Decision Framework for Well Delivery Processes

Application of Analytical Methods to Decision Making

Doctoral Thesis

by

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Abstract

A major portion of unproduced oil and gas resources are located in deep-water areas, often at sea level depths between 1500 and 3000 metres. Development of these fields with conventional technology necessitates increasing costs mainly due to the higher rig- and equipment specification needed. Conventional technology normally implies using a 21” marine riser and a 18 ¾” blowout preventer (BOP) that require heavy rig systems for handling and storage. Larger and more costly rigs in combination with longer time spent on the drilling and completion operations are the main contributions to the increasing cost. Thus, new solutions for cost-effective drilling and completion of deep-water wells have emerged during the recent years as alternatives to conventional technology. Among these new solutions are the big-bore well concepts that are focused on in this thesis.

On the other hand, uncertainty is usually connected to application of new technology. Uncertainty relates both to operational aspects, as well as to the expected production availability of finalized wells. Field development by using a big-bore well concept requires that the expected production rate relies on fewer wells compared to typical conventional well design. Thus, uncertainty needs to be considered carefully, as part of the decision basis.

Given the above challenges, decision makers are seeking appropriate methods and tools to support well engineering and the related decision processes. By combining methods within the area of risk analysis and decision analysis, the relevant properties and characteristics of alternative solutions are linked to the important requirements and decision criteria. Special attention is made to decision-making in project teams, or groups as result of a process. This kind of decision-making is interpreted as the decision process in the current thesis.

The main objective of the PhD project has been to develop a decision framework for deep-water well engineering adapted to the needs of a project team being the decision maker. The main intention is to improve confidence among such decision makers. Indirectly, this should stimulate increased utilization of new and alternative technologies for the drilling and completion of deep-water wells.

The framework includes a decision methodology for assessing the possibilities and limitations of technological options in a decision-making context. The body of the methodology contains the following basic steps: 1) Define the technical decision scope and structure of the well delivery process (WDP), 2) Select the basic well concept, and 3) Conduct the detailed design and approve it. In addition to the new decision methodology, a two-step procedure to guide industry implementation has been developed. This procedure involves the intended user from the early beginning. A case study describes an application of the decision methodology on a hypothetical drilling scenario. The case study also verifies the quality of the selected procedures and validates the methodology.

The combined risk assessment and decision analysis is new to well engineering. Instead of independent risk assessments, the current framework links such assessments directly to the decision processes of well engineering, i.e. to the value chain. It deals with the information of relevance, how assessments should be planned and accomplished, and finally, how the results should best be implemented.

The practical contribution of the framework and its methodology should be proactive support to engineering organizations in their decision processes. Both the quality and efficiency of ongoing decision processes are improved. Feedback from Shell mentioned the usefulness of applying the influence diagram method in the early identification phase of potential well concepts. Being part of the current methodology, this method provides linkages between the detailed factors at an operational level and the values aggregated at a higher managerial decision level.

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Preface

This thesis report summarises my work carried out during a three year PhD study at the Norwegian University of Science and Technology (NTNU), Department of Petroleum Engineering and Applied Geophysics.

The thesis is addressed to decision makers acting in a well engineering organization, or in a well delivery environment. This target group of decision makers operate at the tactical and operational levels when viewing the organization from a decision-making perspective. The tactical level implies all planning work to implement the decisions made at the highest level of the organization. Decisions with respect to acquiring the necessary resources to maintain desired capacities and output at the operational level are taken at a tactical level.

It is anticipated that readers of this thesis should have general knowledge within the area of offshore petroleum technology. Additionally, university-level knowledge within common risk assessment methods and basic reliability theory, like (Rausand, Høyland) [1], and in decision support systems like (Marakas) [2], or similar is anticipated. Specific knowledge relevant for this thesis is found in [3, 4].

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1 Introduction to the Thesis

This chapter describes the background for the PhD project, along with the objectives and the limitations. The scientific approach is discussed and the structure of the thesis is outlined.

1.1 Background

A major portion of unproduced oil and gas resources are located in deep-water areas, often at sea level depths between 1500 and 3000 metres. The well development cost of deep-water fields increases if it is solely based on conventional technology. The main reasons are the higher rig specifications and the increasing amount of materials and fluids. A large deck space is required for handling the equipment and drilling fluids that are needed onboard. The need for a 5th or modified 4th generation drilling rig, or a large drill ship in combination with longer time spent on operations increases the well cost significantly. Many operators are in a position to consider innovative- and non-conventional technologies as alternatives in their development projects. Most of the deep-water oil and gas fields are typically distant from existing infrastructure, or require new process infrastructure that needs other developments than conventional ones. Therefore, new solutions for cost-effective deepwater field developments have emerged during the recent years. Among these solutions are the big-bore well concepts.

The big-bore well concepts were introduced because of their means of reducing both the operating and capital expenses. Big bore is associated with well concepts that utilize a 7", or larger production tubing. These concepts have the potential of increasing the net present value of hydrocarbon assets, especially from gas fields. One motivation should also be the ability to exploit a reservoir through fewer wells. Thus, big-bore solutions are increasingly being marketed to the deep-water drilling and completion industry.

In deep-water areas, as in the Gulf of Mexico (GOM), the margin between pore pressure and fracture pressure gradients is typically narrow. That means the drilling operator is forced to run a larger number of casing strings when drilling conventionally. Each new casing is time consuming and thus, quite expensive. One additional implication of additional casings is the reduced internal well bore diameter through the reservoir that restricts the production potential of the well. An effect of this again is the limited ability to install down-hole equipment for processing and monitoring and utilising high flow rate completions. Thus, it is a future goal to realize big-bore tubing throughout the well, both for oil and gas wells.

However, there are uncertainties regarding safety and reliability connected to the big-bore well concepts. This uncertainty both relates to operational aspects, as well as the production availability of finalized wells. The required production rate from the field relies on fewer wells compared to what a conventional development normally should imply. Thus, uncertainty needs to be considered carefully, as part of the decision basis concerning which well concept to apply.

The selection of appropriate technology for a discovered field, involves several decisions during the whole well engineering project. One typical challenge is to obtain sufficient qualified information at the time when it is most needed in the decision process. The value and quality of the information is normally weighted against the cost of processing it, as viewed in a cost/benefit perspective.

Important information might not show up within the time window of the decisions. Then, it might be a challenge to ensure that the right decisions are taken during times when information is missing. It is here more up to the project manager(s) to initiate processes providing the necessary information. Project team members, as well as the other experts are then being involved. At any time in the process the project managers should ensure that the optimal solution is selected based on available information.

Decision makers, like those mentioned above, need appropriate methods and tools to support their decision processes. Using such methods, relevant properties and characteristics of the technical solutions under consideration might be linked to the requirements and decision criteria of importance for the decision situations. Special attention is given to project-team decisions as they typically are conducted in well engineering. It is believed that an increased utilization of alternative methods and tools may generate added value to projects such as those mentioned above. A similar context is the global framework of Shell E&P, named the well delivery process (WDP). This framework is applied by Shell E&P worldwide to ensure quality decisions in well engineering. Hence, the methodology part and the case study of the current thesis are based on the WDP.

1.2 Objectives

The main objective of the PhD project is to develop a decision framework adapted to the needs of decision makers responsible for well engineering, or a WDP. The most relevant application is deep-water gas field developments where cost-effective, big-bore well designs involve the utilization of rather new technology. The framework should constitute a decision methodology for assessing the possibilities and limitations of technology in a decision-making context.

The main intention is thus to improve confidence among the decision makers and to stimulate utilization of new and alternative technologies for drilling and completion of deep-water wells. Important decision criteria are project reliability, project cost and personnel safety. To fulfil the main objective of the PhD project, the following important sub-objectives have been defined:

- Review recent technology in drilling, completion and intervention of subsea, deep-water wells
- Review decision-support literature as the basis for the decision framework

- Identify steps, activities and important decision milestones of a typical well engineering project
- Make accurate adaptations of existing methods and tools, and develop a new decision methodology
- Apply the new decision methodology in a case study and validate it according to the objectives of a hypothetical case scenario
- Verify the dedicated procedures through the case study
- Incorporate learning from the case study into the final methodology
- Specify a strategy for industrial implementation
- Discuss and draw up conclusions of the main results and suggest subjects for further work

The following topics are focused in the literature study to meet the above objectives:

- Review of technologies and experience within the field of advanced drilling and completion realizations that have utilised big-bore well designs in deep-water environments
- Review of decision support systems (DSS) and methodologies applied in risk-based, or scenario based decision making from a wider spectra.

