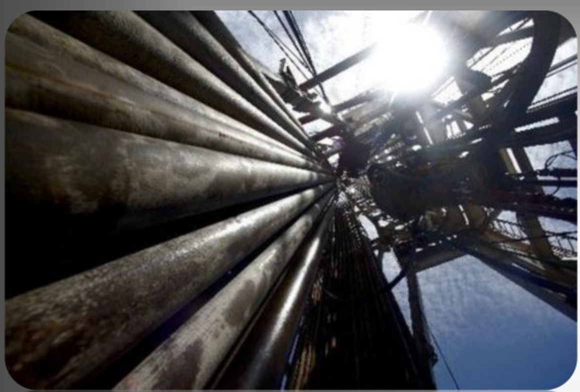
Norwegian University of Science and Technology

TECHNICAL REPORT

OPTIMIZATION OF WELL PROGRAM



Group 1

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Abstract

This report is written as a result of the work carried out by Group 1 in the Gullfaks village 2011. The overall goal of the village was to improve oil recovery in the Beta ridge of the Gullfaks field. The technical report consists of two parts: Part A and Part B.

The main purpose of part A of this project was to demonstrate an understanding of the challenges related to production from the Gullfaks field, with a focus on pressure depletion and aquifer support. Based on information provided it was found an average reservoir pressure depletion. This was compared to the measured reservoir depletion in wells A-32 in the Beta ridge. A graphical presentation of production and injection data was used to identify how and which fields that are connected to each other. An additional plot of production and injection rates was used to estimate a recovery factor of 58.14 %.

The objective for part B was to study the optimization of a well program. We chose that the basis for our project should be done thru addressing the issue of human errors. Currently human errors contribute up to 80% [1] of overall errors that adds to downtime and increased cost. Three key elements that are related to human errors are decision making, level of crew's knowledge and training, and knowledge transfer.

To address these issues, the group first studied government standards and regulations to create a good starting point for the work performed. Afterwards, the group continued working with two main ideas: The introduction of an artificial intelligence, AI, system, and to optimize the use of simulator training.

Making a good decision throughout the process of well planning and during drilling operations, especially at moments that require critical decision making in a relatively short period of time, can be stressful and challenging. This issue was addressed by the introduction of an AI monitoring and counseling system that combines model based knowledge with case based knowledge in an intelligent way, providing new insights and possibilities in decisions making. The system is not intended to implement decisions, but only to provide good assistance to the engineers.

Optimization of the use of simulator training was proposed to increasing the crew's level of competence. Three major improvements were proposed: Increase focus on the human relations in the drilling teams, let the operators try to exchange roles and responsibilities, and to involve more of the drilling organization in simulator training.

The group also looked at how the artificial intelligence monitoring and counseling systems could be implemented in the existing system of process owners, peer assist and review teams and quality rating systems to improve quality assurance, QA. The idea is that this can help to close the loop of information flow and increase the knowledge transfer in the organization.

Finally, these ideas were combined and used as a basis for setting up a series of decision trees for a well program, risk identification and mitigation, learning and training and drilling program.

Preface

This report is written as part of the subject TPG 4851 Experts in Team, Gullfaks Village 2011. The objective of the subject is to conduct an interdisciplinary project with students from various faculties and departments.

We would like to thank our supervisor in Statoil, Johan Eck-Olsen, for his help with guidance, documentation and understanding of the problems related to the planning and execution of drilling operations.

We would also like to thank the village leader professor Jon Kleppe, Jan Ivar Jensen, and the teaching assistants Julie Isdahl and Jacob Hansen for their guidance during the village meetings every Wednesday.

Trondheim, April 13, 2011

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1 Report Part A

1.1 Introduction

1.1.1 The Gullfaks field

The Gullfaks field is located on block 34/10 north west of Bergen. It was awarded in 1978, and the production started in 1986. It was initially developed with three concrete platforms, but later smaller satellite fields nearby the main field were developed using subsea templates. Statoil and Petoro is partners in the field, with 70% and 30% respectively, with Statoil as the operator [2].

1.1.2 Gullfaks Village 2011

The Gullfaks Village is a cooperation between NTNU and Statoil, where students in the Expert in Team subject are challenged to work with problems related to increased oil recovery (IOR) at the Gullfaks field. This year the village focuses on the Beta ridge, west from the main field at Gullfaks. The Beta ridge consist of the fields Gullveig, Tordis, Skinfaks, which is operated by subsea templates, and the long well Gulltopp drilled from the Gullfaks main field. See Figure 1 for an overview of the fields and discoveries in the Gullfaks area.

When Statoil started the production from Gullfaks in 1986, the plan was to recover 46 % of the oil in the reservoir [3]. Today the recovery factor is 59 % [4], and the plan is now to recover as much as 70 % [3]. The significant increase in recovery factor is due to new technology including long-reach and horizontal wells, water alternating gas injection, completion and sand control.

1.1.3 Part A assignment

As an introduction to the project, all groups are given an introductory assignment. In this part A, the production and injection data have been studied, and pressure depletion, recovery factors and interference between the different fields have been discussed. The aim for this study was to increase the understanding on pressure depletion and aquifer support.

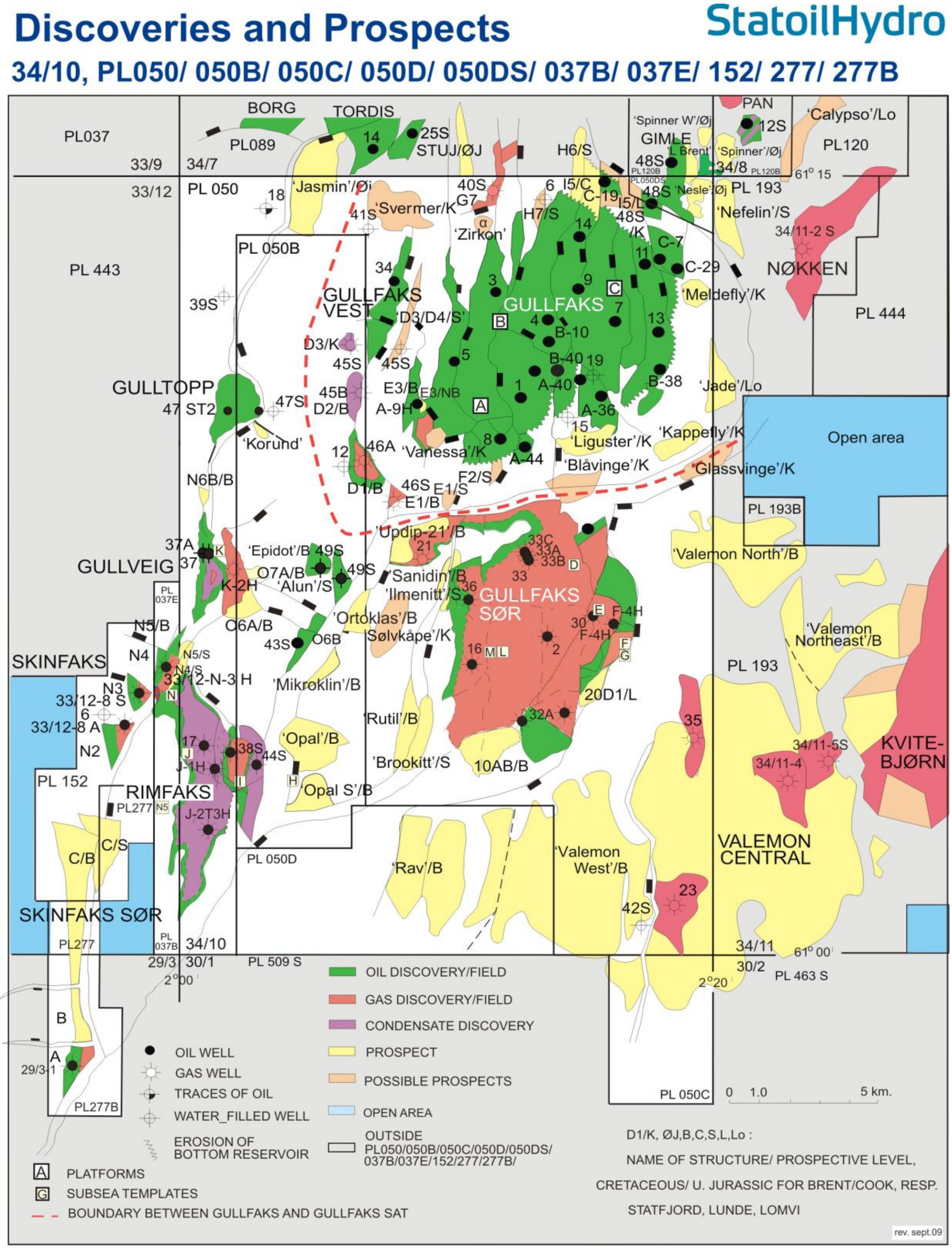

Figure 1: Fields and discoveries in the Gullfaks area [2].

1.2 Project basis

1.2.1 Source for the data

All the data utilized in this reported are supplied by Statoil and their database for the Gullfaks field. The calculations are based on the data found in the document “Production and injection rates”[4]. See Appendix B for data.

1.2.2 Assumptions

Assumptions made are related to reservoir volume and rock compressibility. For the volume we have tested three different reservoir volumes; $1 \cdot 10^9$, $2 \cdot 10^9$ and $3 \cdot 10^9$ [Sm^3]. For simplicity the rock compressibility is set equal to water compressibility.

1.2.3 Uncertainty

There are several uncertainties connected to the calculations. First of all, the rock compressibility is probably different from the water compressibility. How much the calculated values vary from the actual data because of this cannot be established.

Further the assumed reservoir volumes will be an uncertainty. They can vary a lot from reality.

Another uncertainty is related to the assumed formation volume factor.

1.3 Calculations and results

1.3.1 Question 2

Statoil provided production data from the different fields. Based on these, calculations and plots of the average reservoir pressure were performed using equations 3.1.1 and 3.1.2. Different reservoir volumes were assumed, and the results were presented in a plot showing pressure as a function of time, see Figure 2. The reservoir initial pressure was given as 380 bar and the compressibility of water considered 0.0001 bar^{-1} (average). Three different initial reservoir volumes were assumed to plot the reservoir pressure as a function of time. The plot shows that the reservoir pressure declines greatly with respect to time if the initial volume of reservoir is considered small. The pressure depletion is lower when a large reservoir volume is assumed.

$$\Delta V_w = V_w \cdot C_w (P_2 - P_1) \tag{3.1.1}$$

$$V_{w,reservoar} = B_w \cdot V_{w,standard} \tag{3.1.2}$$

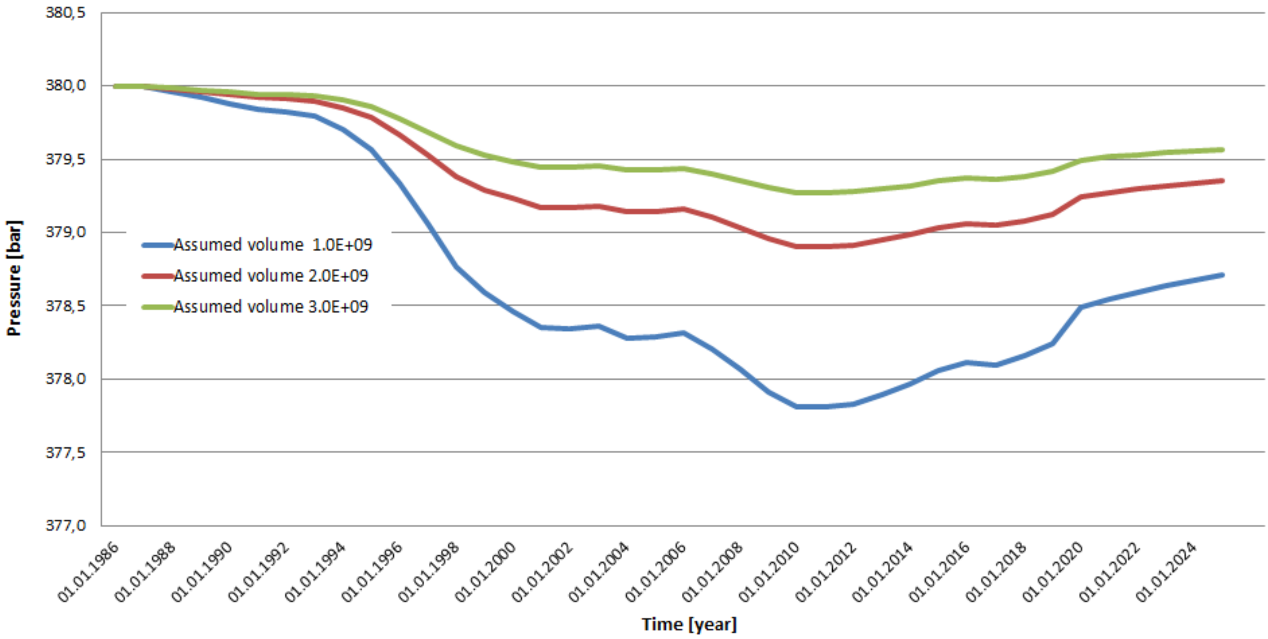

Figure 2: Calculated pressure as a function of time

1.3.2 Question 3

The calculated pressures were compared to measured and simulated pressures for well A-32, see Figure 2 and 3 respectively. It can be seen from a comparison of the figures that the trend of the pressure depletion is the same. At certain points, there is a deviation from the measured and the calculated values. As the total reservoir volume was not known, reservoir volumes of $1{\cdot}10^9$, $2{\cdot}10^9$ and $3{\cdot}10^9$ [Sm^3] were assumed. This leads to a significant uncertainty in the calculated values. Therefore the exact value for the pressure at different times is not the same.

One of the reasons for the difference in measured and calculated pressure is that the reservoir simulation in Figure 3 is from one well on the Beta ridge. The calculations on the other hand, are based on all the fields, Gullfaks main field, Tordis, Vigdis, Gullfaks Vest, Gullveig, Gulltopp and Skinfaks. Even though it is communication among the different fields, the pressure is not necessarily exactly the same in the different parts of the area.

The rock compressibility was assumed to be equal to the compressibility of water. It was also uncertainty related to the formation volume factor. As these values were used in the calculations, this adds an uncertainty to the calculated values.

