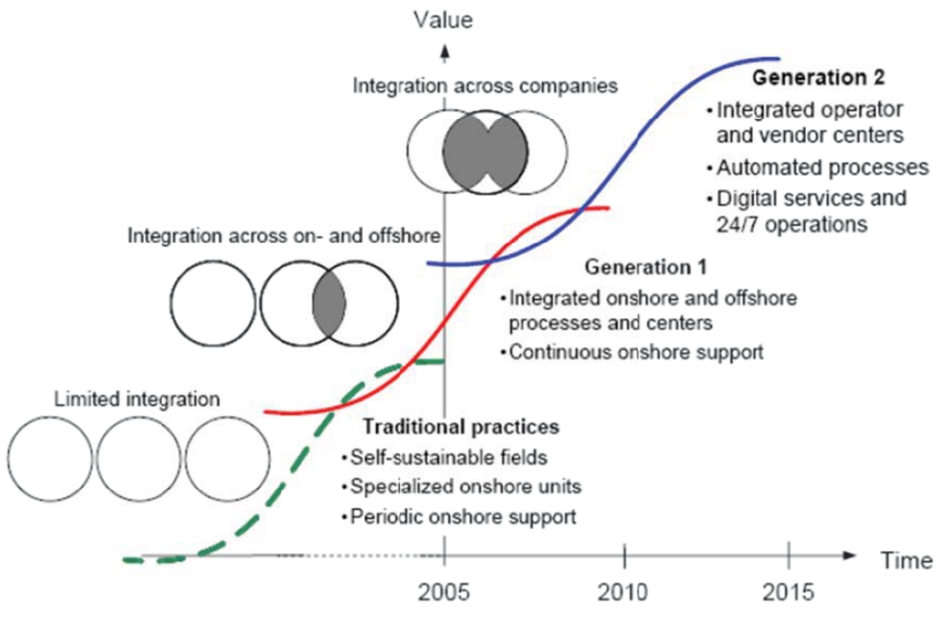

Figure 6.3: **Changes in integrated work processes in drilling are implemented in two change steps (Korsvold et al. 2009).**

6.4 Successful Implementation

All of the requirements mentioned above for system configuration and data management, combined with those related to work processes and organizational change in a timely fashion, show that introduction of real-time drilling systems must be done with care. Even though the technology might be working properly, success also depends on the readiness of the work organization to apply such systems. As implementation of such technologies might change future work procedures dramatically, the different working disciplines and involved parties need to have faith in the new technology. The author fears that the willingness to integrate eDrilling into existing work procedures on a day-to-day basis will take quite some time. This suspicion is mainly due to the fact that there is generally little knowledge about this technology in the industry, and particularly among the people working the rig equipment, e.g., the mud engineer or the driller.

It is recommended that the involved parties, i.e., the support functions and suppliers as well as offshore personnel, attend courses where all necessary information for understanding of the functioning of eDrilling is presented. The author finds this useful in order to build confidence in the new technology. Not to mention the change of the driller's role, as he will depend more on external information managed by other people. For example, maximum tripping velocities might be proposed limited based on calculations performed by the real-time system, but this decision might possibly not be shared by the driller based on his own calculations. This might cause unnecessary dispute and misunderstanding, so it is recommended that the application is integrated into the driller's console to share valuable information. The author realizes that such a change will put additional constraints on the driller given that it is going to take time to establish new work procedures and for him to gain the necessary expertise. As a consequence, the driller must be given appropriate training in a drilling simulator environment to tackle his new role.

Venkatesh et al. (2003) explain how user expectations are important factors for successful implementation of new technologies such as eDrilling. Four factors are argued to be critical in this respect:

1. *Performance expectancy*: the degree to which an individual believes that using eDrilling will help him or her to do a better job

2. *Effort expectancy*: how easy the user expects it will be to use eDrilling

3. *Social influence*: the degree to which users of eDrilling perceives that co-workers and management believe he or she should use eDrilling

4. *Facilitating conditions*: e.g., resources, technical support, and training

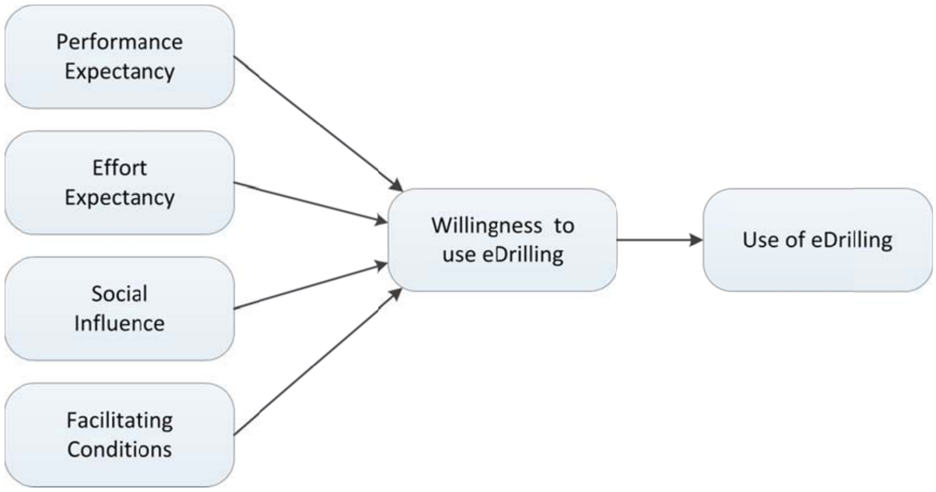

Figure 6.4: Factors influencing the use of eDrilling. Adapted from (Venkatesh et al. 2003).

The author believes that the first two success factors covering the *performance* and *effort expectancy* could possibly be addressed during training and user-testing of the system. Potential users need to understand and trust how eDrilling works, and that it is up and running and adding value to their everyday work processes. This goes to improved interaction across departments and disciplines, and to the fact that relevant information is made more readily available. It is simply assumed that some white-papers describing successful field testing and implementation of real-time drilling systems are surely not enough to trigger the necessary interest and willingness needed to implement these successfully. In order to be successful, the pilots need "champions" that can generate enthusiasm and spread excitement to other drilling teams within the organization. This is in turn believed to have a positive impact on the *social influence* as the technology will gain more support and stronger commitment between co-workers and the management in general.

When it comes to *facilitating conditions*, some skepticism on whether or not the user will have the necessary resources available will probably be present during the implementation phase. It looks like this skepticism has to do with people today not knowing whether or not they will be trained or will get technical support demanded. The author strongly emphasizes how the facilitating conditions, e.g., technical support and training possibilities, must be granted before any successful implementation could be achieved. Users need to know from the beginning that these facilitating conditions are already established and well-working. If they are not, many will see eDrilling just as another fancy tool adding more frustration when it is not working as intended. As the product has reached the commercialization phase, a general recognition is that having a stronger focus on the facilitating conditions is first priority.

