Master's degree thesis

LOG953 Logistics

Optimization Model For Drilling Fluid Circulation System: A Case Study From Edvard Grieg Field

Authors: Muarif Sana Dar and Mohamed Salaheldin Ibrahim

Number of pages including this page: 111

Molde, 23.05.2017

Molde University College
Specialized University in Logistics

Mandatory statement

Each student is responsible for complying with rules and regulations that relate to examinations and to academic work in general. The purpose of the mandatory statement is to make students aware of their responsibility and the consequences of cheating. Failure to complete the statement does not excuse students from their responsibility.

*Please complete the mandatory statement by placing a mark **in each box** for statements 1-6 below.*		
1.	**I/we hereby declare that my/our paper/assignment is my/our own work, and that I/we have not used other sources or received other help than mentioned in the paper/assignment.**	☒
2.	**I/we hereby declare that this paper** 1. Has not been used in any other exam at another department/university/university college 2. Is not referring to the work of others without acknowledgement 3. Is not referring to my/our previous work without acknowledgement 4. Has acknowledged all sources of literature in the text and in the list of references 5. Is not a copy, duplicate or transcript of other work	Mark each box: 1. ☒ 2. ☒ 3. ☒ 4. ☒ 5. ☒
3.	**I am/we are aware that any breach of the above will be considered as cheating, and may result in annulment of the examination and exclusion from all universities and university colleges in Norway for up to one year, according to the Act relating to Norwegian Universities and University Colleges, section 4-7 and 4-8 and Examination regulations** section 14 and 15.	☒
4.	**I am/we are aware that all papers/assignments may be checked for plagiarism by a software assisted plagiarism check**	☒
5.	**I am/we are aware that Molde University College will handle all cases of suspected cheating according to prevailing guidelines.**	☒
6.	**I/we are aware of the University College's rules and regulation for using sources**	☒

Publication agreement

ECTS credits: 30

Supervisor: Bjørnar Aas

Agreement on electronic publication of master thesis

Author(s) have copyright to the thesis, including the exclusive right to publish the document (The Copyright Act §2).

All theses fulfilling the requirements will be registered and published in Brage HiM, with the approval of the author(s).

Theses with a confidentiality agreement will not be published.

I/we hereby give Molde University College the right to, free of charge, make the thesis available for electronic publication: ☐**yes** ☒**no**

Is there an agreement of confidentiality? ☒**yes** ☐**no**

(A supplementary confidentiality agreement must be filled in)

- If yes: **Can the thesis be online published when the period of confidentiality is expired?** ☒**yes** ☐**no**

Date: 23.05.2017

Standard agreement

Høgskolen i Molde

STANDARD AGREEMENT

This agreement is between

Muarif Dar and Mohamed Ibrahim (Student(s)).

.... (Faculty Advisor at Molde University College),

LUNDIN - NORWAY. AS .... (Company/Institution).

And Molde University College/MSc Logistics Program Coordinator, concerning the use of specifications and results reported in the Master's degree thesis in accordance with the study plan for the Master's degree program in Logistics at Molde University College.

1. The student will complete the work assigned for the Master's degree thesis in cooperation with the company/institution
(Optional):...

The title of the thesis is: .. Optimization model for drilling fluid circulation system

2. The student has copyrights to the thesis. Those copies of the thesis submitted for evaluation along with descriptions and models, such as computer software that is included as part of or as an attachment to the thesis, belongs to Molde University College. The thesis and its attachments can be used by the College for teaching and research purposes without charge. The thesis and its attachments must not be used for other purposes.

3. The student has the right to publish the thesis, or parts of it, as an independent study or as part of a larger work, or in popularized form in any publication.

4. The company/institution has the right to receive a copy of the thesis with attachments, and the College's evaluation of it. The company/institution will have three (3) months from the time the thesis is submitted to the College for censoring to determine whether a patent is possible and to apply for a patent for all or part of the results in the thesis. The specifications and results in the thesis can be used by the company/institution in its own activities.

5. An additional confidentiality agreement may be entered into between the parties, if the company/institution sees this as necessary.

6. Each part of the agreement should have one copy of the agreement. The final signature should be from the Program Coordinator/Dean validating the agreement.

Place...Molde............ Date of final signature....13/1-2017........

Mohamed Ibrahim
Student(s) Muarif Dar

Faculty Advisor

Company/Institution

Program Coordinator / Dean

Supplementary confidential agreement

Høgskolen i Molde

SUPPLEMENTARY AGREEMENT/CONFIDENTIALITY AGREEMENT

(Supplement to Point 5 of the Standard Agreement)

This agreement is between

Muarif Dar and Mohamed Ibrahim (Student(s))

.... (Faculty Advisor at Molde University College),

Lundin Norway AS .... (Company/Institution),

and Molde University College/MSc logistics Program Coordinator. This is a supplement to the Standard Agreement, which defines the use of specifications and results reported in a Master's degree thesis in accordance with the study plan for the Master's degree program in Logistics at Molde University College.

1. As stated in Point 5 of the Standard Agreement the parties named above agree to limit access to the Master's degree thesis for 2 Year(s) from the date of this agreement. The limit should be 1 to 5 years, for longer confidentiality periods, contact the program coordinator for a special agreement.
2. The reason for keeping the thesis results confidential is so that the company/institution can avoid giving away information that would give others a competitive advantage.
3. The thesis must be submitted to Molde University College. It will be kept in a secure room in the main archive at the College during the period agreed upon. The thesis can be borrowed during this period if a written request is submitted and the company/institution gives permission. Academic staff members can access the thesis after signing a declaration of secrecy. After the period of confidentiality is ended the thesis will be placed in the library for general use.
4. Four copies of this agreement must be signed so that each party will have a copy. The agreement is valid when it has been approved and signed by the program coordinator or Dean at Molde University College.
5. The confidentiality agreement does not exclude members of the academic staff from being present at the final oral presentation of the thesis.

Place Molde .... Date of last signature 13/1-2017

Muarif Dar / Mohamed Ibrahim
Student(s)

Faculty Advisor

Company/Institution

Agreement approved by:

Program Coordinator/Dean

Preface

In the name of God, the Most Beneficent, the Most Merciful.

﴿And Allah will raise up in ranks those who believed among you and those who have been given knowledge, Allah is aware of what you do﴾ Surat Al-Mujadila (Ch.58-11)

First of all, praise be to almighty Allah for His welfare, kindness and great mercy. We are pleased to seize this opportunity to express our gratitude to everyone who supported us throughout this master thesis project.

This thesis is the mandatory final part of Master of Science in Logistics **(Petroleum Logistics)** at Molde University College and represents an independent and extensive research work, which was carried out from December 2016 to June 2017 under the guidance of our supervisor Bjørnar Aas.

We would like to express our acknowledgment to Molde University College for giving us this opportunity to do this research work and providing all materials and facilities. To our advisor Dr. Bjørnar Aas, we would like to thank you for his support and inspiring guidance throughout the research. Many thanks to Lundin Norway for giving us the opportunity to write this thesis, special thanks to the head of drilling and production department Bård Fjellså.

We would also like to express our deepest gratitude to Eng. Trym Elseth, Eng. Bengt Sola and Ph.D. student Yury Redutskiy for their truthful and illuminating advice. During their supervision, we got inspiration and learned academic and professional knowledge.

We would also like thank to our family for what they are doing for us, a lot of things would have been impossible without their support and encouragement. And we would like to thank our teachers for making everything understandable and classmates for making this studying period a memorable.

Executive summary

The significant fall in oil and gas prices has led most oil and gas operating companies to cut investments in exploration and production (E&P) and fund research and development (R&D) to improve cost structure. Although drilling fluids count a small fraction of total drilling cost, it contributes to a significant reduction in total drilling cost.

Maintaining drilling fluids is crucial to the success of drilling operations. When drilling fluid carry drill cuttings, the solid content raises. Solid control equipment, a mechanical processing facility, separates solids and maintain the properties of drilling fluid. If solid equipment does not succeed to keep the solid content less than the maximum allowable volume, diluting an extra volume of drilling fluid is a must to avoid many costly drilling problems. One of the main problems with dilution, especially for lengthy sections is storage space. Storage Space is a luxury offshore and must be managed carefully. In addition, building excess fluids will cause extra logistic and material costs.

This thesis aims to answer the question **how much will increase the efficiency of the solid control system is going to influence total drilling fluid cost?** By influence, we mean the capacity of the centrifuge to have an effect on total drilling fluid cost. To approach the research question we used data from four wells at the Edvard Grieg Field, two were drilled by using the centrifuge and two before installing the centrifuge.

Several methods were applied to answer the research question. Firstly, an event tree analysis was conducted to understand the role of the centrifuge in reducing dilution volume and thereby, total drilling fluid cost. Secondly, a qualitative research was conducted to demonstrate both drilling fluids and logistics activities. Finally, Algebraic Mathematical Modeling Programing Language (AMPL) was used to optimize the drilling fluid circulation system in the Edvard Grieg field.

The objective function of this study is to minimize the total system cost. The system cost analysis equation proposed by Warren and Baltoiu, (2001) was used as starting point to identify the drilling fluid system components. In order to precisely measure the cost of offshore logistics, it was necessary to include logistics cost. In addition, the trouble time

cost and ROP impact were excluded as calculating these two elements require advance technical details.

Two computational experiments for the 17 ½ inch section were conducted, with two different solid build-up rates of 155 and 1055 liters per minute. The findings represent the optimal operating parameters of the drilling circulation system in order to minimize total cost. The results show that using the centrifuge is a must when the solid build up rate exceeds 1000 liters. The use of the centrifuge, in this case, is going to reduce about 1000 liters of drilling fluid.

Contents

List of figures

List of tables

List of abbreviations

AMPL - Algebraic Mathematical Modeling Programing Language

CSCMP – Council of Supply Chain Management Professionals

DDR – Daily Drilling Report

DMR – Daily Mud Report

EOW – End of Waste

ETA – Event Tree Analysis

IRIS – International Research Institute of Stavanger

NCS – Norwegian Continental Shelf

OMV – Osterreichische Mineralölverwaltung

SCA – System Cost Analysis

SCM – Supply Chain Management

SCS – Solid Control System

ROP – Rate of Penetration

1.0 Introduction

The history of the petroleum industry in Norway is rather short. In 1969, Ekofisk was the first significant discovery in the North Sea. Since then, oil and gas have been the most significant industry in Norway and plays a vital role in the economy of the country. There are more than 50 oil and gas companies involved in the exploration, production and infrastructure development at the Norwegian Continental Shelf (NCS). The Barents Sea, the Norwegian Sea, and the North Sea are the main oil and gas production areas of Norwegian Continental Shelf (NCS). The Barents is the less explored area, it considered to have wide oil and gas reserves and companies are operating in the area and exploring more reserves (Facts, 2017). As all operating activities are offshore. Offshore exploration and production is more expensive than onshore and requires more efficient and effective logistics system (Aas, et al., 2008a).

The Norwegian petroleum industry plays a vital role in financing the Norwegian welfare and economy. Figure 1-1 shows the contribution of the petroleum industry in Norwegian economy in 2016. This percentage is around 40% less than in 2015 because of the lower oil and gas prices (Norwegianpetroleum.no).

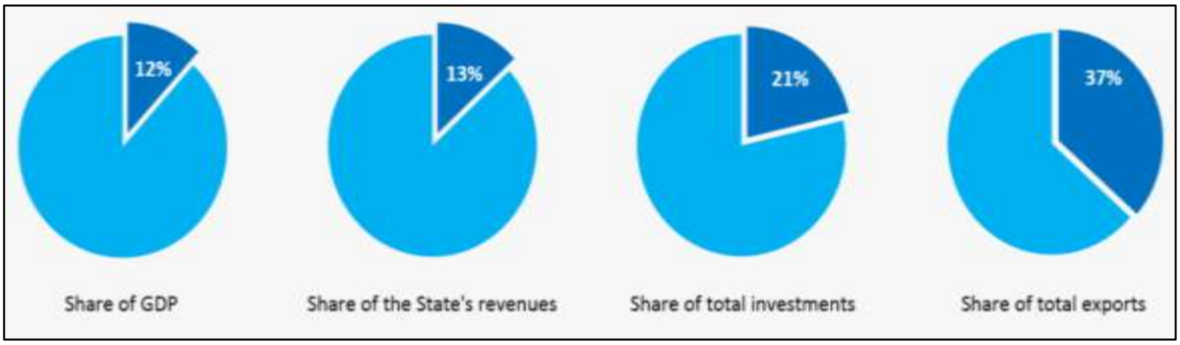


Figure 1-1 Macro-economic indicators for the petroleum sector, 2016. Source: Norwegian Petroleum, 2016 (Norwegianpetroleum.no) refers to statistics Norway, Ministry of Finance

The fall of oil prices affected the Norwegian economy as well as economies of many other countries around the world in several aspects. This price decline is harmful to the Norwegian and other oil and gas exporting economies as it results in lower revenues and higher unemployment rate. On the other hand, it positively effects importing countries and some industries where it led to lower operating costs.

1.1 Offshore cost structure

As a rule of thumb, drilling offshore wells is more costly than drilling onshore. Efficient and cost effective offshore logistic planning contributes a lot in reducing total offshore operation cost (Aas, et al., 2008a).

Between 2000 and 2010, the average cost of an offshore well has increased with about 200% to 250%. It includes higher rig rates (100%-150%), higher well and completion costs (25%-50%) and process inefficiencies (50%-75%) (Brun, et al., 2015). This has motivated many researchers to work in reducing total drilling operating costs. In this paper (Brun, et al., 2015) refers to an operator in the Gulf of Mexico achieved a 19% reduction in average offshore well cost by improving procurement and supply chain management.

During the recent crisis in the oil and gas industry in 2014, crude oil prices suddenly fell to more than half, forcing many oil and gas companies to cut down their investments. Effective logistics is predicted to contribute to reducing drilling cost. In average, drilling and completion account for 40% to 50% of the total offshore capital expenditures, however, drilling and completion cost about 65% of the total onshore well cost (Brun, et al., 2015). Figure 1-2 illustrates the average cost structure for offshore installation. Rig hire, services, and logistics are the major contributors to drilling cost structure (Osmundsen, et al., 2010).

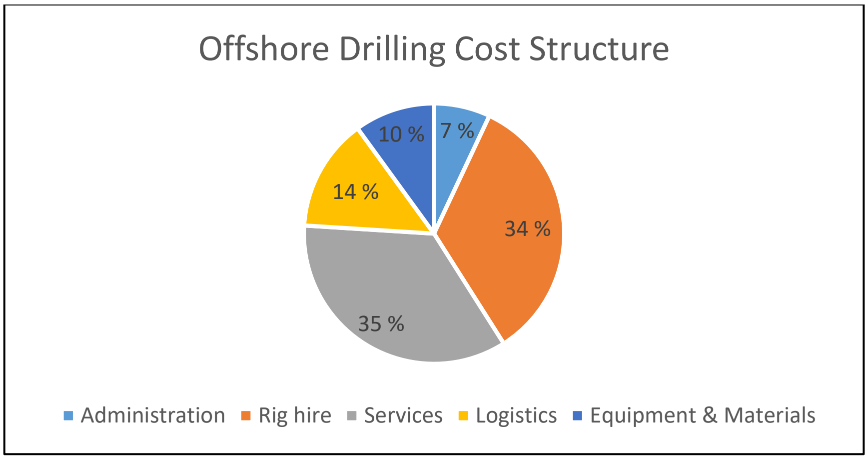


Figure 1-2 Composition of offshore drilling cost structure

1.2 Drilling fluids

Drilling fluid accounts a small fraction of total system cost. Although drilling fluid represents an as small portion of the total well cost, the right selection of drilling fluid and properties can still contribute to minimizing the total well cost by reducing drilling problems (Caenn, et al., 2011).

There are basically three types of drilling fluids; water based mud, oil based mud and synthetic based mud (Bloys, et al., 1994). The cost of drilling fluid depends on many factors including the drilling fluid design and the price of the base fluid. The price of base fluids such as diesel and water and the accessibility to them varies across geographical location around the world.

One of the main functions of drilling fluids is to carry drill cutting during drilling to the surface. To control the solid content of the fluids, a solid control system (SCS) is used. This system is a set of mechanical separators, separates the solids from the fluid and allows us to reuse the drilling fluid (Caenn & Chillingar, 1995). The main component of the solid control system is the shale shaker. In addition to shale shakers, the system can be upgraded by adding a centrifuge. The centrifuge is used to separate the fine solids, something which extends the working life of drilling fluid and reduce the probability of solids related problems.

1.3 Offshore upstream logistics

Logistics is a process of planning, implementing and controlling all the processes involved in logistical activities (Choi, et al., 2016). Several actors are involved in the logistics system including logistics planners, supply bases and supply vessels (Wiig, 2001).

A typical drilling supply chain include different transportation modes and inventory systems, as illustrated in Figure 1-3. All contributors shown in the below figure are dependent on each other; improving a part of this supply chain will usually impact other parts and could reduce the total system cost unless the improvement is not suboptimal (Engh, 2015).

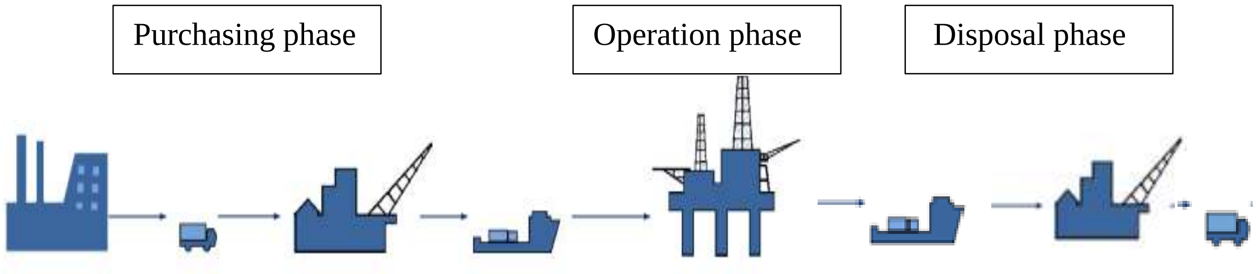


Figure 1-3 Supply chain of drilling fluids

The Barents Sea, the Norwegian Sea, and the North Sea are the main oil and gas production areas of the Norwegian Continental Shelf (NCS), with 78 oil and gas fields (Facts, 2017). These offshore fields are served from several supply bases as illustrated in Figure 1-4. The high activities on the supply base makes supply and services the second largest industry in Norway with more than 1100 companies involved (Facts, 2017). The Barents Sea area is served by Kirkenesbase, Vardø, Norbase and Polarbase supply bases. The Norwegian Sea is served by Norbase, Helgelandsbase and Vestbase supply bases. Finally, the North Sea is served by Tananger, NorSea Dusavik, Stordbase and Fjord Base (Norskolje museum, u.d.).

Figure 1-4 Supply bases in Norway. Source (offshore Norway)

The Main activities at these supply bases include logistics planning, storing of spare parts and in and outgoing cargo and loading and unloading activities. When a vessel arrives at a supply base, loading and unloading start immediately. Loading and unloading time is defined as the time between arrival and departure of a vessel (Aneichyk, 2009). Loading and unloading process is a time-consuming process. The process of loading and unloading offshore is usually more time consuming than onshore, the reason is that one vessel serves several installations in one trip. However, the time of the loading and unloading depends on a number of factors including the capability of the vessel and installation. (Aas, et al., 2009).

The schedule of the supply vessels is mainly done on weekly basis (Maisiuk & Gribkovskaia, 2014). The daily rent of supply vessels is the main cost element in the offshore logistics. A good vessel management should aim to reach a high utilization factor and minimum loading and unloading times. The important of quick and efficient loading and unloading process increases as the trip includes more installation. (Drift & Weeke, 2015).

1.4 Lundin petroleum

Lundin Petroleum is an independent Swedish company, working in oil and gas exploration and production industry with a prime focus on operations in Norway. In addition to Norway, Lundin operates internationally in Russia, Malaysia, France, and Netherlands. Lundin Norway AS was established in 2004 and predominantly managed by Norwegians to carry out oil and gas operating activities in the Norwegian Continental Shelf (NCS). The head quarter of Lundin Norway AS is located in Lysaker, Oslo while the Northern Norway office is in Harstad. There are approximately 300 full-time employees working in Lundin Norway. (Lundin, 2017). Lundin Norway AS is operating in the following areas of the Norwegian Continental Shelf (NSC):

- **Barents Sea:** In 2013/2014 significant oil discoveries were announced in this area. This area is the less explored on the NCS and yet expected to hold vast quantities of oil and gas resources.
- **Central North Sea:** Most of the company`s production is from this area consisting of the fields such as Edvard Grieg, Luno South and Luno II in this area. Furthermore, Lundin holds the owner interests of other fields, Alvheim, Volund, and Bøyla.
- **Northern North Sea:** Lundin Norway AS is the owner for four licenses in this area. In addition, the company holds owner interest in four other licenses.
- **Norwegian Sea:** Lundin Norway is the operator of two exploration licenses in this area and license partner in the five additional licenses.
- **Southern North Sea:** Lundin Norway is operating several exploration and production licenses in this area.

The focus of the company is to explore the hydrocarbons in the three core areas of Norwegian Continental Shelf, the North Sea, the Norwegian Sea and the Barents Sea and prioritize the exploration in areas with shallow depths less than 500 meters.

1.4.1 Edvard Grieg field

Lundin Norway has drilled more than 80 exploration and appraisal wells during the last decade including the Edvard Grieg field, see Figure 1-5 (Lundin, 2017)

Figure 1-5 Edvard Grieg field. Source: Norwegian Petroleum Directorate

Edvard Grieg is a giant oil field, discovered in 2007 by Lundin Norway AS. The field is located in block 16/1 of the North Sea area. The owners of the field`s license are Lundin Norway AS 50%, OMV Norge 20%, Wintershall 15% and Statoil 15%. The field includes 11 production wells and 4 water injection wells. (Lundin, 2017)

1.5 Research structure

Chapter 2.0 of this study pursues the research problem and research methodology. The main purpose of this chapter is to describe the research problem, the research tasks and the objective of the study.

The methodology of this study is described in chapter 3.0. This chapter also includes the techniques of data collection and research study progress.

Chapter 4.0 is devoted to the literature review. This chapter includes several theories; supply chain management, system cost analysis, mathematical modeling and event tree analysis.

Chapter 5.0 of this study include a qualitative study about drilling rig components, drilling fluid circulating system, solid control equipment, drilling fluid types and functions. It also includes information, data, and pictures from our case study: Edvard Grieg Field, Norway. Lundin petroleum, the operator of Edvard Grieg is the provider of all the information related to the Edvard Grieg field.

Chapter 6.0 of this study include a qualitative study about offshore upstream logistics activities. It discusses logistics management, transportation, loading unloading and drill cutting disposal activities. It also includes information, data, and pictures from our case study: Edvard Grieg Field, Lundin Norway AS. The collected information allowed us to identify the cost elements of transporting drilling fluids and describe the loading and unloading activities in Edvard Grieg.

Chapter 7.0 and 8.0 of this study are the preliminary and empirical analysis, these chapters are carried out to answer the main research question of this study. These chapters include an illustrative case-study, Event tree analysis, data screening and the empirical experiments.

Finally, chapter 9.0 concludes the research, the first part of this chapter summarizes our findings. The second part is dedicated to the limitations and recommendations for further studies.

2.0 Research problem and research methodology

A four steps method is applied to write a problem definition. The first step is a brief background about the problem. Next, a scope of the relevance where we identified the different factors addressed by the study. Then, a problem statement and finally, the objective of conducting this study.

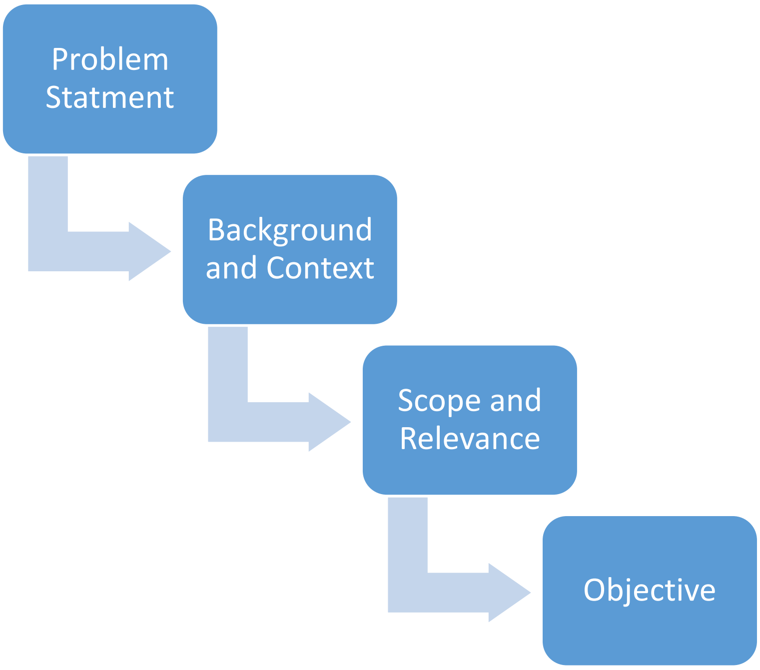


Figure 2-1 Research problem

In order to avoid drilling problems, the right selection of drilling fluid and its properties is a key factor. Due to a limited space at offshore installation, drilling fluids are stored at the supply base and transported from the base to installation while needed. Drilling fluids can be reused by using the solid control system to separate solids. The solid control system can be **upgraded** by adding a centrifuge to improve the capacity of separating solids and reduce the total system cost.

In this study, we will focus on the advantages of upgrading the solid control system by extending the use of centrifuges and explore how it can contribute to reducing the total system cost. We have been provided data of four drilling wells from Lundin Norway. Two of them were drilled with an upgraded solid control system and the other two wells drilled with a system consists of shale-shakers only. This will provide the data basis for our analysis.