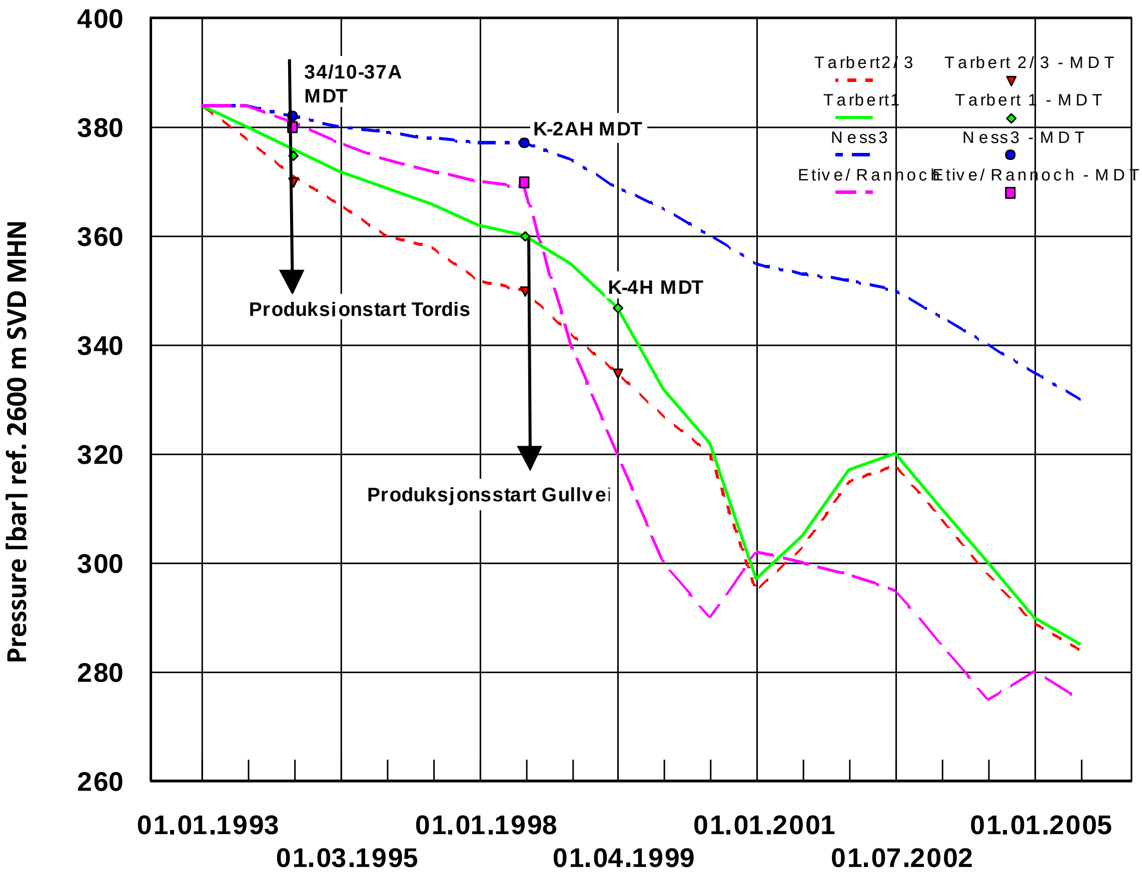

Figure 3: Pressure in Gullveig Brent. Simulated reservoir pressures and meassured MDT formation pressure

1.3.3 Question 4

Figure 5 presents an overview of the production and injection rates of the different fields in the Gullfaks area as a function of time. The curves in Figure 5 was used as a basis for the discussion in question 4. After comparing production and injection rates of the fields with the dates when each of the fields started production, and dates when in stopped production, it was deduced that Gullfaks Vest is most probably connected to the Gullfaks main field and it is leaking some injected water here.

From the production and injection rates graph, see Figures 4 and 5, the expected recovery factor for the fields was assumed, see table 1Expected recovery factor over the full production life of the fields was assumed to be 58.14%.

Differences in recovery factor between the fields may come from various factors, such as:

- Different types of fields (Skinfaks and Gullveig are oil and gas fields, while Tordis, Gulltopp and GF Vest are only oil fields).
- Different geology

Table 1 Assumed recovery factors for the different fields in the Gullfaks field

Field	Recovery factor [%]
Gullfaks main field	62
Tordis	55
Vigdis	60
Gullfaks Vest	65
Gulveig	55
Gulltopp	55
Skinfaks	55
Total	58,14

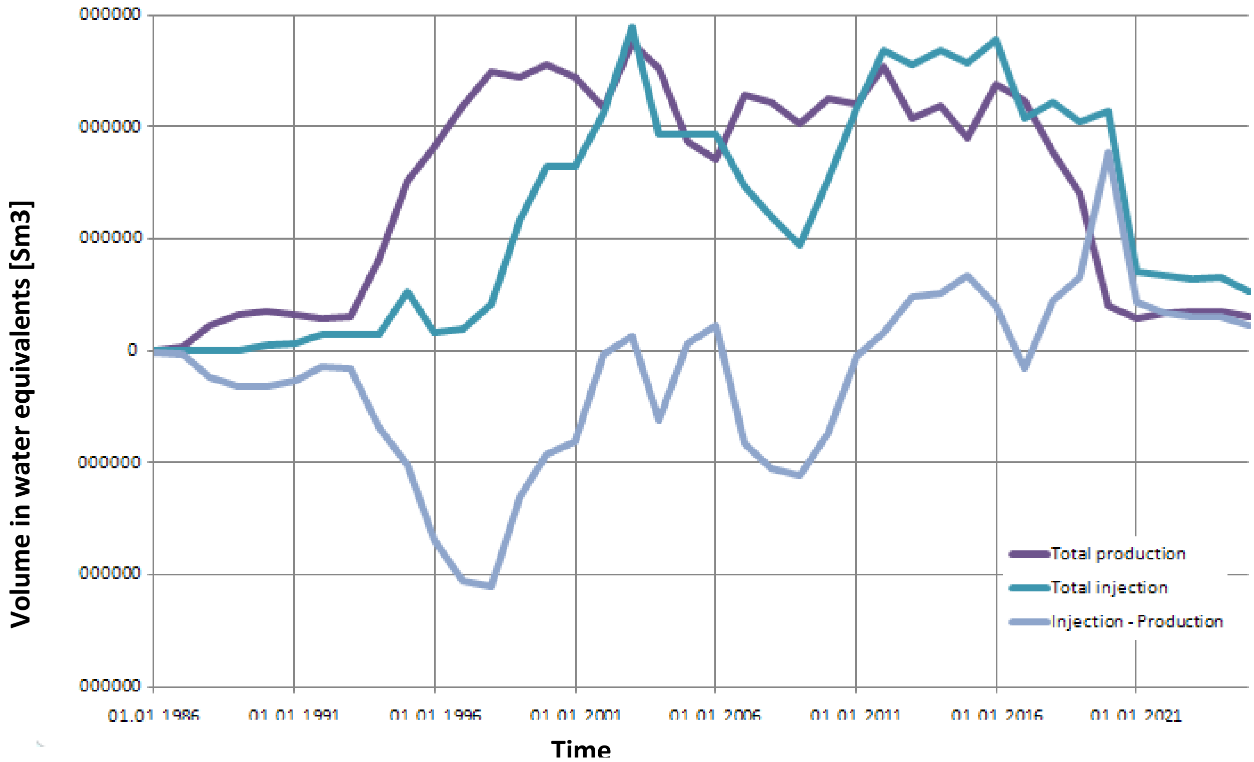

Figure 4: Total production and injection as a function of time

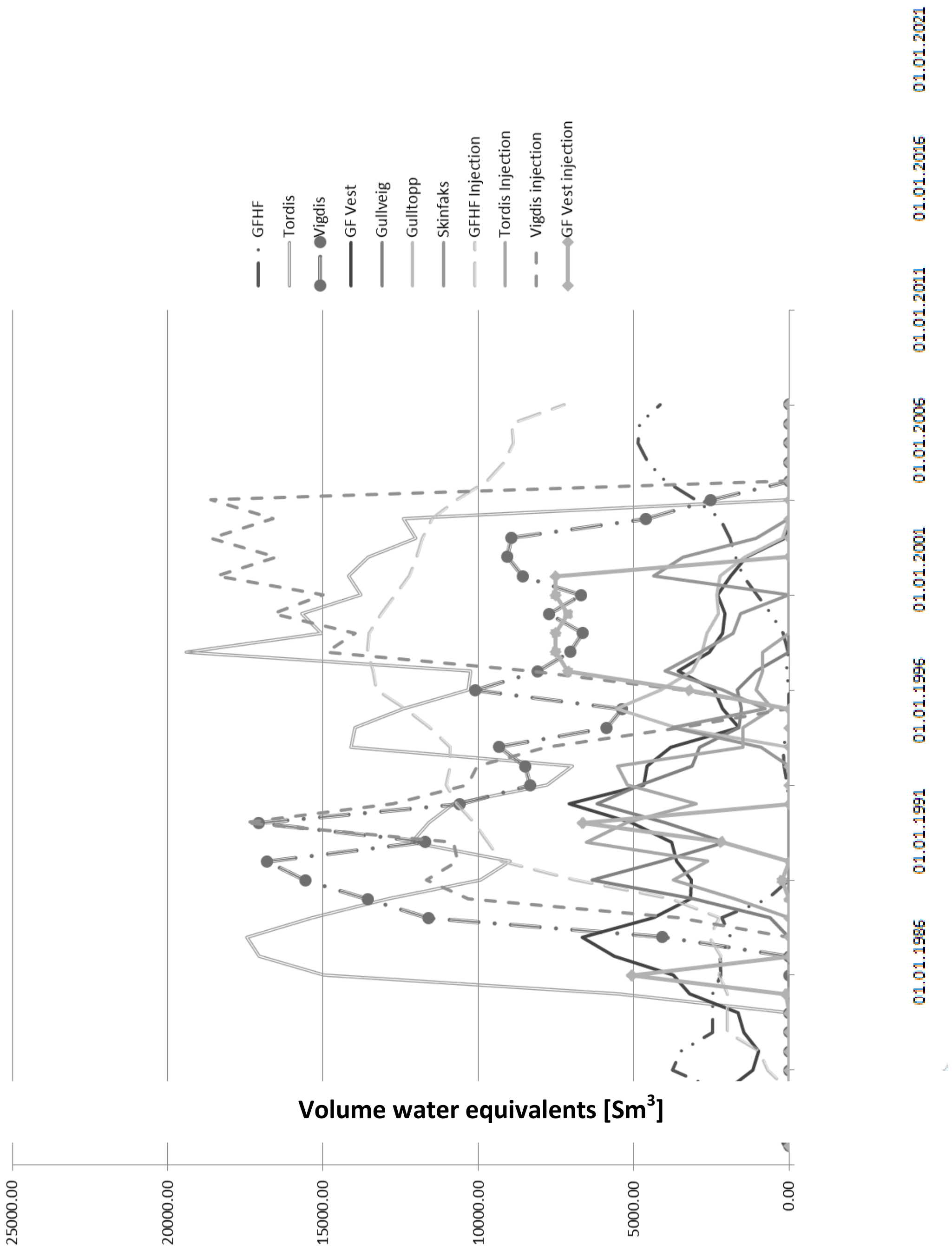

Figure 5: Production rate as a function of time for different fields in the Gullfaks field

1.4 Discussion

All data delivered by Statoil is assumed correct, but there may be some built in errors from instrumentation etc. The data were used for comparison of the calculations in question 2. Since the data provided only covers one field, and the calculations comprise all the fields, there will be some sources of error here.

In question 4 there was not possible to calculate recovery factor due to lack of information on cumulative production. Instead data of production and injection rates were used to estimate recovery factor for the different fields, and the overall recovery. This, and the lack of experience within the group, will probably be a source of error.

1.5 Conclusion part A

An average reservoir pressure depletion for the fields on the Beta ridge was calculated and compared to the measured reservoir depletion in wells A-32. The communication between the fields on the Beta ridge was discussed, and the recovery factor for the different fields were calculated.

2 Report part B

2.1 Introduction

This is part B of the technical report in the course Experts in Teams – Gullfaks village. The main task was to find a way to improve major parts of the well program, such as:

- Planning
- Evaluating
- Making drilling program
- Risk identification and mitigation
- Use of decision trees
- Learning and training

Human errors were identified as the largest contributor, almost 80% [1], to lost time, and therefore the biggest contributor to cost. Addressing that issue and lowering human error can increase productivity, lower the cost of production and maximize utilization of the well program.

Developments in the field of Artificial Intelligence, AI, and AI monitoring and counseling systems can decrease human errors, and lead to improvements in capturing best practices, gaining hidden knowledge, and utilization of that knowledge. The suggested artificial intelligent monitoring and counseling system is based on an AI system developed at NTNU by professors Skalle and Aamodt. It's current use is in the drilling process, but due to its vast and always growing database, we see it utilized in all aspects of the well planning. The system focuses on capturing useful experiences related to a particular job and situation, and on their reuse within future similar contexts. The overall objective is to increase the efficiency and safety of the drilling process. Application of Artificial Intelligence systems in setting up a complex drilling program is discussed in Chapter 4.

Crew training is also an important part in lowering human errors. A simulator that is fed with real data and general knowledge data can therefore increase the crew's level of competence. A drilling simulator is a tool for training crew to operate drilling equipment, train on well control, practice techniques and prepare for specific drilling operations. Further discussion about optimal use of simulator training can be found in Chapter 5.

Quality assurance, QA, is the systematic monitoring and evaluation of the various aspects of a project, service or facility. It aims at maximizing the probability that standards of quality are being attained by the production process. Quality assurance is discussed in Chapter 6.

3 Overview of standards and guidelines for the creation of a well program

3.1 Governmental Rules and Regulations

The governing documents have a comprehensive focus on safety, both related to humans and the environment. In addition, the working environment is of importance. The competence of the workers must be sufficient to handle the tasks they are set to do, if this is not fulfilled, they are not allowed to carry them out. Changing of crew must be evaluated against the consequences related to HSE.

Most of the rules for petroleum related activities on Norwegian Continental shelf is set by Petroleumstilsynet, Ptil. Their “activities regulations” is applicable for execution of activities in the petroleum industry. The “facility regulations” describes how petroleum related facilities shall be shaped and equipped. Another organization is Oljeindustriens Landsforening, OLF. This is an interest group for oil and supply companies. OLF does not publish regulatory rules, but they have several called recommended guidelines on how to handle problems in the best possible way. Standards like NORSOK describe the technical aspects of installations and equipment. Following, a summary of rules related to personnel and drilling activities found in documents from Ptil.

Arrangement of work should be based on accessible competence and human needs, this way the interaction between personnel, technology and organization is optimized [5]. This rule supports the idea of the performance team where the focus is well functioning and sufficient competence. Picking the right people could mean time saved on both execution and reduced downtime. When the amount of errors that is human related is considered, it speak for itself that a well-functioning team is important to reduce this factor.

In the well program, there is a requirement that all activities and equipment to be used are described [5]. A plan with 15 min breakdown is required for drilling operations. If this is seen in relation to the performance team, it clearly shows the importance of a well-functioning team to live up to a plan like this.

Facility regulations state that all systems and equipment must be designed in a way which limits the possibility for human error [6]. This brings us to the discussion about limiting the number of personnel working on the deck by remotely handling pipes. Paragraph 89 in the same regulation states: “All pipes should be handled (as long as it improves the overall safety) using remote handling systems. The personnel access should be limited in the area of remote handling.” This report will later discuss the possibility for artificial intelligence and software for controlling the drilling operations.

In OLFs recommended guidelines for competence of drilling personnel [7] the need for a supervisor and head in drilling operations is stressed. A supervisor is the person responsible for managing operations, and as needed participate, to carry them out professionally, safely and in accordance with procedures. The head is ultimately responsible for the operation. This report would like to emphasize the need for experienced managers to secure the correct execution of operations. Today there exists a culture for more and more specialized personnel. Everyone is specialized in handling one specific task. As time passes, and current supervisors disappears, there will be a shortage of qualified personnel to take their place.