1.3 Limitations

It was important to distinguish between two alternative approaches to the research problem and the subsequent planning of a case study, namely:

1. System evaluations: Evaluation of a limited number of well systems or concepts in order to recommend the most appropriate solution for a specific field or application based on evaluation criteria.
    - Expected deliverable: Recommended well system or concept
2. Methodology design: Testing a dedicated decision methodology for selecting the most appropriate well configuration and the subsequent detailed design. Through the case study, the procedures included are verified and the methodology as a whole is validated. Afterwards, the relevant parts of the methodology are updated based on the experience from the case study.

- Expected deliverable: A new decision methodology

The current PhD project is within this second approach. The main deliverable from the work is to be a decision methodology as part of a decision framework. The decision methodology should support well engineering from the early identification phase, through the selection phase of a basic well concept, and further into the detailed design phase of subsea-, deep-water wells. In addition to the methodology part, the framework includes a case study where the methodology is tested and a strategy is given for implementing it to the industry. System descriptions of relevant drilling and completion technology are attached to the framework in order to draw attention to the exact decision problems under study.

Commercial reasons make the big-bore technologies of special interest to the industry, especially for deep-water gas wells. Hence, the well systems focused in this PhD project have been big-bore well concepts, although, the methodology may be looked at as being independent of such a limitation.

Several decisions in well engineering are regarded as decisions under risk and uncertainty. These categories of decisions are focused on in the decision methodology. Upon application, it is assumed that information about technology as well as the geological and operational aspects of the field under development can be provided at the time it is needed.

Given the information, the suggested methodology provides a generic approach to decision-making. However, it may not be practical, or even required, to apply formal decision procedures. Many decisions, either of minor importance, obvious nature, or easy character are handled without any such formalities. Decisions might be taken on an individual basis, either by special skilled personnel and experts, or by the managers themselves. Decision makers are then put in these positions by virtue of their special competence. They should have the necessary authority and mandate to make certain kinds of decisions. This type of decision-making is not defined within the scope of the current PhD project.

1.4 Scientific approach and scope

This research work is regarded as applied science, i.e. the research has a direct practical application for industry. The work must be seen in a developmental and explorative context, rather than in an experimental context. It constitutes the development of a decision methodology from which the decision framework as a whole is established. Thus, the quality of the work must not only be evaluated from a scientific point of view, but also from the user's point of view.

The research problem was initially the result of discussions with the supervisors at NTNU and with Shell E&P which is an operator with experience from well engineering projects around the world. Shell E&P is mainly process oriented in their way of conducting development projects. Based on these early discussions and the subsequent literature review, the following research problem was formulated:

> *Well delivery processes (WDP) are not optimal with regard to effective decision processes as they are typically conducted by engineering organizations.*

An important question is then to ask:

> *To what extent, and how can increased utilization of alternative methods and tools for decision-making improve the situation in such a way that added value to the project is generated, while the safety and environmental concerns are taken care of?*

The scientific basis applied to the research work is gathered from a literature review of recognised sources for decision support systems (DSS), and related methods and tools. Recent industry articles describing processes of concept selection from different branches were reviewed. Part of the review was articles and publications containing recent technology advances in the area of offshore well drilling and completion. The majority of these were the documented experience of operators and contractors from earlier well design projects. Special focus was on operational experience gathered from deep water that utilised big-bore wells. Thus, the following requirements were considered relevant for the decision framework, both from a practical and a scientific point of view:

- Include references to previous evolved methodologies of relevance
- Secure robust project results
- Obtain traceability of important decisions
- Support reporting needs in a specific project
- Secure united decisions
- Balance different interests of importance to decision-making
- Arrange for sensitivity analysis of different parameter changes
- Provide an "easy" user interface
- Utilize appropriate tools for the work sessions in a project team, as well as tools to carry out evaluations and the implementation of the results (DSS)

The decision processes of well engineering are preferably described as sequenced decisions distributed in time. The relevant information for decision-making might well be collected and prepared during the whole project lifetime. The suggested framework will address these challenges. As an example scenario, a team leader struggling for consensus in project meetings should gain benefit by improving the cooperation in multidisciplinary teams. Such meetings typically deal with incomplete and distorted information at the same time. Then the major task is more to make appropriate plans for the further work and reveal accurate information. Thus, some decisions might be on hold waiting for more information to be collected. It is believed that these problems can be revealed more beforehand, and the suggested decision framework will focus on that.

For the purpose of verification and validation, the methodology part will be applied to some comparable well systems in a case study. The main intention is testing out the procedures and thereof proving the credibility of the suggested approach. The case study will document the decision support offered to a virtual well delivery project.

The proposed decision framework should improve the probability of success for the operators, but might not provide any guarantee of success. Such a guarantee is almost impossible to make due to many uncertain factors influencing the design process. The large number of influential factors, both internal and external, makes a precise repetition of a design process virtually impossible. Consequently, it may be difficult to separate the effects of applying a certain method from any other methods, or to prove afterwards that other methods would have led to better results [5]. Nevertheless, the case study should validate the framework. The validation process identifies and describes how the decision makers improve the decision processes, given the decision methodology and the available basic information. Prior to the validation, it should be verified that the decision methodology prescribes effective procedures as they are documented to the decision makers and are adapted to decisions over a period of time.

Through the structuralised review of DSS some common methods will be described and discussed in the context of the thesis objective. The new decision methodology incorporates useful elements in these methods and will use them in a somewhat new context.

The decision information and the evaluation criteria may be calibrated and adapted at a similar level of detail to accommodate the comparison of different concepts and systems. However, collecting the information needed for decision-making should be limited to a reasonable amount of work.

1.5 Structure of the thesis

The structure of the thesis is mainly in the form of a main report. After this introduction to the thesis in Chapter 1, there is a description of technical systems that are relevant to the thesis in Chapter 2. Chapter 3 presents a structured review of decision support. The description of the new decision methodology follows in Chapter 4. A procedure for an industry implementation is outlined in Chapter 5. Then, the case study presented in Chapter 6 describes an application of important parts of the decision methodology. Expected contributions of the thesis, both scientific and operational are outlined in Chapter 7 together with an evaluation of the research process. Discussions of the main results with some conclusions regarding the application are given in Chapter 8. This chapter finalizes the thesis and ends with recommendations for further work. Appendix A.1 lists some basic acronyms used in the thesis, and Appendix A.2 consists of a glossary. Appendix A.3 includes technical descriptions regarding the evolution of recent drilling and completion technology. The big-bore well design represented by the improved Arun design is described in Appendix A.3.1, and a description of relevant MPD technology used in the case study is found in Appendix A.3.2. Appendix A.4 presents conference paper No. 1, and Appendix A.5 presents conference paper No. 2. These two papers describe individual methods that are referred to in the methodology description (Chapter 4).

The review of decision support systems basically serves as a background to the decision methodology part of the framework. An application of the current decision methodology is described in the case study. The objective of the case study in Chapter 6 is mainly to test the methodology and verify that the suggested approach actually does what it claims. Finally, it validates the methodology according to its accuracy and usefulness.

The main parts of the thesis, like the descriptions of the decision methodology, the results from the case study and the procedure for implementation, have been written in a form that should easily facilitate publishing at a later date.

2 Technical Description

A brief description of drilling and completion technology of relevance to the thesis is presented in this chapter. Aspects of the technology that are most relevant to decision-making in well engineering are given special focus.

2.1 Introduction

Drilling deep-water wells is challenging, mostly due to the narrow interval between the pore pressure and fraction pressure gradient. Shallow water flow may require additional casing strings and the potential for hydrate formation exists. The large weight and volume of the conventional marine drilling riser requires large handling and motion compensating systems and large quantities of materials and drilling fluid. To handle the operational aspects of drilling and completion under such conditions is demanding when solely utilising conventional technology.