However, the author knows that the eDrilling development team is putting a lot of effort in presenting their technology “as is” in real-time simulator environments where valuable information and knowledge about the product is provided to potential users (Hovland and Svendsen 2011). In this context, potential users could possibly be more open-minded in order for eDrilling to be able to show its full potential. The major issues concerning this go to the fact that the users do not have the sufficient time available to test the product and to communicate with the developers. The drillings teams testing eDrilling have been told by the management to facilitate the developers when required, but operational problems require full attention of the users such that no extra manpower has been allocated to the pilots. Several engineers and team leaders are also assumed not to attend information meetings and training workshops due to the time issue mentioned above. Consequently, the management should state more clearly their support to eDrilling by allocating the resources necessary to meet the lack of knowledge and to ensure more successful pilots.

6.5 Today's Overview and Future Visions

Based on the findings carried out in this study, it is a good time to analyze the current status, look ahead, and discuss how to bring forward and improve real-time drilling technology to meet future visions of optimal drilling. The following sections sum up benefits, roadblocks, and the need for future improvements in order to successfully introduce eDrilling to the industry.

6.5.1 Advantages

The purpose of eDrilling is to optimize drilling by utilizing simulations and measured data, reduce frequency of "catastrophic" drilling problems, and give automatic diagnosis and decision support. A weakness of today's work processes is that the involved actors lack a total and shared view of the drilling process, including relationships between various actors and how different parts of the operation are connected and influence each other. There is need for a more automatic, shared, and structured practice implying that the different actors, as one unified team, can work and operate more efficiently in a collective way by means of real-time collaboration. eDrilling is, among other things, designed to meet these challenges or, if you will, enable these opportunities.

Some of these opportunities are addressed by:

- Improving operation monitoring and analysis. It is easier to discover changes that occur at uneven intervals and slowly changing parameters based on deteriorating trends detected by the system.
- Enabling more holistic decision-making by communicating vital information in a user-friendly GUI. The dynamic models are able to run what-if evaluations and automatic forward-looking to provide advanced decision support during operations.
- Increasing integration across different departments, disciplines, and companies by giving a true overview of the well by displaying all relevant information in real-time 2D and 3D.
- Enhancing planning, training, and experience transfer by running eDrilling in replay-mode. Similar wells can be drilled on the computer to increase understanding and risk pictures before drilling live.

6.5.2 Challenges

The following essential question might however still be asked: If the technology is so promising, why has it not yet been able to take-off in the drilling industry, which is working towards more integrated operations? eDrilling has definitely the potential to revolutionize future drilling operations in terms of a prominent assessment of the drilling process in real-time, providing a more comprehensive approach in decision-making, and enhancing collaboration between participants involved. However, there are several roadblocks that must be overcome before this is true reality. The author comes to an end that there are not technical problems that first and foremost hold the technology back, but more administrative and organizational problems.

Adding up the experiences gained during this study, the following bottlenecks are identified:

- System configuration requiring manual control
- Complex data routes crossing multiple complex infrastructures
- Communication between different departments, disciplines, and companies
- Company culture (differences in internal policies, work procedures, units etc.)
- Lack of support by the teams involved

Solutions to these challenges are different for every drilling operation, but the following guidelines could be a good start:

- Include the on-site expert into the finalized product, preferably with no additional costs for the customer
- Incorporate various operator departments and 3rd parties into the project from the very start. Studies addressing possibilities and limitations on data handling and system infrastructure should be conducted to promote standardization
- Assign contact persons from every party and keep the communications going, making sure everyone is aware of the status all the time
- Focus on administrative efforts that are required to achieve the solution in mind. The drilling industry must aim towards the G2 level of integration
- Conduct instruction courses and training workshops to get the needed support of the teams involved

6.5.3 The Way Forward

So what kinds of future improvements are necessary in order to realize the potential of real-time use of dynamic drilling models? Further refinements of the advanced models themselves will be an important part of improving the performance of eDrilling. There is need for a continuous development of the system's reliability and its ability to handle all kind of data deficiencies better. In addition, tuning of sensitivity parameters and calibration of models should be more automated and flexible to easily account for all the information gathered while drilling. In this context, the efforts described by Lohne et al. (2008) is believed to be a good start in this direction. They have demonstrated how automatic calibration of real-time computer models is achievable by utilizing an unscented Kalman filter technique. By any means, all improvements should be done with improved user-friendliness and minimal need for model experts as important goals.

In order for eDrilling to fulfill its potential, it is found essential that the operational knowledge of future users are utilized in the further development and implementation of the system. Insufficient involvement of future users might reduce user-friendliness, system quality, and ultimately the trust in the product. As far as implementation is concerned, problems might arise from inadequate management of change related to people's roles, work processes, and organization. Another potential setback is seen from people getting too dependent on or too confident in the technology. As a consequence, reduced ownership to the drilling process, reduced communication, and decreasing knowledge might follow; challenges that eDrilling is intended to contradict.

With this background, one cannot emphasize enough that human interpretation always is necessary, regardless of how innovative and beneficial real-time drilling systems might be. Although today's drilling operations are perceived to be functioning well, the author concludes that the application of real-time drilling technology has not been tapped so far, despite its potential. In order to do so, the challenges and bottlenecks addressed in this thesis must first be sorted out and overwon.

7. Conclusions

The main objective of this study was to evaluate the potential of real-time use of dynamic drilling models. For this purpose, a new and innovative system for real-time simulation, 3D visualization, and remote control called eDrilling was utilized and tested. A case study was performed by running the system in replay-mode with actual real-time drilling data to address its capabilities, challenges, and overall potential. Based on this work, the following important conclusions could be drawn:

- Case study results have proven to give a correct representation of the drilling process with reproducible results and no system errors. The modules and models integrated in eDrilling have sufficient functionality with respect to accuracy, robustness, and calculation speed and processing requirements.

- Mathematical analyses of certain model results have shown that advanced dynamic drilling models utilized by real-time applications build on fundamental engineering principles presented in drilling literature.

- Issues related to manual configuration of input data have been demonstrated. A qualified person having the necessary knowledge about the drilling process as well as sufficient understanding of how the real-time system works, is probably needed to ensure that model parameters and configuration data are continuously calibrated and up-to-date at all times. This manual control should be performed on a 24/7 basis, and it is found beneficial that the expert is located at the rigsite to be as close to the operation as possible.

- eDrilling has not been able to detect unwanted events in terms of pack-off tendencies, which was present when actually drilling the well examined in the case study. Even though this deteriorating behavior could be addressed by analyzing deviating trends for certain parameters, no warnings were given indicating this. The latter goes to the fact that tuning of system sensitivity limits was not found to be satisfactory. In contrast, false alarms indicating possible wash-out have been raised due to MWD downlinks being sent from surface.

- Real-time systems are totally dependent on good-quality input data. Errors are not uncommon, and integration of data from 3rd parties might prove to be very challenging. Data inconsistencies might lead to misleading results calculated by the models, which in turn might create confusion and potentially jeopardize operational safety.

- System functionality assuring sufficient quality control of input data needs stronger focus in order to be able to meet data quality requirements. Challenges related to data transmission might potentially be reduced utilizing WDP technology.

- With the introduction of eDrilling, people's roles and responsibilities will change dramatically. Full utilization of this real-time technology spans multiple departments, disciplines, and parties, making communication and cooperation across companies and organizational borders even more crucial. Achieving a culture of common understanding and mutual trust is essential in this context.