2.1 Problem statement

How is this upgrade in the solid control system going to influence total drilling fluid cost? The Centrifuge is a mechanical separation device use to separate fine solids from drilling fluids. Reducing the solid content produces high-quality drilling fluid with good physical and chemical properties. Changes in these properties can be harmful as it can cause well stability related problems such as a stuck pipe. The centrifuge has been used recently in the Edvard Grieg field to process high solid build up rates caused by the caving problem. Caving problem is a partial collapse of the well-hole walls and it generates a high volume of solids. In addition to solving this problem, the centrifuge is expected to contribute in eliminating high solids build up related problems and reduce the total drilling system cost by reducing both purchasing and logistic costs.

However, there are several limitations to using the centrifuge such as limited fluid processing capacity, high operation cost and ability to operate in clay formation. Centrifuges have limited processing capacity of about 25% of total active drilling fluid system, the practical parameters in the Edvard Grieg show that the centrifuge can process up to 400 liters per minute which account for less than 8% of total active drilling fluid system. The cost of installing and operating the centrifuge at the Edvard Grieg is about NOK 8 million, this high cost and the limited processing efficiency in clay formation are also among the limitations. (Bouse, 2005)

2.2 Background and context

The volume of drilling fluid consumption contributes significantly to the total well cost. Optimizing the consumption of fluids will minimize fluid purchasing cost, generated drill cuttings from a solid control system, disposal and waste volume and the associated logistics activities.

In the last few years, the environment awareness increases as the total volume of hazardous waste generated on the Norwegian continental shelf jumped to 465 000 tons. Wastes from Drilling accounts for more than 80% of total waste, “this is largely due to the difficulties the industry has experienced in injecting drill cuttings into the underground on several fields on the Norwegian continental shelf". (EnvironmentalNorwegianAgency, 2017)

"In fact, the research design is the conceptual structure within which research is conducted; it constitutes the blueprint for the collection, measurement, and analysis of data." (Kothari, 2004, p. 31). In this research, different tasks are conducted to reach the concluding part. The first task aims to identify all logistic activities associated with drilling fluids in the Edvard Grieg Field. In this task, a qualitative discussion of the logistics activities and the cost elements of planning, transporting and loading unloading of drilling fluids in Edvard Grieg was determined. The second task aims to introduce the upgrade of the solid control system in Edvard Grieg field. In this part, a qualitative study about "drilling fluid circulating system" was conducted. It includes the components of the drilling fluid circulating system, the solid control systems, types and functions of drilling fluids. Finally, how much of drilling fluid consumption can be reduced by using the centrifuge? The third task is to build a mathematical optimization model, coded by Algebraic Mathematical Programing Language (AMPL) to predict the performance of the drilling fluid circulating system in different solid build up rates. This task aims to calculate the total drilling fluid system cost.

2.3 Scope and relevance

The study focuses on comparing drilling fluid consumption while drilling with and without using a centrifuge in the Edvard Grieg field, Norway. The study also describes different types of drilling fluids and functions in drilling operations. Furthermore, it includes all logistic activities associated with transporting the drilling fluid. Although this study focuses on the Edvard Grieg offshore oil field, this study including the optimization model is considered valid in other geographical locations both on and offshore. Drilling operations and are quite similar in and offshore, however, logistics activities are slightly different, as the onshore transportation mode is a vessel and the onshore transportation mode is truck or train.

There are several motivators to write this master thesis and answer the main research question "how upgrading the solid control system can reduce the total system cost and reduce logistical challenges. The significant fall in oil and gas prices in the second half of 2014 has led many oil and gas operators to decommission most of their rigs and cut the investment in exploration and production. Drilling fluid is a key cost element in drilling operations, this study proposes a quantitative tool to contribute to better understand the role of a centrifuge in reducing total drilling system cost. The increasing environmental awareness of hazardous drill cutting waste generated in drilling fluid is another motivators, as this study aims to reduce total discharge volume of drilling fluid.

2.4 Objective

The data used in this research study, obtained from a single company for a specific area of study. Most parts of the data used in this study were derived by analyzing and interpreting the information collected during the meetings and interviews.

The main objective of this study is to build a quantitative tool that allows us to simulate and optimize the drilling fluid system. This tool considers all the system elements; 1) solids generated while drilling, 2) solid control equipment shale shakers and centrifuge, 3) drilling fluid dilution volume and 4) drill cutting waste volume.

3.0 Methodology

There are four primary objectives of conducting a research; exploration, explanation, description and prediction. In this study, both qualitative and quantitative methods are used for description and prediction. (Ellram, 1996)

This chapter describes the process and participants of this study. It illustrates the method of case selection and data collection. In addition, it describes the progress of selecting a topic, writing the thesis and building a mathematical model. Finally, a brief discussion on the research trustworthiness and limitations is conducted.

3.1 Case selection and data collection

It was important to select an offshore oil and gas operator where all necessary information and data of logistics, drilling operation, and disposal management was available for analysis purposes.

Logistic data includes the storage of drilling fluids both on the supply base and the platform, loading and unloading operations data both from the supply base and the platform and finally, transportation of drilling fluids from the supply base to the platform and backward.

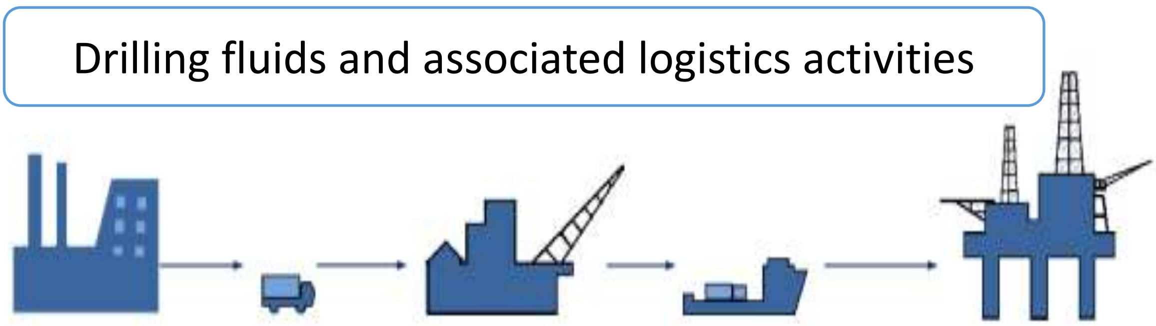


Figure 3-1 Supply chain of drilling fluids

Drilling operation data include information about the solid control system components and drilling fluid related problems. Finally, drilling disposal data was needed. Lundin Norway AS provided us with all the necessary data. Data of four drilling wells from Edvard Grieg field were provided to conduct the study. The wells studied are 16/A-1, 16/A-6, 16/A-10 and 16/A-

12. The following section will provide information about Lundin Norway AS and the process of data collection.

3.1.1 Data collection

The task of data collection began after defining and designing the research problem. To conduct the tasks of this study both qualitative and quantitative data collection technique are conducted. "*The three primary qualitative techniques that may be used as a part of the case study method are direct observation, recordings and interviews*" (Ellram, 1996, p. 100), According to Ellram (1996), these techniques are described for qualitative data collection, it can also be applied to collect quantitative data.

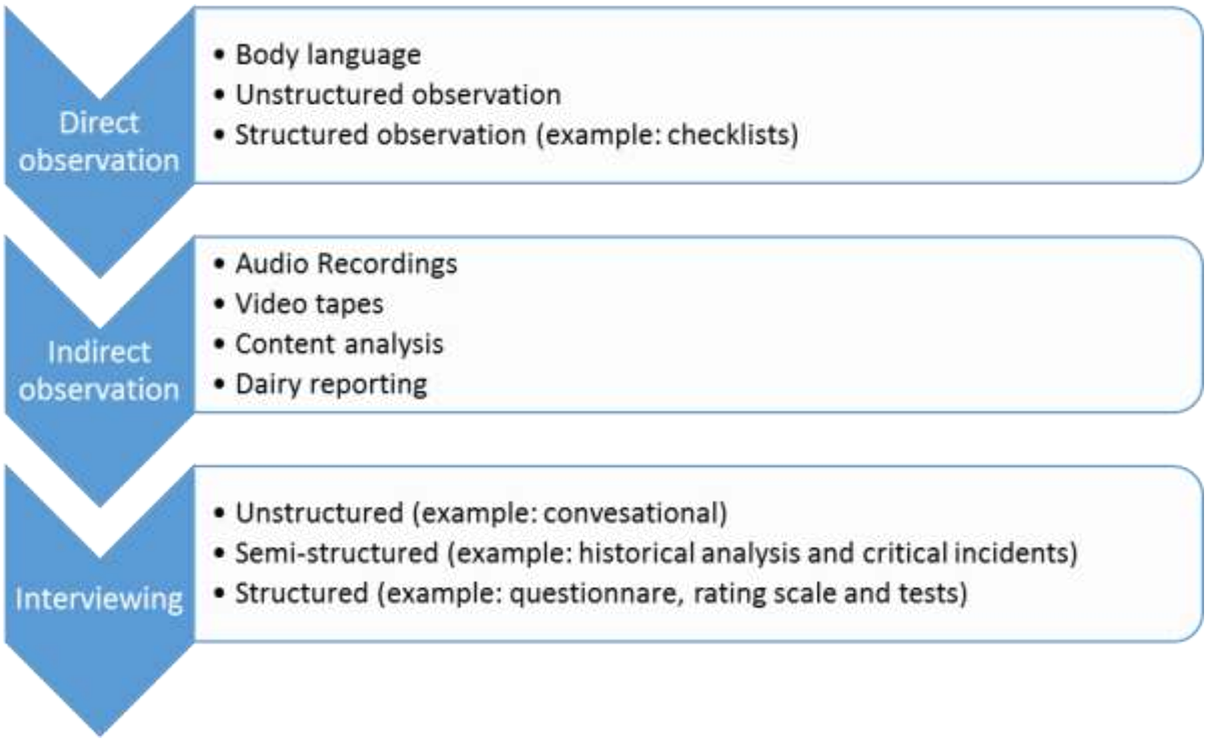


Figure 3-2 Data collection techniques

Primary data are the data collected for the first time in interviews, questionnaires or observation methods while secondary data are the data which have already been collected and analyzed. Secondary data can be found in states and government publications, magazines, books and scientific reports and articles. (Kothari, 2004)

Interviewing have been used several times to collect data, furthermore, several techniques have been applied to collect primary data including content analysis, conversational interviews, historical analysis interviews and questionnaire interviews. Four meetings and interviews with drilling engineers, drilling fluid specialists and logistics coordinators were conducted during the study period. The collected data include daily drilling reports, daily drilling fluids reports, environmental reports, and all necessary logistic data.

Primary data collected

The below Table 3-1 illustrates the interviews conducted to collect primary data, see Appendix 1 for more details about interviews.

Date	Employees	Topic	Technique
16 February 2017	Drilling engineer and mud engineer	Analyzing the drilling reports	Indirect observation
23 February 2017	Logistics Coordinator and mud engineer	Solid control system and common drilling problems	Semi-structured interview
9 March 2017	Drilling engineer, logistics coordinator, and mud engineer	Supply chain, storing and transportation of drilling fluids	Unstructured interview
20 April 2017	Drilling engineer, logistics coordinator, and mud engineer	Presentation of results	Conversational interview

Table 3-1 List of interviews

Secondary data collected

The collected secondary data include:

- Daily drilling report (DDR) is a daily basis report shows drilling activities and results of the past 24 hours of drilling operations.

- Daily drilling fluids (Mud) report (DMR) is a daily basis report shows drilling fluid parameters, consumption and discharge volumes of drilling operations.
- Environmental report (EOW) is a daily basis report shows drilling fluid parameters, consumption and discharge volumes of drilling operations.

3.2 Research study progress

A combination of a qualitative and quantitative approach was used to conclude this study. This part of the methodology is a roadmap plan for the case selection, data collection, and analysis. Table 3-2 describes the summary of study progress.

Period	Task
August 2016	Topic selection
July - October 2016	Preliminary analysis
November – December	Case selection
January	Data collection
February	Technical background: drilling fluids and associated logistics activities.
March	Build an optimization model for drilling fluid circulating system.
April	Analysis presentation to Lundin AS
May	Review and Modification

Table 3-2 Study progress

- August 2016: “Topic selection phase”

During the two years of our master studies in Molde specialized university of logistics, several excursions have been conducted. The excursions mostly targeted supply bases and logistics departments in oil and gas companies. It includes visits to Vest base supply base in Kristiansund, Nyhamna gas field in Aukra, Statoil logistics department in Kristiansund, Bergen and Stavanger and finally, the International Research Institute of Stavanger (IRIS).
During our visit to the International Research Institute of Stavanger (IRIS), latest developments and most recent improvements of drilling operations in the Norwegian Continental Shelf (NCS) were discussed. This visit allowed us to learn about rig components, drilling fluids and the recent use of centrifuges in the Norwegian Continental Shelf (NCS). In

addition, it motivated us to search for possible improvements and research studies in this field of study.

- July - October 2016: Preliminary analysis

For a period of three months, a wide online search about drilling fluids was conducted, several drilling and drilling fluid professionals were interviewed. Furthermore, two proposed topic were discussed with several potential supervisors. Two of the most common questions we have received at that point are, how is this relevant to logistics? Are you considering a qualitative or quantitative approach?

A preliminary analysis was conducted to measure the influence of drilling fluid consumption on logistics activities in Saudi Arabia. The Results were discussed with our supervisor and several specialized engineers. It was then necessary to contact companies to understand more about real life situations and discuss applicability.

- November – December 2016 : Case selection

It was necessary to select a horizontally integrated company, where both logistic and drilling fluid operation data is available. Several oil and gas companies in the Middle East, Sudan and Norway were contacted. At the end, Lundin Norway was selected. The recent upgrade of the drilling fluid circulating system in Lundin by adding a centrifuge to their solid control system was a key advantage for selecting Lundin Norway AS.

In December 2016, a meeting was held at Lysaker with drilling and production department, Lundin Norway AS. An introductory presentation included a personal background, problem definition, objectives and a preliminary analysis was presented at this meeting. In this meeting Lundin agreed to work with us on this case and provide us with all necessary data. In addition, a confidential agreement and contracts were signed.

- January 2017: Data collection

Lundin AS provided us data of four drilling wells from Edvard Grieg field. Data includes daily drilling reports, drilling fluid data and drill cuttings environmental reports. In addition, logistics data and drilling system costs were provided.

In January, data screening analysis was conducted to understand offshore drilling operations, the use of drilling fluid and total drilling system cost in Edvard Grieg.

- February 2017: Technical background

For better understanding, different books, articles, magazines and websites were visited. In several interviews with Lundin AS were conducted. In these meeting drilling engineers, drilling fluid coordinators and logistics coordinators were interviewed. Each of the meetings lasted for around two hours, a PowerPoint presentation was made by us followed by a discussion.

In the first meeting, we discussed upgrading the solid control system and the most common drilling problems related to it in Edvard Grieg field. Furthermore, a detailed information about the contribution of the centrifuge in reducing solid contents and total drilling fluid consumption.

In the second meeting, we interviewed the logistics coordinator on logistics activities in Edvard Grieg and the cost elements of transporting drilling fluids. Furthermore, we asked him whether the upgrade of solid control system influences any of logistics activities.

- March 2017: Optimization model

Lundin has approved to build a mathematical model to optimize the operating parameters of their solid control system in Edvard Grieg field. We have built this model under supervision of Yury Redutskiy, Ph.D. student at Molde University College. A meeting with Lundin was held in March 2017 to present a draft model and collect necessary data.

- April 2017:

Presented findings to Lundin AS for discussion and suggestions. Meanwhile, a draft of the thesis was sent to the supervisor to review and suggest modifications.

- May 2017: Final review

Sent out findings to our supervisor for comments and continue on carrying out the conclusion part.

3.3 Evaluating the quality of the research methodology

To conduct any qualitative, research a quality of research methodology has a great importance, the research method has both advantages and disadvantages. The methodology for any qualitative or quantitative cannot be right or wrong, but it may be less or more useful. (Silverman, 2006; Silverman, 2001)

3.3.1 Research trustworthiness

It is very important for a researcher to generate a confidence about the research findings. There are four basic elements of trustworthiness to examine the quality of the research, these elements are credibility, transferability, dependability and conformability. (Guba, 1981; Shenton, 2004).

4.0 Theory

This chapter describes concepts and theoretical approaches which have been used to complete this research.

4.1 Supply Chain Management (SCM)

In the recent decade, supply chain management has been an effective tool to minimize the order time, cost of supply chain and increase quality of customer services (Saad, et al., 2014).
The Council of Supply Chain Management Professionals (CSCMP) defines supply chain management as "*The planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities. Importantly, it also includes coordination and collaboration with channel partners, which can be suppliers, intermediaries, third party service providers, and customers. In essence, supply chain management integrates supply and demand management within and across companies".* (CSCMP, 2017)

4.2 Supply chain in petroleum industry

The supply chain of petroleum industry, is divided into two supply chains; upstream and downstream. Upstream supply chain process includes exploration, production and transportation of crude oil from remote installation to onshore refineries. On the other hand, downstream supply chain includes the distribution of petroleum products to the final customers. (Hussain, et al., 2006)

In petroleum industry, the trend of offshore drilling operations makes the supply chain more challenging and complex. A continuous supply of material is a key element to continue operations (Aas & Wallace, 2008b). In order to describe supply chain in the petroleum industry, it is essential to identify all the actors involved in this supply chain. The actors involved in the upstream supply chain are manufacturers (origin), intermediates (supply bases) and offshore installations (customers).

4.3 System Cost Analysis (SCA)

"System cost analysis is a methodology used to quantify the actual cost of the drilling fluids". (Warren & Baltoiu, 2001)

4.3.1 Drilling fluid system cost analysis

"The system cost analysis is a measuring stick on how well an operator and service company perform." (Warren & Baltoiu, 2001). In order to explain and predict the performance improvement, it is necessary to identify all system elements.

To apply the system cost analysis on a drilling fluid system, it is necessary to generate an equation where all the related cost elements are included.

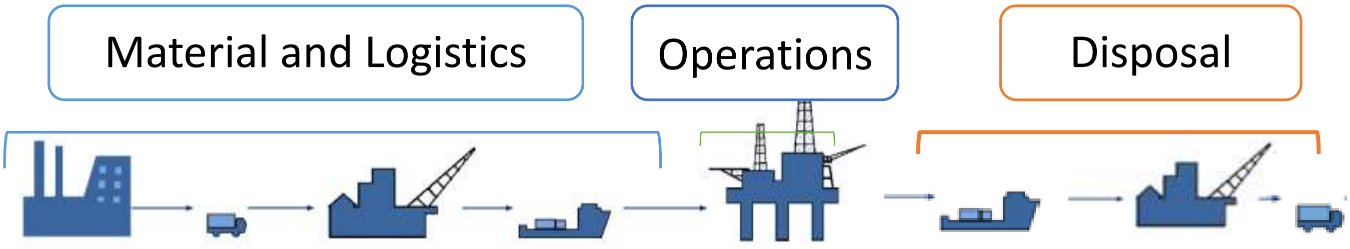


Figure 4-1 Supply chain of drilling fluids

The first step is to identify all elements of the system. Warren and Baltoiu (2001) proposed a simple and expanded version of a system cost analysis for drilling fluids.

$$\text{System cost} = \text{Material Costs} + \text{unproductive time} \tag{1}$$

Material cost is the cost of purchasing drilling fluid materials. The cost of the material varies depending on the type of drilling fluid, for instance, oil based drilling fluid is more costly than water and synthetic based fluids. This cost also includes trucking and other associated logistics services.

Unproductive time is the time consumed to solve drilling problems related to drilling fluid. This depends on the governed rig cost which usually determined on an hourly basis. The expanded form of equation (1), include three additional elements as they are also impacted by drilling fluid. These elements are Rate of Penetration (ROP), volume of solid waste and finally the production of hydrocarbons, given in equation (2).

$$\text{System Cost} = \text{Material Cost} + (\text{Trouble time} * \text{Rig cost/h}) + \text{ROP impact} + \text{Solid Control/disposal} + \text{Production} \tag{2}$$

This equation is used as a starting point to conduct the analysis part of this study. However, several changes have been made to apply it on our case study. Logistics cost is one of the cost element we added to the equation. Vessels is the offshore transportation mode, the higher cost of vessel transportation comparing to trucks is the main reason for adding this element.

This system can give good results for any drilling project, but to get the best results, there are some conditions set to implement this system. Warren and Batoiu, (2001) described two conditions; Well which is included in the study should not be older than the two years because improvements in the technology and should be with the same deviated design and possibly drill through the same formation/lithology. Both conditions are satisfied in our case study. All the wells in our case study have the same design and were drilled between 2014 and 2016.

4.4 Mathematical modelling

Mathematical modeling is a mathematical representation of large-scale optimization problems in order to find the behavior of system. Mathematical modelling can be used to developing scientific understanding, test the effect of changes in a system and predict the result of decision making. (Lawson & Marion, 2008)

4.4.1 Algebraic Mathematical Programming Language (AMPL)

Algebraic Mathematical Programing Language (AMPL) is a tool designed specifically for mathematical programming. The AMPL supports building, testing and analyzing optimization models. To solve any problem, a number of steps are to be followed;

I. Formulate a model, to represent the general form of the problem, a set of variables, objectives and constraints are required to represent the general form of the problem.
II. Specify the objective function and constraints.
III. Collect the data.
IV. Solve the problem, the solver will apply an algorithm to find the optimal solution of the problem.
V. Analyze the results.

AMPL is used to code and formulate the drilling fluid circulation system in the Edvard Grieg field. This model allows us to understand the current behaviour of the drilling fluid circulation system, test the effect of the centrifuge to the system and predict the outputs in different operating parameters.

4.5 Event Tree Analysis (ETA)

"This is an inductive logic and diagrammatic method, used to identify the possible risks associated of initiating any event." The main purpose to do this analysis is to find the most important cause of the system failure or high cost and focus on the problem. (Huang, et al., 2001)

Event tree analysis is a tool to find and deal with the problems, starts with an event, provide inductive logical relationship and the information about the risks/outcomes associated with the hazard (You & Tonon, 2012). Event tree analysis is an approach to find undesired and desired results from the occurrence of initiating event (Ramzali, et al., 2015).

- **Event tree construction**

Usually, event tree analysis has two outcomes "Yes (True)" or "No (False)", but there are possibilities to have more than two outcomes (You & Tonon, 2012). The methodology of constructing an event and identifying the possible consequences are given below; (Rausand, 2013; Ramzali, et al., 2015)

i. Identification of the initial event that may lead to unwanted consequences.
ii. Identify the barriers that can mitigate or eliminate the resulted consequences.
iii. Construct an event tree.
iv. Describe the potential sequences.
v. Determine the frequency and the probabilities of each event tree.
vi. Calculate the probabilities/frequencies for the identified consequences (outcomes).
vii. At the end, compile and present the results from the analysis.

Event tree analysis is conducted to understand the role of the centrifuge in the drilling fluid circulation system. A three stages tree describes the main possible scenarios to overcome high solids build up rates during drilling, more details are provided in section 7.4. Data to conduct this analysis is collected from interviewing drilling and drilling fluids specialized engineers.

5.0 Industrial background: Drilling fluids

5.1 Introduction to drilling fluids

The cost of drilling fluids itself have a small contribution in the total well cost, but the right selection of drilling fluid and properties can reduce the total well cost and potential drilling problems (Caenn, et al., 2011).

Drilling operations are the processes of extracting subsurface hydrocarbons using a drilling bit. To drill a well, it's necessary to use a drilling fluid, also named drilling mud. Water based and oil based muds are the most popular drilling fluid types. Both water and oil based muds are built by mixing/dissolving a group of raw materials in water or oil. Materials are such as weighting materials and lost circulation materials. Each of these materials has its own function. After preparing the drilling fluids, they are pumped into the bore hole through the bit to perform its functions. The process of pumping drilling mud into the well and receiving back at the surface is known as mud circulation. (Growcock & Harvey, 2005)

Drilling mud has several functions in drilling operations. They are formulated to control the formation pressure, maintain well bore stability, lubricate and cool the drill-string and to remove cuttings from the borehole. Drill cuttings contaminate the drilling fluid, as a result the functionality and lifetime of drilling fluids decrease. To reuse the drilling fluid it is necessary to remove the cuttings continuously and efficiently.

There are two basic methods to control the content of the cuttings in the mud. The first is to dump some of the contaminated drilling fluid and replace it with a new diluted volume. The second is to use the solid control system (SCS). The SCS allows us to mechanically control the solid content, keeping the properties of drilling fluids within the required level. Today, to keep the drilling fluids functioning properly, usually a combined method is used. (Growcock & Harvey, 2005)

Finally, it very important to mention that drill cuttings management is governed by strict regulations. Drilling fluids contain hazardous contaminants such as petroleum hydrocarbons and heavy metal. Oil-based and synthetic drilling muds are more harmful to the environment because of diesel and mineral oil content, however, there are strict regulations even for water-based drill cutting disposal. (Leonard & Stegemann, 2010)

5.2 Drilling rigs

A typical drilling rig consists of five principle components. The Power system provides the electrical power. Both hoisting and rotary systems are to handle, connect run-in and out the drilling pipes and equipment. The well control system is the main safety system. It works as a barrier to control well kicks and blow out. Finally, our main focus in this chapter is the circulating system where drilling fluids are prepared, pumped through the drill-string into the well, through the annulus to surface. When it reaches the surface it passes through the solid control equipment. Typically, this system consists of shale Shakers, a Desander, a Degasser, a Desilter and a Centrifuge (Growcock & Harvey, 2005). However, in recent applications, modern solid control system consists of shakers and centrifuges only.