Conventional drilling in deep waters relies on setting additional casing strings to reach the expected total depth (TD) without provoking formation damage and/or loss of circulation. The use of alternative and innovative drilling techniques and advanced completion technology may overcome some of the important deep-water challenges. Examples of innovative drilling techniques are the managed pressure drilling systems (MPD), including the dual gradient systems (DGD) and the lower riser return and mud-lift system (LRRS). Different expendable casing solutions and recent big-bore designs for gas wells are among the important completion technologies to consider.

Big-bore wells are desirable to utilize the production potential of the well through a higher expected production rate. Fields of major interest are then remotely located deep-water gas fields with prolific reservoirs. These fields are believed to have the greatest advantage from the big-bore technologies.

However, the world is not ideal and the trend towards using big-bore implies uncertainties of different types and levels. Thus, most of the advanced technologies introduced to the industry are considered to be evolutions of existing technologies more than revolutions.

Within the context of the current PhD project, there is a need for technical descriptions to distinguish between technical solutions. This description regards specific features, possibilities and limitations as well as typical applications. Such a technological platform is mandatory in order to utilize the suggested framework. Thus, the intention of this chapter is to describe the most relevant well systems and their interfaces to address important technical considerations. The scope and extent of the framework is clearly addressed, and the action space is sufficiently delimitated by this technological platform.

The technological systems are described at a level of detail found necessary for the assessments taking part in the decision methodology. These may be principal features such as the maturity of the technology, or specific information about the options of relevance in trade-off evaluations. Examples are information about the contributing factors to procurement cost, operational and maintenance cost, safety and environment, or even information concerning the system abandonment. However, it is assumed that the project team who make use of the methodology possess detailed knowledge about the technology under consideration beyond the present descriptions.

Drilling and completion are regarded to be integrated operations, and the technical solutions are often built with that in mind. The basic focus when applying big-bore concepts is to obtain a large production tubing (I.D.) down through the lower completion. The big challenge in deep-water drilling is, however, to maintain the desired I.D. all through the drilling and completion phases of the well, down to the TD. Several solutions are commercially available. The next sections give an overview of drilling and completion technology that can make up big-bore wells, or is related to big-bore developments. The technical description is grouped into the following main system categories:

- Drilling rig and equipment
- Drilling process
- Marine equipment
- Drilling technology
- Completion technology
- Intervention technology

2.2 Drilling rig and equipment

2.2.1 Drilling rig

Rotary drilling rigs are currently used for almost all drilling for hydrocarbon resources [6]. The rigs are broadly classified as 1) Land rigs, or 2) Marine rigs, where of cause only the marine rigs are relevant offshore. The main design features of a marine rig are portability and maximum water depth of operation. Marine rigs are classified as bottom supported or floating rigs. Typical bottom supported rigs are the rigid platforms and jack-up platforms. The floating rigs are divided into semi-submersibles and drill ships. Alternative platform concepts for deep-water drilling and production are typically semi-submersibles, tension leg platforms (TLP), floating production, storing and offloading units (FPSO), and the spar platforms. When water depths become too great for any economic and technical use of fixed platforms, the wells are drilled from floating vessels. The wellhead equipment is then typically installed on the seabed. The large 4^{th} and 5^{th} generation semi-submersible drilling rigs can operate in water depths in the order of 2500 metres. For larger depths, drill ships have to be used.

The existence of a much lower formation fracture gradient in deep waters, and an increased probability of striking shallow water or gas, mean that there is a need for a higher number of casing points. Increased storage capacity on the rig, due to the casing steel weight, is then expected. Additional loads are also introduced by the weight and volume of the marine drilling riser, equipment and drilling fluid. Thus, much space is needed on deck for the drilling operation to be commenced and for the processing of drilling fluids and returns. The increased rig size and loads on deck require larger handling and motion compensating systems attached to the rig. In fact only the large 4th or 5th generation rigs or drill ships satisfy such requirements.

Typical features of a 5th generation drilling rig, or an upgraded 3rd or 4th generation rig are [7]:

- Large operation displacement: 35000-50000 tonnes
- Large variable deck load: > 4000 tonnes (> 10000 tonnes on a drill ship)
- Large deck area for extended storage of riser, casings, tubing strings, etc.
- Large moon pool areas
- Large derrick capacity: up to 1000 tons
- Four mud pumps with 7500 psi pressure rating
- Active drill string compensator
- Mechanised tubular handling and racking systems
- Riser recoil system
- Upgraded BOP and well control system
- Assisted dynamic positioning (DP), or a full DP to class 3 or 2

Due to the above features, platform costs rise rapidly with water depth. Innovative drilling and well technologies thus are intended to reduce the rig requirements for deep-water drilling. An example is the utilization of a high-pressure riser with a surface BOP. The smaller marine riser, e.g., 12.5” or 14” instead of 21” O.D., gives a significant lower net weight for the riser itself and even a greater weight reduction from the slimmer mud column. It may require only a 2nd or 3rd generation rig to drill the 10000 ft water depth with a slim, high-pressure riser. However, to fully utilize a slim riser (12.5” - 14”), the rig requires new developments in drilling and well completion technology. Figure 1 illustrates the trend with respect to rig generations when entering deeper waters.

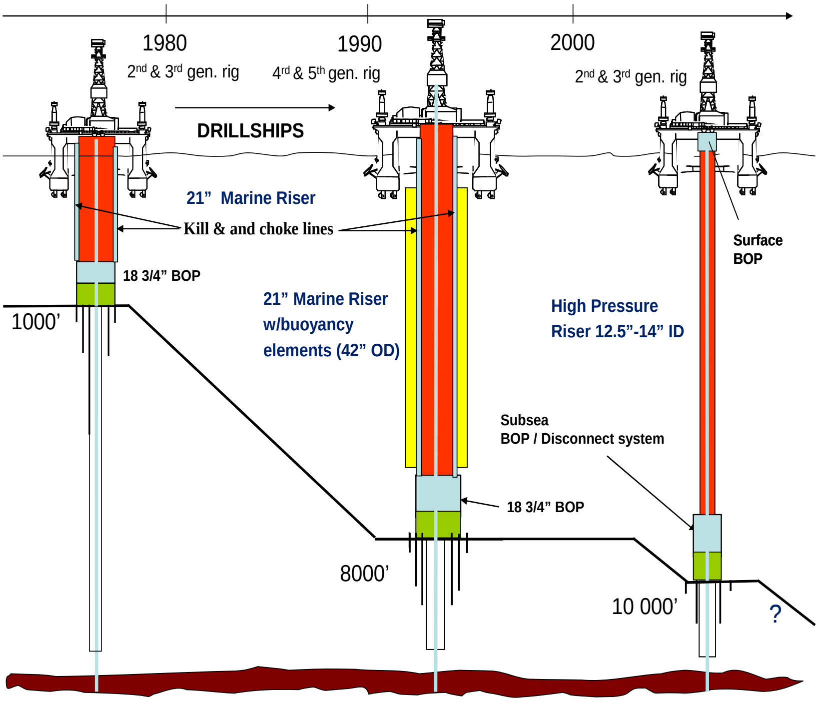

Figure 1 Rig development (adapted from [8])

2.2.2 Drilling equipment

Information about sub-systems and components involved in rotary drilling are found in [6] and is not described in any more details. However, Figure 2 shows a typical drilling rig arrangement. The riser has here been equipped with buoyancy elements to reduce the heavy deck load in deep water.