- Clearly defined work procedures must be established in order to:

    a. ensure sufficient data provision and quality control of sensor measurements
    b. make sure that manually performed measurements and configuration data are continuously updated and tuned
    c. enable improved and safer data communication between the different parties, preferably using industry standard formats
    d. provide the necessary decision support functions where different roles and responsibilities are crystal clear
    e. increase the awareness and readiness of the work organization to apply real-time systems by training the involved personnel

- In order for real-time systems to be implemented successfully, confidence and faith in the new technology must be built. User expectations play a significant role in this respect, and these might partly be answered promoting education and training.

- Technical support from developers is necessary to assist if sudden system errors etc. do occur. Close dialogue between involved personnel and the on-site expert will be meaningful in view of this.

- The potential of real-time use of dynamic drilling models has not been tapped so far. In order to realize its full potential, the bottlenecks mentioned herein must be overcome.

8. Recommendations

The following is recommended for further work:

- The presented case study should be run with proper adjustments of sensitivity parameters and limits in order to evaluate whether or not eDrilling is able to detect the mentioned pack-off tendencies.

- Several more case studies should be conducted by running eDrilling in replay-mode with playback data from different wells. Obtained results should be evaluated carefully with respect to the findings presented in this thesis to address overall efficiency potential.

- "Success stories" from field pilots are vital in order to reveal the capabilities and full user-potential of eDrilling. Thus far the necessary attention needed for full utilization of the technology has not been allocated adequately during pilots, causing unexpected issues that easily could have been avoided. The most imminent challenge is to create a more structured pilot, in which management and the drilling teams involved need to be more deeply committed to a successful outcome.

Nomenclature

List of Abbrevations

AC	Alternating Current
BHA	Bottom Hole Assembly
BHP	Bottom Hole Pressure
CoP	ConocoPhillips
CPU	Central Processing Unit
DAM	Diagnosis and Advisory Module
DC	Direct Current
DDR	Daily Drilling Reporting
DDS	Data Distribution System
DQM	Data Quality Module
ECD	Equivalent Circulating Density
ESD	Equivalent Static Density
FM	Flow Model
GUI	Graphical User Interface
IDS	Integrated Drilling Simulator
LAS	Log ASCII Standard
LWD	Logging While Drilling
MD	Measured Depth
MEM	Mechanical Earth Model
MPD	Managed Pressure Drilling
MSE	Mechanical Specific Energy

MWD	Measurement While Drilling
NCS	Norwegian Continental Shelf
NNS	Norwegian North Sea
NPT	Non Productive Time
NS	North Sea
OBM	Oil Based Mud
ODBC	Open Database Connectivity
OPC	OLE for Process Control
OSC	Operation Support Center
PC	Personal Computer
PROFIBUS	Process Field Bus
RFID	Radio Frequency Identification
RKB	Rotary Kelly Bushing
ROP	Rate of Penetration
RPM	Revolutions per Minute
RTOC	Real Time Operations Center
SG	Specific Gravity
SM	Session Manager
SPM	Strokes per Minute
SPP	Standpipe Pressure
TDM	Torque and Drag Module
TVD	True Vertical Depth
WDP	Wired Drill Pipe
WITS	Wellsite Information Transfer Specification
WITSML	Wellsite Information Transfer Standard Markup Language
WOB	Weigh on Bit
WSM	Wellbore Stability Module

List of Symbols

A_0	7.24032
A_2	2.75660 x 10^{-5}
A_1	-2.84383 x 10^{-3}
A	cross-sectional area of flow line
c	constant that depends on mud properties and wellbore geometry
c	formation cuttings
d	diameters, in.
d	pipe diameter
$E_T^{new}(i, j)$	new thermal energy in box with radial position *i* and axial position *j*
$E_{other}(i, j)$	large "bag" of different contributions. It is possible to put the forced-convection contribution, the heat generated in the drillstring by the bit, and thermo-chemical reactions into this "bag"
fo	formation oil
$fric$	frictional pressure loss
fw	formation water
g	gas
g	gravity, 9.81 m/s^2
Gb	Gigabit
h	vertical height, i.e., TVD
H	enthalpy per unit mass, J/kg
Hz	Hertz, 1/second
l	liquid, i.e., drilling fluid,
K	consistency index
m	constant that theoretically has a value near 1.75
m	drilling mud
$\dot{m}_{g,m}$	rate of gas dissolution in drilling mud
$\dot{m}_{g,fo}$	rate of gas dissolution in formation oil

Mb/s	Megabits per second
n	flow behavior index
p	downhole pressure, psia
Q_c	conductive and natural-convective heat flow, J/sec
Q_f	forced-convective heat flow, J/sec
$Q_R^L, Q_R^R, Q_Z^U, Q_Z^D$	heat flux through the left radial boundary, right radial boundary, axial upper boundary, and axial lower boundary
s	spatial variable along the flow lines
t	time
T	mud temperature in Fahrenheit, °F
T	temperature field
$\bar{v}$	mean fluid velocity, ft/s
$\vec{V}$	velocity vector
V_{mix}	average flow velocity, i.e., net volume flux divided by cross-sectional area
$x_{a,b}$	mass fraction of “a” in “b”
Δp_{ann}	pressure loss in annulus
Δp_{bit}	pressure loss at bit nozzles
Δp_d	parasitic pressure loss
Δp_{dc}	frictional pressure loss in drill collars
$\Delta p_{dc,ann}$	frictional pressure loss in drill collar annulus
Δp_{dp}	frictional pressure loss in drill pipe
$\Delta p_{dp,ann}$	frictional pressure loss in drill pipe annulus
Δp_s	frictional pressure loss in surface equipment
Δt	time step size
α_z	volume fraction of component “z”
ρ	density
ρ_{OBM}	density for OBM, lbm/gal
μ	fluid viscosity, cp.

γ	shear rate
τ	shear stress
τ_y	yield shear stress
σ	surface tension between gas and mud
λ	thermal conductivity

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Appendices

Appendix A: Appendix A gives some well configuration data for Well X-16A. Data from the Mud Summary Report is used in the mathematical analyses for modeled SPP and ECD.

Appendix B: Appendix B list the programmed MATLAB-code used to utilize the calculated model outputs and to plot them in a representative manner. An example of an output file generated by eDrilling is also listed.

Appendix C: Appendix C show the MS Excel-spreadsheet designed to calculated changes in SPP by using fundamental equations presented in the literature. “Goal seek” is utilized to find fanning friction factors by an iterative approach.