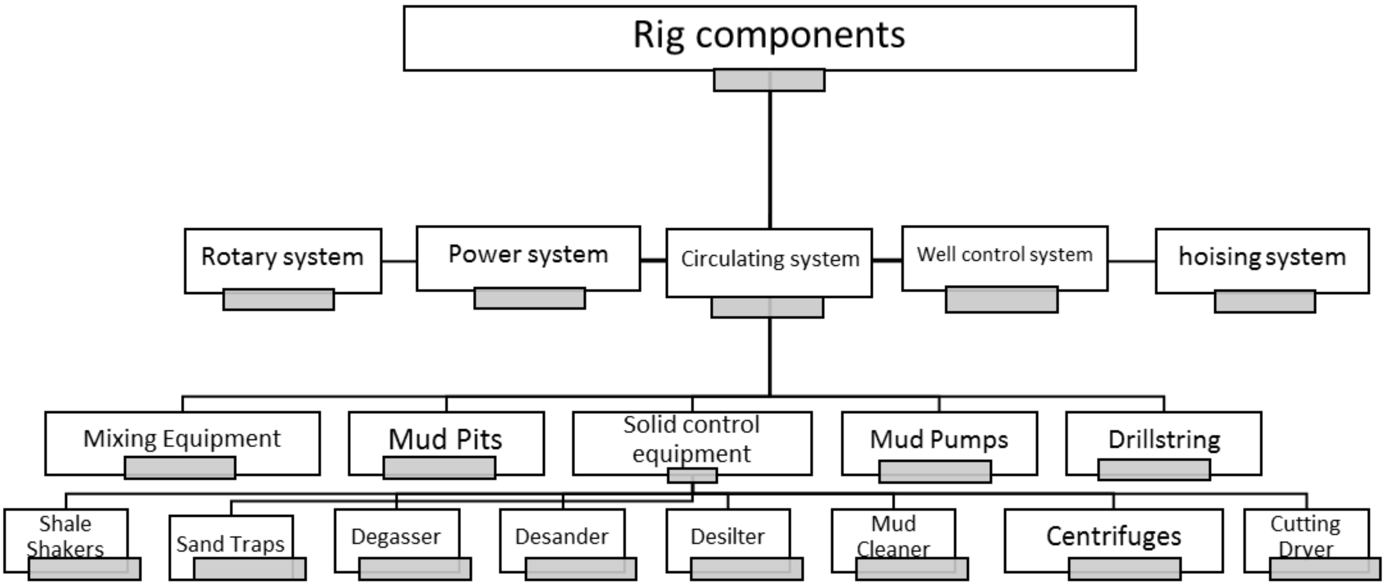
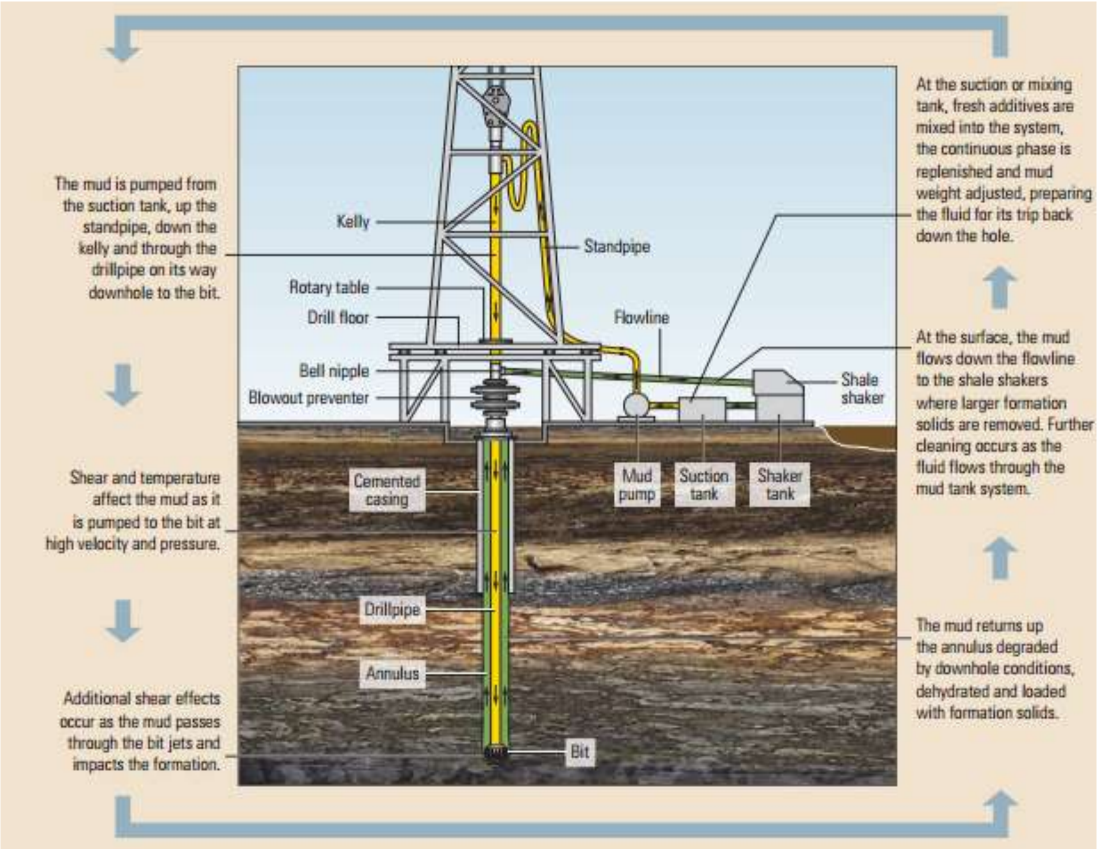


Figure 5-1 Drilling rig components

5.3 Drilling fluid circulation system

The circulation system is the complete path that the drilling fluid travels, this journey starts at the mud pumps through the well. In a complete cycle, drilling mud travels from the suction tank to the mud pump, mud is then pumped through a high-pressure surface connections (standpipe) to the drill-string and then downhole through bit jets, the mud returns up the annuals to the surface, at surface it passes through the solid control equipment for treatment before it flows back to mud pits (Williamson, 2013). The complete circulation system is shown in the figure below.



^ Drilling fluid life cycle. Throughout the circulation cycle, the mud is subjected to a number of processes that alter its physical parameters. The drilling fluid treatment plan must evolve to keep pace with these changes.

Figure 5-2 Drilling fluid circulation system. Source: (Williamson, 2013)

A major function of the circulation system is to carry the drilled cuttings to surface, remove solids and pump it back to the well. The principal components of this system include mud pumps, mud pits, mud mixing equipment, and solid control equipment, also known as contaminant-removal equipment. (Bourgoyne Jr, et al., 1986)

5.4 Drilling fluid types

Drilling fluid is a suspension of clay and other materials in a base fluid. Traditionally, there are two types of drilling fluids used in the industry, water, and oil based muds. In the recent times, a synthetic based mud also used. This classification is based on the type of the base fluid. The selection of the mud type depends on several factors such as well depth and formation type (Caenn & Chillingar, 1995).

In the planning phase, drilling fluid experts design a mud system for each drilling section. "The system is designed to meet several specifications including density requirements, borehole stability, thermal gradient, logistics and environmental concern." (Bloys, et al., 1994)

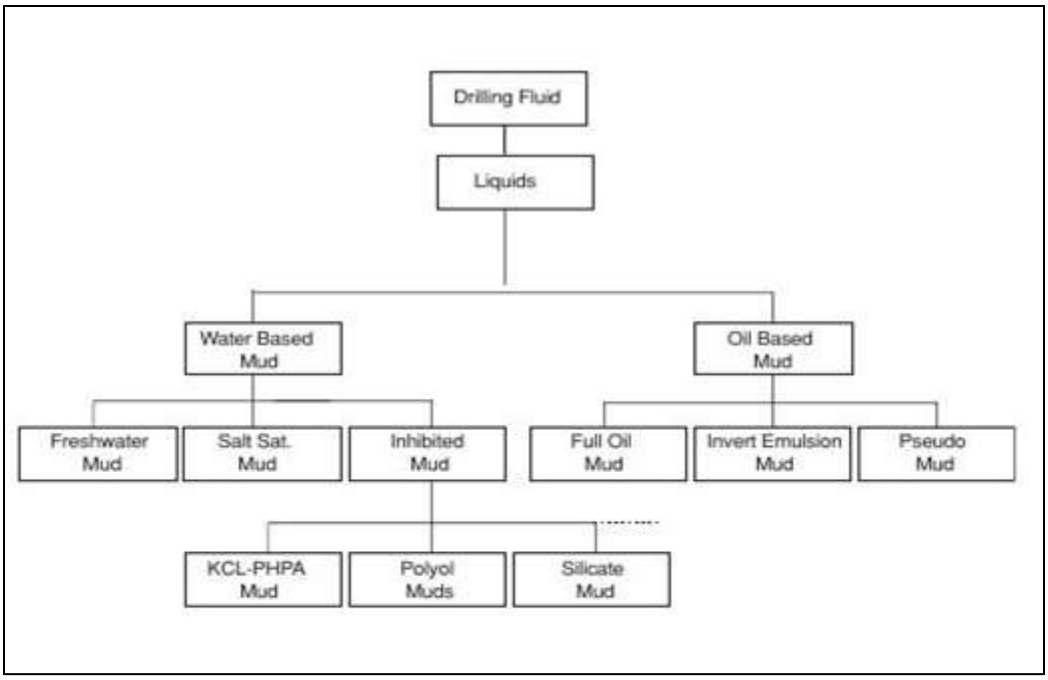


Figure 5-3 Drilling fluid types

5.4.1 Water-based mud

Water-based mud is widely used in the upper sections, where formation pressure and the cutting rate is the lowest. The accessibility to water resources makes the cost of the water based mud less than other mud types. The proprieties of water-based mud varies from one well to another. (Yunita, et al., 2016).

In many complex drilling structures, water based mud has unstable performance and application limitations. Several properties of the oil-based mud make it a better option, especially when drilling through a pay zone, the hydrocarbon producing formations.

5.4.2 Oil-based mud

The use of oil-based mud in such application is an advantage as we get less damage to the pay zone, better lubrication and higher temperature resistance (Zhou, et al., 2016). Oil based drilling fluids are more expensive than water based. However, the building cost of oil based mud varies from one country to another depending on the diesel prices. The major disadvantage of using oil based muds is the environmental concern. (Shah, et al., 2010)

5.4.3 Mud design at Edvard Grieg field

Drilling in the Edvard Grieg is divided into five sections. Each of the section has different formation type, therefore, the design of the drilling is different. Firstly, the conductor 36" hole is drilled with water based mud then, the KCl-polymer mud is used to drill the surface hole of 24" as in this hole the formation is clay. In the intermediate section, 17 ½" section, the drilling fluid is water-based mud. Next, oil-based mud is used to drill the production section and finally, water-based mud is used to drill the 8 ½ " section.

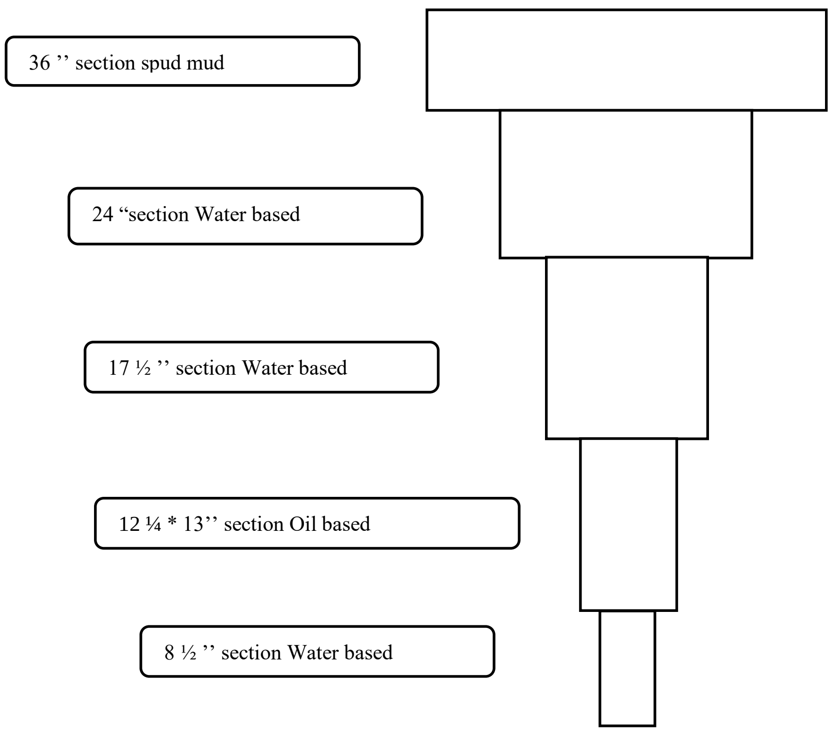


Figure 5-4 Drilling fluids per section in the Edvard Grieg

5.5 Solid control equipment

"Circulation of drilling fluid can be considered a chemical process with the wellbore acting as a reactor vessel. In this reactor, the composition of the drilling fluid will be changed dynamically" (Bloys, et al., 1994, p. 39). The solid control equipment strips solids out of drilling fluids allowing the reuse of this fluid. The solid control system minimizes the risk of several drilling problems related to solid content in the mud, it also contributes to reduce the consumption of the drilling fluid and minimize the drill cuttings waste amount. (Bloys, et al., 1994)

The solid control system is a set of mechanical-separation devices. Selecting and designing a solid control system depends on several factors including well depth, drilling penetration rates, formation type and size of solids. The right design of the solid control equipment is a key factor in minimizing total system cost. In a recent application, including the Edvard Grieg field, solid control equipment has downsized to include only two devices; shale-shakers and centrifuges, Figure 5-5 shows the layout of the solid control equipment in Edvard Grieg.

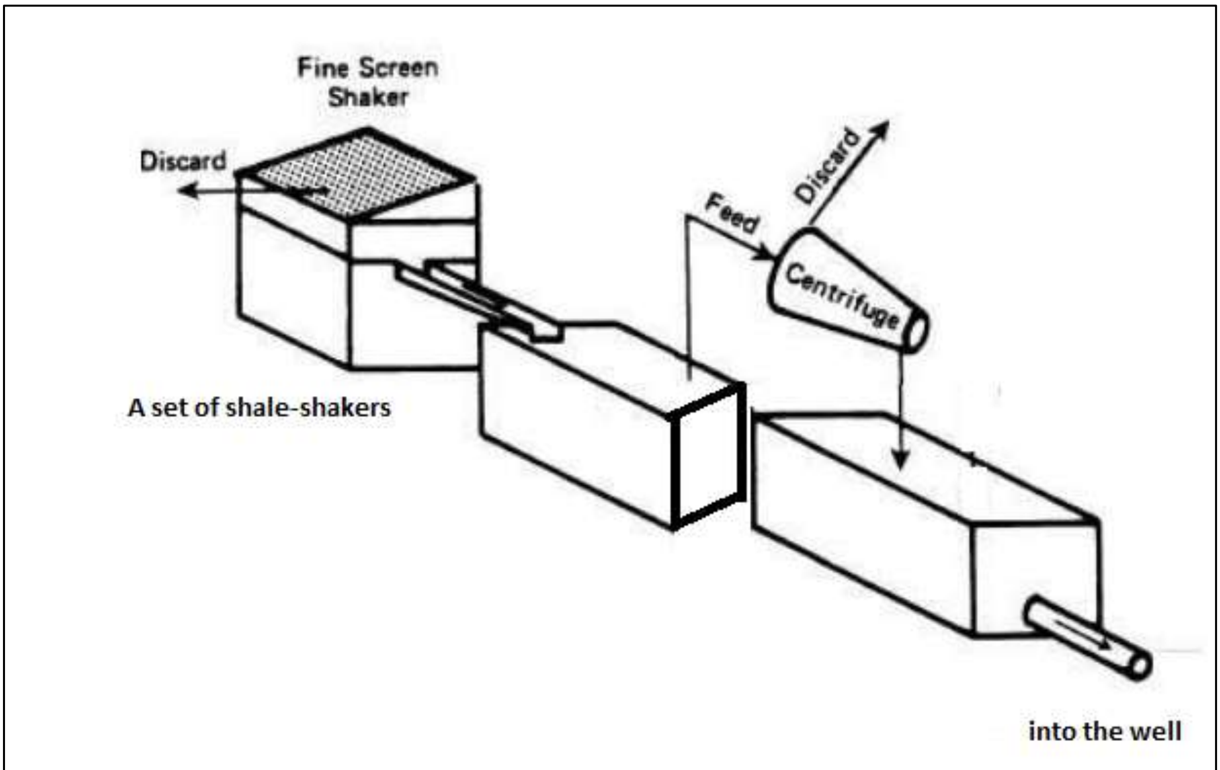


Figure 5-5 Solid control system consisting of shale-shakers and a centrifuge

The system process solids allowing to reuse drilling fluids. The process of separating solids out of drilling fluid results in separating some of the active drilling fluid this called slippage volume. Slippage waste is approximately 10% for all case wells in the Edvard Grieg field.

5.5.1 Shale-shakers

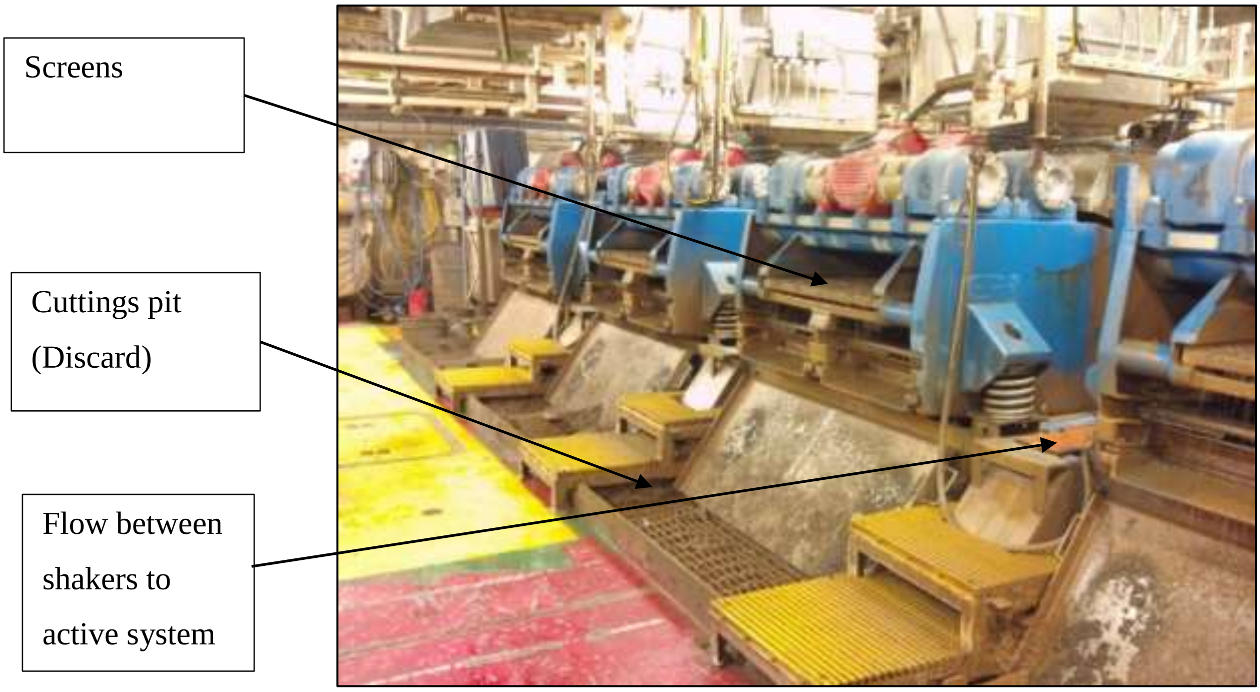


Figure 5-6 Four sets of shale shaker in the Edvard Grieg field. Source: Lundin Norway AS

Shale shakers have the advantage of a simple design, a wide range of solid size processing and high flow rate processing capabilities. This device is used to screen a wide range of solid sizes from the circulating drilling fluid. Shale shaking is the easiest way to remove the solids but the improper design and use of this device may affect the other devices in the solid control system.

In Edvard Grieg operations, a set of five Shale-shakers is used to process circulation drilling fluids. The reason for using more than one shale shaker is to assure high processing efficiency different flow rates and solid contents. The total solid separation efficiency of the five shakers is slightly higher than 75% of the total solid content (interview, 2017). In 17 ½‘’ section shakers handle 5000 liters per minute. In Figure 5-6, the blue part is where shale shaker screens are. Contaminated drilling fluid passes through these screens down to the bottom part then to underground pits.

5.5.2 Centrifuges

Centrifuges are used to separate the small sized particles from the circulating drilling fluid. By accelerating the sediments, it permits to separate high density from low-density solids (Bouse, 2005).

Figure 5-7 The centrifuge device in the Edvard Grieg field. Source: Lundin Norway AS

Centrifuges were first adapted to drilling operations in the early 1950s. They were used first to reduce the drilling fluid weight by separating lower gravity contents. In recent years, centrifuges have been used to remove fine size solids to assure good quality and minimize dilution rate. The centrifugal pump discards the heavy slurry containing drilled solids down to around 7 to 10 microns and the light slurry with solids and chemicals (less than 7 to 10 microns) is returned to the drilling fluid. This process reduces the contamination in drilling fluid and thereby, total drilling fluid cost, however, these machines are quite expensive and require a great amount of maintenance. (Bouse, 2005)

5.6 Advantages of upgrading the solid control system in the Edvard Grieg field

In the Edvard Grieg field, Lundin has invested in upgrading their solid control system by adding a centrifuge. Therefore their current system now consists of five sets of shakers and a centrifuge. The centrifuge adds a permanent cost to the solid control system, and the total estimated yearly fixed cost of the centrifuge is approximately NOK 8, 200 million. This cost includes the daily rent of the centrifuge, a digraph pump, mobilization/demobilization cost and the cost of two offshore supervisors to operate the centrifuge.

The main reason for upgrading the solid control system in Edvard Grieg is the high volume of drilling cuttings generated in the Hordaland and the Grid formation. This upgrade is expected to pay off by mitigating and eliminating several costly drilling problems related to solid content build up. It's also expected to reduce dilution rates thereby, reducing total mud costs.

5.6.1 Drilling problems related to solid content

"Mud may represent 5% to 15% of drilling costs but may cause 100% of drilling problems" (Bloys, et al., 1994, p. 33). Drilling fluids contribute to virtually any drilling problem. Inadequate drilling Muds may lead to stuck pipes, poor completion, inadequate logs and pay zone damage.

Solids are classified as high gravity solids and low gravity solids. Barite and other weighting materials are classified as high gravity solids, however, drilled solids, clays, polymers and bridging materials are classified as low gravity solids.

The type and the content drilled solids in the drilling fluid affect a number of chemical and physical properties. The increase in the content of low gravity solids will increase plastic viscosity and gel strength. In addition, it will result in thicker filter cakes and slower drilling rates, it could also cause abrasion on pump parts, and downhole equipment (Bloys, et al., 1994)

5.6.2 Maintaining drilling fluids

"Selecting a reliable chemical formulation for the drilling fluid so that it exhibits the required properties is one part of the job, maintaining these properties during drilling is another" (Bloys, et al., 1994).

As we mentioned earlier in this chapter, “to reuse drilling fluids, it is necessary to remove the cuttings continuously and efficiently”. There are two possible methods used to treat the content of cuttings in drilling fluids. The first is a mechanical separation, a solid control system is a group of mechanical devices in which the solids are stripped out of the drilling fluid.

The second treatment is to replace some or of contaminated fluid with a new diluted volume. In drilling industry, dilution is the process of building and adding an extra volume of mud to the existing volume in order to control mud proprieties. Dilution can be made by adding base fluid or/and chemical additives such as weighting material, lost circulation materials or bridging materials. (Bouse, 2005)

5.6.3 Environment concern and mud disposal

In 2015, about 465 000 tons of hazardous waste was generated on the Norwegian shelf. Most of the waste are drilling waste, chemicals, and oil waste. Drilling wastes are 402895 tons, accounts more than 80% of total waste.

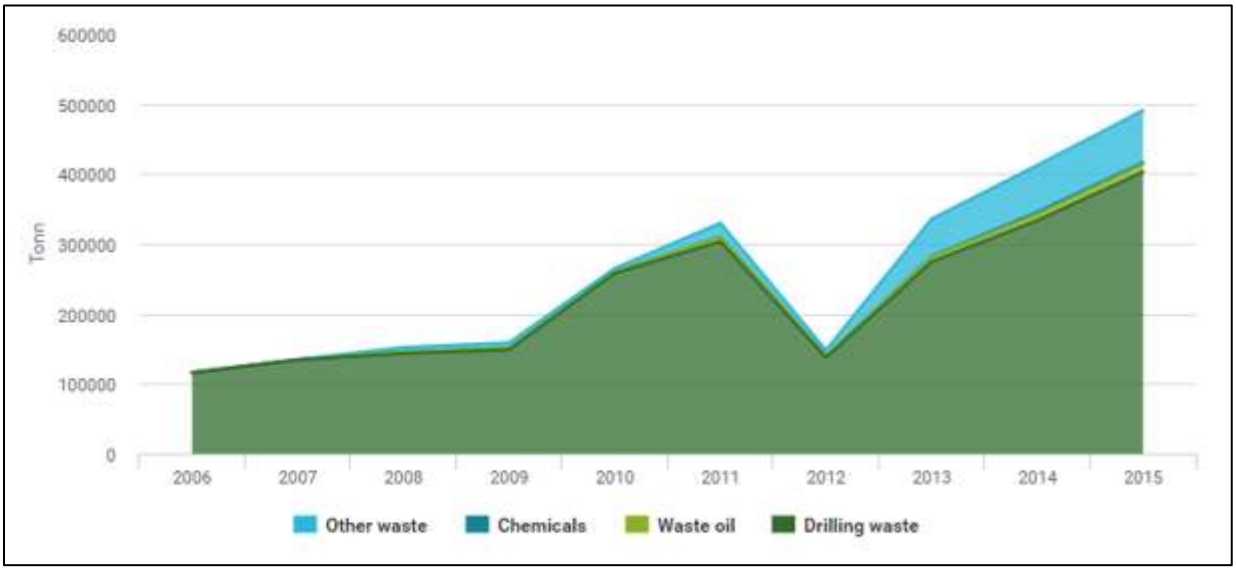


Figure 5-8 Hazardous waste from offshore activities on the Norwegian shelf. Source: Norwegian Environmental Agency and Norwegian oil and gas Association License: NLOD.

Drilling waste skyrocketed from around 140 000 to 402 895 tons in the last few years, this results in more greenhouse emissions while transporting the cuttings, higher risk of pollution to soils, rivers, and lakes, and coastal waters. (EnvironmentalNorwegianAgency, 2017)

6.0 Offshore upstream logistics

"Supply chain is a process of transformation of all the activities and goods from the origin of the raw material to the final customers" (Arne Wiig, 2001). Logistics management is a part of supply chain management and can be defined as "the process of planning, implementing and controlling the procedures for efficient and effective transportation and storing the material including services and related information from the origin to the final customers" (Choi, et al., 2016).