3.2 HSE & Training standards

The Working Environment Act and Regulations for Systematic Health, Safety and Environmental Activities in Businesses (ref Statoil HSE Regulations) require employers to:

- Maintain a list of hazards in the workplace
- Evaluate risks of health injury and accidents
- Initiate activities and measures to prevent and reduce risks
- Follow-up, correct and make improvements if there are deficiencies
- Identify factors that may cause problems in the workplace, physical and mental
- Plan to solve the problem, find the responsible person and target the implementation date
- Follow-up the decisions that are made and to be done or not
- Why and how any changes occurred underway

Under the HSE Regulations, employers are required in their systematic preventive health, safety and environment work to cooperate with employees and their representatives so that:

- Employees are informed
- Employees have an opportunity to contribute with their knowhow and experience
- Employees experience codetermination

Cooperation and codetermination by employer and employees is crucial because:

- Employees know their job and its hazards best
- Employees' rights and obligations to participate in HSE work depend on information and training.

3.2.1 Guiding principles of HSE

Alternative concepts and technologies shall be identified and evaluated. Technology selection shall be prioritized in the following order: Prevent, minimize, mitigate and compensate. All selections of concepts and technical solutions shall for the economic and expected life time be documented by an environmental budget including as a minimum:

- Energy demand
- Energy utilization (efficiency)
- Air emissions
- Discharge to sea
- Chemical usage and discharge
- Waste handling
- Decommissioning

The issues that are involved in HSE:

- Energy management
- Air emissions
- Use of areas
- Liquid discharges to sea
- Drilling Fluids and Cuttings

- Produced sand
- Chemicals
- Waste
- Decommissioning
- Emergency Shut Down (ESD)
- Hot surfaces
- Electrical source
- Non-electrical source
- Blowdown and Flare

3.2.2 Regulations for training of the crew

The demand to competence for training of the crew are described in § 12 in the framework regulations [8] and § 9-7 in "Lov om Petroleumsvirksomhet"[9]. The regulations mentioned states that the operator need to have an organization in Norway that can ensure that the petroleum activities are being carried out according to the regulations. The person responsible must ensure that everyone working for the operator has the necessary competence to carry out their work in a prudent manner. It also states that the Petroleum Safety Authority Norway can require changes to the organization of petroleum activities. More detailed requirements for competence are found in "Management Regulations" [10], "Activities Regulations" [11] and "Technical and Operational Regulations [12].

In the Management Regulations, it is stated that it should be a minimum demand to staffing and competence to take care of situations where mistakes can have great consequences for health, safety and environment (HSE), and functions to reduce the probability for the development errors, dangerous situations and accidents.

The Activities Regulations contain three paragraphs, § 21, 22 and 23, that are relevant for the discussion in this section. § 21 about competence add that the personnel should be able to handle dangerous situations and accidents. § 22, Safety and working environment training pursuant to the Working Environment Act, states that the training given to operative personnel also should be given to leaders and other persons responsible for decision-making affecting the work environment. It also states that clear criteria for what training is needed should be set, when the workers should repeat or get additional training, and that the training should take place during working time. Regulations about practice and exercises are stated in § 23, and say that the personnel should be given the appropriate training so that they are able to handle operational disorders, accidents and danger-situations in an efficient way.

§ 50 to § 54 in the Technical and Operational Regulations are relevant for this section. The information in § 50, 51 and 52 are already covered in the other regulations. § 53 are about information about risk executing the work, and it states that the worker should be given information about the health risk and risk of accidents when performing their work. Documentation about assessments of risk and related surveys should be accessible, and workers and their representatives should be familiar with this information. § 54 regulates transmission of information, and states that by shift and crew change the person responsible have to ensure the necessary transfer of information on the status of the safety systems and ongoing work, and other information related to HSE.

3.3 Drilling program

Well planning is the crucial for safe and economical drilling of a well oil and gas production. The economic feasibility of drilling a well is recognized from cost-estimation of drilling, completion and production operations, while safety and cost control are realized through the suitable planning of all the appropriate programs that have an impact on the planned well.

Drilling developments require comprehensive evaluations of every aspect that directly or indirectly influences the successful economic outcome of the project. Designing require an intuitive, common-sense judgments regulating decision making, along with complete analyses representing the coordinated efforts of many persons involved with specific skill to the task.

A good plan requires a coordination of a team that includes drilling engineer, drilling supervisor, drilling superintendent, geologist, production engineer, and reservoir engineer, as well as individuals responsible for safety, environmental, and governmental matters.

Objectives of the drilling program are to recognize and address all significant engineering parameters, events, regulations, and other situations that are having a direct or indirect influence on the projected drilling project. Also secondary objective is preparation of a well plan that is addressing all problems and that has to improve success of the projected well by drilling in a safe, efficient and economical way, in compliance with all governmental rules and regulations.

3.3.1 Information needed for well planning

In development well drilling, the best source of information is offset well data.
Information found here are included in daily drilling report summaries:

- Hydraulics
- Tubular
- Mud
- Directional survey's
- BHA's
- Drill bits
- Logging
- Casing and cementing
- Geological information
- Reservoir characteristics
- Logistics
- Weather
- Service companies' and product suppliers' recommendations
- Government regulations
- Personnel and type of contract agreement
- Problems encountered and the success or failure of attempted solutions.

In exploratory well drilling there are always a shortage of information available from surface geology and seismic data.

3.3.2 Drilling Engineer's Responsibilities

Drilling Engineer is representing a well designer and coordinator for project planning with these tasks:

- Expenses authorization – estimating overall cost
- Collection and review of available data on all offset wells in area
- Design of drilling programs
- Anticipation of drilling programs likely to be encountered and working out contingencies
- Selection of the drilling rig and its specifications
- Preparation of drilling-cost and drilling-time curves
- Coordination of bid requests and contractor assessments in order to ensure optimum rig selection and rig personnel efficiency and safety records

- Ensuring economical, safe and on schedule well program by coordination of the activities of purchasing, environmental, regulatory, and other engineering groups

3.3.3 Considerations

During well planning, various considerations have to be made [13]. They are presented in Figure 6, and explained in more detail in the text below.

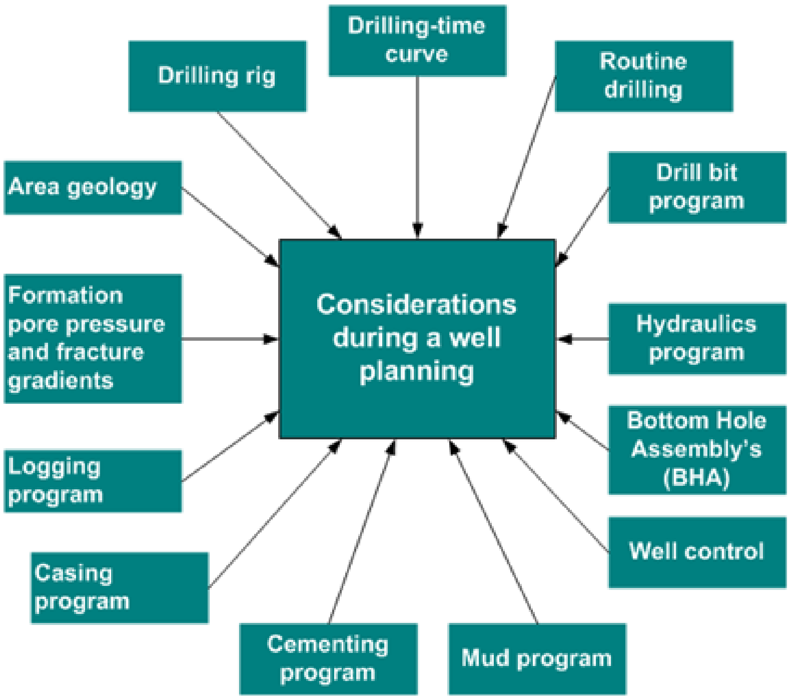

Figure 6: Considerations to be made for planning a well

Area geology. Including identification of formation tops that are to be penetrated, problematic zones (e.g., loss circulation zones), shales, abnormal conditions (pressure, temperatures, etc.), and possible intervals for production.

Formation pore pressure and fracture gradients. An accurate understanding of formation pressures and fracture gradients is one of the most important parts of geological information for the drilling engineer. It allows apposite choice of casing-setting depths in combination with the optimal type of drilling fluid that should be used in each interval of the wellbore.

Logging program. This program should be coordinated with the geologist in charge. Details as to type of log to be run and data to be derived should be worked out well in advance of drilling.

Casing program contains a casing schematic that represents well construction details. In addition, each casing string should have complete, detailed design data.

Mud program presents comprehensive discussion, by interval, of desired drilling-fluid type, properties, and maintenance. Many downhole problems are the direct results of improper use of drilling fluids.

Cementing program should include amounts of additives, probable bottom-hole temperatures, estimated amounts and types of cement to be used, setting time allowed, curing time required, and types of shoe, floats, centralizers, and scratchers required for cementing each string of casing. In addition, casing running and handling must be included.

Well control. Specifications and drawings of the BOP stack and all other supporting auxiliary equipment (choke manifold, kill and ill lines, etc.) should be included. The engineering design of the well control program should be established, along with the procedures to be followed by the drilling crew, the tool pusher, and the drilling supervisor.

Bottom Hole Assembly's (BHA's). Reamers, centralizers, shock absorber subs, short drill collars, large diameter drill collars, and other types of equipment that lend themselves to general improvement of drilling should be specified here. Proper use of BHAs can eliminate very costly hole deviation problems.

Hydraulics program dictates the rig hydraulic power requirements. It consists of the calculations of all pressures (friction and dynamic) in the rig circulating system. Optimum utilization of hydraulic horsepower at the bit improves ROP and increases bit life. Proper design of hydraulics can also ensure effective drilled-cuttings removal and safe equivalent circulation density (ECD) of mud.

Drill bit program Types of bits to be used must be specified, and optimum operating conditions (WOB, rpm, optimum low rates, and corresponding optimum nozzle sizes) should be selected for each bit. Post-analysis of previous bit records is an essential part of this program.

Routine drilling includes the operator's desires as to routine daily procedures that the drilling contractor should follow

Drilling-time curve. A drilling-time curve (a plot of time vs. depth out) should be included in the program plan and compared daily with actual progress. When differences occur between predicted performance and actual performance, the reasons should be found, and appropriate adjustments should be made to the drilling parameters.

Drilling rig. A thorough evaluation of all rig systems (power, circulating, hoisting, rotary, well control, and data acquisition/monitoring) must be conducted if proper implementation of optimized drilling programs is to be achieved.

3.3.4 Planning and updating drilling program

The purpose of planning the drilling program is to provide a basis for the safe and successful drilling and completion of a well at the lowest total well cost. The amount and details of planning required differ significantly with the well complexity, Figure 7. For example, when development wells are drilled, most of the information is taken from offset wells. However, with the rapid changes in drilling technologies and products, it is important to take a new look at each well, making certain that no issues critical to drilling efficiency have been overlooked.

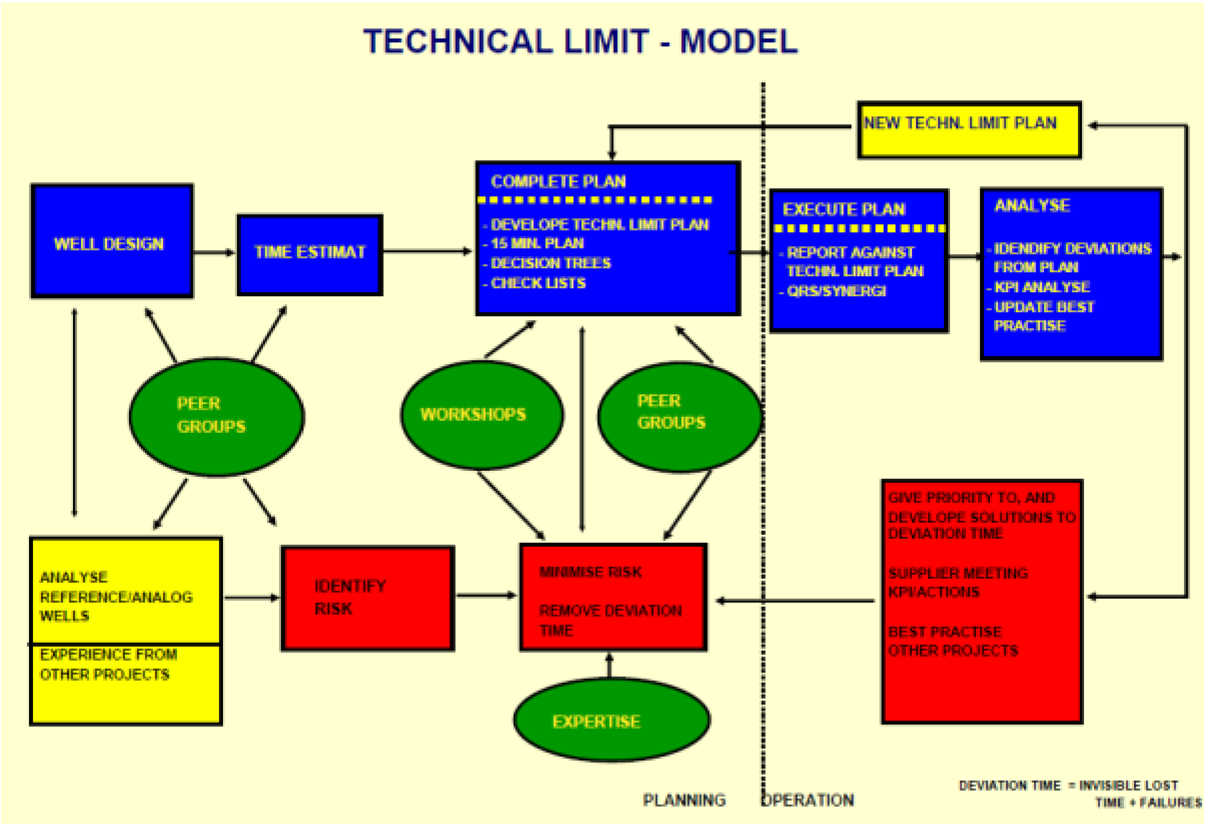

Figure 7: Technical limit model [14]

Although certain conditions relating to a given well will dictate the final form of the drilling-program plans, the following summary is serving as a guide:

- Well summary (drilling and geological prognosis, pore/fracture pressures, drilling time and cost curves, casings, drilling procedures, well construction schematics, completion, abandonment)
- Drilling programs
    - Mud program (mud type, properties, and maintenance)
    - Drill bit program (drill bit type, WOB, rpm, and hydraulics)
    - Drill string program (drill pipe, drill collars, and BHA)
    - Hydraulic program (ECD and rig hydraulic power requirement)
    - Casing/cementing (equipment, materials, and accessories)
    - Well control program (equipment, control methods, pump pressure schedule, and pressure profile in the annulus during well control)
- Wellhead equipment
- Rig specifications
- Evaluation phase (sampling, coring, logging, and testing)
- Emergency (contingency plans for all encountered problems)
- Miscellaneous (AFE, reporting, permits, offset records, contracts, rentals, etc.)

All drilling programs should be designed with some flexibility, to accommodate changes in response to unexpected encountered problems. Initial plans are based on assumptions that will be confirmed or corrected as the well is drilled.

However, major changes in well plans require thorough review, analysis, and redesign.
Even though the plans are flexible to some degree and safety factors are built into the critical design parameters, the mechanical and economic impact of major proposed changes must be reviewed, documented, and approved in the same manner as the original plans. Anticipating or knowing potential problems and designing contingency plans to combat them is a major issue in well planning.