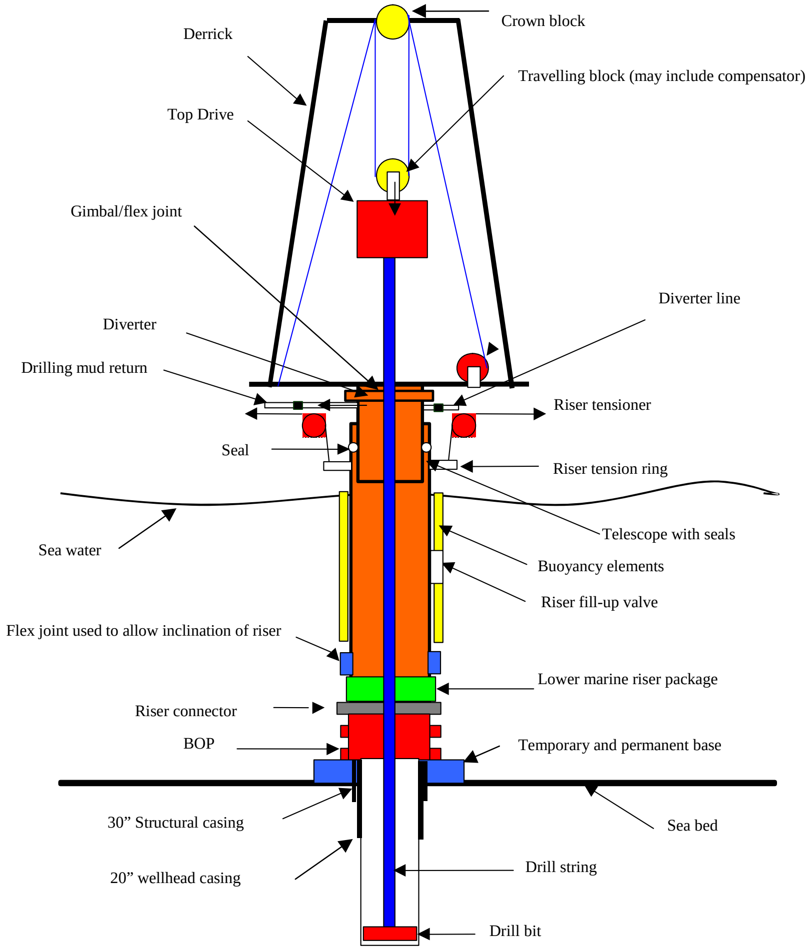

Figure 2 Main drilling equipment (adapted from [8])

2.2.3 Marine equipment

Special marine equipment and procedures are required when drilling from a floating vessel. It is necessary to hold the vessel on location over the bore hole and to compensate for the vertical, lateral, and tilting movements caused by wave action against the vessel and riser. Mooring systems with different anchor arrangements and large thruster units, called dynamic positioning system (DP), are used to maintain position. As seen in Figure 2, a slip joint at the top of the marine riser compensates for the vertical movement of the vessel. Surface motion-compensation equipment called "heave compensation" is used to eliminate the effect of heave on the oscillatory.

2.3 Drilling and completion processes

2.3.1 Drilling process

Drilling from a floating vessel imposes some basic requirements. Drilling fluid is circulated down the rotating drill string and up again through the annulus to the surface. However, the 36” and 26” holes for the 30” conductor and 20” casing are normally circulated with the drill cuttings disposed of on the seabed. After the 20” surface casing with wellhead has been installed and cemented in place, the marine drilling riser and blowout preventer (BOP) are connected to the wellhead. The marine drilling riser and the BOP will remain in place for the rest of the drilling operation.

The rig systems must be designed to handle challenges with deep water and big-bore well concepts. Hence, some important characteristics of the drilling process in deep waters and the use of big-bore well concepts are now discussed.

Drilling fluid circulating system

The major function of the fluid-circulating system is to remove the cuttings from the hole as drilling progresses. The drilling mud flows from the steel tanks to the mud pump and is pumped through the high-pressure surface connections to the drill string and the bit. The mud passes through the nozzles of the bit and goes up the annular space between the drill string and hole to the surface. Finally, the mud passes through the mud processing equipment back to the suction tank.

Well control system

The well control system prevents any uncontrolled flow of formation fluids into the well bore. When the bit penetrates a permeable formation that has a fluid pressure in excess of the hydrostatic pressure exerted by the drilling fluid, the formation fluids will begin displacing the drilling fluid from the well. The flow of formation fluids into the well in the presence of drilling fluid is called a kick. The well control system permits 1) detection of the kick, 2) closing the well at the surface, 3) circulating the well under pressure to remove the formation fluids and increase the mud density, 4) moving the drill string under pressure, and 5) diverting flow away from rig personnel and equipment.

The flow of fluid from the well caused by a kick is stopped by use of blowout preventers (BOPs). Multiple BOPs used in a series are referred to collectively as a BOP stack [6]. The BOP must be capable of terminating flow from the well under all drilling conditions. When the drill string is in the hole, movement of the pipe without releasing well pressure should be allowed for. In addition the BOP stack allows fluid circulation through the annulus under pressure. These features are accomplished by using several ram preventers and one annular preventer. Pipe rams match the size of the drill pipes in use to drill the well. Blind rams are designed to close when no pipe is in the hole. Blind rams will only flatten the drill pipe if inadvertently closed with the drill pipe in the hole but cannot stop the flow from the well. Shear rams are blind rams designed to shear the drill string when closed. Shear rams are closed on pipe when all pipe rams and annular preventers have failed.

2.3.2 Drilling technology

The drilling technology described in the following is example of conventional, cost-effective drilling in deep waters, and some immature casing designs to achieve big-bore completions.

A typical conventional casing programme consists of a 30” conductor casing, a 20” surface casing, 13 3/8” and 9 5/8” intermediate casings, and finally, a production tubing of between 4 ½” and 7”. For a conventional casing programme, cost savings in deep-water drilling are mainly achieved by riser-less drilling of the upper sections. This may be the 36” hole for the conductor, the 26” and 17 ½” hole-sections for the 20” and 13 3/8” casings, respectively. Then a much smaller riser than a 21” marine riser can be used that requires only a lower specified rig at a significantly lower rig rate. Two categories of alternative casing designs are considered:

1. Reaching TD with a reduced number of casing points
2. A modified conventional casing programme

Within category one, there are the slender technologies [9] and the expendable technologies, such as the mono-diameter drilling liner [10], the solid expandable tubular (SET) [11], and the later mono-hole drilling technologies. Within category two there are the reduced clearance casing programmes [12], and the lean-profile casing technologies [13].

Casing designs

A common feature of most of the alternatives to conventional casing design is that these concepts relate to specific geological properties and aspects of the reservoir which makes them more suitable for deep-water applications. In that respect, the following innovations are the most important:

- Slender technology
- Pre-installed liner
- Solid expandable tubular
- Mono-diameter drilling liner
- Reduced clearance casing programmes
- Lean profile

Slender technology

Slender technology [9, 14] is an integrated solution for drilling, completion, production, and intervention. The technology consists of the elimination of the 20" casing in combination with some new completion techniques. It was originally made possible in the Campos Basin (GOM) because of the peculiar geological characteristics revealed in that area. The elimination of the 20” casing allows the utilization of a 15 ¼” (O.D./I.D.) drilling riser for drilling, completion and intervention of the well. Prior to that operation, the 17 ½” hole for the 13 3/8” casing is drilled with mud return to the seabed. The main advantages of utilising a slender wellhead system in deep-water drilling are:

- Reduction in riser design loads due to smaller riser volumes
- Higher water zone penetration rates while drilling, due to reduced drill bit diameter
- Reduced loads on the drilling vessel by the smaller riser allow the use of a low specified rig. It provides an operator with a wider spectra of rigs to select between that may reduce the total rig cost
- Reduced hardware costs both in terms of a smaller riser and cost savings due to removal of the 20’’ casing string
- Reduced fluid cost, due to the reduction in the volume of drilling fluids and cement
- Provides additional life-cost savings by utilising the smaller riser for intervention purposes also, in addition to the drilling and competition

Pre-installed liner

The pre-installed liner [15] is achieved by applying, e.g., a 12 1/2” I.D. marine drilling riser, a 11” BOP and a 11” wellhead, as illustrated in Figure 3. The conductor casing is drilled and installed conventionally. After the hole section for the 13 3/8” surface casing has been drilled, one or two concentric liners are installed inside the surface casing which is suspended in a spider arrangement from the drill floor. Then, an 11” wellhead is connected onto the top of the surface casing before the conductor assembly is run and cemented in place. Further drilling for the pre-installed liners, an additional liner or a casing takes place by conventional techniques.