Logistics activities are challenging for planners either onshore or offshore. In this chapter, we will mainly focus on the offshore logistics activities. More specifically, the settings of offshore upstream logistics in the Norwegian Continental shelf (NCS).

6.1 Offshore upstream logistics system

Logistics system can be divided into two groups, **onshore logistics** (transportation is usually done by train and trucks) and **offshore logistics** (vessels are the main source of transportation). The Figure 6-1 shows a simplified model of the logistics system.

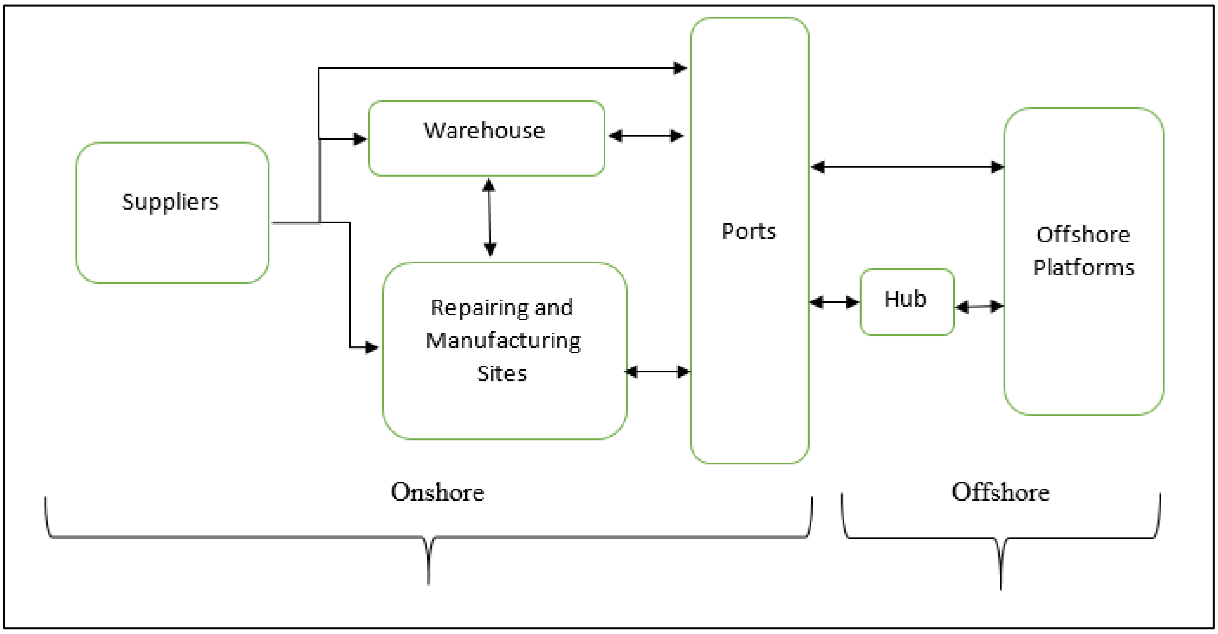


Figure 6-1 The flow of cargo to the offshore units

In the petroleum industry, transportation of oil and gas from installation to land is called **“downstream logistics”** and supply of the demanded material from supply base to offshore installations is known as **“upstream logistics”** (Aas, et al., 2009).

6.2 Logistics management

This is a key part of supply chain and mostly cover the routing of the vessels, inventory control at the supply base and installations. A complete, correct and in time information to all the actors involved in the logistics activities is a key factor. Supply vessels and logistics planning play a vital role in the offshore exploration and production (E&P) activities (Aas, et al., 2008a; Maisiuk & Gribkovskaia, 2014).

Supply vessels are designed for multi-purposes. Supply vessels are used for transportation of materials from the supply base to the installations and bring back waste and empty containers to the supply base. The selection of vessels depends on the geographic location of targeted installation and type of material to be transported because some materials require special needs while transporting e.g. food and drinking water. (Aas, et al., 2009; Maisiuk & Gribkovskaia, 2014). The offshore logistics planning is challenging due to the large variety of items, different container size and distance from base to the installation, weather conditions and storage availability (Aas, et al., 2009). Many actors are involved in offshore logistics activities including planners, vessels, warehouse, ports, helicopters (usually for personnel transportation) etc. All are dependent on each other and minor delay in any part of logistics system will lead to high cost. This will become more challenging during the exploration activities and an era of low oil and gas prices (Engh, 2015; Wiig, 2001).

6.3 Transportation

Vessels are used to providing the services to the offshore installations and transporting the demanding material to the installations. There are two types of materials, bulk or deck cargo. These vessels can transport deck like pipes and casing at the top and below the deck, there are tanks used to transport drilling fluids, chemicals, fuel etc. The drilling fluids (mud) are transported in tanks in a liquid form. (Drift & Weeke, 2015; Aas, et al., 2009)

The most common material, which is transported through supply vessels are fluids, diesel, dry bulk, industrial water, food and drinking water, chemicals, pipes and risers, equipment, and general goods, salt and other supplies for fluids, barite and bentonite, cement and waste material.

6.3.1 Transportation cost elements

Several cost elements are associated with offshore upstream logistics but supply vessels are an expensive (Norlund, et al., 2015). There are several cost elements associated with operating a supply vessel. Some of these costs are fixed while others are variable. There are three principle cost elements, the daily vessel rent, planning cost and operating cost. The daily rent is the fixed cost that an operator pays to the vessel owner. Planning includes determining the optimal routes, optimal fleet size, and the corresponding weekly voyages and schedules. The operating cost is a variable and it includes the fuel consumption, (speed and weather and load) crew and emission cost.

6.3.1.1 Vessel rent

Vessels are designed for multi-purposes and categories on the basis of their fleet size, functions (transport or service) and usage. The rent of the vessel is a major cost element in offshore upstream logistics. The cost depends on the capabilities and features of the vessel and availability. Features are mainly operational capability, load carrying capacity for both deck and bulk cargo, sailing capabilities and finally loading and unloading capabilities. (Aas, et al., 2009)

The operation capability is the actual operation time a vessel is capable to operating within rent period. An ideal vessel will have minimum routine maintenance and service time. A bigger carrying capacity is usually an advantage for a supply vessel. Supplies transported are classified into deck and bulk cargo. Deck cargo includes pipes, offshore containers and other supplies transported on the deck of the vessel. Bulk cargo includes drill-fluids, brine, water and oil. Most of the offshore cargo are loaded in offshore containers, skips or baskets. Sailing capability is the capability of a vessel to operate in different weather conditions. “Unlike carrying capacity, which is more of a fixed cost, sailing capability varies in accordance to the weather and it influenced by the cargo transported” (Aas, et al., 2009; Aas, et al., 2007). Minimizing the time of loading and unloading activities at the installation and supply base increases the sailing time thereby, save money for the company. Lifting capability and vessel's capability are the key factors affecting the loading and unloading operations (Aas, et al., 2009).

6.3.1.2 Planning

In Norway, the production of oil and gas in the remote areas e.g. the Barents Sea. The planning of vessels is much difficult especially in the winter season the sailing and service time increase (Norlund, et al., 2015). The Planning phase includes determining the optimal routes, optimal fleet size, and the corresponding weekly voyages and schedules. An ideal plan should include a minimum number of vessels to serve all installation, a maximum deck utilization and a zero cargo delay time (Maisiuk & Gribkovskaia, 2014; Sopot & Gribkovskaia, 2014).
Each installation has a demand of a different kind of material. Routing is to find the optimal path, for each vessel, in which the maximum number of installations are served. The main purpose of routing is to minimize the number of vessels, the operating times and thus the total cost (Maisiuk & Gribkovskaia, 2014; Sopot & Gribkovskaia, 2014). As vessels are the main cost element in the offshore upstream logistics, deck utilization is another factor through which a significant cost saving can be produced. There are two basic ways to increase deck utilization, effective supply chain management, and good demand management. Daily rent cost of the offshore drilling activities is high. So, delay in deliveries will result in a high cost. The cost is mainly associated with personnel or operations are waiting for equipment or equipment is waiting for personnel. Different reasons have been reported for a delay in offshore deliveries, weather conditions, poor material scheduling and unscheduled technical maintenance of vessel (Aas, et al., 2009; Sopot & Gribkovskaia, 2014; Maisiuk & Gribkovskaia, 2014).

6.3.1.3 Operating cost

The operating cost of vessels in offshore upstream logistics consist of cost of fuel consumption, harbor fees, operating crew cost and the cost of greenhouse gasses. The operating cost depends on sailing speed, load and weather condition.

Fuel consumption depends on the sailing time, speed and load. Especially in winter times, bad weather conditions increases fuel consumption. High wind speed and waves result in longer sailing times and lower the speed (Norlund, et al., 2015). The harbor fee is marginal in Norwegian ports as compared to the other places. The operating crew on the supply vessel depend on the size of vessel and weather conditions. Usually, there are up to 30 people on the vessel. The job of the crew includes to operating the vessel, maintenance, and cargo handling. Supply vessels are the main source of emission of greenhouse gasses in the upstream logistics. Bad weather conditions lead to high fuel consumption or emissions (Norlund, et al., 2015). By increasing the offshore oil and gas production, the vessel traffic also increased and air pollution is a barrier for the supply vessels operations and planners. There are many regulations have been proposed and design of vessel are given to overcome this problem. (Diaz-de-Baldasano, et al., 2014)

6.4 Loading and unloading

The arrival and departure time of the supply vessels at the installations and supply base is specified in a weekly plan (Maisiuk & Gribkovskaia, 2014). However, the time difference between arrival and departure of the vessels from the supply base or installation is considered as the time of loading and unloading process (Aneichyk, 2009).

The high daily rent of the vessel increases the importance of the loading and unloading times. The efficient and effective process of loading and unloading at the installation and supply base allows us to increase the sailing time thereby, cost saving as well.

Several factors make this process complicated especially at offshore installations. Before talking about these factors, it’s necessary to mention that one vessel may visit more than one installation and go through this process of loading and unloading many times in one trip (Rowe, et al., 1995).

6.4.1 Key factors

Many incidents are reported in the past decades, many of them are due to the poor positioning of the crew during the operations. We can sort the factors affects the offshore loading and unloading activities into two main categories, controllable and uncontrollable. The controllable factors include the lifting capability of the offshore installation and capability of supply vessels. On the other hand, wind speed and weather conditions are the most common uncontrollable factors. (Drift & Weeke, 2015)

The loading and unloading of a deck and bulk cargo can be done simultaneously if the weather is suitable. However, in a case of high speed wind or waves, this process can be very complex. The chief of the platform, crane operator, and the captain of the supply vessel are the key personnel involved in the decision making to either pursue this process or not. This decision may depend on the geographical location of the platform, the capability of the crane and vessel capability in keeping its position in a high degree of accuracy during the operation (Drift & Weeke, 2015; Aas, et al., 2009).

6.5 Logistic activities in the Edvard Grieg field

Edvard Grieg, the case study of this thesis, is an oil field located in the Utsira High area in the central North Sea, about 180 Km west of Stavanger. This field contains more than 20 wells. The main supply base of the logistics activities is Tananger (Lundin, 2017)

Figure 6-2 The Edvard Grieg field. Source: Lundin Norway AS

6.5.1 Loading and unloading of drilling fluids

On the base, Drilling fluids are prepared in tanks. Each type of drilling fluids (water based, oil and Synthetic based) has a different onshore storing tank. Similarly, there are several tanks on the vessel. A hose is used to Load/unload drilling fluids from the onshore tanks, or the offshore installations to/from the vessels. The Figure 6-3 shows the loading and unloading of

Figure 6-3 The loading and unloading of drilling fluids.
Source: Lundin Norway AS

drilling fluids by hose (an orange color pipe is a hose).

Drilling fluid loading and unloading activities are done twice each trip. First drilling fluids are loaded in Tananger base and then unloaded as the Edvard Grieg installation. Two employees are involved in the communication part of this operation, one at the base and the other is on the vessel. The process starts when both parties confirm the settings of the process. When drilling fluid flows, both inlet and outlet meters are used to measure the flow amount. The amount to send depends on the storing capacity of the installation and the demand.

6.5.2 Storing drilling fluids in the Edvard Grieg field

Total drilling fluid storage capacity on Edvard Grieg is 1024 m^3. Total brine (water) capacity is 790m3. The Figure 6-4 below shows pit layout on Edvard Grieg. Total storage capacity includes Pit 1, 2,3,4,5,6,7,8. Here are 2 brine tanks with 395m3 capacity each. In situations where the drilling fluid need exceeds available capacity, a temporary vessel is used to as storing facility to store drilling fluids

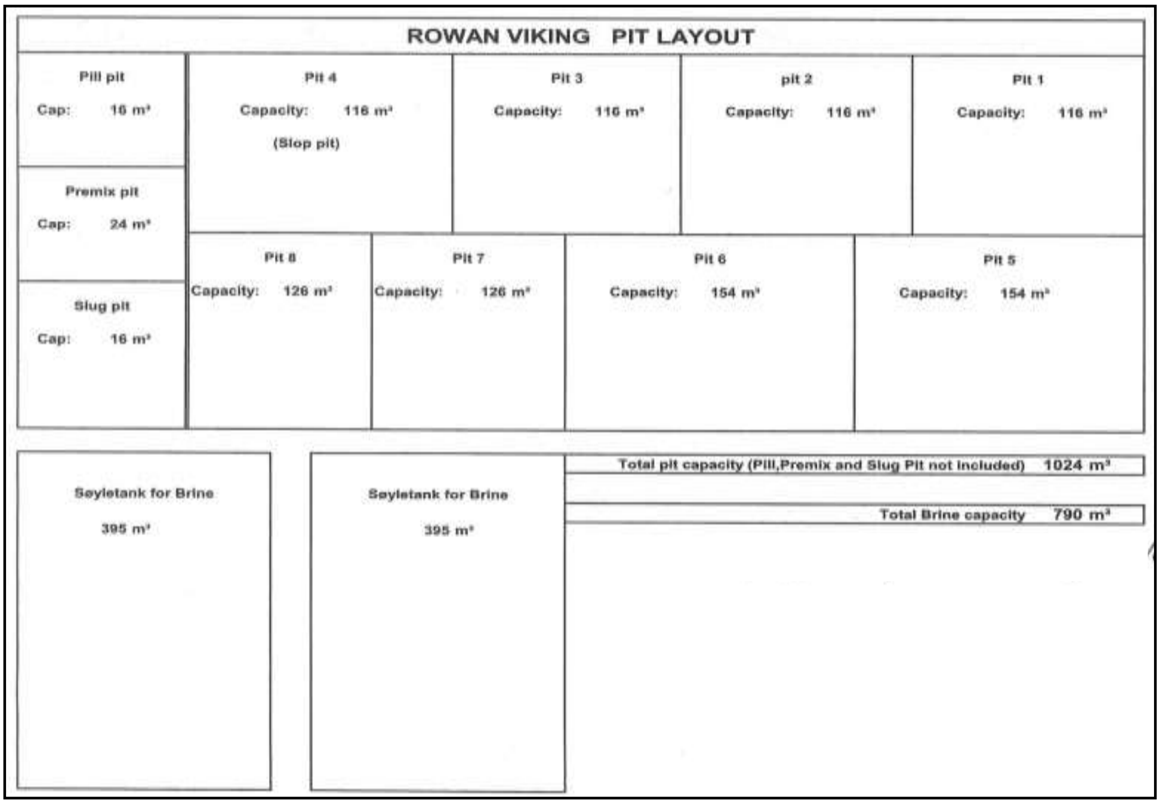


Figure 6-4 Pit Layout at the Edvard Grieg field. Source: Lundin Norway AS

6.6 Transportation cost elements

Lundin is renting two supply vessels to transport cargo from Tanager to the Edvard Grieg field. The vessels are Viking prince and Island Commander. These vessels are multipurpose vessels, meaning that they are used to transport both deck and bulk cargo. The daily rent of the vessels is 80,000 and 189,000 NOK respectively. Each vessel is capable of transporting up to 800 m^3 of drilling fluids per trip.

6.6.1 Operating cost

A trip from Tananger to Edvard Grieg is about 180 kilometers. The fuel consumption is a function of vessel load and sailing speed. In good weather conditions, the average fuel consumption is 2 to 4 meter cubes. One meter cube of fuel costs 5,500 NOK. In case of an urgent cargo, the consumption will jump to about 4 to 8 meter cubes. The average total cost of fuel consumption in good weather is about NOK 18,000 per trip, however, the cost jumps to NOK 35,000 in a case of urgent cargo. The cost is expected to be higher in a case of bad weather condition. Loading and unloading of drilling fluids are done through hoses. There is no additional cost associated with loading and unloading other than the time used to load and unload.

6.6.2 Planning cost

There are two full-time employees responsible for planning and coordinating logistics activities for Edvard Grieg. One full-time employee located at the headquarter in Lysaker is responsible for the logistics planning and logistics coordinator in Tananger. The planning of the cargo and the volumes is done in Lysaker while the coordinating of loading and unloading activities is done in Tanager. Lundin pays its supply base provider 3,000 NOK per day for coordinating the loading and unloading activities at the supply base.

6.6.3 Additional cost

There are other marginal costs for instance harbor fees, administrative cost and temporary drilling fluid storing cost. These costs are marginal and will be excluded in this study.

6.6.4 Summary

Transportation element	**Value NOK**
Daily rent of Viking prince including vessel crew	80,000 **NOK** per day.
Daily rent of commander including vessel crew	189, 000 **NOK** per day.
Fuel consumption in good weather conditions	18,000 to 35,000 **NOK** per trip.
Fuel consumption in bad weather conditions	Up to 70,000 **NOK** per trip.
Logistics planning in Lysaker	Full time employment
Coordinating logistics activities in Tanager	3000 **NOK** per day.
Harbor fees and other administrative cost	Marginal

Table 6-1 Transportation cost elements in Edvard Grieg field

7.0 Preliminary analysis:

Before data collection, a preliminary analysis was conducted to understand and predict the potential benefit of upgrading/adding a centrifuge to the solid control system. The preliminary analysis consisted of an illustrative case study, data screening, and event tree analysis. The aim of this preliminary analysis was to in general define the role of the centrifuge and measure its contribution in reducing drilling fluid consumption.

7.1 Illustrative case study:

A preliminary illustrative case study was conducted on a drilling well in Saudi Arabia. The availability of data was the main reason for selecting this case.

The case study showed that using a centrifuge reduce 1.2 m^3 per meter, this results in saving around 5000 USD dollars in total for the drilled section, the section length is 500 meter. In addition to drilling fluids cost saving, each m^3 of drilling fluid has an associated logistics cost. This cost includes transportation, storing and drilling fluid disposal cost. See Appendix 2

From this study, we have learned that the use of the centrifuge contributes in reducing drilling fluid consumption volume. It also has a positive effect on onshore logistics activities as it provides more storage area, less transportation, and fewer disposal volumes and it's expected to have better results if applied offshore where logistics activities are more challenging and expensive.

The main goal of our study is to investigate the influence of upgraded solid control system on dilution rate and total system cost. In this onshore illustrative case, results show savings both in drilling fluid cost and logistics. The higher offshore cost structure encouraged us to investigate the influence of upgrading the solid control system offshore. Furthermore, in Norway, the vast majority of drilling activities are offshore and the offshore penetrating pattern is further expanding, thus, it was essential to select a Norwegian offshore operator. The high offshore drilling activities in the Edvard Grieg, drilling more than 15 wells, and the recent upgrade of the solid control system by adding the centrifuge were the main reasons for selecting the Edvard Grief field for this study.

7.2 Data screening

The initial data screening is conducted to monitor the operating times and technical parameters of the centrifuge. In addition, it was also important to study the total drilling fluid consumption, solid control system and discharge disposal volume. These are the main variables of the drilling circulation system, the four variables are dependent on each other. That's why it was important to study these variables in all case wells both when the centrifuge was used and when it was not. Monitoring the use of centrifuge is conducted on the wells A1 and A12, where the centrifuge was used, however, drilling fluid consumption, solid control system and waste volume study is conducted on all the wells in the case A1, A6, A10, and A12.

7.2.1 Well A1

In A1, the centrifuge was only used in the last two drilling sections 12 ¼ * 13″ and 8 ½" sections. However, the running hours of the centrifuge in section 36", 24 ½″ and 17 ½" is zero hours.

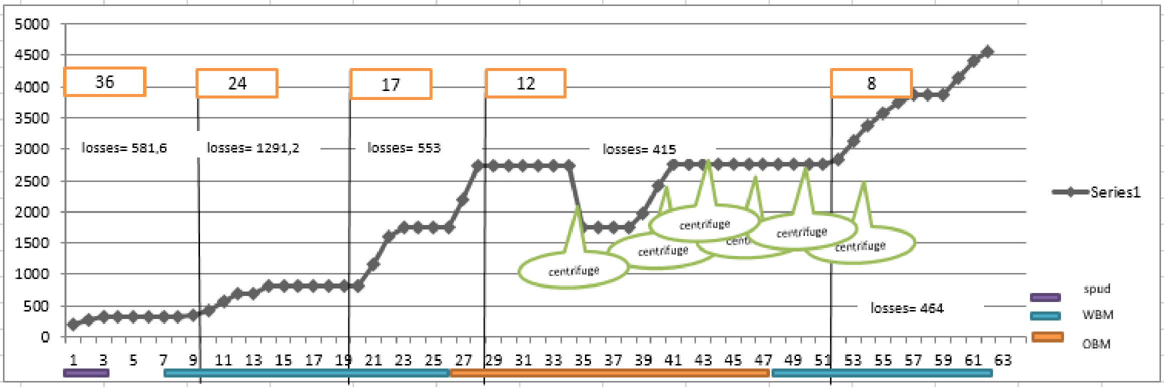


Figure 7-1 The operating times of centrifuge in well A-01

One of the main reasons for not taking the advantage of using the centrifuge in these sections was the good drilling conditions as no carvings or other wellbore stability problems were noticed. This also led to lower mud consumption per meter compared to other wells. The operating mode in section 12 ¼ ″ * 13″ was "continuous", see Table 7-1.

Date	On / Off
06/08	15:00 - 00:30
07/08	14:30 – 24:00
10/08	21:00 – 09:30
12/08	00.30 – 11:30
13/08	01:15 – 16:00
15/08	09.30 – 20.15
16/08	10:30 – 22:30
17/08	14:30 – 16:30, 19:30 – 24.00
18/08	14.00 – 17:20, 20:20 – 23:15

Table 7-1 Running hours of centrifuge in well A-01

7.2.2 Well A12

In well A12, the centrifuge was used in three sections; 17 ½" 12 ¼" *13" and 8 ½" sections. The reason for operating a centrifuge in these sections was to process the high solid build up rates reported in day 23rd and 27th. However, unlike A6, the running hours of a centrifuge in section 12 ½ *13" is discontinuous. This means that the solid build up rate in average is processable without using the centrifuge but there are few cases where the centrifuge is required to process the high solid build up rates. The main reason for this high solid build is caving problem, caving is a partial collapse of a well-hole wall which generates a high amount of solids. More information is provided in Appendix 4

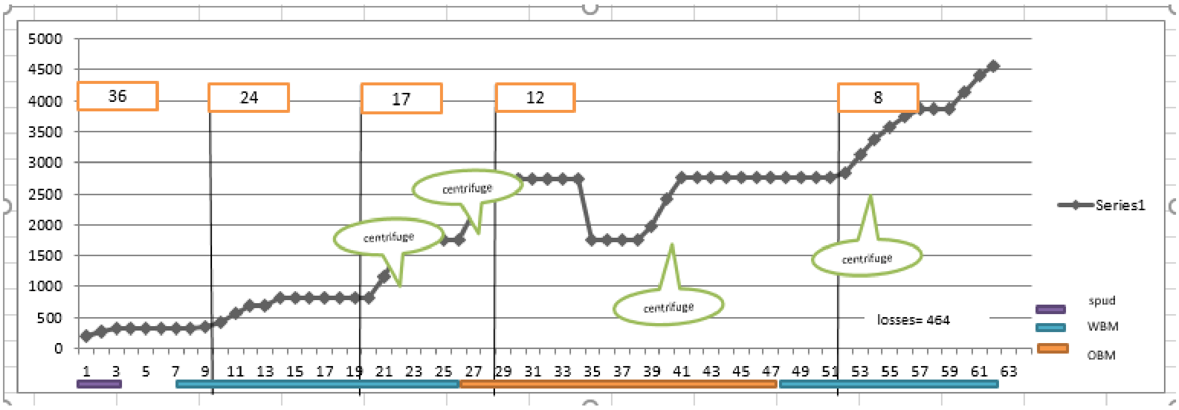


Figure 7-2 The operating times of centrifuge in well A-12

7.3 Drilling fluid consumption.

Total drilling fluid consumption varies depending on several factors including the efficiency of the solid control system and drilling problems that occur during the drilling operations. The comparison below shows that total drilling fluid consumption in each section for all case wells A1, A6, A10 and A12, two of these wells were drilled after installing the centrifuge, we referred to these wells as an upgraded system.

Drilling fluid consumption per meter is between 1.30 to 2.64 m3/meter in section 24" section for all case wells, one of the main reasons for this high consumption is that the formation type is clay, separating solids in clay is very difficult and results in high discharge volumes, discharge require to dilute fresh fluid to recover fluid loss and thereby, increases total consumption.