4 Application of Artificial Intelligence systems in setting up a complex drilling program

Defining Artificial Intelligence, AI, succinctly is difficult, because it takes so many forms. One area of agreement is that artificial intelligence is a field of scientific inquiry, rather than an end product. Perhaps the best definition is that stated by M.L. Minsky: "Artificial intelligence is the science of making machines do things that would require intelligence if done by men." Making decisions require an intelligent agent which is a system that perceives its environment and takes actions that maximizes its chance of success [15]. The drilling process produces a huge amount of data and often leads to operational problems[16]. An intelligent system may support the information handling, learning and decision making. The system captures and stores information about executed operations, and makes decisions similar to what a human expert would do. One advantage is of course that the human factor can be eliminated. Another is time and resource saving, both because errors are reduced, and tasks are completed more efficiently than a human being are able to do.

The practical aspects of such a system can be described by the process of well planning. This example is found in the journal “Development of intelligent systems for well drilling and petroleum production” [17]. When initiating the planning of a well, the standards to follow already exist. These standards are built on a learning process, and the more wells that are drilled in a region, the more aspects of the drilling are learned. Even where standards are not established, necessary information from earlier operations are consulted. Figure 8 shows a typical step-by-step buildup of a well plan. Few situations needs a complete review of these stages, thus it is more profitable to reuse existing plans. This process is called case-based reasoning, CBR. Different companies work with the development of AI solutions, such as Schlumberger [18] and Halliburton [19]. In the next chapter there will be a more thorough review of a system called Troll Creek, which utilizes this process.

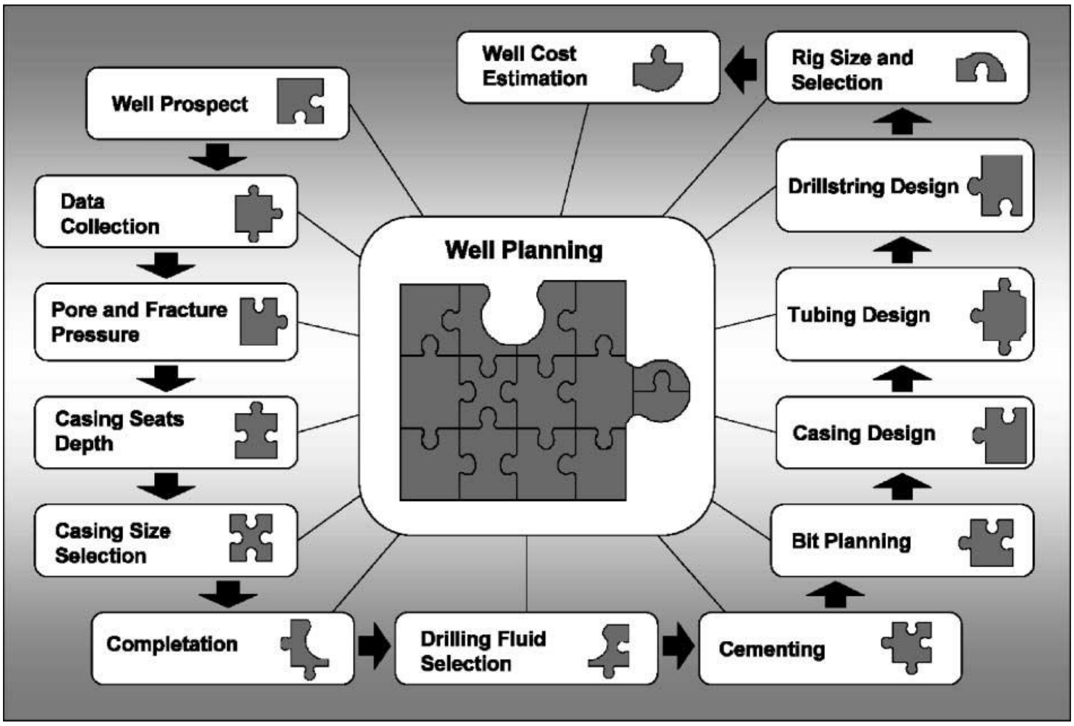

Figure 8: Steps in the Well Planning [17]

Our idea is to make use of this system in several disciplines within the drilling process: In the drilling operation itself, the risk identification and mitigation, training, simulator testing, and, as mentioned, well planning. The system will be built to reduce downtime due to problem solving, and increase the efficiency of crew training. In addition, there could be contingency plans for critical situations where split-second decisions are needed.

The basic setup of a case-based reasoning system can be seen in Figure 9. This system contains four steps; Retrieve, reuse, revise and retain. Retrieving means finding similar cases from a historical database. This database will often contain two types of knowledge; General and specific. General knowledge could be information about activities, equipment, process, symptoms, failures and cause-effect from previous cases. Specific knowledge are answers to questions like whom, when, where and why. If the search picks up similar cases, the information and knowledge to solve the existing problem can be reused. Some revising will often be needed to adjust it to the problem at hand. And last, information and experience is retained back to the system for later use.

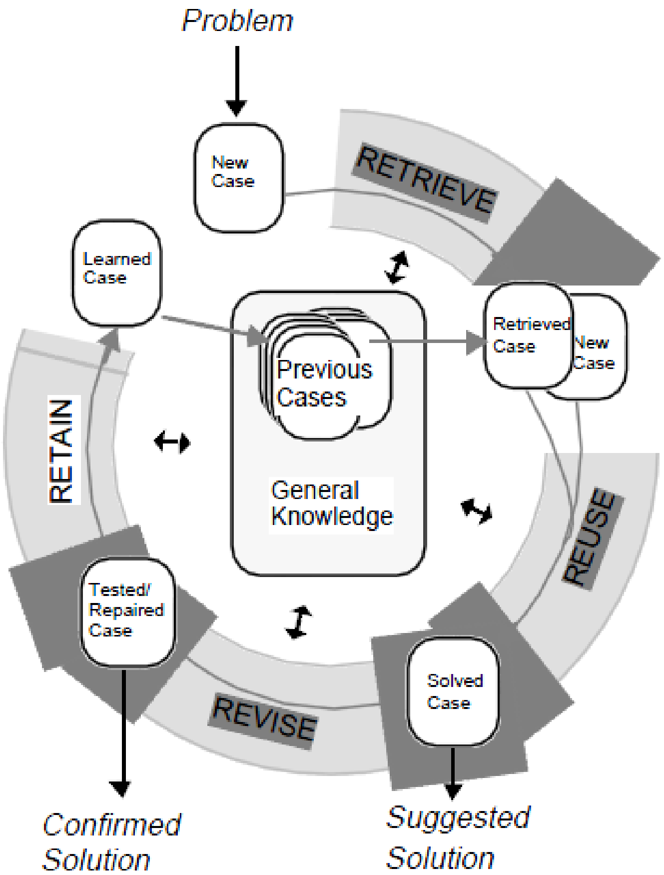

Figure 9: Basic layout of CBR system [20]

4.1 Data cloud

Data cloud refers to the establishment of computational resources on demand via a computer network. The data cloud can be compared to the supply of electricity and gas. These services are presented to the users in a simple way that is easy to understand without the users needing to know how the services are provided. This simplified view is called an abstraction. Similarly, a data cloud offers computer application developers and users an abstract view of services that simplifies and ignores much of the details and inner workings. See Figure 10 for conceptual diagram on how a data cloud are built.

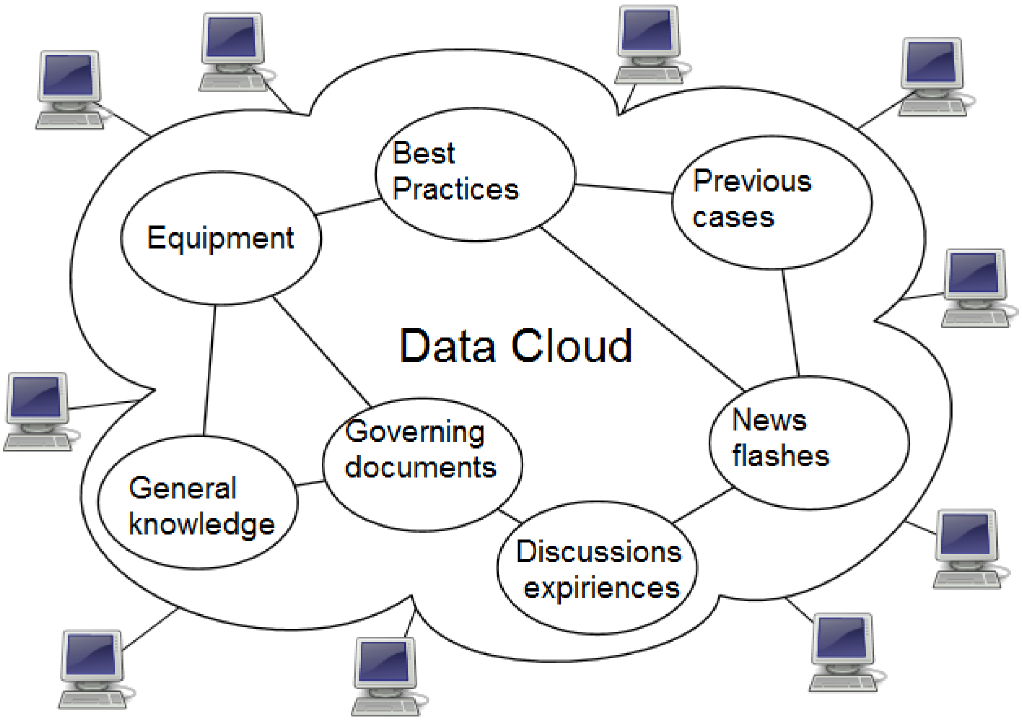

Figure 10 Data cloud conceptual diagram

In our case the data cloud is filled with data from:

- General Knowledge
- Best Practices
- Equipment information
- News flashes
- Governing documents
- Captured experiences thru various discussion groups and previous cases
- Other Networks

4.2 Application of artificial intelligence in drilling – TrollCreek tool

4.2.1 Introduction

There are many Artificial Intelligence tools present in the market today, and they are presented in section 4.6. The suggested artificial intelligent system will be built with basis in the TrollCreek tool made and described by prof. Pål Skalle and Agnar Aamodt. Most of the information in this section is found in the report "Knowledge based decision support in oil well drilling" [16] written by the two professors mentioned. It shows how the combined reasoning method enables focused decision support for fault diagnosis and predicts potential unwanted events in that domain.

The TrollCreek system focuses on capturing useful experiences related to a particular job and situation, and on their reuse within future similar contexts. The overall objective of TrollCreek is to increase the efficiency and safety of the drilling process. Efficiency is reduced due to unproductive downtime. Most problems, leading to downtime, need to be solved fast. Since most practical problems have occurred before, the solution to a problem is often hidden in past experience, experience which either is identical or just similar to the new problem. With that it comport to Figure 9 and its description.

This section is an overview of how TrollCreek's combined case-based and model-based reasoning method works. An oil well drilling scenario with a problem solving example given by the authors is presented in Appendix C.

4.2.2 Knowledge intensive case-based reasoning

4.2.2.1 Definitions

Case-based reasoning, CBR, as a technology has reached a certain degree of maturity, but the current dominating methods are heavily syntax-based, i.e. they rely on identical term matching. As a method in which general domain knowledge is used to support and strengthen the case-based reasoning steps, was suggested by the authors for extending the scope of case matching. Through the model-based reasoning, MBR, method, general domain knowledge serves as support for case retrieval and reuse processes.

Integration of CBR and MBR methods lead to "knowledge based decision support in oil well drilling", Ki-CBR, that is allowing making explanations which are not syntactically similar, but pragmatically similar case features with local relevance of similar features.

Methods for development of knowledge models for drilling engineering have over the last years improved due to contributions both from the knowledge-based systems field of artificial intelligence, and the knowledge management field of information systems. The knowledge models are often expressed in a standard XML-based language. This facilitates that knowledge structures can end up in shared libraries, to become available for others. This report suggests using previously described cases which are collected in libraries, also called data clouds.

At the simplest level, the TrollCreek's general domain model can be seen as a labeled, bi-directional graph. It consists of nodes, representing concepts, connected by links, representing relations. Relation types also have their semantic definition, i.e. they are concepts. The uppermost idea of the TrollCreek model is illustrated in Figure 11.

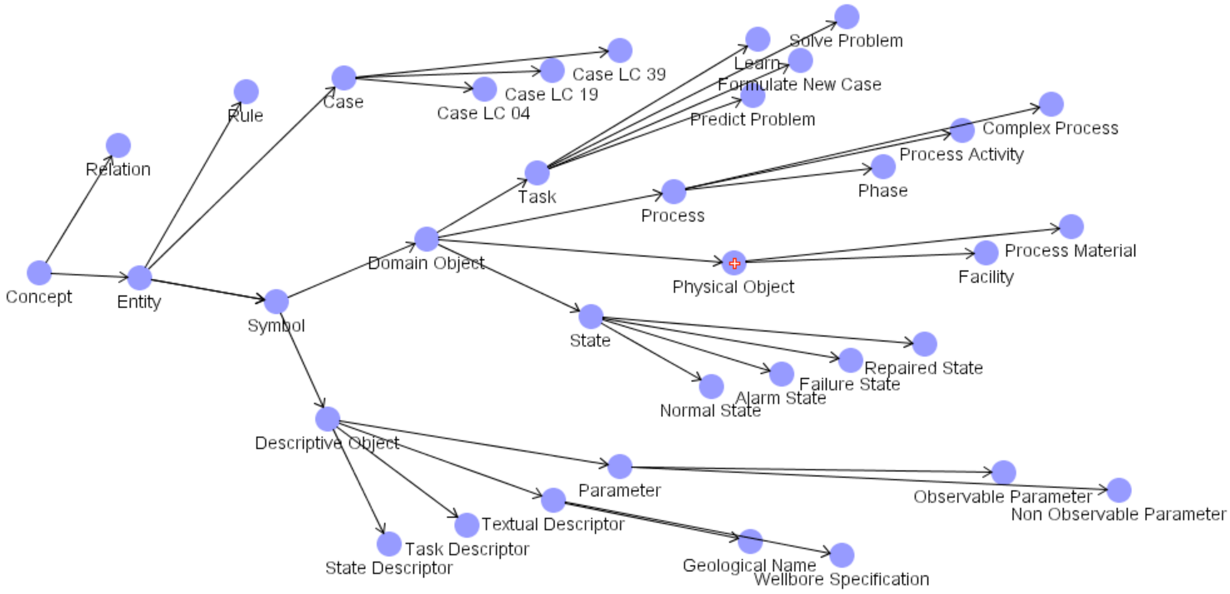

Figure 11 A part of the top-level ontology, showing concepts linked together with structural relations of type "has subclass". Each relation has its inverse (here "subclass-of", not shown) [16].

Cases are descriptions of specific situations that have occurred, indexed by their relevant features. Cases may be structured into subcases at several levels. They are indexed by direct, non-hierarchical indices, leaving indirect indexing mechanisms to be taken care of by the embedding of the indices within the general domain model. Initial case matching uses a standard weighted feature similarity measure. This is followed by a second step in which the initially matched set of cases are extended or reduced, based on explanations generated within the general domain model. Cases from the oil drilling domain have been structured in a manner which makes them suitable for finding the solution of a problem and/or search for missing knowledge.