Appendix A: Well X-16A Specifications

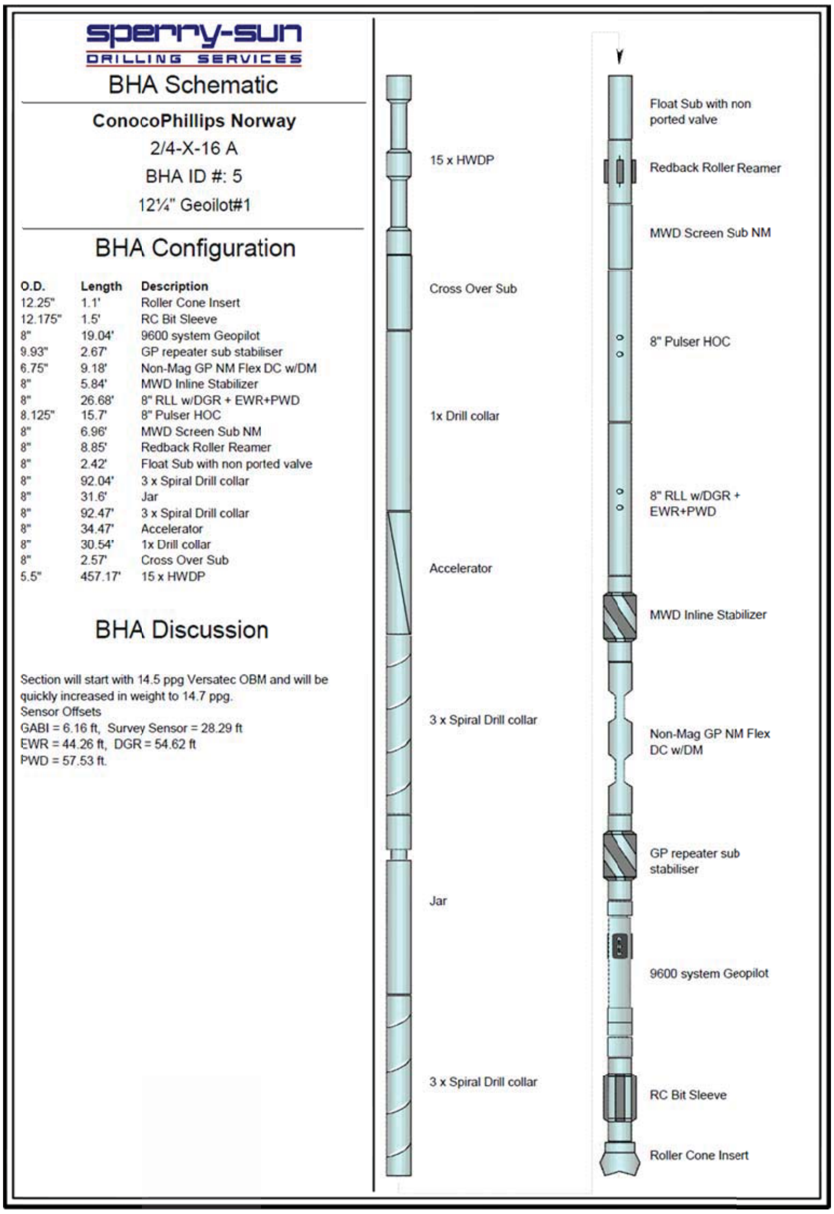
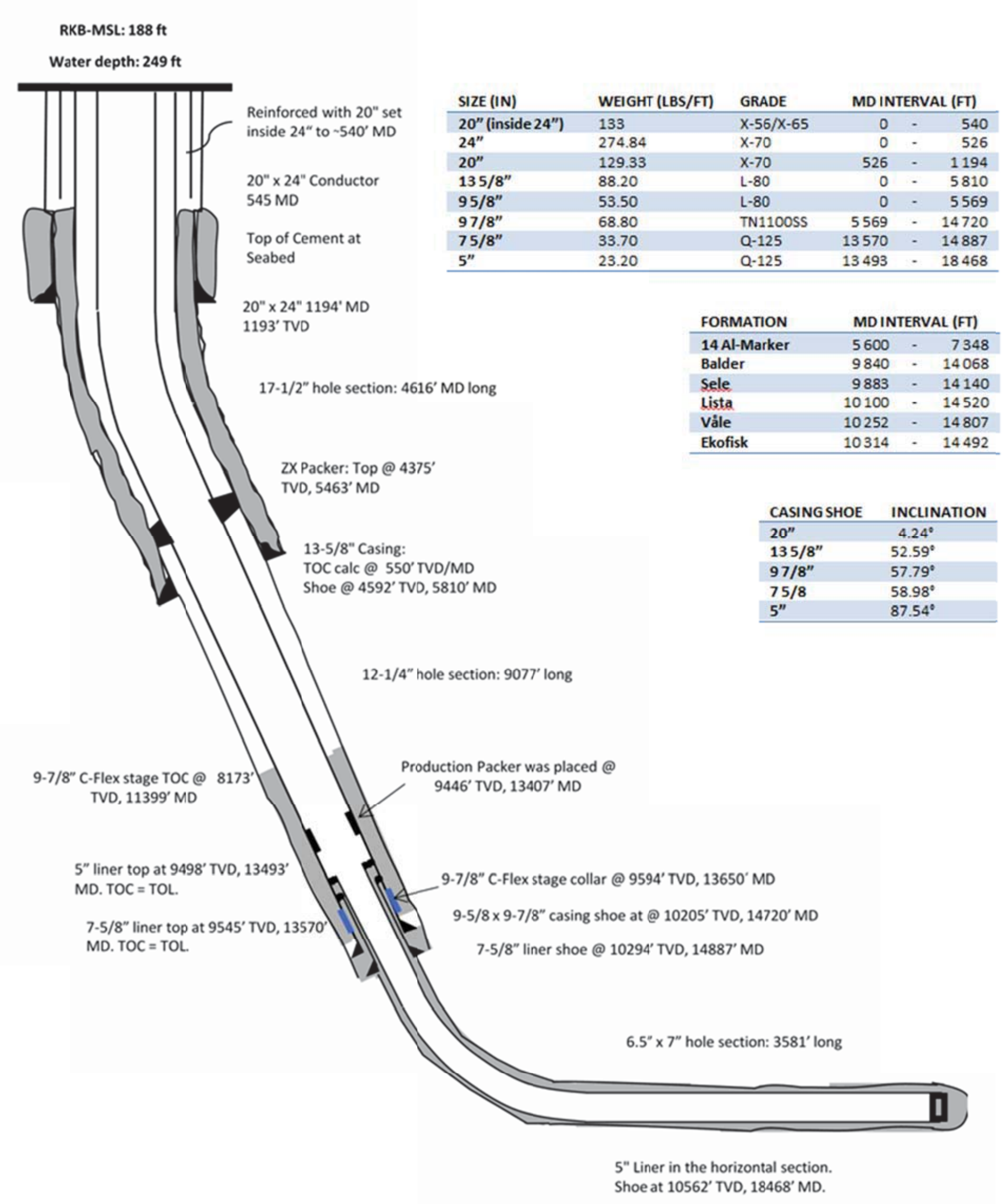


Figure A. 1: BHA configuration for the drilling operation during the case study.