The consumption per meter per hole-sections is quite similar for all case wells however, it varies as drilling operations are not identical. Wells are always exposed to drilling problems which requires extra fluid volume. After all, it's quite difficult to measure the influence of the centrifuge on drilling fluid consumption per meter. Consumption per meter is a function of a number of factors such as formation type and well-bore stability. See Appendix 3

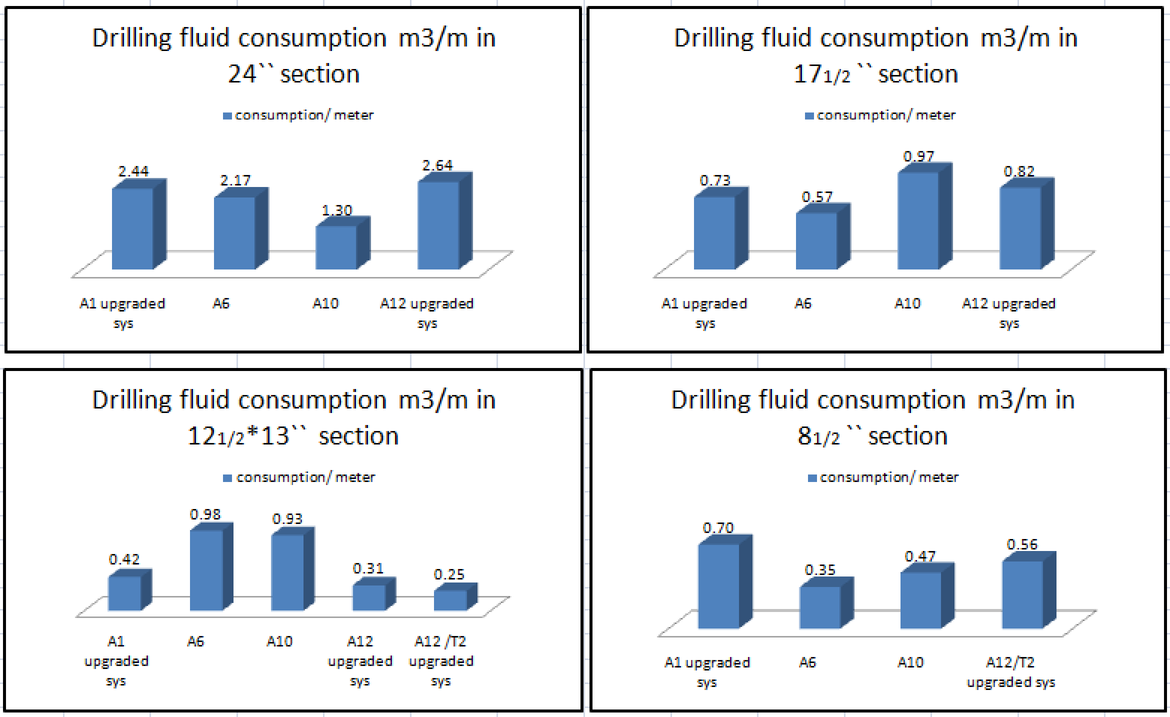


Figure 7-3 Comparison of drilling fluid consumption

This encouraged us to carry out an event tree analysis and ask specialists about the role of the centrifuge in reducing drilling fluid consumption in high solid build up rates. In addition, a quantitative model was built to precisely estimate the influence of upgrading the solid control system on total drilling fluid consumption and associated logistic cost.

7.4 Event tree analysis

To understand how the centrifuge contributes in reducing dilution rate, it was necessary to conduct a decision/Event tree analysis. Event tree analysis is conducted to understand the role of centrifuges in processing drilling fluids. In Figure 7-4, initial event is the high solid build up. The figure represents the sequence of decisions to be taken and events to occur in order to process high solid build up rates. A three stages event tree is suggested to overcome high solids build up rates after interviewing drilling engineers and drilling fluids specialized engineers.

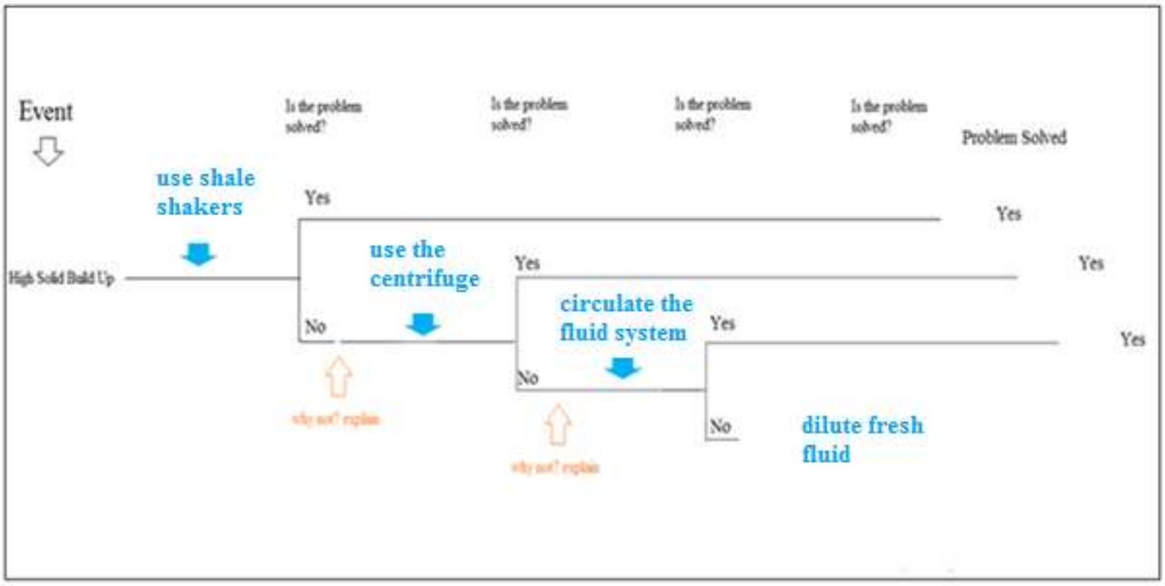


Figure 7-4 The event tree analysis for high solid build up

In the first stage, the decision is to monitor the shakers closely and screen up with finer screens when possible. The success of this approach depends on several factors, such as the actual performance of the shakers, the dexterity of the shaker hands, and more importantly drilling rate of penetration ROP and the temperature of the mud. Cold mud will plug fine screens and just overflow, likewise with high ROP. Screening up is thus the preferred approach but may result in losing more mud.

In the second stage, the decision is to run the centrifuge to process more solids. The success of this approach depends on the processing capacity of the centrifuge. Usually, centrifuges have a limited processing capacity of less than 25% of total active drilling fluid system.

In the third stage, the decision is to circulate the mud system whenever possible when not drilling. This allows to clean the hole as circulating the drilling fluid system runs the mud over the fine shaker screens and removes more solids. So, again it depends on the actual performance of the shakers.

In the fourth stage, the decision is to dilute fresh fluid, which is often used in addition to the other two methods. One of the main problems with dilution, especially for lengthy sections is pit space. Space is a luxury offshore and must be managed carefully. In addition, building excess mud that must be disposed of causes logistic cost in addition to material costs.

As a conclusion, the analysis explains the role of the centrifuge in processing high solid build up rates. The analysis shows that the use of centrifuge is going to mitigate the sequences of the solid build up. If the centrifuge is not used, the next two events are going to occur; circulating the drilling fluid system and diluting extra drilling fluid volume. These two steps are time consuming and costly, the time consumed in circulating the mud system is unproductive time, as no drilling penetration occurs at this time. In addition, diluting extra drilling fluid is an extra cost and will result in additional logistics cost of drill cutting waste. The next chapter includes more precise analysis on determining the size of the benefit of using the centrifuge.

8.0 Empirical analysis

This chapter begins by describing the circulation drilling fluid system and the algorithm to model this system. Next, the objective function, variables, and constraints are formulated in mathematical notations. Finally, the computational experiment section presents the findings.

The aim of this exercise is to determine the influence of using the centrifuge on the fresh fluid dilution rate and thereby, the total drilling fluid consumption volume. The objective function of the algorithm is to minimize total drilling fluid cost. The algorithm is designed to operate the system, including the centrifuge, in the best way in order to minimize total dilution rate.

8.1 System description

The operating parameters of drilling fluid circulating system varies from one drilling section to another. It depends on several factors, for instance, well scheme, formation type, drilling speed and solids build up rate. In this section, as an illustrative example, we will represent the operational parameters of the fluid circulation system in drilling the 17 ½" sections in the Edvard Grieg Field, Norway, see Table 8-1.

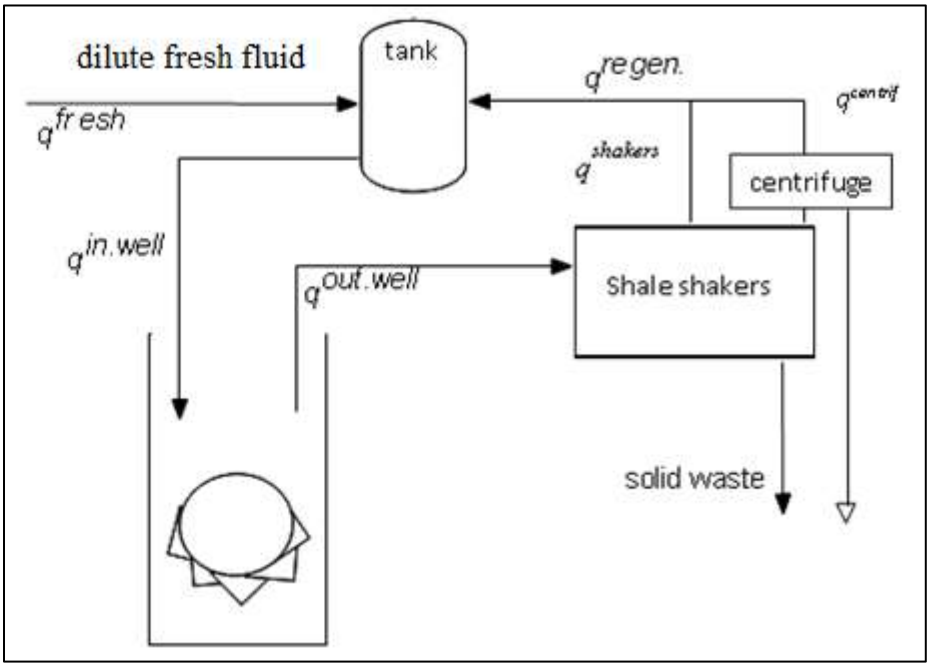


Figure 8-1 Drilling fluid circulating system

The drilling fluid is pumped into the well (q in.well) while the well is drilled using a mud pump. The solid content of the mud raises as it reaches the hole (Sc out.well). The increase in the solid content depends on several factors, such as the Rate of Penetration (ROP), well schematic and formation type. Drilling mud flows through the mud return line upon its return from the hole to the surface (q out.well). In order to control the solid content, drilling mud flows to the shale shakers, then some of the outflow of shale shakers (q shakers) flows to the centrifuge, this depends on the maximum processing capacity of the centrifuge. "Centrifuges can typically handle only about 15% of the active system". The summation of the outflow from shakers and centrifuge (q regenerated) returns back to the tank.

Notation	Description	value
$q^{in.well}$	The flow rate of the drilling fluid delivered to the well.	≥4500, ≤ 5000
$Sc^{in.well}$	Solids content in the fluid delivered to the well.	≤6%
$q^{out.well}$	The flow rate of the used drilling fluid delivered from the well to the Solid control system.	≥4500, ≤ 5000
$Sc^{out.well}$	Average solids content in the fluid coming from the well.	155 Liters/minute
$Sc^{out.well}$	Solids content in the fluid coming from the well in case of caving problem.	1055 liters/minute
$q^{shakers}$	The flow rate of the drilling fluid out of the shakers.	Variable
$C^{shakers}$	Maximum fluid processing capacity of shakers	≤ 5000 liters/minute
$Sc^{shakers}$	Solids content in the drilling fluid out of the shakers.	75%
$q^{centrifuge}$	The flow rate of the drilling fluid out of the centrifuge.	25%
$C^{centrifuge}$	Maximum fluid processing capacity of centrifuge	≤ 400 liters/minute
$Sc^{centrifuge}$	Solids content in the drilling fluid out of the centrifuge.	Variable
q^{fresh}	Dilution rate of "fresh" drilling fluid to the tank.	Variable
$q^{regenerated}$	Mud outflow from the solid control equipment.	Variable

Table 8-1 Operating parameters of section 17 ½" in the Edvard Grieg field

In order to recover the volume lost in the well and solid control equipment **(solid waste)**, an extra volume of drilling mud must build and pumped to the tank. ***(****q regenerated + q fresh****)***. The process of adding a fresh mud to the system is known as a dilution in the drilling industry. Dilution is also used when the efficiency of the solid control system is not sufficient to keep the solid content as required. In this case, some of the existing fluid is dumped and replaced with a fresh mud with a lower solid content. The notations used in this circulation system are given in the table below with the description.

8.2 Algorithm description

The considered problem is a simple continuous flow problem. The idea of our algorithm is based on the assumption that the system consists of four main components, the components are; well, shale-shakers, centrifuge, and the fresh drilling fluid tank.

For modeling purposes, two variables were made to model drilling fluid flow. This flow is a mixture of two components drilling fluid and solid content, both components are changing in each cycle over the system. The model assumes that these are two separate flows and the summation of these two variables represent the actual fluid flow. Also, in order to model the initial solid content, a constraint is made with an index of (t -1) when t = 2... T, this allows us to define the solid content value in the first cycle. Another constraint was made to define the total initial fluid flow.

In Edvard Grieg Field, the maximum allowed drilling rate of penetration (ROP) is 35 meters per minute (hour?), this rate generates a fixed rate of 155 liters of solids per minute. It means that each minute, the solid content of drilling fluid outflow increases by 155 liters. This model considers a constant parameter to represent solids generation, however, in the real life, ROP is a variable rate, and the generated solids vary widely on this variable.

Four balance flow constraints are built for the four system components to assure that inflow equals to outflow at each point. However, this is not the case for shale-shaker and centrifuge, as they were modeled with a specific separation efficiency and operating capacity. In each cycle, both the shale-shaker and centrifuge processes a specific amount of solid flow and a small fraction of fluid flow, the separation of fluid flow is undesirable in real life situations but it exists and known as slippage volume.

The model suggests two conditions to dilute fresh drilling fluid, either to recover the fluid loss in solid control equipment (shale-shaker and centrifuge) or to keep total solid content rate below 6 percent. A specific cost was used for each liter of dilution volume, this cost includes purchasing drilling fluid cost and the cost of associated logistic activities.

8.2.1 Objective function

In order to define the objective function, the equation described in 4.3.1. Drilling fluid system cost analysis, was used as a starting point, however, it was necessary to identify all the system's elements to fit the system we are considering in this study. Several changes have been made to apply it in this case study.

Logistics cost is one of the cost element we added to the equation. Vessels is the offshore transportation mode in this case study, the higher cost of vessel transportation comparing to trucks is the main reason for adding this element. The previous equation merged the cost of transportation (trucks) to the cost of materials. In order to precisely measure the cost of offshore logistics, it was necessary to add logistics cost to the equation.

On the other hand, the trouble time cost and ROP impact were excluded, see equation (3). Although, the event tree analysis showed that the centrifuge is expected to have some effect on both elements. Warren and Baltoiu (2001) described the unproductive time as the cost of any drilling problems related to the function of drilling fluids. It can also call the trouble time, which represent the time a company spend to solve drilling problems related to drilling fluids. These elements require advance technical details and knowledge about offshore drilling, however, we encourage drilling engineers to include these elements in further studies.

$$\textbf{System cost} = \textbf{Material cost} + \textbf{Associated logistics cost} + \textbf{Solid control system Waste / Disposal cost}. \tag{3}$$

8.3 Mathematical formulation

Nomenclature

Notations	Description
Indices	
t	Time periods
Parameters	
S^{per}	Percentage of fluid waste flow from shakers
S^{rem}	Efficiency of shakers to remove solids
C^{per}	Percentage of fluid waste flow from centrifuge
C^{rem}	Efficiency of centrifuge to remove solids
S^{pro}	Production of solids
C^{fresh}	Cost of fresh fluid (dilution)
C^{cent}	Cost of centrifuge operations per liter of fluids
C^{fw}	Cost of fluids waste handling per liter of the fluid
C^{sw}	Cost of solids waste handling per liter of the solids
$\Delta\tau$	Duration of every time period
T	Number of tie periods
Variables (fluid flow)	
I_t	Amount of fluid injected into the well, $t = 1,..,T$
O_t	Amount of fluid come out from the well, $t = 1,..,T$
α_t	Fluid inflow to shakers from well, $t = 1,..,T$
β_t	Outflow from shaker to tank, $t = 1,..,T$
γ_t	Outflow from shakers to centrifuge, $t = 1,..,T$
μ_t	Waste generated by shakers, $t = 1,..,T$
N_t	Inflow to centrifuge from shakers, $t = 1,..,T$
U_t	Outflow from centrifuge to tank, $t = 1,..,T$
ω_t	Waste generated by centrifuge, $t = 1,..,T$
k_t	Inflow to tank from centrifuge and shakers, $t = 1,..,T$
f_t	Amount of fresh fluid added, $t = 1,..,T$
x_t	Outflow from tank to well (injection again), $t = 1,..,T$

Variables (solids flow)	
y_t	Solids in fluid injected to well, $t = 1,..,T$
z_t	Solids come out from the well, $t = 1,..,T$
l_t	Solids comes to shakers, $t = 1,..,T$
m_t	Solids outflow from shakers to tank, $t = 1,..,T$
n_t	Solids outflow from shakers to centrifuge, $t = 1,..,T$
p_t	Solids waste from shakers, $t = 1,..,T$
q_t	Solids inflow to centrifuge, $t = 1,..,T$
r_t	Solids outflow from centrifuge to tank, $t = 1,..,T$
ϖ_t	Solids waste generated by centrifuge, $t = 1,..,T$
s_t	Solids into the tank from shakers and centrifuge, $t = 1,..,T$
v_t	Solids injected into the well, $t = 1,..,T$

Objective function: minimization of total cost by reducing the amount of diluting fresh drilling fluid. The first term corresponds to the cost of fresh fluid and amount of fresh fluid added to the system. The second term corresponds to the cost of handling the fluid waste from centrifuge and shakers. Similarly, the third term corresponds to the handling cost solids waste generated from centrifuge and shakers.

$$minimize \sum_{t=1}^{T} C^{fresh} . f_t . \Delta\tau + C^{fw} (\omega_t . \mu_t) \Delta\tau + C^{sw} (p_t . \varpi_t) \Delta\tau \qquad (4)$$

Constraints:

1. **Constraints for fluid flow:**

   Subject to

- The amount fluid injected into the well must be equal to the amount of fluid comes out from the well.

$$I_t + y_t = O_t + z_t , \qquad t = 1,..,T \qquad (5)$$

- The amount of fluid comes out from the well must be equal to the inflow to shakers.

$$O_t = \alpha_t , \qquad t = 1,..,T \qquad (6)$$

- The amount fluid comes to shakers must be equal to the outflow from shakers (e.g. tank, centrifuge and removal efficiency).

$$\beta_t + \gamma_t = \alpha_t\,(1 - S^{per}), \quad t = 1,..,T \tag{7}$$

- Constraint about fluid waste shakers, the outflow of fluid waste is equal to the inflow to the shakers and percentage of shakers fluid waste.

$$\mu_t = \alpha_t\,(S^{per}), \quad t = 1,..,T \tag{8}$$

- The amount of fluid send to centrifuge from shakers must be equal.

$$\gamma_t = N_t \;, \qquad t = 1,..,T \tag{9}$$

- The amount of fluid send to tank from centrifuge must be equal to the inflow to centrifuge and percentage of centrifuge fluid waste.

$$U_t = N_t\,(1 - C^{per}), \;\; t = 1,..,T \tag{10}$$

- Fluid waste generated by centrifuge must be equal to the inflow to the centrifuge and percentage of centrifuge fluid removal.

$$\omega_t = N_t\,.\,C^{per}\,, \qquad t = 1,..,T \tag{11}$$

- Outflow from shakers and centrifuge must be equal to the tank inflow.

$$U_t + \beta_t = k_t\,, \qquad t = 1,..,T \tag{12}$$

- Outflow from the tank is equal to the inflow to tank and addition of fresh fluid (dilution).

$$U_t + f_t = x_t\,, \;\; t = 1,..,T \tag{13}$$

- Outflow from the tank is equal to the amount of fluid injected into the well.

$$x_t = I_t\,, \;\; t = 1,..,T \tag{14}$$

2. Constraints for Solids:

- Quantity of solids coming out from the well is equal to the solids generated during the drilling operation and quantity of solids fluid contain while injecting into the well.

$$z_1 = 0 + S^{per} \tag{15}$$

- Connectivity constraint to previous cycle of fluid.

$$z_t \,.\, \Delta\tau_t = y_{t-1} \,.\, \Delta\tau_{t-1} + S^{pro} \,.\, \Delta\tau_{t-1}, \quad \mathrm{t} = 2,..,\mathrm{T} \tag{16}$$

- Inflow of solids into the shakers is equal to the quantity of solids coming out from the well.

$$z_t = l_t \,, \quad t = 1,..,T \tag{17}$$

- Solids waste generated by shakers and solids send to the centrifuge is equal to the solids inflow to shakers from well and solids removed by shakers from total quantity of solids.

$$m_t + n_t = l_t \,(1 - S^{rem}), \quad t = 1,..,T \tag{18}$$

- Solids generated by the shakers, shakers solid removal efficiency.

$$p_t = l_t \,.\, S^{rem} \,, \qquad t = 1,..,T \tag{19}$$

- Solids outflow from shakers and inflow to the centrifuge.

$$n_t = q_t \,, \quad t = 1,..,T \tag{20}$$

- Solids waste generated by centrifuge and efficiency of solid removal from total quantity of solids fluid.

$$r_t = q_t \,(1 - C^{rem}), \quad t = 1,..,T \tag{21}$$

- Solid waste generated by the centrifuge and efficiency of centrifuge to remove solids from fluid.

$$\varpi_t = q_t \,.\, C^{rem} \,, \quad t = 1,..,T \qquad (22)$$

- Solids outflow from shakers and centrifuge must be equal to the solids inflow to tank.

$$r_t + m_t = s_t \,, \quad t = 1,..,T \qquad (23)$$

- Solids balance constraint for tanks: inflow of solids to tanks equal to the outflow from tanks.

$$s_t = v_t \,, \quad t = 1,..,T \qquad (24)$$

- Solids balance constraints for well: solids injected to the well equal to the outflow from tanks.

$$v_t = y_t \,, \quad t = 1,..,T \qquad (25)$$

- The maximum quantity of solids in the fluid can be injected into the well.

$$\frac{v_t}{v_t + x_t} \leq 0.06 \,, \quad t = 1,..,T \qquad (26)$$

- Minimum amount of fluid injected into the well.

$$I_t + y_t \geq 4500, \quad t = 1,..,T \qquad (27)$$

8.4 Computational experiment

The optimization model is coded in AMPL and solved with a student version of MINOS 5.51. The solver MINOS is used for both linear and nonlinear optimization problems. MINOS is developed by Stanford Systems Optimization Laboratory and "It incorporates proven methods for large-scale sparse nonlinear constraints, and its methods are especially effective for nonlinear objectives subject to linear and near-linear constraints". (ampl.com)

Two experiments with two different data sets were performed, the purpose of these experiments is to predict the system performance in two different solid content build up rates. The first experiment considers a solid build rate of 155 liters per minute, this number is valid in 17 ½ inch section when the rate of drilling penetration is 35 meters per minute. The second experiment considers a high solid build up rate of about 1055 liters of solids per minute, this solid build rate is valid for all sections when a caving problem occurs.

- **Computational experiment 1**

This experiment estimates the system performance in ten cycles when each cycle is 1000 minutes long. The optimal solution for this experiment was found in 66 iterations. The below Figure 8-2 represents the average parameters of drilling circulating system.

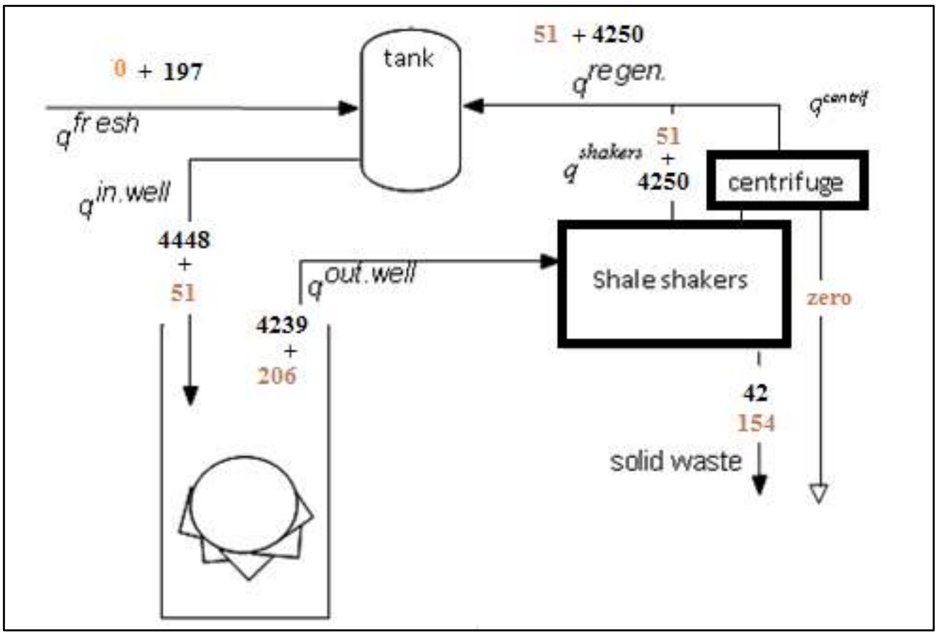


Figure 8-2 Results of computational experiment 1

The figure shows that when the solid build rate is 155 liters per minute, the solid content in the well outflow is going to be 4.9%. Shale shakers will then reduce this percent to 1.1 %, producing 196 liters per minutes. As shale-shakers handles solids to below the maximum allowable content 6%, the system suggests to not flow through the centrifuge.

Findings show that total volume of solids generated in 10 cycles is 1998 liters. Processing this amount of solids the solid control system generates total waste of 1929 liters. To recover this volume, the system dilution cost is 5884 NOK including logistics cost.

- **Computational experiment 2**

This experiment estimates the system performance in ten cycles when each cycle lasts for 1000 minutes. The optimal solution for this experiment was found in 40 iterations. The below Figure 8-3 represents the average parameters of drilling circulation system.