All cases therefore contain the following knowledge:

- Characteristics that give the case a label like owner of problem (operator), place/date, formation/geology, installation/well section, depth/mud type
- Definition of the searched data, recorded parameter values, specific errors or failures
- Necessary procedures to solve the problem, normative cases, best practice, repair path consists normally of a row of events. An initial repair path is always tried out by the drilling engineer and usually succeeds. If his initial attempts fail, then the situation turns into a new case, or a new problem
- The final path, success ratio of solved case, lessons learned, frequently applied links

4.3 Application of artificial intelligence with training simulators

Application of mentioned system is possible to use outside monitoring drilling mainly due to its vast data-base stored in the data cloud. Due to the fact that it is being fed with data from real-life cases, as well as model cases, can be implemented in the best way in training simulators for crew training. Also, the data cloud is feeding AI unit data that is being processed. AI unit is then continuously monitoring and counseling throughout the use of training simulators.

Feedback data, that is acquired through the process of evaluation of crew's competence is fed to the AI unit via the data cloud for further use and improvements in the training program.

There are four main parts in the simulator based training:

- The background information found in the data cloud
- The TrollCreek artificial intelligence program
- The training in the simulator and the feedback given after the training. In the simulator training program, training and evaluation of the crew are included
- The data from the test have to be returned to the data cloud, to improve the support in the artificial intelligence database. After completion the evaluation of the results, feedback will be stored to the data cloud for further assessment. See Figure 12

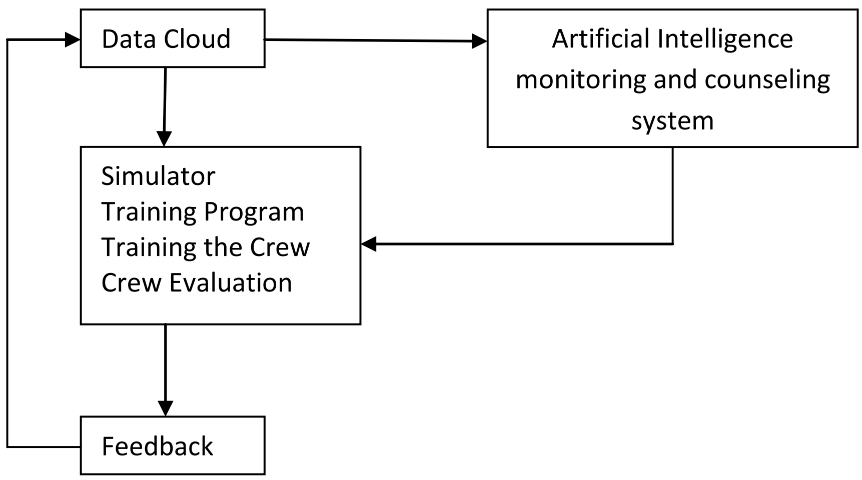

Figure 12: Schematic diagram of training simulator

4.4 Application of artificial intelligence in risk identification and risk mitigation

Risk management in projects includes various activities in order to assume what kind of risks faced and how to overcome them. Risk management includes activities such as:

- Planning of way to manage risk during the project
- Assigning a risk officer
- Keeping project risk data-base
- Creating way for anonymous risk reporting, so that each team member have possibility to report risk
- Preparing mitigation plans for risks that are chosen to be mitigated

These activities can be summarized in a risk matrix that is presented in Figure 13.

Artificial Intelligence can be utilized in risk identification by applying the existing risk matrix and comparing indexed previous cases and general knowledge databases with relevant case, drilling program chosen and level of crew competence. This can provide probability rates described in table below, as well as ways of dealing with the problem and minimizing risk.

RISK MATRIX WITH RISK FACTORS

	Consequence					Increasing probability				
						5 > 5 years	4 > 1 year	3 > 6 months	2 > 14 days	1 < 14 days
	Personal Injury	Discharge Oil spill to sea	Discharge Chemicals in Group 1	Economical Lost rig time /equippment	Reputation	Never heard of in the industry	Has occurred in Statoil	Occurs several times a year	Occurs several times a month	Occurs once a week
						Highly Unlikely	Unlikely	Low Likelihood	Possible	Probable
1	Fatality	>1000 m3	> 1000 m3	> 50 mill. NOK	National impact. National media coverage.	75	150	225	300	375
2	Serious pers. injury w/possible permanent injury	> 100 m3	> 100 m3	> 25 mill. NOK	Considerable impact. Regional media coverage.	25	50	75	100	125
3	Serious pers. injury	> 1 m3	> 10 m3	> 10 mill. NOK	Limited impact. Local media coverage.	10	20	30	40	50
4	Medical treatment	> 0.1 m3	> 1 m3	> 500000 NOK	Slight impact. Local public awareness.	5	10	15	20	25
5	First Aid	< 0.1 m3	< 1 m3	< 500000 NOK	No Impact	1	2	3	4	5

Intolerable | All incidents to be approved by Asset Mgr. | All incidents to be approved by B&B/RESU Mgr.

Figure 13: Statoil risk matrix [14]

4.5 Application of artificial intelligence in decision making

Decision making processes are important for creating, maintaining and finishing projects. Process in general has several objectives that should be included such as establish goals, goals have to be categorized and sited in order of importance, alternative actions have to be established, alternative should be evaluated against goals.

As mentioned previously, Artificial intelligence is can be employed as a supplementary tool in decision making for all aspects of well program such as risk identification and mitigation, learning and training, evaluating, and in the end – drilling itself.

All presented schematics have three major components (see Figure 14):

- Data cloud
- Artificial intelligence monitoring and counseling system
- Algorithm of decisions

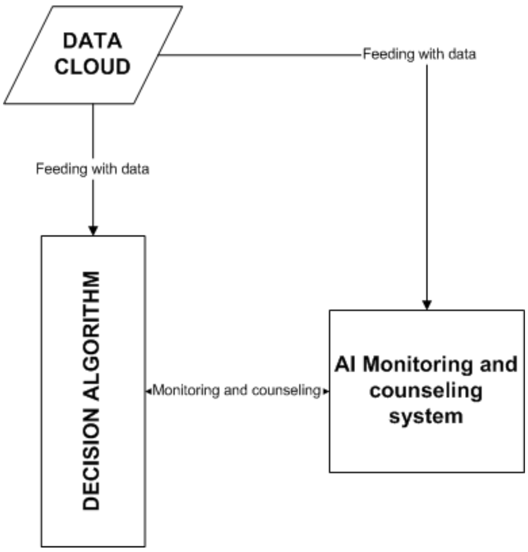

Figure 14: General scheme of decision tree

The date is being fed to the AI monitoring and counseling system for processing by means of CBR and MBR methods combined. Processed data is then used my AI system throughout process for purposes of monitoring and counseling. AI system is continuously monitoring developments of the process and comparing with values that have received. Also it is suggesting solutions to the designated engineers or persons in charge (Geological engineer, drilling engineer, HSE engineer, economist, etc.).

In cases that solution proves to be invalid, or not possible to preform, data is being returned to the beginning of the process for further work and finding new solutions (by use of different technologies, approaches, etc.). Additionally for overall process QA is added to monitor and secure good working practice.

Schematics of how the AI monitoring and counseling system is adapted for well program and its parts are shown in Figure 17-20. Previously mentioned principle is applied both to the whole process and all of its separate parts.

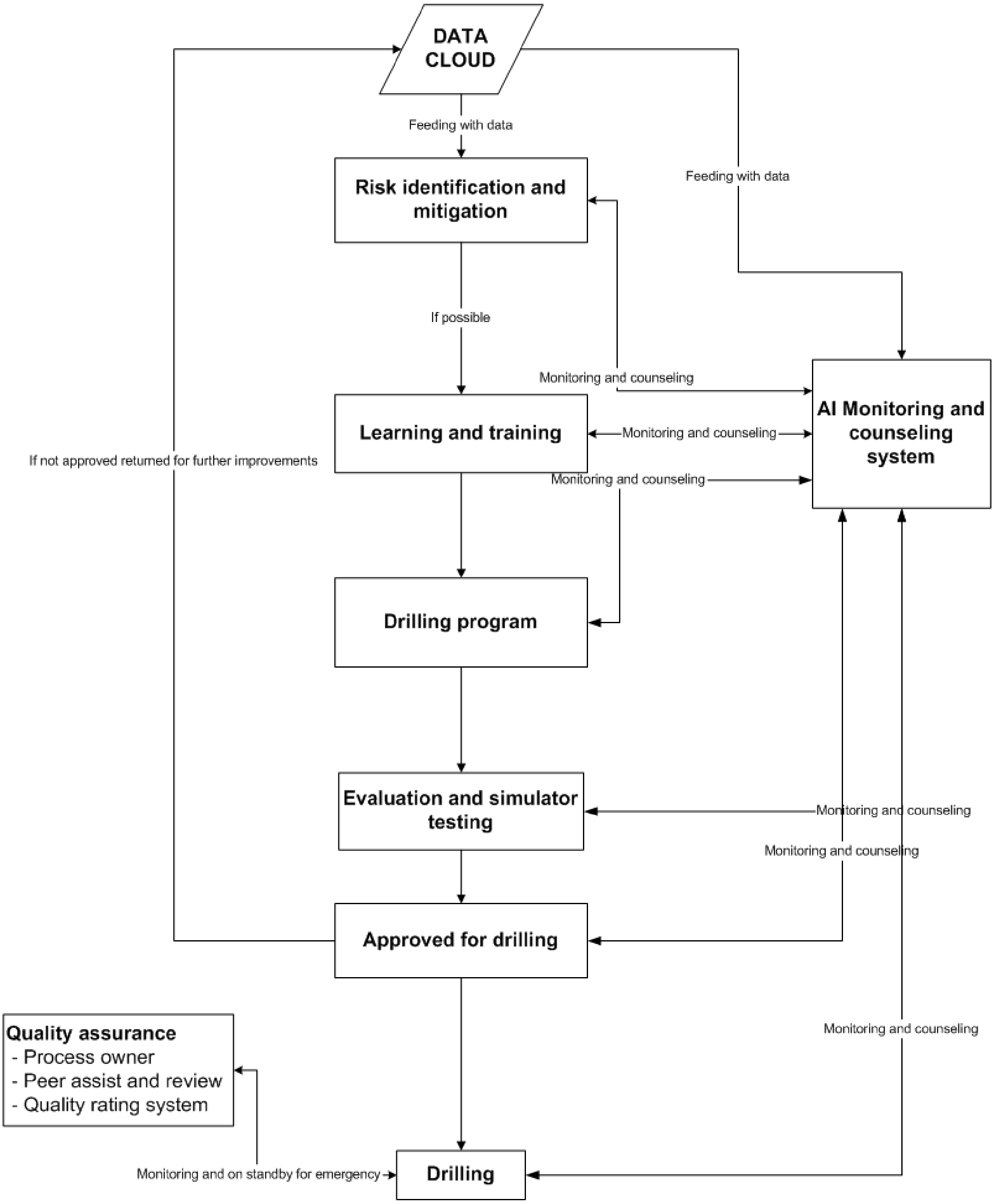

Figure 15 Decision tree for well program with Artificial Intelligence implemented as a monitoring and counseling tool.

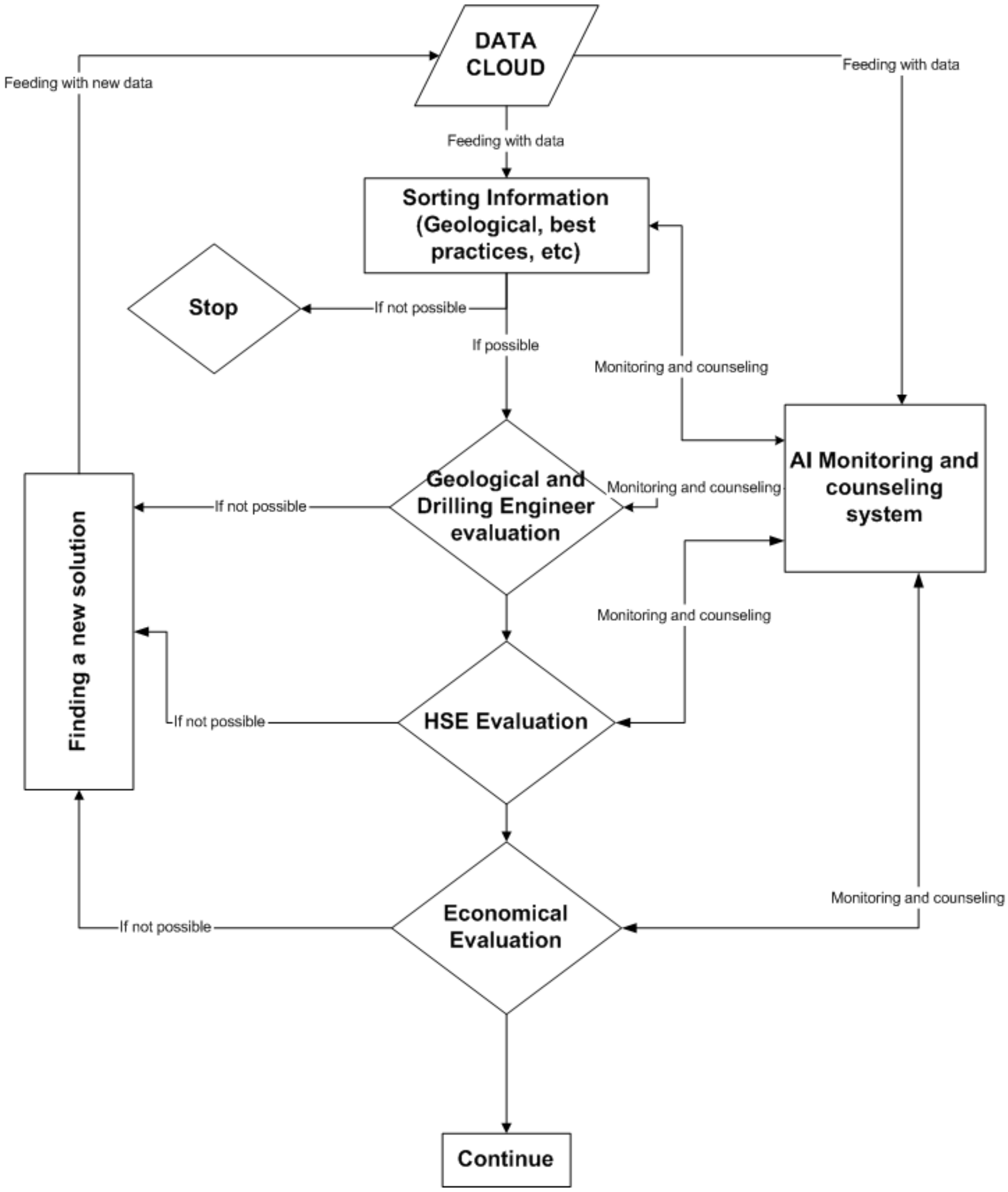

Figure 16 Decision tree for risk identification and mitigation with Artificial Intelligence implemented as a monitoring and counsel tool.