SIZE (IN)	WEIGHT (LBS/FT)	GRADE	MD INTERVAL (FT)		
20" (inside 24")	133	X-56/X-65	0	-	540
24"	274.84	X-70	0	-	526
20"	129.33	X-70	526	-	1 194
13 5/8"	88.20	L-80	0	-	5 810
9 5/8"	53.50	L-80	0	-	5 569
9 7/8"	68.80	TN1100SS	5 569	-	14 720
7 5/8"	33.70	Q-125	13 570	-	14 887
5"	23.20	Q-125	13 493	-	18 468

FORMATION	MD INTERVAL (FT)		
14 Al-Marker	5 600	-	7 348
Balder	9 840	-	14 068
Sele	9 883	-	14 140
Lista	10 100	-	14 520
Våle	10 252	-	14 807
Ekofisk	10 314	-	14 492

CASING SHOE	INCLINATION
20"	4.24°
13 5/8"	52.59°
9 7/8"	57.79°
7 5/8	58.98°
5"	87.54°

Figure A. 2: Wellbore schematic of Well X-16A (Vargas 2009).

Table A. 1: Mud summary report for Well X-16A.

ConocoPhillips

Mud Properties Summary (legal size)

2/4-X-16

API / UWI	Surface Legal Location	License No	Well Configuration Type	Ground Elevation (m)	Casing Flange Elevation (m)	KB-Ground Distance (m)	KB-Casing Flange Distance (m)
	550 563251120N 31308470E	PL018	Deviated		21,95		35,36

Rigs

AFE / RFE	Type	Sub-type	Plan TMD (mKB)	Plan Form	Contractor	Rig Name#	Rig Type	Rig Accept Date	RR Date
WUD.008.G872.CD	DRILLING SIDETRACK		5 376,98	Ekofisk EL2	ODFJELL DRILLING MANAGEMENT AS	EKOFISK X	DRILLING	07.02.2009	

Fluid / Mud Checks

Date	Depth (mKB)	Depth (TVD) (mKB)	Type	Dens (kg/m³)	Vis (s/L)	PV Calc (cp)	YP Calc (Pa)	Gel (10s) (Pa)	Gel (10m) (Pa)	API Filtrate (mL/30...	pH	Pom (mL/mL)	Retort Solids (%)	CaCl (ppm)	Ca (mg/L)	Chlor (mg/L)	K	Vendor	Lime (kg/m³)	LGS (%)	Mg (mg/L)	MBT (kg/m³)	n	OW Ratio	Pf (mL/mL)	Pm (mL/mL)	Pot (mg/L)	Sand (%)	Solids Corr. (%)	Wellbore
																														2/4-X-16
			Versatec			69,0	15,8	7,2	12,0									MI											29,4	2/4-X-16
			Versatec					8,1	11,0																					2/4-X-16
			Versatec	1773,4		69,0	15,8	7,2	12,0									MI											29,4	
			Versatec																											2/4-X-16
07.02.20...	436,47		Versatec	1378,0		24,0	7,2	5,7	5,7			2,700	17,0			100 ...	26,07987		10	21,0			0,275	78,3/...					16,3	2/4-X-16
08.02.20...	730,91		Versatec	1378,0		27,0	6,7	6,7	9,1			2,000	18,0			100 ...	41,32573		7	40,0			0,242	78/22					17,4	2/4-X-16
09.02.20...	955,55		Versatec	1402,0		30,0	9,6	6,7	9,1			2,200	19,0			99 400	40,65581		8				0,252	77,8/...						2/4-X-16
10.02.20...	1 051,56		Versatec	1461,9		33,0	10,1	6,7	9,1			2,200	22,0			115 ...	36,37745		8	6,6			0,267	79,5/...					21,5	2/4-X-16
11.02.20...	1 071,98		Versatec	1473,9		33,0	11,0	7,7	10,1			2,200	21,0			115 ...	45,00053		8	4,4			0,239	79,7/...					20,3	2/4-X-16
12.02.20...	1 071,98		Versatec	1473,9		32,0	11,5	7,7	10,1			2,200	21,0			115 ...	43,66803		8	4,4			0,257	79,7/...					20,3	2/4-X-16
14.02.20...	1 277,11	1 073,63	Versatec	1473,9		43,0	10,5	8,1	10,1			2,100	21,0			107 ...	37,75277		8	4,6			0,297	78,5/...					20,3	2/4-X-16 A
15.02.20...	1 529,79		Versatec	1485,8		56,0	13,4	8,6	12,0			2,200	23,0			104 ...	38,47334		8	6,9			0,335	77,9/...					22,4	2/4-X-16
16.02.20...	1 668,48		Versatec	1485,8		56,0	13,4	8,6	11,5			2,200	23,0			111 ...	35,00067		8	6,1			0,344	79,2/...					22,4	2/4-X-16
17.02.20...	1 668,48		Versatec	1485,8		58,0	12,0	7,7	10,5			2,200	23,0			111 ...	35,00067		8	6,1			0,344	79,2/...					22,4	2/4-X-16
19.02.20...	1 730,35		Versatec	1485,8		60,0	11,5	7,2	10,5			2,200	23,5			116 ...	35,41582		8	7,0			0,336	79,7/...					22,9	2/4-X-16
19.02.20...	1 775,46		Versatec	1509,8		59,0	12,4	8,1	11,0			2,200	24,0			115 ...	35,00067		8	7,0			0,344	78,9/...					23,3	2/4-X-16
20.02.20...	1 775,46		Versatec	1509,8		61,0	12,4	8,1	11,0			2,200	26,0			115 ...	35,00067		8				0,344	78,9/...						2/4-X-16
21.02.20...	1 775,46		Versatec	1509,8		53,0	21,5	8,1	11,0			2,100	24,0			115 ...	34,60046		8				0,351	78,9/...						2/4-X-16
22.02.20...	1 775,46		Versatec	1509,8		53,0	21,5	8,1	11,0			2,100	24,0			115 ...	34,60046		8				0,351	78,9/...						2/4-X-16
23.02.20...	1 775,46		Versatec	1509,8		52,0	21,5	8,1	10,5			2,000	24,0			112 ...	35,00067		7				0,344	78,9/...						2/4-X-16
24.02.20...	1 775,46		Versatec	1521,8		52,0	21,5	8,1	10,5			1,800	24,0			112 ...	35,00067		7				0,344	78,9/...						2/4-X-16
25.02.20...	1 775,46		Versatec	1509,8		52,0	21,5	8,1	11,0			1,800	24,0			112 ...	35,00067		7				0,344	78,9/...						2/4-X-16
26.02.20...	1 775,46		Versatec	1390,0		53,0	21,5	8,1	11,0			2,100	24,0			115 ...	34,60046		8				0,351	78,9/...						2/4-X-16
27.02.20...	1 775,46		Versatec	1737,5		45,0	10,5	5,7	7,7			1,800	28,0			102 ...	28,89946		7	3,7			0,349	75/25					27,4	2/4-X-16
28.02.20...	1 810,51		Versatec	1737,5		47,0	11,0	7,7	9,6			1,900	28,0			100 ...	37,24651		7	3,7			0,305	75/25					27,4	2/4-X-16
01.03.20...	2 146,10		Versatec	1737,5		50,0	11,5	7,7	9,6			2,600	30,0			125 ...	36,2949		10	5,4			0,321	77,1/...					29,3	2/4-X-16
02.03.20...	2 231,14		Versatec	1761,4		48,0	10,5	6,7	8,6			2,600	30,0			125 ...	32,78667		9	5,4			0,33	77,1/...					29,3	2/4-X-16
02.03.20...	2 429,26		Versatec	1761,4		49,0	11,0	6,2	8,6			2,200	30,0			123 ...	32,35931		8	5,3			0,338	78,6/...					29,3	2/4-X-16
03.03.20...	2 503,02		Versatec	1773,4		48,0	11,0	6,2	8,1			2,000	30,0			127 ...	32,78667		7	5,3			0,33	79,3/...					29,3	2/4-X-16
03.03.20...	2 533,19		Versatec	1773,4		48,0	10,5	5,7	7,7			2,000	30,0			131 ...	33,23232		7	5,3			0,322	79,3/...					29,3	2/4-X-16
03.03.20...	2 533,19		Versatec	1773,4		48,0	11,5	6,2	8,1			1,800	30,0			127 ...	32,78667		7	5,3			0,33	79,3/...					29,3	2/4-X-16
03.03.20...	2 560,32		Versatec	1773,4		51,0	10,5	6,2	8,1			2,400	30,5			127 ...	32,35931		9	5,6			0,338	79,1/...					29,8	2/4-X-16
04.03.20...	2 560,32		Versatec	1773,4		51,0	10,5	6,7	9,1			2,400	30,5			127 ...	36,76101		9	5,6			0,313	79,1/...					29,8	2/4-X-16
04.03.20...	2 590,80		Versatec	1773,4		50,0	12,4	6,7	9,1			2,100	30,5			127 ...	35,41582		8	5,6			0,336	79,1/...					29,8	2/4-X-16
04.03.20...	2 611,53		Versatec	1773,4		50,0	13,9	7,7	11,5			2,100	30,5			127 ...	39,82443		8	5,5			0,313	79,3/...					29,8	2/4-X-16
04.03.20...	2 650,54		Versatec	1773,4		51,0	14,4	8,1	12,4			2,200	30,5			127 ...	43,87357		8	5,6			0,3	79,1/...					29,8	2/4-X-16
05.03.20...	2 904,74		Versatec	1773,4		56,0	13,9	9,1	14,8			2,400	30,5			148 ...	42,42041		9	5,4			0,32	80,6/...					29,8	2/4-X-16