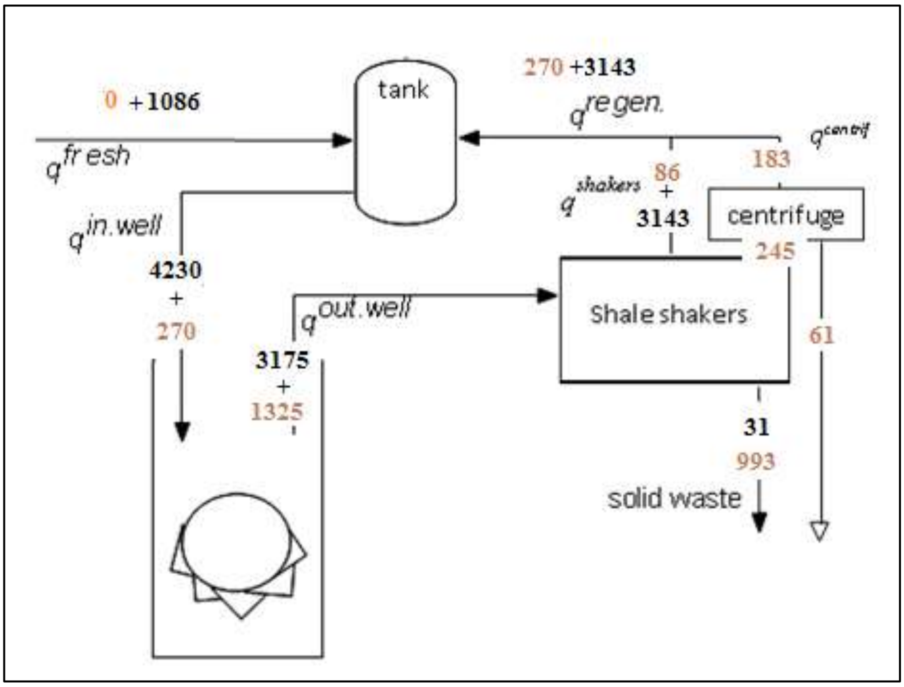


Figure 8-3 Results of computational experiment 2

The figure shows that if the solid build rate increased to 1055 liters per minutes, the solid content in well outflow is going to raise to 29.4%. Shale shakers will then reduce the solid content to 10.5%, producing 1024 liters of waste per cycle. As this percent is above the allowable percent of 6%, the system suggests to use the centrifuge, the centrifuge is going to separate 61 liters of waste per cycle, reducing total solid content to 5.9%.

Findings show that total solids generated in 10 cycles are 12974 liters. Processing this amount of solids in the solid control system will result in generating total waste of 10575 liters. To recover this volume, the system dilution cost is NOK 35956 including logistics cost, which is NOK 7785.

- **Sensitivity Analysis**

In order to estimate the influence of using a centrifuge on the other variables of the drilling fluid circulation system, dilution rate, and disposal volume, we ran the model without a centrifuge and added one more variable **'tank fluids waste (Ω_t)'**. This variable was added to the constraints (24) and (25) to allow the model to dump a specific volume of the drilling fluids and dilute the same volume of fresh drilling fluid in order to keep the solid content less than 6%. The results show that, when centrifuge was not working, the disposal volume increased from 10860 to 11730 liters and dilution rate increased by 1,000 liters in ten cycles.

- In order to define the objective function, several changes were made on the equation proposed by Warren and Baltoiu (2001). To precisely measure the cost of offshore logistics, it was necessary to add logistics cost to the equation. In addition, two elements, trouble time cost, and ROP were excluded, although, the centrifuge is expected to have some effect on both elements. These elements require advance technical details, knowledge about offshore drilling and more time to be estimated.

- The results show that in the current operating parameters of the section 17 ½", the shale shakers can handle the 155 liters of solids generated per minute when drilling fluid flow rate is between 4500 and 5000 liters per minute. For these system parameters, the use of the centrifuge is not required and will result in increasing total operating cost. However, for the many cases when the solid build up rate increases dramatically, using the centrifuge is going to reduce total disposal by 15.3% and 8% of dilution rate.

- The processing capacity of the centrifuge is going to increase total separation efficiency of the solid control equipment. The upgraded solid control system is going to produce 10860 liters of solids. The dilution rate is going to be 10860 in total. This means that the system dilutes only to recover the lost volume of fluids in the solid control system, no extra dilution is required to balance the total solid content in the tank. In this experiment, for 10 cycles, running the centrifuge, saved 1,000 liters of fluid. In addition, it reduced the disposal volume from 11730 to 10860 liters.

There are two purposes of dilution, either to recover separated amount in the solid control system or to keep total solid content less than 6 percent. When the centrifuge is working, the separation efficiency is sufficient to handle the generated volume of solids, therefore dilution rate equals total separated solid volume, however, if the solid control efficiency is not enough, the centrifuge is not working, and a specific volume of fluid must be dumped and replaced with fresh dilution to keep total solids content less than 6%.

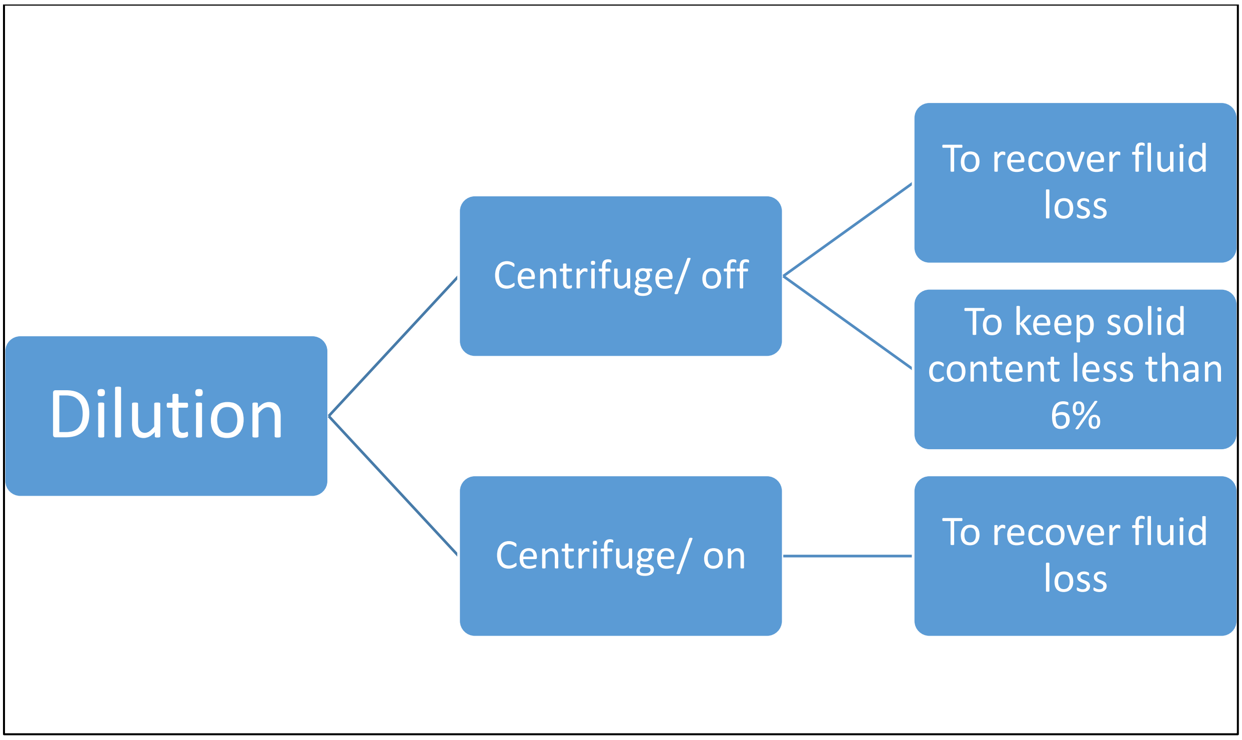


Figure 8-4 Dilution rate

9.0 Summary and conclusion

The oil and gas price fall in 2014 has led operating companies to cut further investment in exploration and production. According to Norwegian Petroleum Directorate 2017, only 36 wells were drilled in 2016 which 47% less than the maximum number of drilled wells in previous years. This also motivates us among other researchers and research institutes to study and develop methods to reduce drilling cost structures.

The design of solid control equipment depends on several technical parameters including well scheme, geological structure, drilling fluid design and solid content rate. Caving problem is the main cause of high solid build up rate in the Edvard Grieg field, especially during drilling Hordaland formation. Caving is a partial collapse of borehole walls, it generates a high amount of cuttings, increasing solid content rate from 155 liters per minute to more than 1000 liters per minutes in average. In the Edvard Grieg, a set of five shale shakers processes high rate of solids with solid processing efficiency of about 75%. In addition, a centrifuge installed to process fine solids, practical parameters in the Edvard Grieg proves that the actual processing capacity of centrifuges is about 400 liters per minute.

Logistics is a key element when it comes to effective and efficient operations and revenue optimization. Logistics accounts 14% of total offshore drilling cost structure (Osmundsen, et al., 2010). Core activities of offshore upstream logistics are storage, transportation and loading and unloading process. Transportation is the most expensive element and it consists of three major cost elements: daily vessel rent, planning and routing cost and operating cost. In addition, there are other marginal costs such as harbor fees. In the Edvard Grieg field, the high daily rent of two vessels is about NOK 269,000. This makes offshore transportation more expensive than other logistics activities, reducing this cost is a difficult task especially if the vessel has only one installation to serve. However, if the vessel is serving several installations, routing, planning and vessel utilization management can contribute to reducing this cost significantly. Operating cost can widely vary depending on sailing conditions. In the Edvard Grieg field, fuel consumption is a major cost element in operating cost, it cost about NOK 18,000 in good weather conditions, however, and this cost jumps to more than double per trip in case of bad weather condition.

The purpose of formulating this research study is to answer the main research question: how upgrading the solid control system influences total system cost and logistical activities. An optimization model is built to describe and predict the behavior of drilling circulating system by using a mathematical programing language. This model allows to understand the current performance and predict the effects of each component in the system on total system production and cost. A continuous flow model was built to simulate drilling fluid circulation system and predict different operating parameters of solid content, disposal amount and dilution volume in Edvard Grieg field. The model calculates values for the three mentioned variables within strict constraints of the maximum allowed solid content into the well, a specific fluid flow rate and operating capacity.

In order to define the objective function, several changes were made on the equation proposed by Warren and Baltoiu (2001). To precisely measure the cost of offshore logistics, it was necessary to add logistics cost to the equation. In addition, two elements, trouble time cost, and ROP were excluded, although, the centrifuge is expected to have some effect on both elements. These elements require advance technical details, knowledge about offshore drilling and more time to be estimated.

The event tree analysis conducted in this study shows that the use of centrifuge contributes in reducing total drilling fluid consumption in case of high solid content rate. The first step when solid content raise is to check the performance of shale shakers and run the centrifuge. Then, if the first step didn't work, the second step is to circulate drilling fluid allowing to carry out more cuttings. The last option is to dilute fresh fluid. To conclude, running the centrifuge reduces the need for diluting fresh drilling fluid when solid content increases and thereby, total drilling fluid consumption.

The findings show that the centrifuge is not used in case of average solid built up rate. In order to make a decision of installing the centrifuge, the preliminary study before drilling a well can play a vital role. Having a complete information about the behavior and strength of the formations to be drilled is a key factor in decision making.

Our findings show that there is no need to run the centrifuge when the solid build rate is 155 liters per minute. However, if the solid content exceeds 1000 liters per minute, the total volume of solids sent of solids to the centrifuge is 2450 liters, this results in a reduction in dilution rate.

The model demonstrates that in 17 ½" section when active circulating fluid is 5000 liters per minutes, drilling operation generates 155 liters of solids per minute, the duration of fluid circulation is 1000 minutes, will generate 155 of solids per minute. The current efficiency of shakers separates 9700 of drill cutting, additionally, 420 liters of associated fluid is wasted as slippage. Finally, the total dilution rate to recover drilling fluid and cutting waste is 1970 liters.

This study concludes the relationship between drilling circulating components, logistics activities and waste volumes. In general, the design of solid control equipment influences total dilution rate and thus total drilling fluid consumption. In Edvard Grieg, the upgrade of the solid control system by adding centrifuge has a small influence on total drilling fluid consumption in regular drilling conditions, however, when solids raise the use of the centrifuge may significantly affect dilution rates. On the other hand, the study concludes that the influence on logistic activities is marginal in Edvard Grieg however, the influence may be greater when several installations are being served.

9.1 Limitations and further research

One of the limitations related to this study is the lack of replications. A study including multiple cases can be more valid and reliable. In this research, a single case study is used out thousand offshore wells is used, this study as a basic tool for further studies.

The analysis is based on data collected from different resources and also uses estimated numbers. Although, authors tried to use numbers as accurate as possible but still there will be a chance of uncertainties. However, this does not have severe effects on the main conclusion of the thesis.

Limitations related to the quantitative part of the study is mainly connected to the lack of availability of secondary data. To the best of the author's knowledge there is no previous studies cover solid control system optimization modeling. Most of the Information used to conduct this research work was mainly based on primary data provided by the Lundin AS in the form of daily drilling reports, daily mud reports, and interviews.

In this case study, 17 ½ inch section was selected to be modeled, however a more integrated model which includes all the five drilling sections is expected to produce more practical and accurate results than smaller per section models.

A fixed rate of 155 liters of solids per meter is applied, this amount of solids is valid in the maximum drilling penetration rate of 35 meters per minutes in the Edvard Grieg field, however, and if the rate changed the volume of solids generated would also change. A further study considering a variable ROP rate of penetration can be more realistic. In addition, an approximate figure was used for waste and discharge cost. The importance of this figure increases when considering an integrated model that includes all drilling sections, as the cost varies from drilling fluid type to another and one hole section to another.

Drilling fluid consumption is a function of several factors. Although this model considers real-life situations and uses real data, several additional practical measures can improve this study e.g. drilling problems. Drilling problems have a significant impact on dilution rates and total drilling fluid consumption.

This study investigates and identifies transportation cost elements in the offshore upstream industry, however, further studies in different geographical locations and company structures can be interesting.

References

Aas, B., Buvik, A. & Cakic, D., 2008a. Outsourcing of logistical activities in a complex supply chain: a case study from the Norwegian oil and gas industry. *International Journal of Procurement MAnagement,* Vol. 1(3).

Aas, B., Gribkovskaia, I., Halskau, Ø. & Shlopak, A., 2007. Routing of supply vessels to petroleum installations. *International Journal of Physics Distribution & Logistics Management,* 37(2), pp. 164-179.

Aas, B., Halskau, Ø. & Wallace, S. W., 2009. Role of supply vessels in offshore logistics. *Maritime Economics and Logistics,* 11(3), pp. 302-325.

Aas, B. & Wallace, S. W., 2008b. Management of logistics planning. *Production Planning and Control.*

Aneichyk, T., 2009. Simulation model for stratigical fleet sizing and operational planning in offshore supply vessels operations. *Master Thesis, Molde University College (HIM).*

ASME, A. S. o. M. E., 2005. Drilling fluids processing handbook.

Bloys, B. et al., 1994. *Designing and Managing Drilling fluids,* s.l.: s.n.

Bourgoyne Jr, A., Millheim, K., Chenevert, M. & Young Jr., F., 1986. *Applied drilling engineering.* s.l.:Society of Petroleum Engineers (SPE).

Bouse, E., 2005. Centrifuge. In: *Drilling fluid processing handbook.* s.l.:s.n., pp. 303-325.

Brun, A., Aerts, G. & Jerkø, M., 2015. *How to achieve 50% reduction in offshore drilling costs,* Designed by Visual Media Europe, Oslo: Oil and gas Practices, Mckinsey & Company..

Caenn, R. & Chillingar, G. V., 1995. Drilling fluids: State of art. *Journal of Petroleum Science and Engineering,* Volume 14, pp. 221-230.

Caenn, R., Darkey, H. & Gray, G. R., 2011. *Composition and Properties of Drilling and Completion Fluids.* Seventh Ed. ed. s.l.:s.n.

Choi, T. M., Chiu, C. H. & Chan, H. K., 2016. Risk Management of logistics system. *Transportation Research Part E,* Volume 90, pp. 1-6.

CSCMP, 2017. *Council of Supply Chain Management Professionals.* [Online] Available at:

http://cscmp.org/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms/CSCMP/Educate/SCM_Definitions_and_Glossary_of_Terms.aspx?hkey=60879588-f65f-4ab5-8c4b-6878815ef921
[Accessed 05 05 2017].

Diaz-de-Baldasano, M. C., Mateos, F. J., Nunez-Rivas, L. R. & Leo, T. J., 2014. Conceptual design of offshore platfrom supply vessels based on hybrid diesel generated fuel cell power plant. *Applied Energy,* Volume 116, pp. 91-100.

Drift, M. v. d. & Weeke, A., 2015. *Offshore Cargo Handling,* Rotterdam: s.n.

Ellram, L. M., 1996. The use of the case study method in logigistics research. *Journal of Business Logsitics,* 17(2), pp. 93-138.

Engh, H. D., 2015. Optimization of an upstream supply chain. *Master Thesis, Norwegian University of Science and Technology (NTNU).*

EnvironmentalNorwegianAgency, 2017. *Environmental Norwegian Agency.* [Online] Available at: http://www.environment.no/topics/marine-and-coastal-waters/oil-and-gas-activities/waste-from-offshore-activities/
[Accessed 20 03 2017].

Facts, 2017. *Ministry of Norwegian Petroleum Directorat.* [Online] Available at: http://www.norskpetroleum.no/en
[Accessed 25 3 2017].

Fourer, R., Gay, D. M. & Kernighan, B. W., 2003. *AMPL: A Modelling Language for Mathematical Programming.* Second Ed. ed. s.l.:s.n.

Growcock, F. & Harvey, T., 2005. Drilling fluids. In: *Drilling fluids processing handbook.* s.l.:American Society of Mechanical Engineers (ASME), pp. 15-66.

Guba, E. G., 1981. ERIC/ECTJ Annual review paper: Criteria for assessing the Trusttworthiness of naturalistic inquiries. *Education, Communication and Technology: Journal of Theory, Research and Development,* 29(2), pp. 75-91.

Huang, D., Chen, T. & Wang, M. J. J., 2001. A fuzzy set approach for Event Tree Analysis. *Fuzzy Sets and System,* Volume 118, pp. 153-165.

Hussain, R., Assavapokee, T. & Khumawala, B., 2006. Supply chain management in the petroleum industry: Challenges and Opportunities. *International Journal of Global Logistics & Supply Chain Management,* 1(2), pp. 90-97.

Jain, V., Wadhwa, S. & Deshmukh, S. G., 2009. Select supplier - related issues in modelling a dynamic supply chain: potential challenges and direction for future research. *International Journal of Production Research,* Volume 47, pp. 3013-3039.

Kothari, C. R., 2004. *Research Methodology: Methods and Technology.* Second ed ed. s.l.:New Age International.

Lawson, D. & Marion, G., 2008. *An Introduction to Mathematical Modelling,* s.l.: s.n.

Leonard, S. A. & Stegemann, J. A., 2010. Stabilization/solidification of petroleum drill cuttings. *Journal of Hazardous Materials,* 174(1-3), pp. 463-472.

Lundin, 2017. s.l.: s.n.

Maisiuk, Y. & Gribkovskaia, I., 2014. Fleet sizing for offshore supply vessels with stochastic sailing and service times. *Procedia Computer Science,* Volume 3, pp. 939-948.

Norlund, E. K., Gribkovskaia, I. & Laporte, G., 2015. Supply vessel planning under cost, environment and robustness considerations.. *Omega, Part B,* Volume 57, pp. 271-281.

Norskolje museum, n.d. s.l.: s.n.

Osmundsen, P., Roll, K. H. & Tveterås, R., 2010. Exploration drilling productivity at the Norwegian Shelf. *Journal of Petroleum Science and Engineering.*

Ramzali, N., Lavasani, M. R. M. & Ghodousi, J., 2015. Safety barriers analysis of offshore drilling system by emplying fuzzy Event Tree Analysis. *Journal of Safety Science,* Volume 78, pp. 49-59.

Rausand, M., 2013. Risk assessment: theory, method and applications.

Rowe, S. J., Gilmore, A. H. & Martin, E., 1995. Improving the safety of offshore supply vessels cargoes. *Transaction on the Built Environment,* Volume 11.

Saad, S., Zulklifli, M. U. & Norlena, H., 2014. Dynamic supply chain capabilities: a case study in oil and gas industry. *International Journal of Supply Chain Management,* 3(2).

Shah, N. K., Li, Z. & Ierapetritou, M. G., 2011. Petroleum refining operations: key issues, advances and opportunities. *Industrial and Engineering Chemistry Research,* Volume 50, pp. 1161-1170.

Shah, S. N., Shanker, P. E. N. H. & Ogugbue, C. C., 2010. Futuer challenges of drilling fluids and their rheological measurements. *American Association of Drilling Engineering, AADE-10-DF-HO-41.*.

Shenton, A. K., 2004. Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information,* Volume 22, pp. 63-75.

Silverman, D., 2001. *Interpreting Qualitative Data: Methods for Analysing Talk, Text and Interaction.* Second Ed. ed. London: Sage.

Silverman, D., 2006. *Qualitative Research: Theory, Method and Practice.* Second Ed. ed. London: Sage.

Sopot, E. & Gribkovskaia, I., 2014. Routing of supply vessels to with deliveries and pickups of multiple commodities.. *Procedia Computer Science,* Volume 3, pp. 939-948.

Warren, B. & Baltoiu, L., 2001. Using a System Cost Analysis to quantify drilling fluids and solid control costs. *AADE, National Drilling Technincal Conference.*

Wiig, A., 2001. Supply chain management in the oil industry: The Angolan case. *Chr. Michelsen Institute Development Studies and Human Rights.*

Williamson, D., 2013. *Oil field review,* s.l.: s.n.

You, X. & Tonon, F., 2012. Event Tree Analysis with imprecise probabilities. *Risk Analysis,* 32(2).

Yunita, P., Irawan, S. & Kania, D., 2016. Optimization of Water based drilling fluid using Non-ionic and Anionic surfactants additives. *4th International Conference on Process Engineering and Advanced Materials,* Volume 148, pp. 1184-1190.

Zhou, D. et al., 2016. Applied propeties of oil based drilling fluids with montmorillonites modified by cationic and anionic surfactants. *Applied Clay Science,* Volume 121-122, pp. 1-8.

Ministry of Petroleum and Norwegian Petroleum Directorate, Facts 2017 – The Norwegian Petroleum Sector. Available at http://www.norskpetroleum.no/en Accessed 25/03/2017

Norskolje Museum Norway, Available at: http://www.norskolje.museum.no/en/category/kadmemap-features-en/bases-kadme-map-features-en Accessed at (29/03/2017).

Appendix

Appendix 1

This interview guide was used in the group interview related to the research study 'Influence of upgraded solid control system on the dilution rate and associated logistical activities'.
The interviews were conducted as semi structured and questions were asked related to the specific field of study to answer the main tasks in the research study. The summary of the questions, asked during the interviews, is given below.
Introduction: Presented ourselves and research topic.
Employees: following employees were usually interviewed during the meetings.

- Bård Fjellså (Production Drilling Manager, Lundin AS)
- Trym Elseth (Lead Drilling Engineer, Lundin AS)
- Bengt Sola (Operation Manager Drilling and Completion Fluids, Baker Hughes)
- Olav Overskott (Head of Logistics, Lundin AS)

The description of each meeting is given below.

I. Analyzing the drilling reports. (1st meeting – 16/02/2017)

Mainly discuss the daily drilling reports, daily mud reports, drilling fluid types and drilling problems related to drilling fluids. In addition, the consumption of drilling fluids for each section. The questions were;

i. What is the average rate of penetration (ROP) and what are the parameters to change the ROP in different sections of the well?

ii. What is the average length of each section and consumed volume of drilling fluids in each section?

iii. How many types of drilling fluids used in different sections?

iv. What is the solid built up rate with normal ROP and in case caving problem?

v. What are the environmental regulations related to the offshore drilling operations and disposal?

Presentation

First meeting

16 february- lysaker

This is how we are doing it!

- **1st Meeting** , which factors in DDRs&DMRs should foucs on investigating the drilling problems and how the use of centrifuge reduced or could reduce the risk of these potential problems. Does it contribute in keeping our mud fresh and decrease mud losses.

What else should we consider?

A/12

- Total drilling time : 63 days.
- productive drilling period: 28 days.
- Non productive drilling period: 35 days.
- Waiting time on solving drilling problems: 20 days (1 problem including cement plug)
- Average ROP: around 25m\hr
- Highest ROP: 52m/hr
- Waiting time on Weather:
- Total mud losses(m3):3695,2
- Total mud discharge: 2346,3

A/10

- Total drilling time : 132 days.
- Productive drilling period: 26 days.
- Non productive drilling period: 106 days.
  - Waiting time on solving drilling problems: 12 days (1 problem stuck pipe)
  - Waiting time on Weather (WOW): 6 days.
  - Wireline & Logging job: 6 days.
  - Coring: 8 days.
  - WOE: 25 days.
- Highest ROP: 35m/hr.
- Total mud losses(m3): 3238,64.
- Total mud discharge: 1711,64.

First meetings agenda

- Look into drilling problems and how the use of the centrifuge reduced or could reduce the risk of these potential problems.
- What are the common problems in Edvard Grieg field
- Caving, tigh hole and stuck pipe
- How much would a problem cost us
- The use of the centrifuge in eliminating these problems/mitigating its sequences .

II. Solid control system, common drilling problems and logistics system. (2^{nd} meeting – 23/02/2017)

Mainly discuss about the recent upgradation in solid control system and role of drilling fluids and solid control system to overcome the common drilling problems. The question were;

Logistics

Cost of the following:

- Drilling Fluids loading and unloading cost?
- Why do you have two vessels with the same capacity but different cost?

What’s your average deck utilization percent?

- Is there any other associated cost related to the transportation of mud from supply base to offshore platform? (Purchasing raw material, transportation, loading and unloading and storage cost, any other cost?

- Operating cost (fuel and operating crew)
- Administrative cost planning and routing
- Fees of harbor
- Handling equipment’s in the base.
- What about maintenance cost?

- The logistics planning, if we need a specific amount of Mud, do you send an extra volume as a back-up? If yes, how much more do you send (%)?