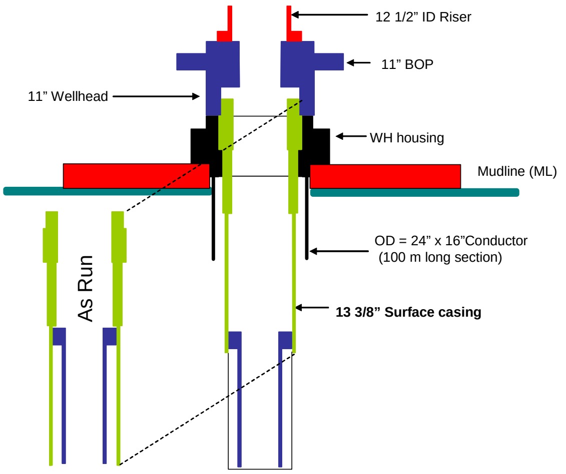

Figure 3 Pre-installed liner (adapted from [8])

Solid expandable tubular

Solid expendables are divided into phases of diametric efficiency [10].

The open hole liner is the initial phase in diametric efficiency (DE) in which a single drilling liner is expanded to the I.D. of the base casing.

The next higher order of DE is called nesting that means two or more tubular sequentially expanded back to back. Nesting is similar to single expansion in that the base casing is not expanded.

Slim-well is the next order of DE that consists of a mix of single expansions or nested expansions. It is used to reduce the shallow casing size whereas the size of completion is maintained or increased.

The mono-diameter is the final ultimate order of DE in which both the expandable liner and the overlap in the base casing are expanded to create a continuous internal diameter.

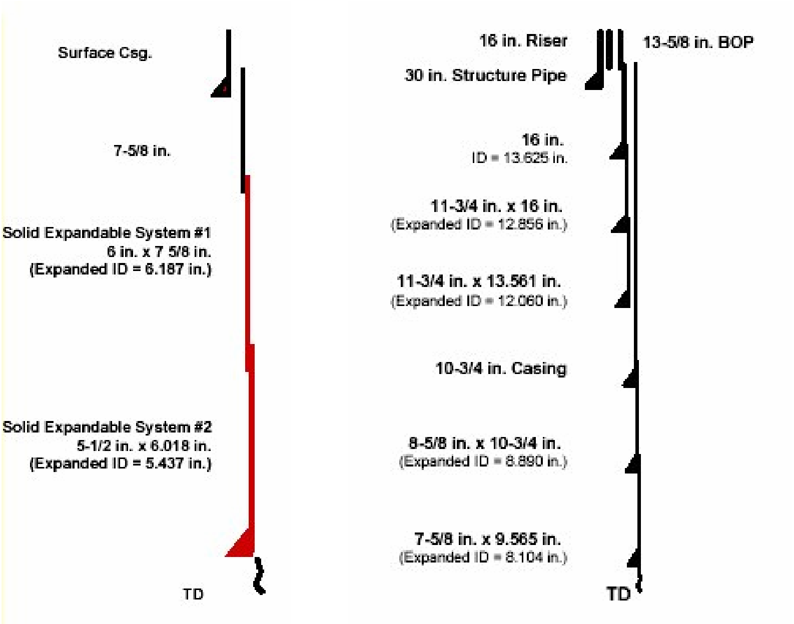

Figure 4 Nested and Slim-well expendables (copied from [10])

Expandable tubular technology (ETT) or "X well" is a Shell Group initiative to achieve a step change in drilling operations [11]. It was one of the key technologies identified to improve production in Shell Petroleum Development Company of Nigeria (SPDC) by 20% in 2001. (ETT) is grouped into expandable slotted tubular (EST) and solid expandable tubular (SET).

- ESTs are pipes with staggered but overlapping slots cut axially along their entire length. Expansion depends on the dimension and placement of slots and the size of expansion cone.
- SET on the contrary involves the cold working of steel to the required size at down-hole conditions. It expands based on the principle of 3-D plastic deformation of the material. The expansion forces are in the order of 10-30 times that of an average EST. SET can be utilised in all phases of well life (drilling, intervention, and abandonment). It has the potential of reducing the unit development costs significantly by down-sizing wells, and improving opportunities for complex designs.

The amount of expansion applied to a solid expandable tubular is controlled by the size of the expansion cone. The expansion cone stresses the pipe above the yield limit and into the plastic region giving a permanent deformation to the tubular. The ultimate tensile strength and its relationship to the yield point controls both the range of expansion and the limit of expansion applied to the pipe. As an example, Figure 5 illustrates a hydraulically driven cone.

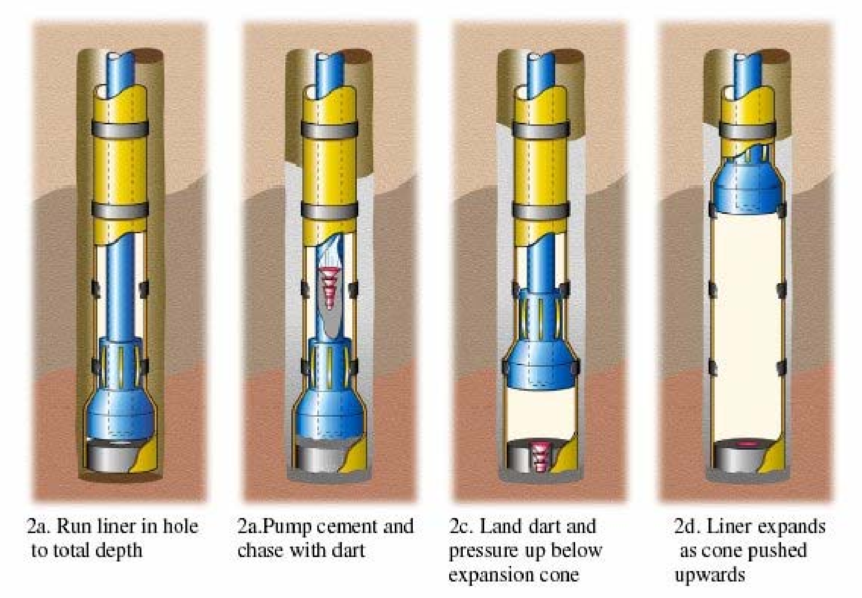

Figure 5 Cone expansion of solid tubular (copied from [16])

Mono-diameter drilling liner

The mono-diameter drilling liner technology [10] allows multiple strings of the same size to be installed in a well without a decrease in internal diameter (I.D.). The elimination of a reduced I.D. is accomplished by an over-expansion of the mono-diameter drilling liner and the base casing in the overlap section.

The mono-diameter well construction process involves installing a mono-diameter drilling liner below the casing and expanding it together with the overlap. The resulting I.D. allows additional mono-diameter drilling liners to be installed and expanded without reducing the I.D. of a standard telescopic casing programme. Thus, the expansion of the mono-diameter liner creates a single I.D. A comparison of conventional/expandable designs and a mono-diameter casing design is shown in Figure 6.