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Appendix B: MATLAB Program Code and Files

Table A. 2: MATLAB language code for plotting model results.

```
% Script that reads model results and generate plots
%
% Plotting SPP with multiple line colors when displacing to heavier mud
%
% #####################################################
% # Potential use of real-time dynamic drilling models #
% #####################################################
%
% Mads Johan Brasøygård, MSc 2011, NTNU, Norway
%

clc

% Open/read input files

folder ='C:\eDrilling\Replay\12042011\FM\';

files = {
    'FlowModelResults_2011-04-12_11.23.txt'
    'FlowModelResults_2011-04-12_12.00.txt'
    'FlowModelResults_2011-04-12_18.00.txt'
    'FlowModelResults_2011-04-13_00.00.txt'
    'FlowModelResults_2011-04-13_06.00.txt'
    'FlowModelResults_2011-04-13_12.00.txt'
    'FlowModelResults_2011-04-13_18.00.txt'
    'FlowModelResults_2011-04-14_00.00.txt'
    'FlowModelResults_2011-04-14_06.00.txt'
    };

noHeaderLines = 1;
x = [];
for i = 1:length(files)
    filename = strcat(folder,files{i});
    try
        fid = fopen(filename);
        xi = textscan(fid,['%s%s%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f' ...
            '%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f%f' ...
            '%f%f%f%f%f%f%f'], ...
            'headerLines',noHeaderLines);
        days = datenum(xi{1},'yyyy/mm/dd');
        time = datenum(xi{2},'HH:MM:SS');
        x = [x;days,time,xi{3:end}];
        fclose(fid);
    catch
        warning(['File not found: ',filename]);
    end
end

% Import input data to table x

BitPosition  = x(:,3);
RotarySpeed  = x(:,4);
RotaryTorque = x(:,5);
MudFlowIn    = x(:,6);
MudDensityIn = x(:,7);
DepthHole    = x(:,8);
DesiredEMW   = x(:,9);
SetPointPos  = x(:,10);
ChokePres    = x(:,11);
MudTempIn    = x(:,12);
FlowAcross   = x(:,13);
ROP          = x(:,14);
```

```
PWDPressure  = x(:,15);
MudFlowOut   = x(:,16);
MudDensOut   = x(:,17);
TankVolume   = x(:,18);
BufferPress  = x(:,19);
PWDTemp      = x(:,20);
RCDPress     = x(:,21);
SPP          = x(:,22);
MudTempOut   = x(:,23);
bhPresCalc   = x(:,24);
bhEcdCalc    = x(:,25);
bhTempCalc   = x(:,26);
csPresCalc   = x(:,27);
csEcdCalc    = x(:,28);
csTempCalc   = x(:,29);
pitGainCalc  = x(:,30);
sppCalc      = x(:,31);
flowOutCalc  = x(:,32);
tempOutCalc  = x(:,33);
pChokeCalc   = x(:,34);
fricFactCalc = x(:,35);
ropCalc      = x(:,36);
surgeVolCalc = x(:,37);
tvdBitCalc   = x(:,38);
pwdPresCalc  = x(:,39);
pwdTempCalc  = x(:,40);
pwdEcdCalc   = x(:,41);
currFluidNo  = x(:,42);
boundryType  = x(:,43);
ecdAtPos     = x(:,44);
pAtPos       = x(:,45);
TAtPos       = x(:,46);
pChokeStat   = x(:,47);

% Need to plot data points versus time, i.e., in hours

tt           = x(:,2);
xlength      = 1:length(tt);            % Number of values on x-axis
HrFraction   = 48/length(xlength);      % Operation lasts for 48 hrs
xHr          = xlength*HrFraction;      % Number of "time-points" in hours

% Want to change color of plotted line when displacing to heavier mud.

Disp_time    = 37.8;                    % Displacing to heavier mud at 37.8 hours

% Call function searchclosest.m to find closest matrix index number "i" of xHR at 37.8
hours
% "i" defines when on x-axis to change to new displacement line color
% "cv" is the matrix to search through. In this case cv is matrix xHr

[i,cv] = searchclosest(xHr,Disp_time);

%% Plotting

close all;

figure(1)
hold on;

y1 = SPP;
y2 = sppCalc;

z1 = y2;
z1(xlength>=i) = NaN;                   % Need to generate two SPP matrices
z2 = y2;                                % in order to get two different colors.
z2(xlength<i)  = NaN;

meas = plot(xHr,y1/1e5);                % Assign three different plot-variables
calc = plot(xHr,z1/1e5);
disp = plot(xHr,z2/1e5);
```

```
% Managing style and appearance of plots

set(meas                                   , ...
  'LineStyle'       , '-'                  , ...
  'LineWidth'       , 1.5                  , ...
  'Color'           , 'r'                  , ...
  'Marker'          , 'none'               , ...
  'MarkerSize'      , 1.0                  , ...
  'MarkerFaceColor' , 'r'                  );

set(calc                                   , ...
  'LineStyle'       , '-'                  , ...
  'LineWidth'       , 1.5                  , ...
  'Color'           , 'b'                  , ...
  'Marker'          , 'none'               , ...
  'MarkerSize'      , 1.0                  , ...
  'MarkerFaceColor' , 'b'                  );

set(disp                                   , ...
  'LineStyle'       , '-'                  , ...
  'LineWidth'       , 1.5                  , ...
  'Color'           , [0 .75 0]            , ...
  'Marker'          , 'none'               , ...
  'MarkerSize'      , 1.0                  , ...
  'MarkerFaceColor' , 'b'                  );

hTitle  = title ('Standpipe Pressure'    );
hYLabel = ylabel('Bar'                   );
hXLabel = xlabel('Hours'                 );
xlim([0 48]);
ylim([0 390]);

hLegend = legend( ...
 [meas, calc, disp]                        , ...
  'Meas'                                   , ...
  'Calc, Before Displacement'              , ...
  'Calc, After Displacement'               , ...
  'location', 'NorthEast'                  );

set(gca                                    , ...
    'FontName'   , 'Helvetica'             );
set([hTitle], ...
    'FontName'   , 'AvantGarde'            );
set([hLegend, gca]                         , ...
    'FontSize'   , 8                       );
set([hYLabel]  , ...
    'FontSize'   , 10                      );
set( hTitle                                , ...
    'FontSize'   , 12                      , ...
    'FontWeight' , 'bold'                  );

set(gca                                    , ...
  'Box'         , 'off'                    , ...
  'TickDir'     , 'out'                    , ...
  'TickLength'  , [.02 .02]                , ...
  'XMinorTick'  , 'on'                     , ...
  'YMinorTick'  , 'on'                     , ...
  'YGrid'       , 'on'                     , ...
  'XGrid'       , 'on'                     , ...
  'XColor'      , [.3 .3 .3]               , ...
  'YColor'      , [.3 .3 .3]               , ...
  'LineWidth'   , 1                        );

% Determining size of plot

set(gcf,'position',[ 100,   300,   1000,   370]);

% Adding text to plot automatically

hText1   = gtext('\it {Displacing from}');
hText2   = gtext('\it {1.76 SG to 1.78 SG}');
```