Back-up volume will be mixed and stored at Bakers base facility

- Some of the drilling fluids are sometimes stored on the laid up vessel beside the platform. To calculate this, we need to know the following?
- How often do you send drilling fluids? Ex. each section.
- If you send a specific volume for each section how much is loaded to the platform (%) every day?

This depends on the situation, a boat load will normally be loaded to the rig at arrival.

Weather can be a challenge so mud can be stored on the boat for some days

Logistics costs

Lundin has 2 vessels one for shipping and the other works as storage facility.

Lundin`s logistics coordinator said that up to 800 m^3 of drilling fluids can be shipped each trip. According to this we did the calculations below, and we decided to take an average as there are two prices.

	daily vessel rent	deck space m2	cargo of mud m3	1 m3 cost	average cost
island commander	80,000	650	800	100	168.6875
Viking prince	189,900	650	800	237.375	

We are requesting info about planning, how often they ship mud in order to calculate the storage cost and we will assume that the storage rate for 1 m^3 is the same as transportation, unless a better way is found.

What are your technical parameters for running the centrifuge?

Do you have a specific parameter?

Other questions in the meeting were:

i. What are the common drilling problems, mainly related to the drilling fluids?

ii. What are the steps to overcome these problems?

iii. The role of the drilling fluids and efficiency of solid control system to overcome the problems?

iv. How much a capacity of the solid control system increased by adding a centrifuge? Capacity of the centrifuge?

v. What is the annual cost of using centrifuge?

vi. How much the upgraded solid control system influence the ROP?

vii. How much using a centrifuge minimize the dilution volume?

viii. How many vessels are involved in logistics operations to serve the Edvard Grieg field?

ix. What are main challenges for the logistical activities?

x. The daily rent of vessels?

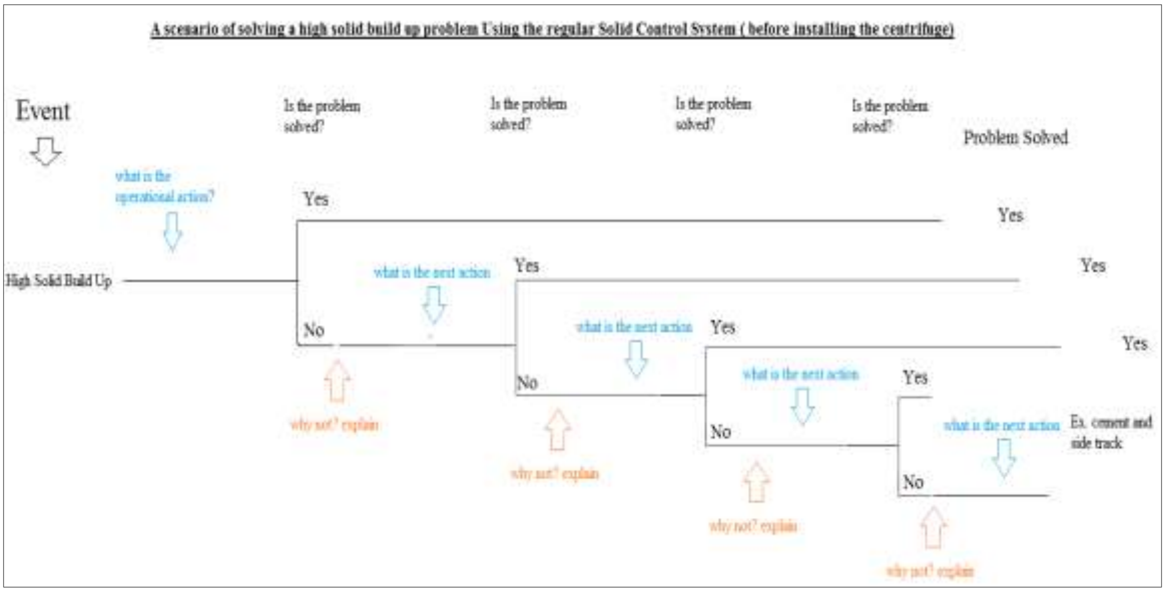
xi. Average fuel consumption in one trip and other related costs?

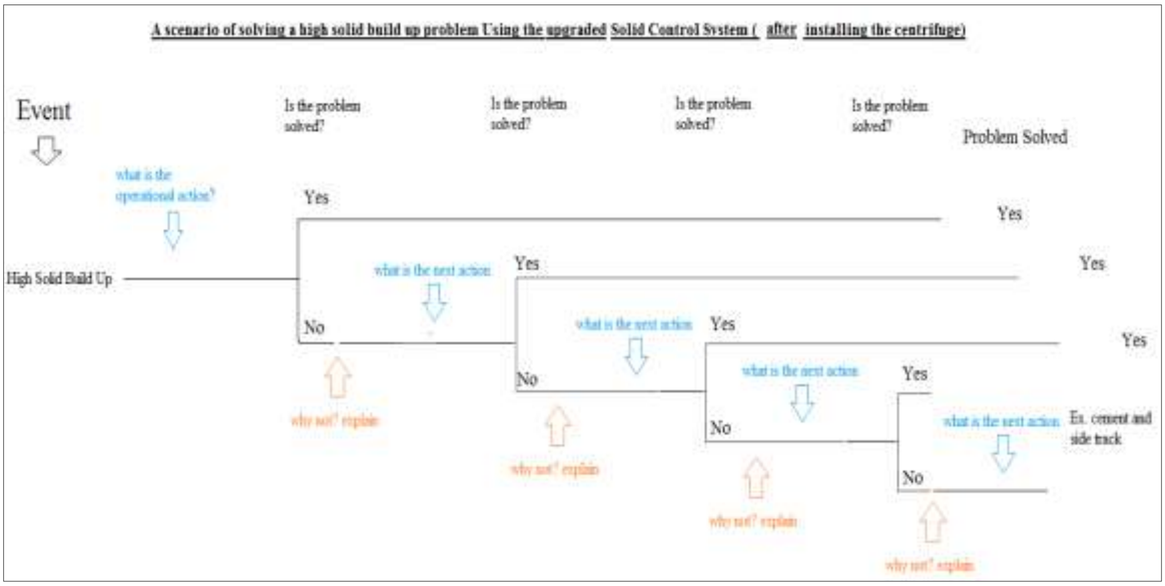
xii. Is there any HSE measures for using and not using the centrifuge? We would like to consider this in our calculations.

Drilling Problems

The below event tree analysis will enable us to quantitatively describe and discuss the effect of the centrifuge in mitigating the sequences of drilling problems. Please have a look on the two scenarios (before/after installing the centrifuge) below and answer the following questions?

- Is it possible to describe the sequences of the solid build up in this way?
- What is the first technical action you do on the platform when the solid content raise?
- Does it always solve the logistics problem? Can you explain why it sometimes doesn't work?
- What are the next actions? Explain.





III. Transportation of drilling fluids and storage. (3rd meeting – 09/03/2017)

Mainly discuss the transportation activities of drilling fluids and inventory management at supply base and offshore platforms. The questions were;

i. How much volume of drilling fluids transported in one trip?

ii. What is the storage plan of drilling fluids at supply base and offshore installation?

iii. How would an upgraded solid control system influence the transportation and storing the drilling fluids?

iv. What are the activities in case of urgent demand of drilling fluids?

v. How they conduct the process of loading and unloading of drilling fluids at the supply base and installation?

- Cost of disposal (the average cost of disposing 1 m^3 of each type of drilling fluids)

Can you explain the disposal process, its types?

- WBM / Slop : 1850,- NOK/MT
- OBM will not be disposed, some slop will be generated ant the above cost will be Used.
- 2400 NOK/MT for cuttings
- In the DMRs, what is the difference between mud losses per length and mud additives per length?

Mud losses is the hole volume lost during drilling Additives will be reported to NEMS (usage of each product- environmental product reporting software)

Note:

The drilling fluid in section 12 ½ " is oil based that's why there is no discharge.
The drilling of A10 was extremely complicated and I wasn't able to find the total discharge.

After approving these results from Lundin AS, we will calculate how much does 1 m^3 of drilling fluid cost them. By adding the transportation, loading unloading storage and disposal cost of 1 m3 of drilling fluid to the purchasing cost of raw materials.
Drilling fluids have different costs for 1 m^3
24" section = NOK 2500

17 ½" = NOK 2800

12 ¼" = NOK 6100

8 ½ " = N/A as we were focusing on the upper sections.

IV. Presentation of results and discussion. (4th meeting – 20/04/02/2017)

We presented the results of the case study and main purpose of this meeting to show the progress so far and get recommendations to improve the results. The main points are;

i. Presented the results of the study and detailed discussion of the results.

ii. Make a comparison of our results with the real life situation.

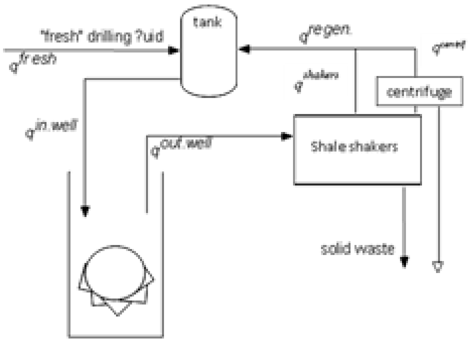
iii. Get the feedback of the professionals to make these results more realistic.

Presentation for 4th meeting

Influences of Upgrading Solid Control System on the Total Sytem Cost and Logistical Activities in Edvard Grieg field

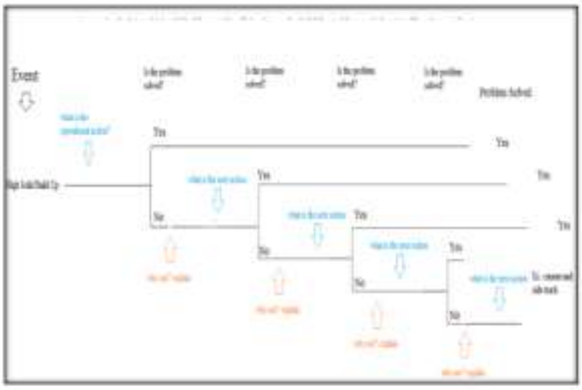
Muarif Sana Dar
Mohamed Ibrahim

Solid Control System at Edvard Grieg field



Solid content and dilution decision

You can think of centrifuge as an additional set of shakers



- Stage One:

Action 1: **monitor** the shakers closely **and screen up** with finer screens when possible.

Possible failure: The success of this approach depends on several factors, such as the actual performance of the shakers + centrifuge, **the dexterity of the shaker hands**, and more importantly drilling ROP and the **temperature of the mud**. Cold mud will plug fine screens and just overflow, likewise with high ROP. Screening up is thus the preferred approach, but you may lose more mud.

- Stage Two:

Action 2: this is a supportive action for the previous one. Circulate the mud system whenever possible when not drilling.

Possible failure: Circulating the mud system runs the mud over the fine shaker screens and removes more solids. So, again it depends on the actual performance of the shakers.

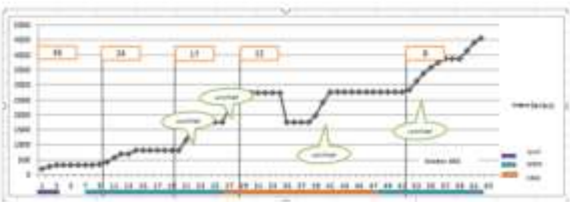
- Stage Three:

Action 3: dilution, which is often used in addition to the other two methods

Possible failure: One of the main problems with dilution, especially for lengthy sections is pit space. Space is a luxury offshore, and you must manage it carefully. In addition, you build excess mud that must be disposed of, causing logistic cost in addition to material costs.

Operating times of Centrifuge (A1 and A-12)

Date	On / Off	Solids Removed (Mt)	Comment
06/08	15:00 – 00:30	19.5	1900 rpm
07/08	14:30 – 24:00	16.1	1900 rpm
10/08	21:00 – 09:30	17.0	1900 rpm
12/08	00:30 – 11:30	23.2	1900 rpm
13/08	01:15 – 16:00	32.6	1900 rpm
15/08	09:30 – 20:15	21.0	1900 rpm
16/08	10:30 – 22:30	19.8	1900 rpm
17/08	14:30 – 16:30	8.3	2600 rpm
17/08	19:30 – 24:00	11.9	2600 rpm
18/08	14:00 – 17:20	12.2	2600 rpm
18/08	20:20 – 23:15	8.0	2600 rpm

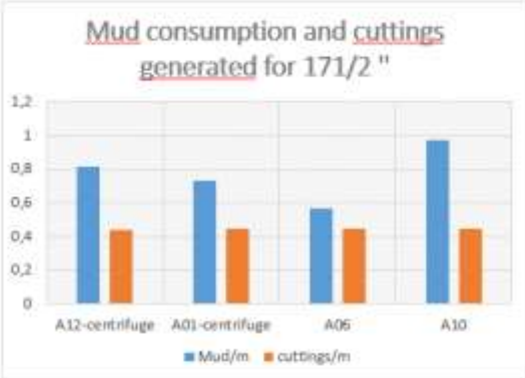


Mud consumption in 17 ½''

	well	drilling Length	mud consumption	cutting to sea	Mud/m	cuttings/m
centrifuge	A12	925	751	410	0,811892	0,4432432
centrifuge	A01	1260	920	559	0,730159	0,4436508
	A06	853	484	379	0,567409	0,4443142
	A10	669	651	297	0,973094	0,4439462

Average drilling length in 17'' section is **927** m
Min- Mud consumption(m3/m) @ A06 = 0,56
Max- Mud consumption(m3/m) @ A10 = 0,97
Min-max difference is 0,410 m3/m
Cost of mud 2800 + logistics cost

Potential savings if we drilled in our min mud consumption rate.
Savings = 0,410 * 927*2800 = 1,064,196 NOK



Cost of diluting 1 m3 mud in 17 ½ ''

buy
- 2800 NOK
- Direct purchasing cost

load & unload
- NOK
- Cost of time spent in loading/unloading

transport
- 250 NOK
- If the consumption exceeds 800m3, 1m3 costs about 500 NOK

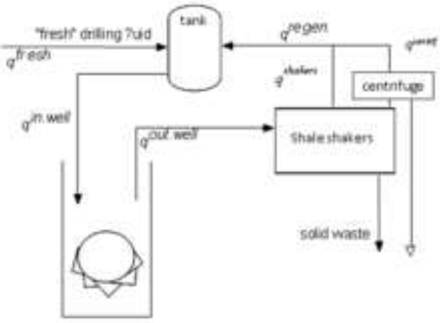
store
- NOK
- What is the max pit capacity + how long will be stored

Disposal & treatment
- NOK
- Environment concern + discharge to sea + treatment (if applicable)

Element	Cost
Daily rent of Viking prince / Max capacity	80,0000 NOK per day / 800 m3.
Daily rent of commander / Max capacity	189, 000 NOK per day / 800 m3.
Fuel consumption in good weather conditions	18,000 to 35,000 NOK per trip.
Fuel consumption in bad weather conditions	Up to 70,000 NOK per trip.
Planning logistic activates at Lysaker	Full time employment
Coordinating logistics activates in Tananger	3000 NOK per day.
vessel's crew	Full time employment
Harbor fees and other administrative cost	Marginal
Mud cargo	Each section
Max- min mud consumption 17" section	Well-A6 = 484 m3 / well-A1 = 920 m3

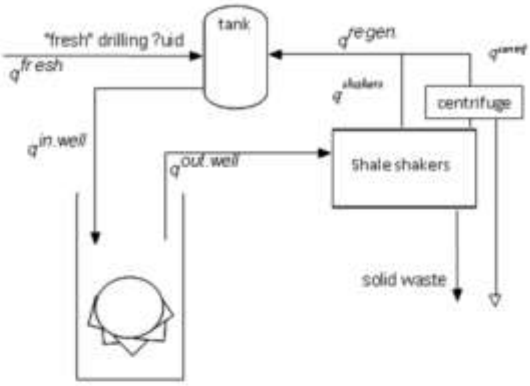
Model of Drilling fluid Circulating System

Notation	Description
$q^{in.well}$	Flow rate of the drilling fluid delivered to the well.
$Sc^{in.well}$	Solids content in the fluid delivered to the well.
$q^{out.well}$	Flow rate of the used drilling fluid delivered from the well to the Solid control system.
$Sc^{out.well}$	Solids content in the fluid coming from the well.
$q^{shakers}$	Flow rate of drilling fluid out of the shakers.
$Sc^{shakers}$	Solids content in drilling fluid out of the shakers.
$q^{centrifuge}$	Flow rate of drilling fluid out of the centrifuge.
$Sc^{centrifuge}$	Solids content in the drilling fluid out of the centrifuge.
q^{fresh}	Dilution rate, flow rate of "fresh" drilling fluid to the pits.



System parameters & variables (17 ½ '')

Notation	value
Min-Max $q^{in.well}$	**4000 to 5000** liters/minute
$Sc^{in.well}$	Less than **6%**
$q^{out.well}$	**4000 to 5000** liters/minute
$Sc^{out.well}$ *ROP*	generated solid = ROP* **4.4** Liters for each meter/hr 35 m/hr
Min-Max $q^{shakers}$	maximum **4000 to 5000** liters/minute
$Sc^{shakers}$	N/A %
Max $q^{centrifuge}$	maximum **757** liter/minute
$Sc^{centrifuge}$	N/A %
Cost $q^{shakers}$	0
Cost $q^{centrifuge}$	0
Cost q^{fresh}	How much does 1 m3 cost
$q^{centrifuge}$	variable
q^{waste}	variable
$q^{regenerated}$	variable
q^{fresh}	variable
q	variable



Assumptions / constraints

- Drilling fluid circulating volume is fixed.
- In flowrate equals out flowrate.

$$q^{in\ well} = q^{out\ well}$$

- Any loss by solid control equipment is recovered by dilution.

$$q^{dilution} = q^{in\ well} - q^{regenerated\ (out\ of\ SCS)}$$

- There is no losses other than solid separation loss.

$$q^{regenerated\ (out\ of\ SCS)} = q^{shakers} + q^{centrifuge}$$

- Fixed ROP is 35 m/h.
- Solid build up rate is fixed.

Objective functions

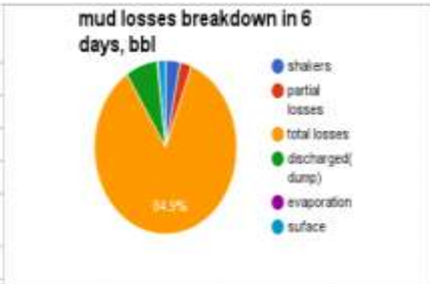
- Is suggesting that we need the centrifuge but is there a better way to operate it and reduce mud consumption.

- Minimize dilution rate
- Maximize $q^{centrifuge}$

Appendix 2

Illustrative case study

mud losses breakdown		
loss	bbl	note
shakers	511	
partial losses	397	formation
total losses	12,973	formation
discharged(dump)	1,105	according to the initial parogram
evaporation	30	
suface	270	



in this case, in 2016, from Saudi Aramco, there were no use of centerfuges in the system. there is no specific reason why cenerfuge is not used.

the total discharge, in 6 days of drilling 16 inch hole, was 1105 bbls, according to the calculations below bulding 1105 bbls costs **9157** usd. However, we could avoid dumping this amount by using the centerfuges costing (6 days *667 usd= 4002 usd). some of the mud components are not icluded in the calcs below they must be used in both cases.

	lb/ bbl	lb/1105 bbl	cost	price per unit	component cost usd	centrefuge	
Water	0.86	950.3				667	
Soda ash	0.25	276.25	110 lb =27.9 usd	0.25	69.0625		
Bentonite	5	5525	2500lb = 450 us	0.18	994.5	4002	
starch	4	4420	*50lb = 38 usd*	0.76	3359.2		
XC Polymer	1	1105.0	50lb/ 133usd	2.66	2939.3		
Defoamer	0.1	110.5	55gal/drum =25	4.55	502.775		
Sodium chloride	7.7	8508.5	2200 lb/sack	n/a	n/a		
ID cap or New drill plus	1.5	1657.5	50 lb/sack=38	0.76	1259.7		
Caustic soda	0.1	110.5	*50lb = 15 usd*	0.3	33.15		
Nut plug	15	16575	50lb/sack=9	0.18	~~2983.5~~		avarage
MICA fine	15	16575	50lb/sack=8	0.16	~~2652~~		
Mica C	5	5525	50lb/sack=8	0.16	~~884~~		
Brofiber M	15	16575	25lb/sack=11	0.44	~~7293~~		
					9157.6875		

Appendix 3

Total Mud consumption
652,6
1120,9
920,1
97

24 "

	total consumption	losses M3/m
A1 upgraded system	1120	1,94
A6	1412	2,164
A10	557	1,3
A12 upgraded system	1291	2,64

Total Mud consumption
853
1412
484
492
330
387

17 ½ "

	total consumption	losses M3/m
A1 upgraded system	920	0,73
A6	484	0,568
A10	651	0,628
A12 upgraded system	761	0,6

12 ¼ *13"

	total consumption	losses M3/m
A1 upgraded system	765	0,42
A6	492	0,982
A10	695	0,927
A12 upgraded system	312	0,32
A12 /T2 upgraded system	261	0,23

Total Mud consumption
478
557
651
695
150

8 ½ "

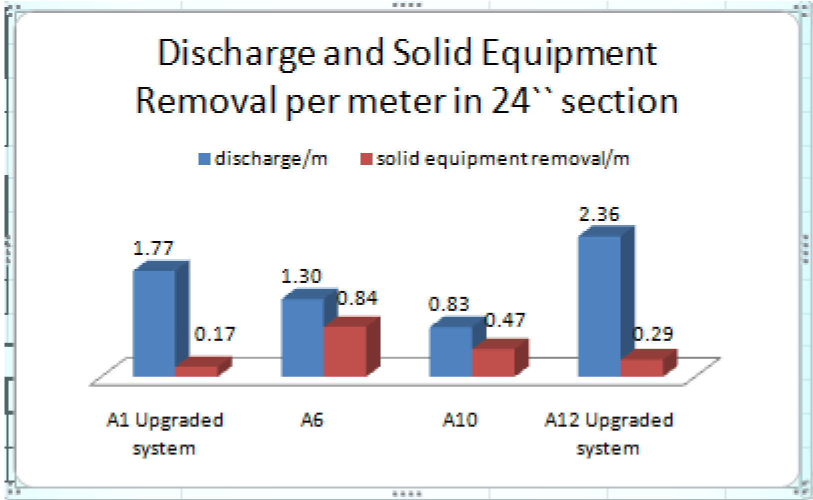
Total Mud consumption
681
1291
761
312

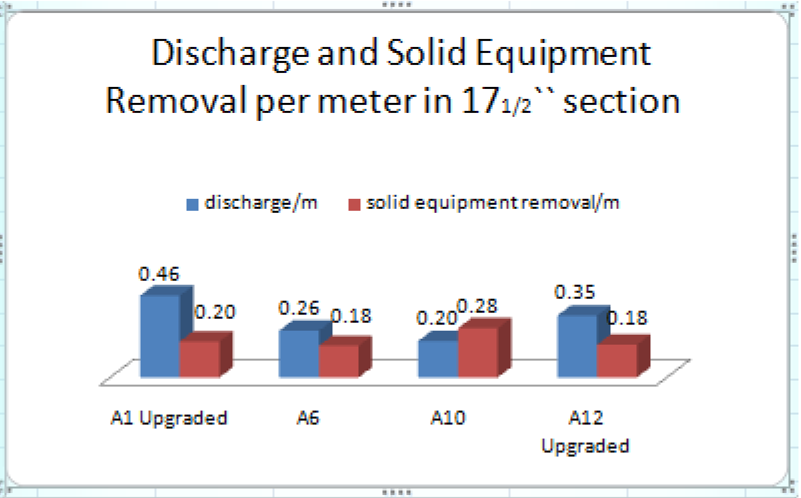
	Total consumption	losses M3/m
A1 upgraded system	413	0,26
A6	330	0,409
A10	150	0,467
A12/T2 upgraded system	1014	0,39

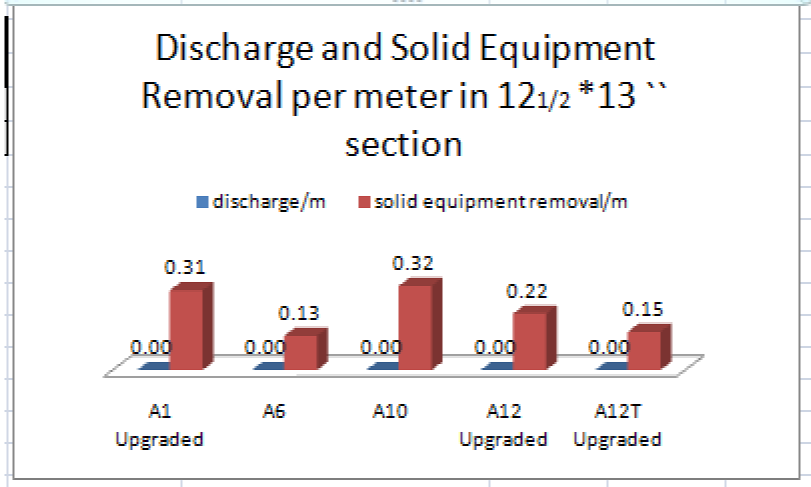
Graphs below show the total consumption and losses per meter in each section for the four drilled wells, the upgraded system is the well with centrifuge. The mud losses per meter is what we will consider as wells have different drilled length.