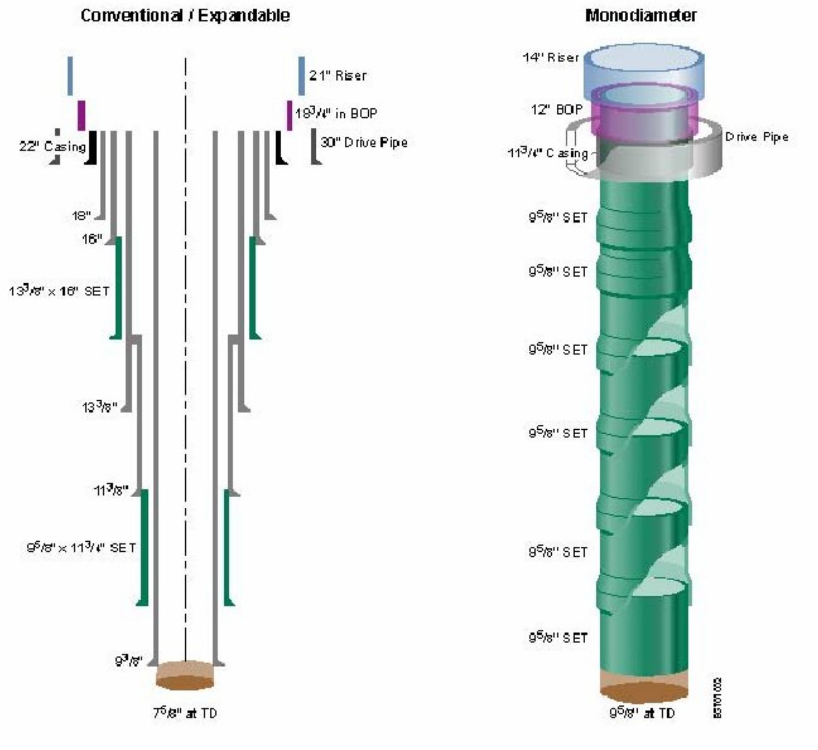

Figure 6 Conventional and a mono-diameter design (copied from [10])

The foremost benefit of the mono-diameter technology is reduced environmental impact in the well construction process. A reduced total drilling cost is obtained, especially in challenging areas, and it enables operator to maintain the optimum completion diameter of the well. The reduction in casing size allows a reduction of the mud line and riser sizes, and thus lowers the riser hook load that the drilling vessel must support. Smaller vessels, like a 3rd generation rig, can even drill in deeper waters by use of this technology. A 3rd generation rig is much less expensive than a 5th generation rig or drill ship. Savings of around 48 % in well construction costs have been experienced compared to a 5th generation drill ship (experience from a 5000 ft. well in GOM) [10].

Reduced clearance casing programmes

From the early days the industry has developed general rules of thumb for clearance requirements between casing strings and bore holes [12]. Commonly used casing clearance is at least 0.6” to 0.8” of radial clearance between a casing coupling and the design I.D. of the next larger casing string. However, acceptable casing clearance may be optimized for particular applications. By introducing reduced casing size additional casing strings may accommodate the well design. This is important for wells with the combined challenges of high pressure and temperature including high mud weight in deep water. Such wells often require more casing strings to reach total depth. Reducing the clearance between casing strings from traditional values will permit use of a smaller BOP and rigs.

The significant engineering problem with a reduced clearance tubular is the surge created in the drilling mud while running casing. An old technique is to reduce mud viscosity just before running casing, e.g., by adding large volumes of water to a water-based mud.

Good engineering judgment must be used before adopting a reduced casing clearance design. Optimum candidates are hole-sections that are free of problems such as tectonically stressed intervals, drawn-down sands and high mud weights. The rig must, however, be capable of proper hole cleaning, be able to maintain optimum mud properties, and be equipped to rapidly handle lost mud returns, well control situations etc.

Lean profile

The lean profile, shown in Figure 7, is practically a redefinition of the well profile based on a "drastic" reduction of the clearance between *casing outer diameter* and *the diameter of the hole* where casing is run [13]. The application of the lean concept is based on the following requirements:

- Absolute control of a vertical trajectory (Straight-hole drilling device, SDD)
- Use of flush (or near flush) joint connections, because of very small clearances between the casing and the open hole

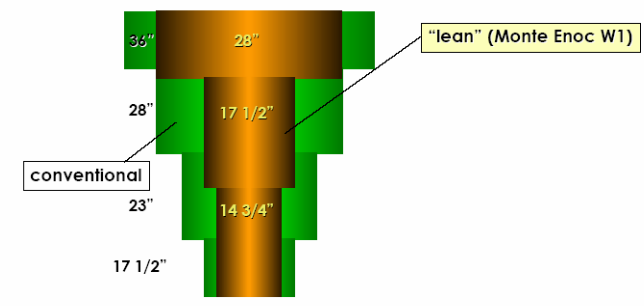

Figure 7 The lean profile (copied from [13])

The main advantages of the lean approach are:

- Better drilling performance (smaller volume of rock)
- Less material consumption (casing, drilling fluids, cement and additives)
- Lower environmental impact (fewer drilling fluids used)
- Improved cementing (smaller holes drilled)
- Reduced risk of stuck pipe (straight vertical hole)
- Improved safety (improved well control operations due to accurate definition of position and depth of the well)
- Slimmer well profiles permit use of a smaller BOP and rigs

Slim risers

The slim riser is actually an alternative procedure to a conventional drilling programme. The concept, which combines slimmer risers and smaller drilling rigs, was presented by Saga (Hydro) in 1996, mainly to reduce deep-water expenditure. The solution includes replacing the 21" riser with a 16", or smaller riser, while still retaining the existing 18 ¾" BOP stack [17]. The use of a slimmer riser leads to loss of the 17 ½" hole size through the BOP stack. This may be offset by:

- Riser-less drilling of the 17 ½" section
- Using one less casing string
- Downsizing an 8 ½" section to around 6 ¾"

The riserless 17 ½” well sections may be drilled with a low specified, shallow water rig, of a lower rig rate. When drilling the 17 ½” section, the rig would only need to handle the pipe and casing strings in open water without a riser.

High pressure riser with surface BOP

A further development of the slim riser concept is the high-pressure riser with surface BOP for deep-water drilling. This riser technology requires alternative drilling and casing designs compared to a straight conventional set-up. The example shown in Figure 8 illustrates a concept of Hydro Oil and Gas [18]. This solution is obtained by utilising a pressure management system, called low riser return system (LRRS), a high pressure riser, a subsea wellhead system and a surface BOP. The LRRS is one of the drilling assistant systems that is categorised as managed pressure drilling systems (MPD). By applying an MPD system in this case, the bottom hole-, and annulus pressure is dynamically controlled. This allows for longer sections to be drilled with a reduction in the total number of casing points.

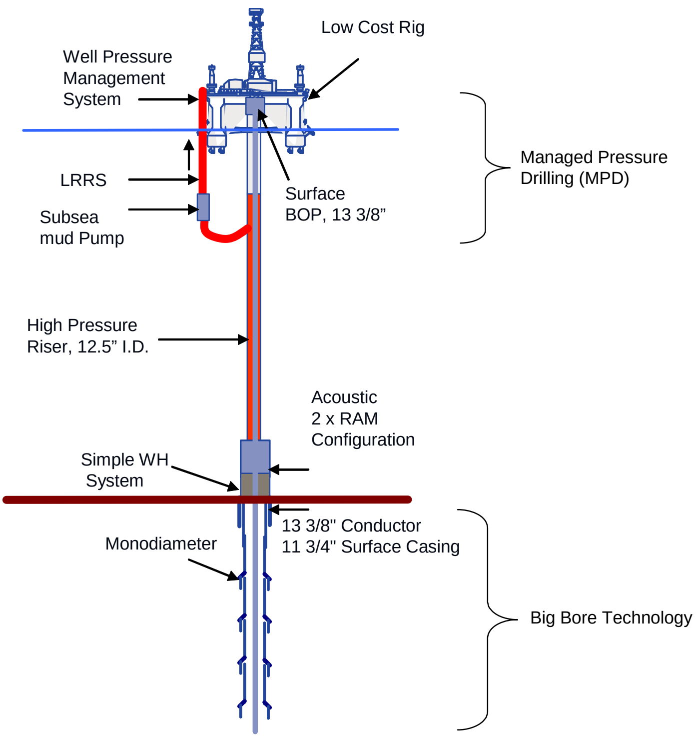

Figure 8 High pressure riser concept (adapted from [8])

Managed pressure drilling (MPD)

A general description of the MPD process including enhanced drilling technologies follows and serves as an introduction to MPD technology. More detailed MPD descriptions are given in connection with the case study in Chapter 6.

Managed pressure drilling (MPD) facilitates precise well bore pressure management, normally through a closed and pressurised mud return system. MPD is described as an adaptive drilling process that is used to precisely control the annular pressure profile throughout the well bore. The main objectives are to ascertain the down-hole pressure environment limits and manage the annular hydraulic pressure profile accordingly [19]. MPD may contribute to cost-effective drilling of problematic formations, as typically found in deep-water environments. Examples include problems associated with narrow down-hole environmental limits, intermediate high pressure- or even depleted zones of a reservoir. These may be handled more effectively and safely by applying MPD.