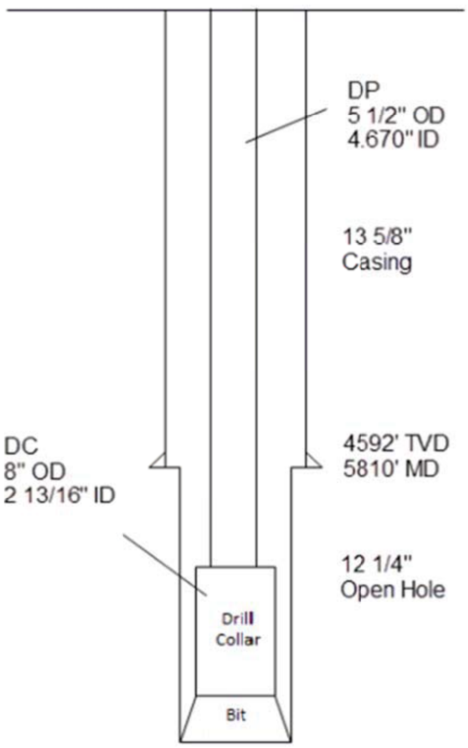
```
set( hText1                        , ...
    'FontSize'   , 8               , ...
    'FontWeight' , 'normal'        , ...
    'Color'      , [.3 .3 .3]      , ...
    'BackgroundColor','w'          );

set( hText2                        , ...
    'FontSize'   , 8               , ...
    'FontWeight' , 'normal'        , ...
    'Color'      , [.3 .3 .3]      , ...
    'BackgroundColor','w'          );

% Copying plot window to clipboard

print -dmeta -painters


% ------------------------
% Function searchclosest.m
% ------------------------

function [i,cv] = searchclosest(x,v)

i    = [];
from = 1;
to   = length(x);

% Phase 1: Binary Search

while from<=to
    mid  = round((from + to)/2);
    diff = x(mid)-v;
    if diff==0
        i  = mid;
        cv = v;
        return
    elseif diff<0     % x(mid) < v
        from = mid+1;
    else              % x(mid) > v
        to   = mid-1;
    end
end

% Phase 2: Linear Search

% Remember Bineary search could not find the value in x
% Therefore from > to. Search range is to:from

y = x(to:from);             %vector to be serach for closest value
[ignore,mini] = min(abs(y-v));
cv = y(mini);               % cv: closest value
                            % mini: local index of minium (closest) value with respect
to y
i = to+mini-1;              % find global index of closest value with respect to x
```

Table A. 3: Parts of output LAS-file generated by eDrilling.

Date	Time	BitPosition	RotarySpeed	RotaryTorque	MudFlowIn	sppCalc
20.05.2011	12:00:00	2189.69	12.462	11039	5.57E-02	2.13E+07
20.05.2011	12:00:01	2189.73	12.462	11100	5.54E-02	2.13E+07
20.05.2011	12:00:02	2189.73	12.462	11100	5.54E-02	2.13E+07
20.05.2011	12:00:03	2189.73	12.462	11100	5.54E-02	2.13E+07
20.05.2011	12:00:04	2189.73	12.462	11100	5.54E-02	2.13E+07
20.05.2011	12:00:05	2189.73	12.462	11100	5.54E-02	2.13E+07
20.05.2011	12:00:06	2189.77	12.462	11363	5.54E-02	2.12E+07
20.05.2011	12:00:07	2189.77	12.462	11363	5.54E-02	2.12E+07
20.05.2011	12:00:08	2189.77	12.462	11363	5.54E-02	2.12E+07
20.05.2011	12:00:09	2189.77	12.462	11363	5.54E-02	2.12E+07
20.05.2011	12:00:10	2189.77	12.462	11363	5.54E-02	2.12E+07
20.05.2011	12:00:11	2189.81	12.462	11367	5.53E-02	2.12E+07
20.05.2011	12:00:12	2189.81	12.462	11367	5.53E-02	2.12E+07
20.05.2011	12:00:13	2189.81	12.462	11367	5.53E-02	2.12E+07
20.05.2011	12:00:14	2189.81	12.462	11367	5.53E-02	2.12E+07
20.05.2011	12:00:15	2189.81	12.462	11367	5.53E-02	2.12E+07
20.05.2011	12:00:16	2189.85	12.462	10760	5.58E-02	2.12E+07
20.05.2011	12:00:17	2189.85	12.462	10760	5.58E-02	2.13E+07
20.05.2011	12:00:18	2189.85	12.462	10760	5.58E-02	2.13E+07
20.05.2011	12:00:19	2189.85	12.462	10760	5.58E-02	2.13E+07
20.05.2011	12:00:20	2189.85	12.462	10760	5.58E-02	2.13E+07
20.05.2011	12:00:21	2189.88	12.462	10823	5.57E-02	2.13E+07
20.05.2011	12:00:22	2189.88	12.462	10823	5.57E-02	2.13E+07
20.05.2011	12:00:23	2189.88	12.462	10823	5.57E-02	2.14E+07
20.05.2011	12:00:24	2189.88	12.462	10823	5.57E-02	2.14E+07
20.05.2011	12:00:25	2189.88	12.462	10823	5.57E-02	2.14E+07
20.05.2011	12:00:26	2189.92	12.462	10975	5.55E-02	2.14E+07
20.05.2011	12:00:27	2189.92	12.462	10975	5.55E-02	2.13E+07
20.05.2011	12:00:28	2189.92	12.462	10975	5.55E-02	2.13E+07
20.05.2011	12:00:29	2189.92	12.462	10975	5.55E-02	2.13E+07
20.05.2011	12:00:30	2189.92	12.462	10975	5.55E-02	2.13E+07
20.05.2011	12:00:31	2189.95	12.462	10797	5.56E-02	2.13E+07
20.05.2011	12:00:32	2189.95	12.462	10797	5.56E-02	2.13E+07
20.05.2011	12:00:33	2189.95	12.462	10797	5.56E-02	2.13E+07
20.05.2011	12:00:34	2189.95	12.462	10797	5.56E-02	2.13E+07
20.05.2011	12:00:35	2189.95	12.462	10797	5.56E-02	2.13E+07
20.05.2011	12:00:36	2189.99	12.462	10899	5.58E-02	2.13E+07
20.05.2011	12:00:37	2189.99	12.462	10899	5.58E-02	2.14E+07
20.05.2011	12:00:38	2189.99	12.462	10899	5.58E-02	2.14E+07