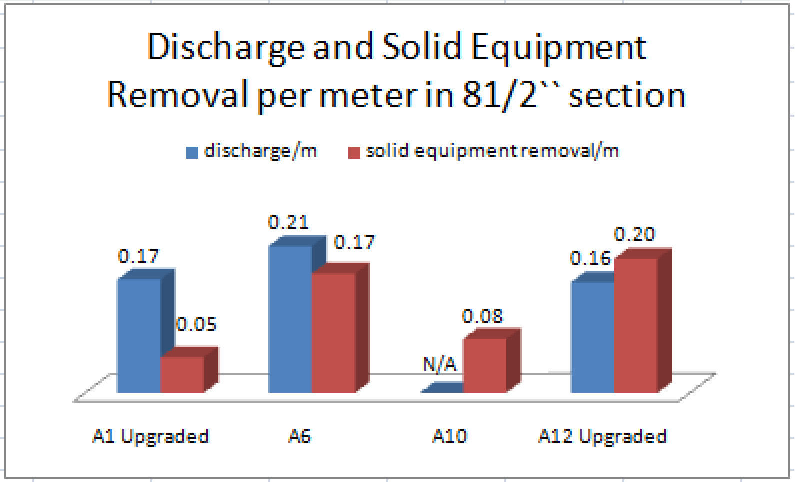
When we discussed the possibility of saving money by reducing discharge and thus dilution, we were advised to study 24" and 17 ½" sections as the savings could be higher there however, the centrifuge were not runing in any of these section , as they were allways starting it in 12 ½ " and 8 ½"sections, We then decided to study the two lower sections, 12 ½" and 8 ½".

In 24" and 17 ½ ", the upgrade of the system has no effect as numbers are random. However, in 12 ¼ " and 8 ½ " sections, its clear that the consumption per meter is lower where the upgraded system operates. The figures in red shows that the consumption is always less (30 to 40%) in the case of the centrifuge.


Discharge and Solid Equipment Removal per meter in 24`` section
discharge/m
solid equipment removal/m
1.77
0.17
1.30
0.84
0.83
0.47
2.36
0.29
A1 Upgraded system
A6
A10
A12 Upgraded system


Discharge and Solid Equipment Removal per meter in 17 1/2`` section
discharge/m
solid equipment removal/m
0.46
0.20
0.26
0.18
0.20
0.28
0.35
0.18
A1 Upgraded
A6
A10
A12 Upgraded


Discharge and Solid Equipment Removal per meter in 12 1/2 *13 `` section
discharge/m
solid equipment removal/m
0.00
0.31
0.00
0.13
0.00
0.32
0.00
0.22
0.00
0.15
A1 Upgraded
A6
A10
A12 Upgraded
A12T Upgraded


Discharge and Solid Equipment Removal per meter in 81/2`` section
discharge/m
solid equipment removal/m
0.17
0.05
0.21
0.17
N/A
0.08
0.16
0.20
A1 Upgraded
A6
A10
A12 Upgraded

Appendix 4

Percentage of raw material in drilling fluid used in all sections of well A-1.

											Loss	Total Mixed				
#	Date	System	Type	Section	Recieved	Returned/Backloaded	Start Volume	Final Volume	Total Mixed	Discharge	m^3/m	Total Loss	Base Fluids	Water	Weight Material	Add. Chemicals
1	10.07.2016			36	598			598								
2	11.07.2016			36			598	526	54,6	126,6	1,46	126,6		53		1,6
3	12.07.2016	Spud		36			526			526	9,92	526				
4	13.07.2016															
5	14.07.2016															
					598		1124	1124	54,6	652,6	11,38	652,6		53		1,6
6	15.07.2016			24	600			615,5	15,5						15,5	
7	16.07.2016			24			615,5	615,5								
8	17.07.2016			24			615,5	615,5								
9	18.07.2016			24			615,5	615,7	0,2							0,2
10	19.07.2016			24			615,7	610,9		4,8		4,8				
11	20.07.2016			24	430		610,9	990,1	17,3	28	0,21	68,1	10		3,1	4,2
12	21.07.2016	AQUA-Drill			311		990,1	1102,2	77,2	239,1	2,05	276,1	40	30		7,2
13	22.07.2016					230	1102,2	854,1		18,1		18,1				
14	23.07.2016		Water				854,1	831		23,2		23,2				
15	24.07.2016						831	725		106		106				
16	25.07.2016						725	340		385		385				
17	26.07.2016						340	340								
18	27.07.2016						340	330,4		9,6		9,6				
					1341	230	8255,5	8585,9	110,2	804,2	2,26	881,3	50	30	18,6	11,6
19	28.07.2016			17,1/2	438		330,4	760,3	22,9	5	0,3	31	12		5,2	5,7
20	29.07.2016				195		760,4	882,4	22	25	0,19	95			15,5	6,5
21	30.07.2016				180		882,4	939,8	14,3	70	0,35	136,9			10,2	4,1
22	31.07.2016				28		939,8	974,6	10,5		0,11	3,8			6,9	3,6
23	01.08.2016						974,6	909,3	14,9	48	0,37	80,2			11,2	3,7
24	02.08.2016						909,4	873,7	9,4			45			7,9	1,5
25	03.08.2016						873,8	864				9,8				
26	04.08.2016					74	864	526,1	0,1	174		264				0,1
27	06.08.2016					271,3	526,1		254,8	254,8						
					841	345,3	7060,9	6730,2	348,9	576,8	1,32	665,7	12		56,9	25,2
28	06.08.2016			12,1/4	545			528,2	0,2		0,77	17				0,2
29	07.08.2016				206		528,2	744,3	31		0,05	20,9		20	5,5	5,5
30	08.08.2016				190		744,3	949,4	36,1		0,06	21	10		19	7,1
31	09.08.2016						949,5	920,5	10,2		0,18	39,2			8,1	2,1
32	11.08.2016						920,5	900	1,7			22,2			1,7	
33	11.08.2016						900	893,5	0,5			7				0,5
34	12.08.2016						893,5	850,8	9,1		0,16	51,8			4,5	4,6
35	13.08.2016						850,8	817,8	8		0,16	41				8
36	14.08.2016				150		817,8	919,6	12,9		0,26	61			8,3	4,5
37	15.08.2016						919,6	892,5	11,9			39			11,9	
38	16.08.2016						892,5	848,6	9,1			53			4,8	4,4
39	17.08.2016	carbo-sea	invert-emul				848,7	769	3,3			83			2,1	1,2
40	18.08.2016						769	739,7	21,7			51			20,7	1
41	19.08.2016						739,6	717,7	54,1			76	20	15	16,9	2,1
42	20.08.2016				274	75	717,7	904,6	13,9			26			13,1	0,8
43	21.08.2016						904,6	900	12,1			16,6			11,9	0,2
44	22.08.2016					113	900,1	784,6				2,5				
45	23.08.2016						784,6	767,7				16,8				
46	24.08.2016					77	767,8	558,7				132,1				
47	25.08.2016					314	558,6	248,5				-3,9				
48	26.08.2016					29,8	248,5	226,9				-8,2				
49	27.08.2016						226,9	226,9								
50	28.08.2016						226,9	226,9								
51	29.08.2016						226,9	226,9								
					1365	608,8	16336,6	16563,3	235,8		1,64	765	30	35	128,5	42,2

52	30.08.2016			8,1/2	469			452,9				16,1				
53	31.08.2016						452,9	448				4,9				
54	01.09.2016						448	456	12			4		10,8		1,2
55	02.09.2016	Perfflow-CM	Water		52		456	510,6	7,1		0,03	4,5				7,1
56	03.09.2016						510,6	483,4	44,6	65	0,22	71,9		40		4,6
57	04.09.2016						483,3	503,4	39,3		0,19	19,3		35		4,3
58	05.09.2016					110	503,3	382,4		10,9		10,9				
59	06.09.2016					360,6	382,5			21,9		21,9				
60	07.09.2016							587,9	587,9				220	348		19,9
61	08.09.2016						588	524,5				63,5				
62	09.09.2016						524,5	240,5		260		284				
63	10.09.2016						240,5	248,2	10,7			3	10			0,7
64	11.09.2016						248,2	607,3	359,1				117	231		11,1
65	12.09.2016						607,3	604,8				2,5				
66	13.09.2016						604,7	575,2	54,4			84	26	26		2,4
67	14.09.2016	Sodium Chloride	Brine	Complition			575,2	596,2	41			20	18	23		
68	15.09.2016						596,2	423,2	100	262		273	15	85		
69	16.09.2016						423,2	416,2				7				
70	17.09.2016						416,1	408,1				8				
71	18.09.2016						408,1	395,5		12,6		12,6				
72	19.09.2016						395,5	386,1	26	35,4		35,4		25		1
73	20.09.2016						386,1	386,1								
74	21.09.2016						386,1			244,9		386,1				
					521	470,6	9636,3	9636,5	1282,1	912,7	0,44	1332,6	406	823,8		52,3

Percentage of raw material in drilling fluid used in all sections of well A-6.

#	Date	System	Type	Section	Start Volume	Recieved	Returned/Backloaded	Total Mixed	Total Loss	Final Volume	Discharge	Loss m^3/m	Total Mixed: Base Fluids	Water	Weight Material	Add. Chemicals	Brine	Density sg	Density AF	LGS/HGS %
1	24.03.2015			36		665		24,16		689,16					23,1	1,07		1.03-1.40	1,03	
2	25.03.2015			36	689,16	164		54,6	148,16	705	148,16	1,46						1.03-1.40	1,07	
3	26.03.2015			36	705				92	613	92	2,14						1.03-1.40	1,4	
4	27.03.2015	Gel/Polymer	Water	36	613				613		613	5,42						1.03-1.40	1,4	
5	28.03.2015			36	Run Casing															
6	29.03.2015			36	Cementing															
7	30.03.2015			36	Miscellaneous															
8	31.03.2015			36	Miscellaneous													1.03-1.40	1,08	
					2007,16	829		78,76	853,16	2007,16	853,16	9,02			23,1	1,07				
9	01.04.2015			24		767		101,54	29,87	838,67	3	0,13	50	50		1,54		1.08-1.20	1,08	<175.00
10	02.04.2015			24	838,67	204		203,59	356,21	890,04	60	1,25	100	100		3,59		1.08-1.20	1,16	<175.00
11	03.04.2015			24	890,05	115		193,18	186,7	1011,52		1,39	100	90		3,18		1.08-1.20	1,17	<175.00
12	04.04.2015			24	1011,53	99	342,5	101,62	27,03	842,62		6,76	45	55		1,62		1.08-1.20	1,17	<175.00
13	05.04.2015	KCL/Polymer	Water	24	842,62				7,66	834,96								1.08-1.20	1,18	<175.00
14	06.04.2015			24	834,96				135,05	699,91	118,78							1.08-1.20	1,18	<175.00
15	07.04.2015			24	699,92		14,7		376,3	308,92	376,3							1.08-1.20	1,18	<175.00
16	08.04.2015			24	308,92					308,92								1.08-1.20	1,18	<175.00
17	09.04.2015			24	308,92				287,92	21	287,92							1.08-1.20	1,18	<175.00
					5735,59	1185	357,2	599,93												
18	10.04.2015			17,1/2	21	602		4,52	55,41	572,11	14,73	0,2			4,52			1.35-1.45	1,35	
19	11.04.2015			17,1/2	572,11	254		29,27	52,29	803,08	5	0,15			25	4,27		1.35-1.45	1,44	
20	12.04.2015				803,08			0,48	13,4	790,16	25	0,46				0,48		1.35-1.45	1,45	
21	13.04.2015	AQUA DRILL	Water		803,08			0,48	13,4	790,16	70	0,46				0,48		1.35-1.45	1,45	
22	14.04.2015				750,85			5	7,24	748,61					5			1.35-1.45	1,45	
23	15.04.2015				748,62		222		100,36	426,26								1.35-1.45	1,45	
24	16.04.2015				426,25				3,08	423,17								1.35-1.45	1,46	
25	17.04.2015				423,18		212	0,05	211,23		209	42,25				0,05		1.35-1.45	1,46	
26	18.04.2015			12,1/4"13,1/2		433		16,5	72,49	377,01		0,17	12		2,86	1,64		1.55-1.60	1,53	<8.00
27	19.04.2015			12,1/4"13,1/2	377,01	210		10,8	124,22	473,59		1,83			10,48	0,32		1.55-1.60	1,55	<8.00
28	20.04.2015			12,1/4"13,1/2	473,59	200		97,81	143,41	627,99			94		3,81			1.55-1.60	1,54	<8.00
29	21.04.2015			12,1/4"13,1/2	627,98			1,9		629,89					1,9			1.55-1.60	1,55	<8.00
30	22.04.2015			12,1/4"13,1/2	629,89	202		1,18	42,12	790,94						1,94		1.55-1.60	1,55	<8.00
31	23.04.2015			12,1/4"13,1/2	790,95				44,47	746,48								1.55-1.60	1,55	<8.00
32	24.04.2015			12,1/4"13,1/2	746,48		381		13,94	351,54								1.55-1.60	1,4	<8.00
33	25.04.2015	carbo-sea	invert-emul	12,1/4"13,1/2	351,54				21,9	329,64								1.55-1.60	1,41	<8.00
34	26.04.2015			12,1/4"13,1/2	329,64				7,1	322,54								1.55-1.60	1,4	<8.00
35	27.04.2015			12,1/4"13,1/2	322,54				1,6	320,94								1.55-1.60	1,4	<8.00
36	28.04.2015			12,1/4"13,1/2	320,94				0,6	320,34								1.55-1.60	1,4	<8.00
37	29.04.2015			12,1/4"13,1/2	320,34				2,4	317,94								1.55-1.60	1,4	<8.00
38	30.04.2015			12,1/4"13,1/2	317,94					317,94								1.55-1.60	1,4	<8.00
39	30.04.2015			12,1/4"13,1/2	317,94				0,4	317,54								1.55-1.60	1,4	<8.00
40	02.05.2015			12,1/4"13,1/2	317,54		300		17,54									1.55-1.60	1,4	<8.00
41	03.05.2015			8,1/2		553		12,48	35,38	530,1		0,18				6,48	6	>1.15	1,16	<6.00
42	04.05.2015			8,1/2	530,1			13,83	31,52	512,41		0,1		9		4,83		>1.15	1,15	<6.00
43	05.05.2015	Perfflow-CM	Water	8,1/2	512,42			78,7	35,9	555,82		0,18		72		6,7		>1.15	1,16	<6.00
44	06.05.2015			8,1/2	555,83			85,12	161,78	479,17	121	0,7		80		5,12		>1.15	1,16	<6.00
45	07.05.2015			8,1/2	479,16			22,07	101,67	399,56	61	20,33		20		2,07		>1.15	1,16	<6.00
46	08.05.2015			8,1/2	399,56		220		21,36	158,2	21,36							>1.15	1,16	<6.00
47	09.05.2015			Lower Comp	158,2	327		5,5	44	446,7	44					5,5		>1.15	1,15	
48	10.05.2015			Lower Comp	446,7			8	54,9	399,8	6						8	>1.15	1,15	
49	11.05.2015	SFCF	Water	Lower Comp	399,8		145		16	238,8	16							>1.15	1,15	
50	12.05.2015			Lower Comp	238,8				12	226,8	12							>1.15	1,15	
51	13.05.2015			Lower Comp	226,9				68,8	158										
52	13.05.2015			Upper Comp	158			400,38	162	396,38	162		300	100		0,38		0	1,15	
53	14.05.2015			Upper Comp	404,38				4	400,38	4							0	1,15	
54	15.05.2015			Upper Comp	[illegible]				1	[illegible]	1							0	1,15	

52	13.05.2015	Other	Water	Upper Comp	158			400,38	162	396,38	162		300	100		0,38		0	1,15	
53	14.05.2015			Upper Comp	404,38				4	400,38	4							0	1,15	
54	15.05.2015			Upper Comp	400,47				1	399,47	1							0	1,15	
55	16.05.2015			Upper Comp	399,47				4,91	394,56								0	1,15	
56	17.05.2015			Upper Comp	394,17				7,03	387,54		23,43						0	1,15	
57	18.05.2015			Upper Comp	387,54				387,54		256,31							0	1,15	
58	19.05.2015			Upper Comp	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
59	05.09.2016				503,3		110		10,9	382,4	10,9							>1.150	1,15	6.00-11.00
60	06.09.2016				382,5		360,6		21,9		21,9							>1.150	1,15	6.00-11.00
					885,8	0	470,6	0	32,8	382,4	32,8	0		0		0				
61	07.09.2016	odium Chlorid	Brine	Complition				587,9		587,9			220	348		19,9		0	1,16	0
62	08.09.2016				588				63,5	524,5								0	1,06	0
63	09.09.2016				524,5				284	240,5	260							0	1,06	0
64	10.09.2016				240,5			10,7	3	248,2			10			0,7		0	1,06	0
65	11.09.2016				248,2			359,1		607,3			117	231		11,1		0	1,06	0
66	12.09.2016				607,3				2,5	604,8								0	1,06	0
67	13.09.2016				604,7			54,4	84	575,2			26	26		2,4		0	1,06	0
68	14.09.2016				575,2			41	20	596,2			18	23				0	1,06	0
69	15.09.2016				596,2			100	273	423,2	262		15	85				0	1,06	0
70	16.09.2016				423,2				7	416,2								0	1,06	0
71	17.09.2016				416,1				8	408,1								0	1,06	0
72	18.09.2016				408,1				12,6	395,5	12,6							0	1,06	0
73	19.09.2016				395,5			26	35,4	386,1	35,4			25		1		0	1,07	0
74	20.09.2016				386,1					386,1								0	1,07	0
75	21.09.2016				386,1				386,1		244,9							0	1,07	0
					6399,7			1179,1	1179,1	6399,8	814,9		406	738		35,1				

Percentage of raw material in drilling fluid used in all sections of well A-10.

	Mud losses						
section	Discharge	solid c sys	ceased off	downhole	left in hole	onshore disp.	Others
36``	478,67	0					
24``	357,47	199.64	0				
17 1/2``	136,5	184,17	68				
13``	0	242,71	52,72	308,66		42	
8 1/4``		24,24					
re\entry	4	63			32,1	141,9	
sidetrack	32	31,2	24,3				
8 1\2 T2	150	75		49	17		
l\u comp	553			14	87		
total	1711,64	620,32	145,02	371,66	136,1	183,9	70
total	3238,64						
	1711,64	620,32	145,02	371,66	136,1	183,9	70

Percentage of raw material in drilling fluid used in all sections of well A-12.

3 **Well status**

3.1 **As drilled Schematic**

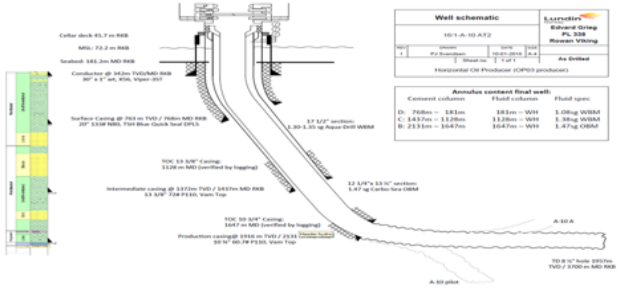
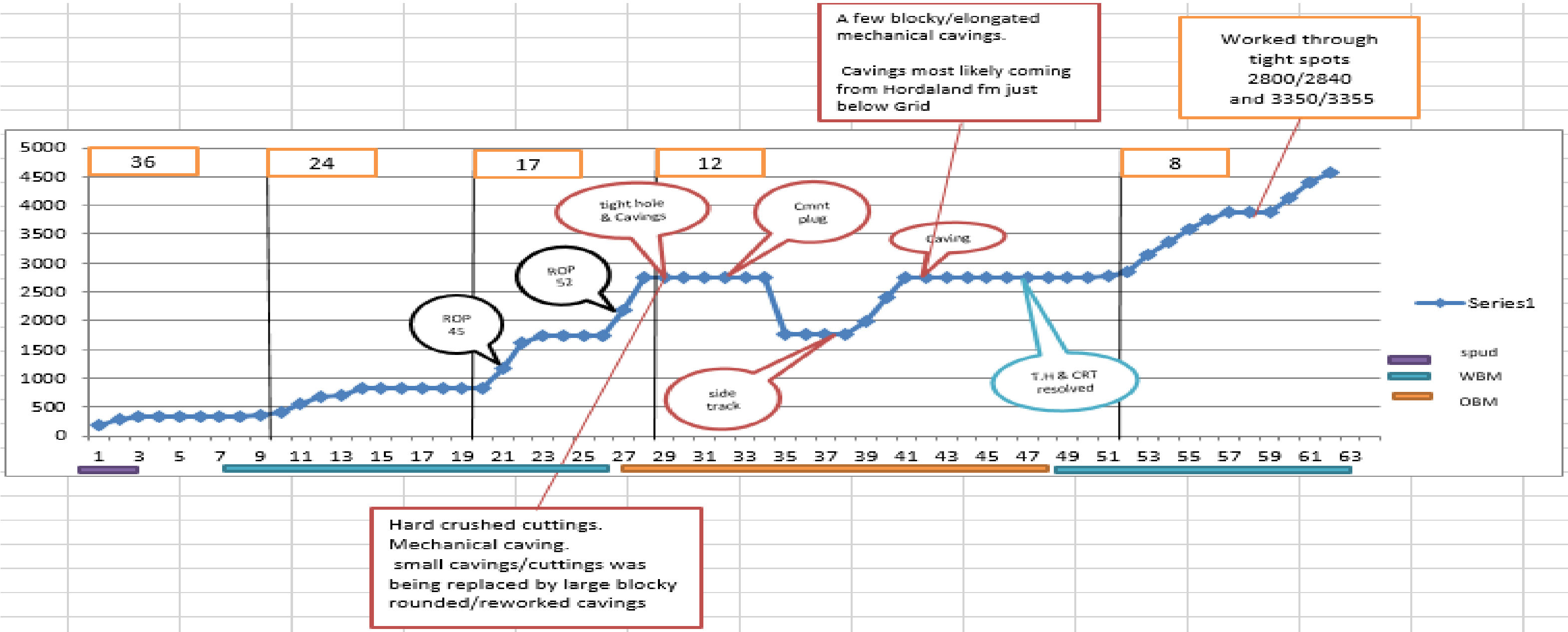
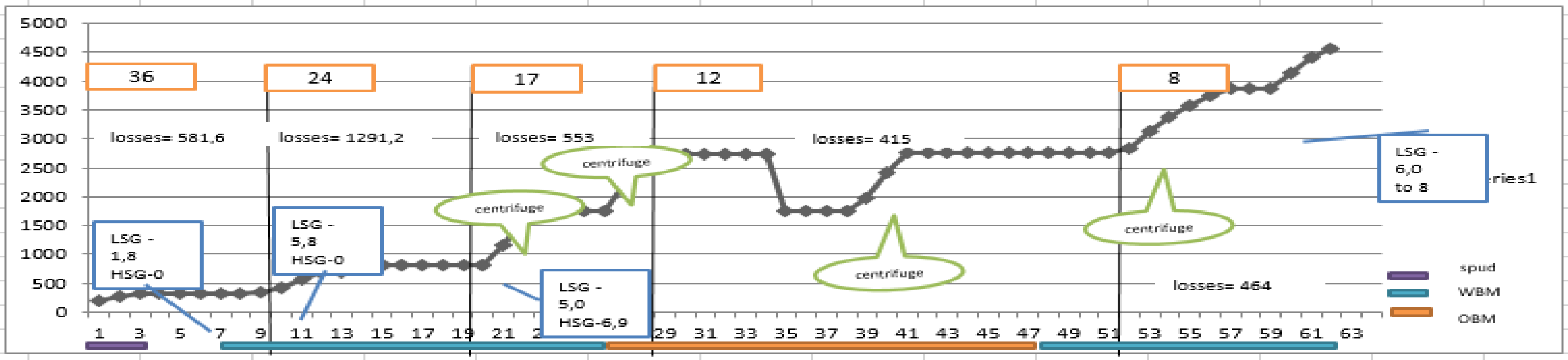


Figure 3-1 As drilled schematic

		interval problem:	
36``	189		
	276	Hydraracker - not able to move	
	329		
	casing		
	cementing		
	skidding	Oil overheat alarm on cantilever skidding unit.	
	Run BOP		
	Test BOP	Not able to close diverter element.	
24``	347	Operations suspended due to labour conflict	
	418		
	560	Unable to set slips - block retracted	
	689		
	601	Labour Conflict - Drill 24" on night shift only	
	818	Topdrive motor encoder problem	
	casing	Franks casing equipment 20" 3hrs	
	cementing	Plug leaking when bump 4:50 hrs	
	BOP		
	Test BOP		
	Prepare nxt section 17 1/2		
	drill plugs		
17 1/2``	1166		
	1614		
	1743		
	circulation+ casing		
	casing + BOP		
	cementing	total 20 hrs problems in this interval	
12*13``	2186		high ROP, 50m/hr
	2735	high rop, then lower , then caving and cir	high ROP, 50m/hr
	hole cleaning		
	flow check + CCD		
	casing		hard crushed cuttings
	POOH casing	Tight hole and possible hole collapse	
	POOH casing + wiper trip		
	wiper trips		
	1755		cementing / Sat a balanced cement plug from 1885 m to 1665 m.
	circulation+ BOP + RIH BHA		
	WOC + circulate		wash out from 1665 to 1693
	WOC + floor maintinance		
	1974		Drilled cement from 1693 to 1755, Initiated kick off and confirmed sidetracked from original track at 1755 m. Contine drilling til 1974
	2410		
	2754		
	Pump LCM		Drag. Ran centrifuge. 40% increase in returns. Mechanical cavings.
	back reaming		
	lubricating + casing		
	casing		
	cementing		
	wellhead / MLS		
	drill cemeny plug		
	handle BHA		
	Test BOP		
8 1/4``	2763		only 4 hrs drilling.
	2837	Lost connection through wired drill pipe	
	3129		
	3373		
	3584	Did not follow relog procedure, resulting	centrfiuge problem
	3752		
	3878	Trip to change BHA due to faulty startrak	vip centrifuge
	handle BHA		
	formation evaluation		
	4129		mud losses on surface and in the centrifuge
	4405		
	4562		



A few blocky/elongated mechanical cavings.
Cavings most likely coming from Hordaland fm just below Grid
Worked through tight spots 2800/2840 and 3350/3355
36
24
17
12
8
tight hole & Cavings
Cmnt plug
Caving
ROP 52
ROP 45
side track
T.H & CRT resolved
Series1
spud
WBM
OBM
Hard crushed cuttings. Mechanical caving. small cavings/cuttings was being replaced by large blocky rounded/reworked cavings



36
24
17
12
8
losses= 581,6
losses= 1291,2
losses= 553
losses= 415
losses= 464
centrifuge
centrifuge
centrifuge
centrifuge
LSG - 1,8 HSG-0
LSG - 5,8 HSG-0
LSG - 5,0 HSG-6,9
LSG - 6,0 to 8
spud
WBM
OBM