An MPD process typically employs a combination of technology and drilling techniques that make up the drilling process. MPD allows for in-balance or even under-balanced operations to take place. The main principle is to utilize the back-pressure in the annulus to control the bottom hole pressure ($P_{downhole}$) based on the following formula [20]:

$$P_{downhole} = P_{surface} + P_{annular} \quad \text{where} \quad P_{annular} = P_{dynamic} + P_{hydrostatic}$$

To maintain $P_{downhole}$ constant, $P_{surface}$ is varied to compensate for changes in $P_{annular}$. Such changes may be caused by variations in the drilling pump rate, mud density or any other causes of pressure transients such as motor stalls, cuttings loading, and pipe rotation. A closed and pressurised mud return system normally consists of a rotating control device (RCD) and a drilling choke. The RCD contains the fluid and diverts pressurised mud returns to the choke manifold. The bearing and drill string seal assembly of the RCD permits drilling ahead, tripping, or taking any other event during drilling without breaking out of the pressure margins of the reservoir.

Through the improved pressure management, the MPD process should enable enhanced well pressure control and deeper casing set points. Thus, the reservoir may be reached with a large enough hole to assure the economic success of the well [21]. The main issue is related to the pore pressure and fracture pressure gradients. The pressure gradient profiles for a conventional and a dual gradient system (MPD), respectively, are compared in Figure 9. It clearly shows the opportunity of drilling longer sections within the given pressure margins when the bottom hole pressure (BHP) is controlled accurately.

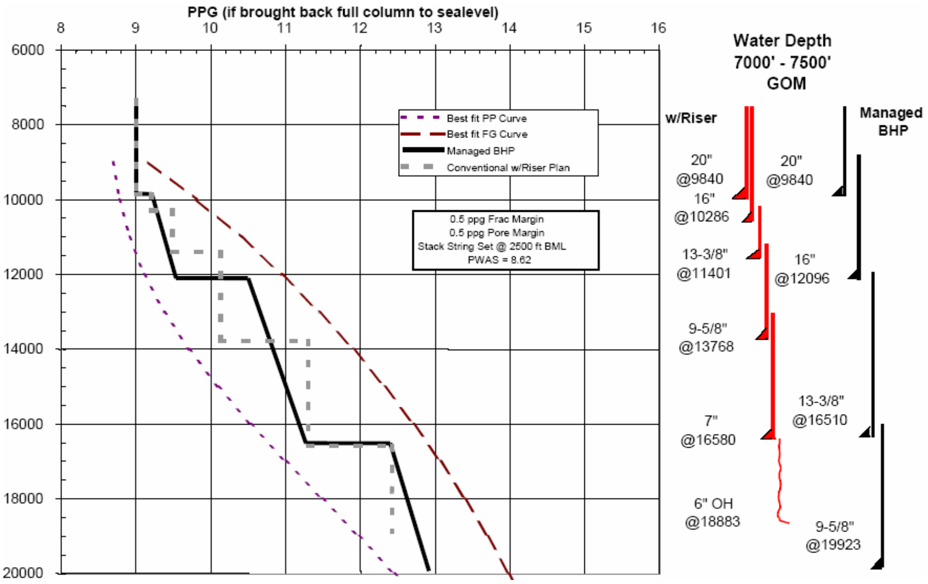

Figure 9 A conventional and dual gradient system (copied from [22])

MPD technologies are categorised into two groups:

1. *Reactive MPD:* The basis is a conventional casing- and fluid programme but further tooled up with at least an RCD, adjustable choke and perhaps a drill string float. This equipment should deal more safely and effectively with any unexpected down-hole pressure regimes.
2. *Proactive MPD:* The casing and fluid programmes of the well are designed from the beginning to take full advantage of the ability to precisely manage the

pressure profile throughout the well bore. This category of MPD offers the greatest benefits in offshore drilling.

The most relevant MPD technologies within the category of proactive MPD [23] are:

1. Dual gradient systems
2. Continuous circulation system
3. Gas lift in riser
4. ECD reduction tool I (pump and a restriction in the riser)
5. ECD reduction tool II (motor and an annulus pump)
6. Secondary annulus circulation
7. Low density drilling fluid, rotating BOP and choke valve for back pressure control
8. Low riser return system
9. Secondary annulus circulation using a mud with varying density

The case study in Chapter 6 focuses on MPD processes as means of achieving big-bore completion in a deep-water gas field. Hence, a more detailed technical description of relevant MPD technologies and processes is given there.

2.3.3 Well completion technology

The completion technology described in the following is limited to the systems and components developed for the big-bore well concepts. Thus, it covers cost-effective solutions to both oil and gas wells in deep water. However, the gas wells have the greatest potential in well capacity enhancement. The description deals with the following systems:

- The Arun and Perseus big-bore designs
- Tubing retrievable safety valve
- High-load permanent packer
- Disappearing plug technology
- Wellhead plug

- Liner hanger
- Wireline retrievable plug
- Expandable screen

Until 2000, big-bore completions were targeted almost exclusively at prolific gas reservoirs. One of the first big-bore completion designs ever was the Mobil Oil Indonesia's Arun field development [24], back in the early 1990s. Much of the later technology are evolutions based on the Arun design, and includes improvements made by different service companies in order to increase the equipment integrity and cost efficiency. Thus, much of the following descriptions are based on the Arun big-bore evolution concept.

Quite recently, a family of big-bore well designs were developed by Woodside Energy Ltd. as results of "front-end well engineering" ahead of the Perseus field gas/condensate development outside Australia [25]. The names of the big-bore designs were "true big bore", "variant big bore", "slick big bore" and "variant slick big bore" (see Figure 10). "Variant" refers to using a 7" TRSSSV and a 7" X-mas tree with a 9 5/8" tubing. "True" refers to utilising a 9 5/8" X-mas tree and TRSSSV. "Slick" refers to setting the packer high, near the top of the 9 5/8" liner. In this "slick-concept" the impermeable formation outside the 9 5/8" production liner, in combination with the 13 3/8" casing shoe cementation, is relied upon to be the second barrier to uncontrolled hydrocarbon flow from the well to surroundings.

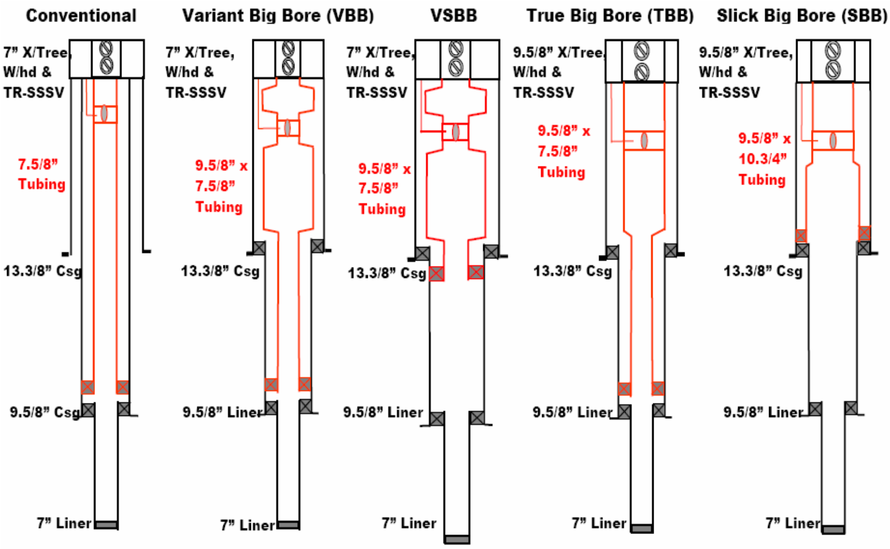

Figure 10 Big-bore wells – design evolution (copied from [25])

"slick" is also known as the long casing flow mono-bore (LCFM). The LCFM concept is similar to the completion technique of the Arun field [26] used by Mobil and Shell, both of whom designed and constructed their own onshore big-bore wells concepts somewhat earlier. By upgrading the material specification of the 9 5/8" production liner to that of the production tubing (i.e. 13% Cr), the "Slick" concept enables an increase in capacity at a reduced cost. This is due to less tubing needed to be run compared to a "variant big bore" well.