Appendix C: Mathematical Analysis Excel Sheet

Well configuration data at 11.0 hours:		
Data		**Comment**
Bit Depth	7590 ft	*Obtained from Figure 5.5*
Drill Pipe		
Length	6750 ft	*Calculated*
Outside Diameter	5.5 in.	*Given*
Innside Diameter	4.67 in.	*Found from API Drill Pipe Specifications*
Drill Collars		
Length	840 ft	*Estimated from BHA data listed in Appendix B*
Outside Diameter	8 in.	*Assumed*
Innside Diameter	2.8125 in.	*Found from API Drill Collar Specifications*
13 5/8" Casing Section		
Length	5810 ft	*Given*
Innside Diameter	12.375 in.	*Found from API Casing Specifications*
Open Hole Section		
Length	1780 ft	*Calculated*
Innside Diamter	12.25 in.	*Given*
Mud Data		
K	32.5	*Found from mud summary data listed in Appendix B*
n	0.33	*Found from mud summary data listed in Appendix B*
Mud Weight	14.7 ppg	*Given*
Flow Rate	900 gpm	*Obtained from Figure 5.6*
Model Friction Factors		
	Calibrated	Uncalibrated
Drillstring	1.34	1.00
Annulus	0.60	1.00



	Step 1. Calculation of Reynolds Numbers:	Step 2. Find Fanning Friction Factors Using Iteration	Step 3. Calculation of Frictional Pressure Loss	Calibrated	Uncalibrated
Inside Drill Pipe	$\bar{v} = \frac{q}{2.448d^2}$ = 16.9 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{25.8d}$ =	0.34 psi/ft	0.25 psi/ft
	$N_{Re} = \frac{89,100\rho\bar{v}^{2-n}}{K}\left[\frac{0.0416d}{3+1/n}\right]^n$ = 1451198 → Turbulent	f_calibrated = 0.00098 f_uncalibrated = 0.00073	Δp_{dp} =	2283 psi	1704 psi
				ΔSSP_{dp} =	579 psi
Inside Drill Collar	$\bar{v} = \frac{q}{2.448d^2}$ = 46.5 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{25.8d}$ =	3.18 psi/ft	2.37 psi/ft
	$N_{Re} = \frac{89,100\rho\bar{v}^{2-n}}{K}\left[\frac{0.0416d}{3+1/n}\right]^n$ = 6677317 → Turbulent	f_calibrated = 0.00073 f_uncalibrated = 0.00054	Δp_{dc} =	2668 psi	1991 psi
			=	ΔSSP_{dc} =	677 psi
Between Drill Collar and Open Hole	$\bar{v} = \frac{q}{2.448(d_2^2 - d_1^2)}$ = 4.3 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{21.1(d_2 - d_1)}$ =	0.05 psi/ft	0.08 psi/ft
	$N_{Re} = \frac{109,000\rho\bar{v}^{2-n}}{K}\left[\frac{0.0208(d_2 - d_1)}{2+1/n}\right]^n$ 146823 → Turbulent	f_calibrated = 0.00165 f_uncalibrated = 0.00275	$\Delta p_{dc,ann}$ =	41 psi	69 psi
			=	$\Delta SSP_{dc,ann}$ =	-28 psi
Between Drill Collar and Open Hole	$\bar{v} = \frac{q}{2.448(d_2^2 - d_1^2)}$ = 4.3 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{21.1(d_2 - d_1)}$ =	0.05 psi/ft	0.08 psi/ft
	$N_{Re} = \frac{109,000\rho\bar{v}^{2-n}}{K}\left[\frac{0.0208(d_2 - d_1)}{2+1/n}\right]^n$ 146823 → Turbulent	f_calibrated = 0.00165 f_uncalibrated = 0.00275	$\Delta p_{dc,ann}$ =	41 psi	69 psi
			=	$\Delta SSP_{dc,ann}$ =	-28 psi
Between Drill Pipe and Open Hole	$\bar{v} = \frac{q}{2.448(d_2^2 - d_1^2)}$ = 3.1 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{21.1(d_2 - d_1)}$ =	0.02 psi/ft	0.03 psi/ft
	$N_{Re} = \frac{109,000\rho\bar{v}^{2-n}}{K}\left[\frac{0.0208(d_2 - d_1)}{2+1/n}\right]^n$ 98432 → Turbulent	f_calibrated = 0.00183 f_uncalibrated = 0.00305	$\Delta p_{dp,oh}$ =	17 psi	28 psi
			=	$\Delta SSP_{dp,oh}$ =	-11 psi
Between Drill Pipe and 13 5/8" Casing	$\bar{v} = \frac{q}{2.448(d_2^2 - d_1^2)}$ = 3.0 ft/s	$\sqrt{\frac{1}{f}} - \frac{4.0}{n^{0.75}}\log(N_{Re}f^{1-n/2}) + \frac{0.395}{n^{1.2}} = 0$ 0	$\frac{dp_f}{dL} = \frac{f\rho\bar{v}^2}{21.1(d_2 - d_1)}$ =	0.02 psi/ft	0.03 psi/ft
	$N_{Re} = \frac{109,000\rho\bar{v}^{2-n}}{K}\left[\frac{0.0208(d_2 - d_1)}{2+1/n}\right]^n$ 94922 → Turbulent	f_calibrated = 0.00185 f_uncalibrated = 0.00308	$\Delta p_{dp,csg}$ =	97 psi	162 psi
			=	$\Delta SSP_{dp,csg}$ =	-65 psi

$$\Delta SSP = \Delta SSP_{dp} + \Delta SSP_{dc} + \Delta SSP_{dc,ann} + \Delta SSP_{dp,oh} + \Delta SSP_{dp,csg}$$ = 1152.5 psi = 79.5 bar

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