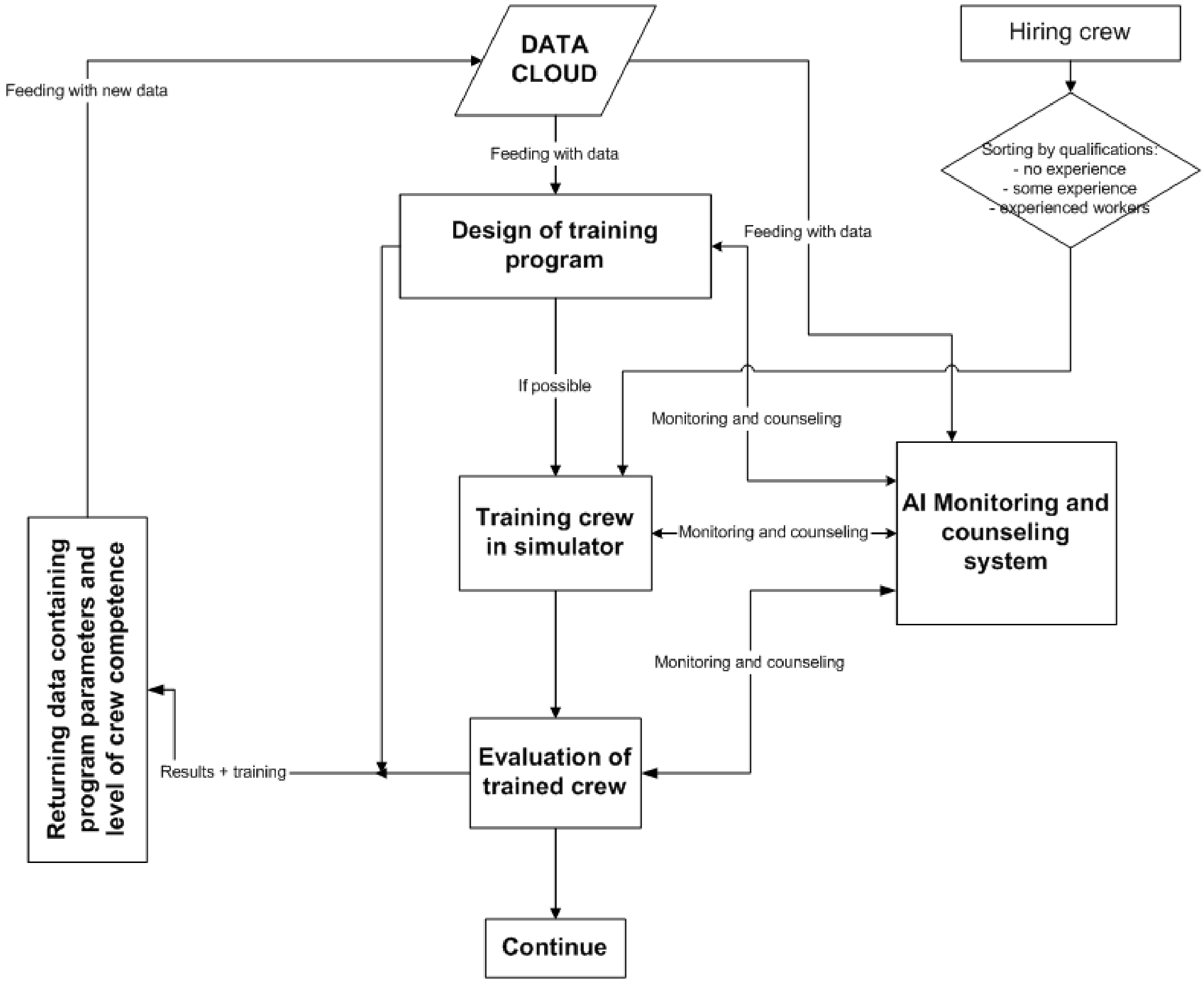

Figure 17: Decision tree for learning and training with Artificial Intelligence implemented as a monitoring and counsel tool

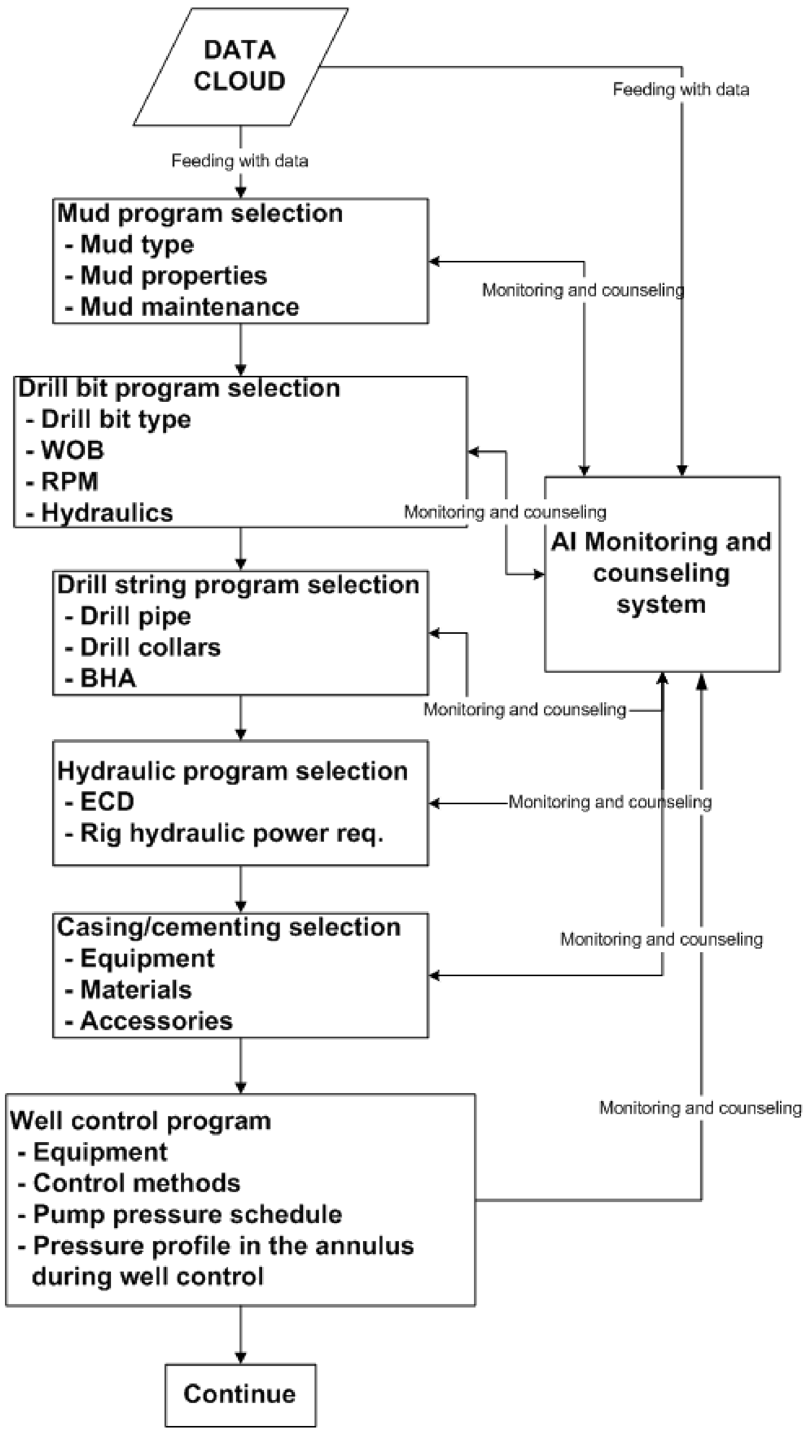

Figure 18: Decision tree for drilling program with Artificial Intelligence implemented as a monitoring and counsel tool

4.6 Related work, future applications and developments

Several oil companies, such as Schlumberger [18] and Halliburton [19], recognize the need to retain and centralize the knowledge and experience of the organization, among other reasons due to outsourcing and spreading of knowledge. Generally, diagnostic tools represent the largest area of application for AI systems.

CBR are known to be well suited for maintenance of other complex processes, related to our domain. TrollCreek approach differs from the above in the combination of case-specific and general domain knowledge. Further, the model-based reasoning module in TrollCreek assumes open and weak theory domains, i.e. domain domains characterized by uncertainty, incompletes, and change. Hence, it's inference methods are abductive, rather than deductive, forming the basis for plausible reasoning by relational chaining.

In the drilling industry the engineers tend to group problem related knowledge into decision trees. Decision trees are inherently instable, and alternative trees may produce different results. A combination of the two may work well, our cases being the exceptions of the more rule based tree. Some frequently re-occurring problems may gradually turn into a decision rule. Such problems will then enter the default best practice of the oil company. Best practice, are notions of large interest in the oil drilling industry.

Challenges that are being faced are:

- Integration of a knowledge-based decision support tool smoothly into the other computer-based systems in an operational environment.
- Integration of computerized decision support into the daily organizational and human communication structure on-board a platform or on shore

In future we see TrollCreek system develop in all-round system that is involved in training and learning program, planning, executing and evaluation stages of drilling. We see it as a tool that will be successfully used in simulator teaching rooms, by drilling engineers when they are planning drilling, drillers and superintendents when they are implementing plans, and by drilling engineers and management in evaluation process.

We see use of data clouds where will be stored – easily accessible information's. This information's we see constantly updated with new data from simulators, and new cases done worldwide.

5 Optimal use of simulator training

5.1 Introduction to simulator training

A drilling simulator is a tool for training crew to operate drilling equipment, train on well control, practice techniques and prepare for specific drilling operations. There exist different simulators, both in Norway and in the rest of the world. Figure 19 show a photo from the Aberdeen DART facility [21].

According to the Sintef webpage [22], Sintef are now building a drilling simulator for Statoil. It was not possible for the group to find the details about the simulators, so the ideas presented in this report are how the simulator can be used to optimize the training of the crews. The group's basis is to include more focus on human relations through evaluations of the team's training in the simulator, and to include an extra part in the training where operators exchange roles and responsibility to get a better overview of the complete drilling operation.

The group would also like to propose that the simulator should be extended so that more of the drilling organization can be included in the training. For example should there be an opportunity to have a video conference from the simulator. Then there can be run video conferences with other drilling teams, service companies and the onshore drilling expert team. This way the entire organization can practice on communication and improve understanding.

Figure 19: The Aberdeen DART facility [21]

From information found about existing simulators [22] and [23], the impression is that the focus is on drilling related topics, but some training institution [24] also mention that they offer to train crew in human relations like communication and cooperation. It is therefore difficult to find details on what the training of the crew contain. A proposal for training programs for drilling crews has therefore been included in section 5.3.

For a fresh operator, training in the drilling simulator is an efficient training method that does not involve the risk associated with real training. For more experiences operators, the simulator offers an opportunity to learn and practice new techniques, and practice on HSE-related cases. The method also includes study of real-time data from the drilling operation and the actual drilling environment during the training. This information is retrieved from and linked to the data cloud in the artificial intelligence system, as described in section 4.

5.2 Using of simulator for knowledge transfer

Initially fresh operators will be given the basics of drilling operation using a simulator, before they go to the field operation. While the training progresses, gaps in knowledge, understanding and application of procedures become apparent, and can be addressed before the actual operation commences. Individual strength and weakness can also be evaluated, and based on this information; the operators can be divided into teams. The team's behavior, knack to the learning, communication, participation, decision making, time management, team spirit, etc can be observed and evaluated. The teams can also exchange knowledge on the different topics in team evaluations and debates on issues related to the training.

The experienced drillers can learn more advanced and new drilling technology using a simulator. They can also share knowledge on their experience, and help to train the fresh operators for the drilling operation. Thus, they can be an inspiration for the fresh operators, and also practice communication with less experienced personnel. The fresh operators then have the opportunity to practice working in the teams they will be working with during drilling operations. This may contribute to be an "ice-breaker", and by building team relations, the barrier to question decisions made can hopefully be lowered. This is especially important for the fresh operators, as they have to build confidence in a new environment.

5.3 A complete training program

A simulator is an essential component of the training curriculum when it comes to complicated systems like oil or gas rigs - where a small mistake can lead to a catastrophic accident. With the help of a training simulator, operators can acquire knowledge both on technical and management skills prior to the field operation.

The training must have a series of lessons that begin with the basics and then advance to more complex cases. The series of lectures should be fully narrated and contain periodic knowledge checks and evaluations throughout, so that the operators can enhance the learning experience.

The simulator training program constructed consists of three parts: Individual and team training for the technical part and a human relation part. The technical part look at basic knowledge about drilling, HSE, more advanced drilling technology and real case studies. It also has a part where the operators exchange roles and responsibility, where the aim is to improve the operator's overview of the drilling situation. The human relations part concentrates on communication, behavior and cooperation in the drilling crew. It consists of a personal evaluation, a team evaluation, a discussion about overall improvements and a final certification.

Fresh operators go through the entire training before starting to work offshore, while more experienced drilling operators should focus on the human relations part as well as to work with team based training for the technical part.

5.3.1 Technical part – individual training

5.3.1.1 Basic knowledge

This part includes the introduction to the simulator, training on the different steps of the drilling process, and to put together the steps and works on simple processes.

5.3.1.2 Health and Safety Environment

It is one of the most important parts of this training, and an important contribution for Statoil to be able to reach their zero-emission goal. It directs how to handle dangerous situation, in example how to avoid accidents and injuries, how to work with drilling chemicals and mud, uncertainties, risk and impact considerations.

5.3.1.3 More advance on drilling operation

Technology in offshore drilling is being improved, and technologies like extended reach drilling, ERD, and managed pressure drilling, MPD, are studied and practiced in the simulator.

5.3.2 Technical part – team training

5.3.2.1 Real case studies

Studying real cases are a very important part of training and transfer of experience. The training should also include drilling wells that had problems when they originally were being drilled. Field excursion where topics related to the reservoir condition during drilling, drilling floor, drilling rig, rotary table and how it works are implemented in this part of the training.

5.3.2.2 Exchanging roles and responsibilities

In order to improve the overview, the operators should try to exchange roles and responsibilities. This can be done in a safe and time-efficient way in the simulator, by letting the different operators train each other.

and can improve communication and understanding between the operators working together. As the different operators see things from a different point of view, this may also reveal possible improvements to the methods used.

5.3.3 Human relations part

5.3.3.1 Personal evaluation:

For the first part of the training, the operator should be given a personal evaluation based on quality, accuracy, time management and HSE.

5.3.3.2 Team evaluation
Later in the training program, when the operators start working in teams, a team evaluation should be given. In the team evaluation everybody should observe a video recording of themselves working on the real case situations in the simulator. The team can then discuss their performance in the video with the help of external support personnel. Keywords for the evaluations are:

- Team management skills
- Communication
- Cooperation
- Decision making
- Problem solving
- Time management
- Quality assurance
- HSE
- Team spirit
- Handling responsibilities

5.3.3.3 Debates
Here the groups have a debate that focuses on the solution of problems and drilling related topics. The debate should end up with a proposal from the group about what can be done better and maybe new ideas for how the process can be improved.

5.4 Benefits of using a simulator
Some of the benefits of using a simulator as an important part of the training of operators have already been mentioned in the text above. A more detailed summary is included in this section.

5.4.1 Improve communication
A lot of this section focuses on human relations, and especially communication, in the team. This is because this can reduce risk, misunderstanding and errors, and improve the team's efficiency. This can again lead to reduced time used to finish an operation and rig downtime, which will give an economical saving.

5.4.2 Reduce risk
A simulator provides realistic moving graphics replicating the sights and sounds the operator will actually experience on the rig for drilling operation. This makes the simulator a good opportunity to practice operations in a risk-free environment, while still keeping the realistic surroundings faced in real operations offshore. For the operator, the great advantage is to work in a completely safe environment, knowing that any mistake made will not end in injury or expensive damage. Simulator reduces the extra maintenance and equipment damage sometimes caused by the inexperienced operators. Training oil and gas rig operators on a simulator, rather than the real-world facility, can also help to reduce the risk to the amount of rig downtime.

5.4.3 Environmentally friendly:
Simulator is environmentally friendly, because it has no negative impact on the environment other than the energy consumption needed to run the simulator. If the training were to be arranged during

offshore operations, real equipment would have to be used. Unnescessary use of drilling equipment would include both an environmental and an economical strain.

5.4.4 Improve skills and build confidence

The use of simulator training can improve an operator's performance and skill level dramatically and rapidly, since he can keep working at a difficult task until he gets it right, whereas in a real situation, he may not get that chance to practice and perfect his technique. Simulator is an invaluable tool for oil rig operational procedure training, which translates into operator confidence and increased level of productivity. As mentioned in section 5.4.1, this can reduce the rig's downtime in the long run.

A simulator gives the artificial results that are nearly similar to that of drilling operation. These results will increase the confidence level of an operator when he finds the same in drilling operation. Thus, operators can be acquainted with the drilling parameters which are essential for the real case.

5.4.5 Improved overview

The exchange of roles and responsibilities, can improve the operators overview of the drilling operation. It can improve communication and understanding between the operators working together. As the different operators see things from a different point of view, this may also reveal possible improvements to the methods used.

6 Quality assurance

Quality assurance, QA, is the systematic monitoring and evaluation of the various aspects of a project, service or facility. It aims at maximizing the probability that standards of quality are being attained by the production process. Still, QA cannot absolutely guarantee the production of quality products.

Two principles included in QA are: "Fit for purpose" - the product should be suitable for the intended purpose; and "Right first time" - mistakes should be eliminated. In this discussion, it is assumed that Statoil would like to follow the “right first time”-approach. QA includes regulation of the quality of raw materials, assemblies, products and components, services related to production and management, production and inspection processes.

The system examined in this report has a double QA system. The primary QA is the AI monitoring and counseling system described in chapter 4. The secondary consists of process owner, peer assist/review team and quality rating system altogether, already implemented by Statoil. Most of the following literature is taken from a presentation given to us by Johan Eck-Olsen [14], our advisor in Statoil.

The process owner’s main task is to identify, document, develop, perform quality assurance and pass on best practice for the corporate work processes.
This process involves:

- Ensuring that best practice forms the basis for designing common work processes, systems and tools, and documenting these in governing documents
- Facilitating expertise development and, together with the managers of the BAs/units, ensuring an appropriate utilization of expertise and allocation of personnel
- Establishing performance indicators for own evaluation of processes and performance indicators which are recommended for use by task managers
- Facilitating interaction and stimulating direct collaboration and developing relations within and between process networks

Peer assist and reviews’ objectives are to challenge the plans, programs and procedures to assure that best practice will be used, and to identify any potential operation-stoppers. The peer assists focus on technical solution, detailed planning, operational management, use of “Best Practice” and networking.

The quality rating system, QRS, is a tool for measuring quality of contractor’s job performance, including monitoring quality trends. Contractors are given a consistent and continuous feedback on performance related to quality of services and products. Quality performance and quality related key performance indicators, KPI, are recorded on a per job basis and stored in the QRS system. KPI's represent a balanced focus on the most important perspectives such as safety, environment and operating performance, and are used as the official measurement of the contract performance.

It is important that the information gained through the use of process owners, peer assists/review teams and quality rating systems are included in the data cloud in the artificial intelligence system. This can, after having built up competence and knowledge from these processes over time, help increase the efficiency of the quality control without compromising the details. The implementation of artificial intelligence will also help to close the loop of information flow and increase the knowledge transfer in the organization.

7 Conclusion part B

This report describes the optimization of a well program, and the ideas presented are based on reducing human errors. Three key elements related to human error are decision making, training of the crew and knowledge transfer. To address these issues the group has looked at construction of decision trees, introduction of an artificial intelligence system and optimization of simulator training. It has also been discussed how the artificial intelligence system can be implemented in the simulator training and quality assurance. Additionally, the group has studied government standards and regulations to create a good starting point for the work in the second part of the project.

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Appendix A: List of symbols

Symbol	Unit	Explanation
B_w	[-]	Formation volume factor of water
C_w	[1/bar]	Compressibility of water
P_i	[bar]	Pressure at state i
V_w	[Sm^3]	Volume in water equivalents

Appendix B: Data and calculations

The data found in ”Production and injection rates” (ref Statoil), and the calculations performed on these data in Excel are summarized in Table 2.

Table 2: Excel sheet with data and calculations

Date	GFHF	Tordis	Vigdis	GF Vest	Gullveig	Gulltopp	Skinfaks	Total Prod. rateSm3/d	TOTAL PROD	Total Injection rate Sm3/d	TOTAL INJECTION	ΔV (SM3)	Water in Res. Cond.	Total volume of water	ΔP (bar)	P2 (1.0E+09)	P2 (2.0E+09)	P2 (3.0E+09)	Inj-Prod rate	total inj-prod	GFHF2	Tordis3	Vigdis4	GF Vest5
01.01.1986	129,77	0,00	0,00	0,00	0,00	0,00	0,00	129,77	47364,48	1,42	518,52	128,35	130,91	47782,88	0,0013	380,0000	380,0000	380,0000	-130,9120	-47782,8800	1,42	0,00	0,00	0,00
01.01.1987	454,33	0,00	0,00	0,00	0,00	0,00	0,00	454,33	165831,62	7,56	2759,04	446,77	455,71	166334,03	0,0046	379,9954	379,9977	379,9985	-455,7097	-166334,0309	7,56	0,00	0,00	0,00
01.01.1988	1285,00	0,00	0,00	1811,89	0,00	0,00	0,00	3096,88	1130361,93	5,59	2040,54	3091,29	3153,12	1150887,82	0,0315	379,9639	379,9820	379,9880	-3153,1173	-1150887,8150	5,59	0,00	0,00	0,00
01.01.1989	2388,44	0,00	0,00	1955,68	0,00	0,00	0,00	4344,12	1585604,90	67,26	24550,78	4276,86	4362,40	1592275,19	0,0436	379,9203	379,9601	379,9734	-4362,3978	-1592275,1939	67,26	0,00	0,00	0,00
01.01.1990	3757,33	0,00	0,00	1179,36	0,00	0,00	0,00	4936,69	1801893,31	681,02	248573,91	4255,67	4340,78	1584385,79	0,0434	379,8769	379,9384	379,9590	-4340,7830	-1584385,7921	681,02	0,00	0,00	0,00
01.01.1991	3485,24	0,00	0,00	988,58	0,00	0,00	0,00	4473,82	1632942,91	952,90	347809,27	3520,91	3591,33	1310836,32	0,0359	379,8410	379,9205	379,9470	-3591,3324	-1310836,3194	952,90	0,00	0,00	0,00
01.01.1992	2457,49	0,00	0,00	1449,10	0,00	0,00	0,00	3906,60	1425908,27	1980,51	722884,33	1926,09	1964,61	717084,42	0,0196	379,8213	379,9107	379,9404	-1964,6149	-717084,4239	1980,51	0,00	0,00	0,00
01.01.1993	2449,65	0,00	0,00	1639,25	0,00	0,00	0,00	4088,90	1492448,14	1988,24	725707,60	2100,66	2142,67	782075,35	0,0214	379,7999	379,8999	379,9333	-2142,6722	-782075,3457	1988,24	0,00	0,00	0,00
01.01.1994	2450,24	5492,50	0,00	3203,02	0,00	0,00	0,00	11145,76	4068202,04	2076,09	757773,03	9069,67	9251,06	3376637,58	0,0925	379,7074	379,8537	379,9025	-9251,0619	-3376637,5826	1987,42	0,00	0,00	88,67
01.01.1995	2191,73	14976,53	0,00	3735,24	0,00	0,00	0,00	20903,50	7629777,14	7308,51	2667606,92	13594,99	13866,89	5061413,62	0,1387	379,5687	379,7844	379,8562	-13866,8866	-5061413,6229	2245,21	13,90	0,00	5049,40
01.01.1996	2235,67	17065,27	0,00	5617,76	0,00	0,00	0,00	24918,70	9095323,68	2200,21	803076,29	22718,49	23172,86	8458092,34	0,2317	379,3370	379,6685	379,7790	-23172,8557	-8458092,3378	2200,21	0,00	0,00	0,00
01.01.1997	1872,51	17454,52	4087,42	6655,84	0,00	0,00	0,00	30070,29	10975655,85	2561,96	935114,31	27508,33	28058,50	10241352,38	0,2806	379,0564	379,5282	379,6855	-28058,4997	-10241352,3759	2561,96	0,00	0,00	0,00
01.01.1998	2178,84	15332,49	11618,33	4370,21	602,02	0,00	0,00	34101,89	12447190,11	5833,20	2129119,46	28268,69	28834,06	10524432,06	0,2883	378,7681	379,3840	379,5894	-28834,0604	-10524432,0584	2253,96	0,00	3579,24	0,00
01.01.1999	701,23	12925,72	13556,62	3183,27	3077,38	0,00	0,00	33444,22	12207139,06	15896,69	5802292,95	17547,52	17898,47	6532943,04	0,1790	378,5891	379,2945	379,5297	-17898,4741	-6532943,0363	3809,40	1754,26	10333,03	0,00
01.01.2000	0,59	9932,73	15565,02	3149,02	6341,08	0,00	0,00	34988,45	12770782,90	22507,12	8215100,08	12481,32	12730,95	4646796,48	0,1273	378,4618	379,2309	379,4873	-12730,9493	-4646796,4788	6886,06	3725,64	11674,85	220,58
01.01.2001	0,00	8984,94	16811,07	3614,33	4108,23	0,00	0,00	33518,57	12234276,96	22533,64	8224778,60	10984,93	11204,63	4089688,32	0,1120	378,3497	379,1749	379,4499	-11204,6255	-4089688,3221	9259,10	2608,72	10665,82	0,00
01.01.2002	0,00	12158,80	11706,09	3783,64	2059,35	0,00	0,00	29707,89	10843378,03	29217,15	10664259,39	490,74	500,55	182701,01	0,0050	378,3447	379,1724	379,4482	-500,5507	-182701,0128	9691,65	6533,64	10800,97	2190,89
01.01.2003	0,16	11592,66	17089,25	5078,01	3995,40	0,00	0,00	37755,48	13780748,92	39540,95	14432447,85	-1785,48	-1821,19	-664732,90	-0,0182	378,3629	379,1815	379,4543	1821,1860	664732,8993	10153,60	5221,16	17521,43	6644,77
01.01.2004	3,89	10804,49	10596,02	7072,59	6190,80	0,00	0,00	34667,79	12653741,63	26446,72	9653051,34	8221,07	8385,49	3060704,10	0,0839	378,2791	379,1395	379,4264	-8385,4907	-3060704,0989	10709,53	2984,22	12752,97	0,00
01.01.2005	48,38	7797,30	8336,87	4679,12	4781,61	0,00	0,00	25643,27	9359794,94	26591,80	9706005,18	-948,52	-967,49	-353134,44	-0,0097	378,2887	379,1444	379,4296	967,4916	353134,4353	11031,87	5204,00	10355,93	0,00
01.01.2006	174,10	6982,84	8501,84	4580,02	3118,64	0,00	0,00	23357,44	8525466,18	26472,74	9662549,01	-3115,30	-3177,60	-1159824,48	-0,0318	378,3205	379,1603	379,4402	3177,6013	1159824,4774	10908,38	5518,63	10045,73	0,00
01.01.2007	187,39	14107,27	9342,70	3821,03	2886,35	0,00	896,47	31241,21	11403041,54	20224,57	7381967,32	11016,64	11236,97	4101495,70	0,1124	378,2082	379,1041	379,4027	-11236,9745	-4101495,7049	10917,68	1481,24	7825,64	0,00
01.01.2008	4,42	13971,87	5896,55	1611,49	1625,50	3649,33	3766,31	30525,46	11141794,22	16502,37	6023365,78	14023,09	14303,55	5220797,00	0,1430	378,0651	379,0326	379,3550	-14303,5534	-5220797,0038	11560,73	1484,33	3457,32	0,00

Date	GFHF	Tordis	Vigdis	GF Vest	Gullveig	Gulltopp	Skinfaks	Total Prod. rateSm3/d	TOTAL PROD	Total Injection rate Sm3/d	TOTAL INJECTION	ΔV (SM3)	Vol. of Water in Res. Cond. Sm3)	Total volume of water	ΔP (bar)	P2 (1.0E+09)	P2 (2.0E+09)	P2 (3.0E+09)	Inj-Prod rate	total inj-prod	GFHF2	Tordis3	Vigdis4	GF Vest5
01.01.2009	4,27	12413,48	5370,52	2148,61	1549,46	5545,58	770,17	27802,09	10147763,00	12908,25	4711512,11	14893,84	15191,71	5544975,90	0,1519	377,9132	378,9566	379,3044	-15191,7148	-5544975,9030	12357,54	523,29	27,42	0,00
01.01.2010	0,00	10329,00	10102,00	2415,89	1681,63	4126,14	2131,80	30786,47	11237060,09	21005,54	7667023,20	9780,92	9976,54	3641437,63	0,0998	377,8134	378,9067	379,2711	-9976,5415	-3641437,6329	13286,25	1061,00	3452,00	3206,29
01.01.2011	86,40	10258,00	8105,00	3578,95	1055,75	3129,50	3996,63	30210,23	11026734,63	29689,04	10836498,87	521,19	531,62	194040,47	0,0053	377,8081	378,9041	379,2694	-531,6177	-194040,4704	13398,98	849,00	8316,00	7125,06
01.01.2012	36,59	19415,00	7047,00	2559,50	0,00	2812,90	2859,27	34730,26	12676543,33	36840,59	13446815,35	-2110,33	-2152,54	-785677,46	-0,0215	377,8296	378,9148	379,2765	2152,5410	785677,4599	13563,03	849,00	14905,00	7523,56
01.01.2013	194,15	15063,00	6658,00	2153,41	0,00	2655,61	1805,57	28529,74	10413354,01	35022,37	12783163,96	-6492,63	-6622,48	-2417206,15	-0,0662	377,8959	378,9479	379,2986	6622,4826	2417206,1490	13519,15	0,00	13980,00	7523,22
01.01.2014	589,07	15680,00	7721,00	2073,58	0,00	2288,43	1568,24	29920,33	10920921,00	36872,57	13458487,32	-6952,24	-7091,28	-2588317,65	-0,0709	377,9668	378,9834	379,3223	7091,2812	2588317,6490	13125,51	0,00	16622,00	7125,06
01.01.2015	1042,19	13789,00	6706,00	2291,76	0,00	2319,16	0,00	26148,11	9544059,06	35187,17	12843315,96	-9039,06	-9219,84	-3365242,04	-0,0922	378,0590	379,0295	379,3530	9219,8412	3365242,0380	12673,95	0,00	14990,00	7523,22
01.01.2016	1484,00	14175,00	8585,00	1871,43	0,00	2214,65	4366,11	32696,18	11934106,80	38181,80	13936357,00	-5485,62	-5595,33	-2042295,21	-0,0560	378,1149	379,0575	379,3716	5595,3293	2042295,2091	12233,24	0,00	18425,00	7523,56
01.01.2017	1733,52	13538,00	9072,00	1369,69	0,00	1425,73	3409,25	30548,20	11150091,54	28488,68	10398368,20	2059,52	2100,71	766757,81	0,0210	378,0939	379,0470	379,3646	-2100,7063	-766757,8068	11983,68	0,00	16505,00	0,00
01.01.2018	1914,66	12009,00	8958,00	141,55	0,00	207,38	1060,30	24290,88	8866172,04	30420,14	11103351,10	-6129,26	-6251,84	-2281922,64	-0,0625	378,1564	379,0782	379,3855	6251,8429	2281922,6417	11803,14	0,00	18617,00	0,00
01.01.2019	2236,35	12420,00	4611,00	0,00	0,00	0,00	0,00	19267,35	7032581,66	28088,08	10252149,20	-8820,73	-8997,15	-3283958,90	-0,0900	378,2464	379,1232	379,4155	8997,1477	3283958,8959	11483,08	0,00	16605,00	0,00
01.01.2020	3027,13	0,00	2519,66	0,00	0,00	0,00	0,00	5546,79	2024577,26	29312,76	10699157,40	-23765,97	-24241,29	-8848071,75	-0,2424	378,4888	379,2444	379,4963	24241,2925	8848071,7479	10695,76	0,00	18617,00	0,00
01.01.2021	3992,54	0,00	0,00	0,00	0,00	0,00	0,00	3992,54	1457277,10	9732,44	3552341,33	-5739,90	-5854,70	-2136965,51	-0,0585	378,5474	379,2737	379,5158	5854,7000	2136965,5146	9732,44	0,00	0,00	0,00
01.01.2022	4553,33	0,00	0,00	0,00	0,00	0,00	0,00	4553,33	1661966,18	9172,59	3347995,35	-4619,26	-4711,64	-1719749,75	-0,0471	378,5945	379,2972	379,5315	4711,6432	1719749,7534	9172,59	0,00	0,00	0,00
01.01.2023	4858,66	0,00	0,00	0,00	0,00	0,00	0,00	4858,66	1773412,00	8868,04	3236832,78	-4009,37	-4089,56	-1492689,20	-0,0409	378,6354	379,3177	379,5451	4089,5594	1492689,1956	8868,04	0,00	0,00	0,00
01.01.2024	4805,01	0,00	0,00	0,00	0,00	0,00	0,00	4805,01	1753827,56	8922,44	3256690,97	-4117,43	-4199,78	-1532920,68	-0,0420	378,6774	379,3387	379,5591	4199,7827	1532920,6782	8922,44	0,00	0,00	0,00
01.01.2025	4155,54	0,00	0,00	0,00	0,00	0,00	0,00	4155,54	1516772,83	7240,63	2642830,68	-3085,09	-3146,79	-1148579,01	-0,0315	378,7089	379,3544	379,5696	3146,7918	1148579,0070	7240,63	0,00	0,00	0,00

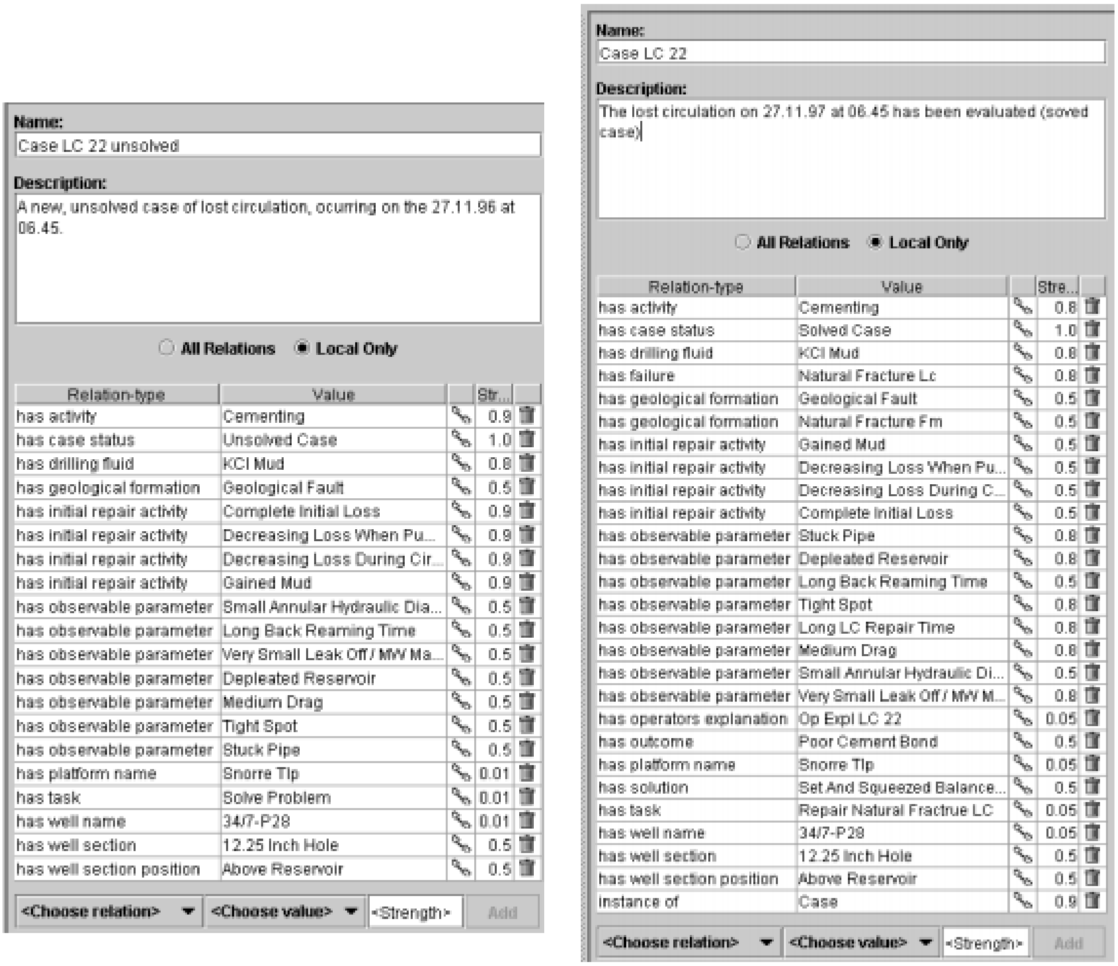
Appendix C: Oil well drilling scenario with example

During oil well drilling the geological object may be as far as 15 km away from the drilling rig, and must be reached through selecting proper equipment, material and processes.

Phases to be addressed in the drilling process:
- Planning
- Plan implementation
- Post analyses

Of all possible problems during oil well drilling scenario only one specific failure mode is selected: Gradual or sudden loss of drilling fluid into cracks in the underground. This failure is referred to as Lost Circulation (LC) that occurs when the geological formation has weaknesses like geological faults, cavernous formations or weak layers. The risk of loss increases when the down hole drilling fluid pressure becomes high, i.e. by restrictions in the flow path or if the drilling fluid becomes more viscous.

Assuming a situation where drilling fluid losses are observed, and further develops to lost circulation. The left hand side of Figure 20 describes the case. TrollCreek first of all produces a list of similar cases for review to the user; see Figure 21, bottom line. From the bottom line, one can see that case LC 40 best matches case LC 22, and case LC 25 as the second best. Degree of similarity is 45%, shown at the top of the figure. The box for “directly matched features” point out that both LC 40 and LC 25 are of the failure type “natural fracture”.



Name: Case LC 22 unsolved

Description: A new, unsolved case of lost circulation, ocurring on the 27.11.96 at 06.45.

All Relations / Local Only

Relation-type	Value	Str...
has activity	Cementing	0.9
has case status	Unsolved Case	1.0
has drilling fluid	KCl Mud	0.8
has geological formation	Geological Fault	0.5
has initial repair activity	Complete Initial Loss	0.9
has initial repair activity	Decreasing Loss When Pu...	0.9
has initial repair activity	Decreasing Loss During Cir...	0.9
has initial repair activity	Gained Mud	0.9
has observable parameter	Small Annular Hydraulic Dia...	0.5
has observable parameter	Long Back Reaming Time	0.5
has observable parameter	Very Small Leak Off / MW Ma...	0.5
has observable parameter	Depleated Reservoir	0.5
has observable parameter	Medium Drag	0.5
has observable parameter	Tight Spot	0.5
has observable parameter	Stuck Pipe	0.5
has platform name	Snorre Tlp	0.01
has task	Solve Problem	0.01
has well name	34/7-P28	0.01
has well section	12.25 Inch Hole	0.5
has well section position	Above Reservoir	0.5

<Choose relation> <Choose value> <Strength> Add

Name: Case LC 22

Description: The lost circulation on 27.11.97 at 06.45 has been evaluated (soved case)

All Relations / Local Only

Relation-type	Value	Stre...
has activity	Cementing	0.8
has case status	Solved Case	1.0
has drilling fluid	KCl Mud	0.8
has failure	Natural Fracture Lc	0.8
has geological formation	Geological Fault	0.5
has geological formation	Natural Fracture Fm	0.5
has initial repair activity	Gained Mud	0.5
has initial repair activity	Decreasing Loss When Pu...	0.5
has initial repair activity	Decreasing Loss During C...	0.5
has initial repair activity	Complete Initial Loss	0.5
has observable parameter	Stuck Pipe	0.8
has observable parameter	Depleated Reservoir	0.8
has observable parameter	Long Back Reaming Time	0.5
has observable parameter	Tight Spot	0.8
has observable parameter	Long LC Repair Time	0.8
has observable parameter	Medium Drag	0.8
has observable parameter	Small Annular Hydraulic Di...	0.5
has observable parameter	Very Small Leak Off / MW M...	0.8
has operators explanation	Op Expl LC 22	0.05
has outcome	Poor Cement Bond	0.5
has platform name	Snorre Tlp	0.05
has solution	Set And Squeezed Balance...	0.5
has task	Repair Natural Fractrue LC	0.05
has well name	34/7-P28	0.05
has well section	12.25 Inch Hole	0.5
has well section position	Above Reservoir	0.5
instance of	Case	0.9

<Choose relation> <Choose value> <Strength> Add

Figure 20: Unsolved case (left) and the corresponding solved case (right) of Case LC 22 [16]

The user can choose to accept the delivered results, or construct a solution by combining several matched cases. The user can also start a new matching process, after having added (or deleted) information in the problem case, or he/she can browse the case base, for example by asking for cases containing one specific or a combination of attributes.

An important notion in identifying a failure mode is the notion of a non-observable parameter, i.e. a parameter which is not directly measurable or observable, usually related to conditions down in the well. Identifying a failure and a repair for the failure are two types of tasks that the system can reason about.

By combining task and state models, with causal reasoning, a solution may be found by model-based reasoning within the general domain model, even if a matching case is not found. If so, the system will, as shown before, store the problem solving session as a new case, hence transforming general domain knowledge, combined with case-specific data, into case-specific knowledge.

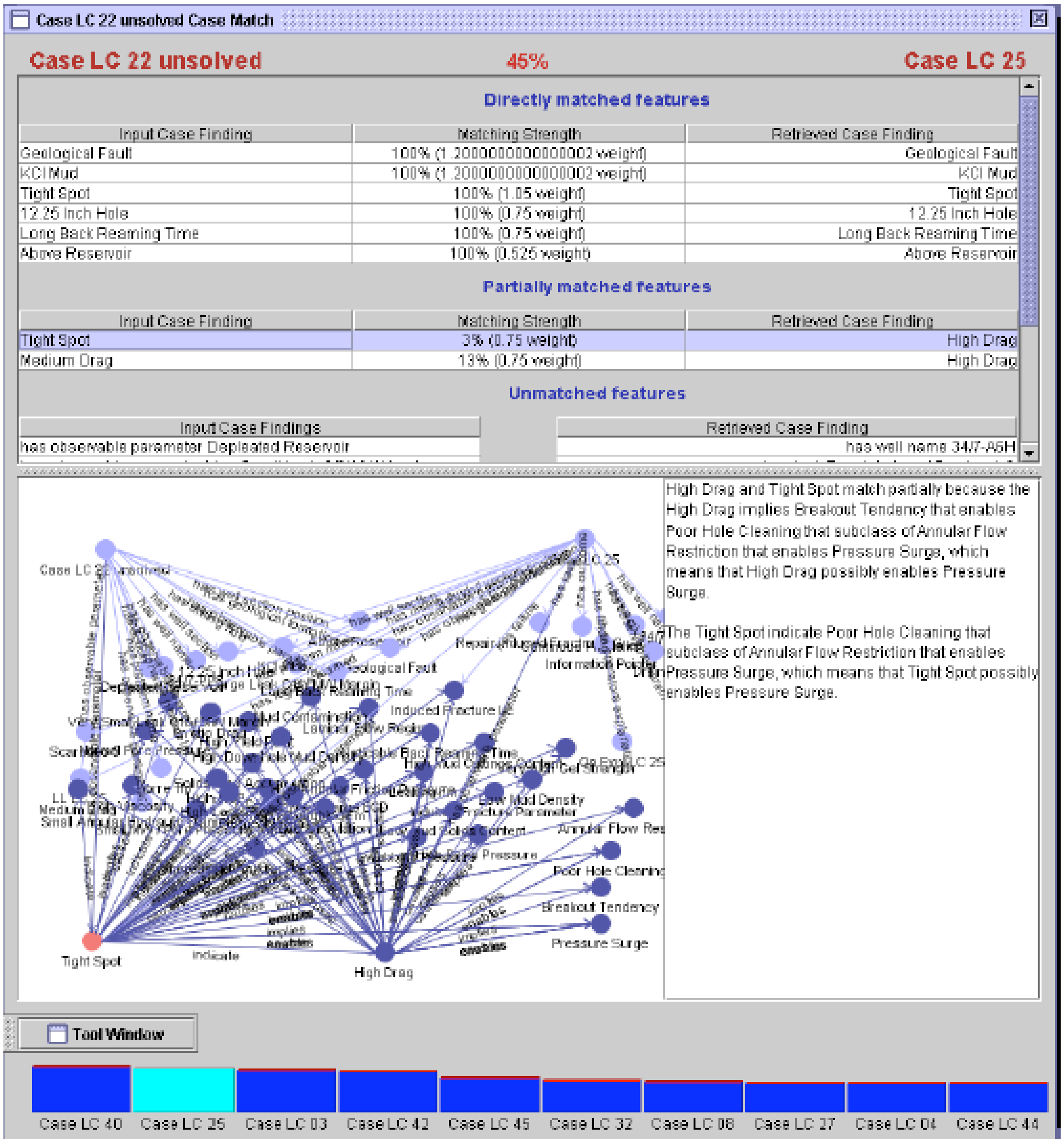


Figure 21: Results of matching a new case (Case LC 22 unsolved) with the case base [16]