The further development of the Arun design, including descriptions of its most important components is given in Appendix A.3.

2.4 Intervention technology

Big-bore applications open the way for different well intervention opportunities. To a large degree the rig specification determines the cost of the intervention activity.

Different well intervention technologies are available to the industry. A brief overview of demands and technologies is given in the following:

Intervention demands

Well interventions are mainly performed in order to improve and/or to maintain the production of a well, but also for maintenance and safety reasons. As many of the recently discovered petroleum fields are located in deep water, the oil industry is facing challenges regarding deep-water intervention philosophy and what methods to apply. The trend in deep waters is subsea completed wells connected to a production rig or tied-in to a shore installation. Subsea intervention tasks are then usually classified in:

- Service through flow line or umbilical
- Service performed on seabed equipment
- Down-hole service without retrieving the tubing
- Down-hole service by retrieving the tubing

Technical descriptions of down-hole operations

Down-hole operations may be accomplished over-balanced or under-balanced. Over-balanced techniques require a drilling rig- or a workover rig to be carried out. The operations are accomplished by using a low-pressure marine drilling riser and a subsea BOP. Under-balanced techniques are classified into wireline-, coiled tubing-, or hydraulic workover techniques. In the latter the well is pressurized and force is applied to run the work string into the hole. These operations can either be performed from a rig or from a lighter vessel. The typical way to categorise well intervention work in connection with the Norwegian Continental Shelf [27] is listed below. The vessel requirements are given in brackets.

A. Wireline operations (mono-hull vessel)
B. High-pressure riser or workover riser operation (drilling rig or a mono-hull vessel)
C. Operations including use of a marine riser and BOP (drilling rig)

Category (A) is light well interventions using a mono-hull vessel with a subsea lubricator and no riser to surface. It is mainly used for wireline services such as data collection, calliper logs, zone isolation and perforation. The arrangements can also be utilised for pumping chemicals. The riserless well intervention (RLWI) stack is an example of category (A) system developed by FMC Kongsberg Subsea and Halliburton in partnership. Experience gained from this system combined with other technologies enable a full range of intervention tasks from a mono-hull vessel even in deeper water fields. Category (B) is intervention with a high-pressure riser, or workover riser in open sea. Both coil tubing and wireline can be run. Thus, the same operations as in category (A) can be performed while circulation to surface is maintained. Category (C) is a full drilling rig operation for heavy operations as removal of X-mas tree, tubing replacement, etc. By using a high pressure riser inside the marine drilling riser and a BOP, all the operations in category (A) and (B) can be done.

An overview of the different intervention operations with advantages and disadvantages are summarised in the three tables below, without any further comments.

Table 1 Wireline operations

Common wireline tasks [28]:	**Advantages/disadvantages**
• Running/pulling of (SCSSSV) • Running/pulling plugs, chokes, valves • Measuring inside diameter, check for debris, cavities, waxes, scale • Tubing perforation • Running and pulling of gas-lift equipment • Opening and closing of circulation devices (sliding sleeves) • Shutting down the production • Logging of pressure and temperature • Depth measurement • Corrosion control • Cleaning the production tubing • Fishing	+Fast operation with a low cost rig/vessel +Works in wells under pressure +Easy to operate +Simple equipment +Lots of experience +Short time for rig up and down +Conductor cable for signal transmission +Reliable +Standard tools available -Limited pulling force (needs a work string) -Limited functions and very risky to perform fishing and contingency operations. -A tractor has to be used in deviated wells -Weather dependent operations -Sensitive to H2S

Table 2 Coil tubing operations

Common coil tubing tasks [28]:	Advantages/disadvantages
• Well cleaning • Starting the production and gas lift • Well stimulation • Logging in high deviated areas • Perforations • Fishing operations • Cementing operations • Drilling of formation • Milling of tubing/casing • Cleaning and sand removal • Production starting and gas lift	+Proven technology +Fast running and pulling speed +Online communication possible +Reduces required rig time +Pushes tools into deviated and horizontal wells +Standard required tools is possible to utilise +Circulation and pressure control all time -No rotation (ineffective well cleaning/drilling operations) -Limited pushing force (pulling) force -Limited flow rate for sand-washing (small diameter) -Limited CT lifetime (plastic deformation of CT) -Very time consuming rig-up and rig-down operations

Table 3 Workover operations

Common workover tasks:	Advantages/disadvantages
• Replacement of production tubing/TRSSSV	+Full access to the well
• Other major interventions	+Multi task operations are possible
• Sidetracking	-Severe cost and time consumption
• Removal of X-mas tree	

3 Structured Review of Decision Support

This chapter presents a structured review of methods and tools within the area of decision support. The review is based on a general literature survey and experience from Shell regarding deep-water well engineering and related decision processes.

3.1 Introduction

It is important for the oil/gas industry to minimize risk and uncertainty connected to utilization of new and immature technology. This is apparent in deep-water field developments that are highly dependent on new technology in addition to the increasing costs and risk, as been described in Chapter 2. Decision makers therefore demand appropriate methods and tools that can support decision processes.

A survey of methods and tools within the field of decision support has been conducted based on the following two main sources of information:

1. Information from Shell, the Ormen Lange well engineering project:
    - Documentation and experience from applying a risk-based decision method, as described in the paper: OTC 16554 [4]
    - Description of the global well delivery process (WDP) [3]
    - Meetings with members of the well delivery team [29]
    - Other non-restricted documentation from the Ormen Lange well engineering project
2. Literature survey covering different branches [2, 30-34]

Application of existing methods and tools may impose important ideas to the relevant decision problem context. These methods are reviewed according to the main objectives of the thesis.

A semi-quantitative risk-based method was developed by Shell for the Ormen Lange well engineering project. It was applied for the technical selection processes that were conducted in detailed design to fulfil the demands of the Ormen Lange wells. The method [4] takes into account the reservoir uncertainties and risks associated with deep-water drilling. Specific risk elements related to the well functionality were identified. Only the most evident well characteristics that add value to project economics were given attention. Consequently the scientific basis for the Shell approach is regarded by this author as too narrow [29], according to what was presented in [4]. Only criteria related to “well efficiency” and “blowout risk” were given attention. It is believed that other criteria would be relevant to decisions at this level. One aim of the present PhD project is thus to provide a somewhat broader approach than the Shell method. The new approach should materialize in a decision framework that satisfies professional and scientific requirements concerning comprehensive decision support within the given context.

A scientific and broad perspective of the problem context requires a literature survey. In addition to the oil industry, documented decision processes and decision support systems utilised in other areas and branches were surveyed. A description of commonly used methods is given in the following sections. The term decision support system (DSS) is widely used in the literature. Very often it relates to the implementation strategy of a decision methodology into an organization, and the utilization of software applications for this purpose.

The literature review included textbooks and a number of articles with documented experience from research over many years. Different sectors and fields of interest are covered. As examples, the review included: planning of transportation systems, placement of main storage capacity, and other major investment strategies. Each DSS concept is briefly described in Section 3.4 including some of their main approaches. Finally, there is a discussion related to benefits and drawbacks of the different approaches.

The first part of the study contains information and knowledge from Shell, which is an experienced operator of deep-water fields from around the world. Several meetings with the Ormen Lange well delivery team in Stavanger were arranged during the present research period. The team was then in the planning phases of the Ormen Lange wells, prior to spud[1]. Insight into the basic work processes and exchange of information were obtained by interviewing the members of the team. More specifically this information was related to the value creation activities of the well delivery process (WDP). Knowledge was gained in two ways: firstly, by studying the WDP documentation, insight into the comprehensive planning processes was obtained, and secondly, by participating in some of the technical sessions. Later in the PhD project, this experience was coupled with the knowledge obtained from the literature survey.

Confidence concerning the credibility and usefulness of the framework is based on the author's understanding of the technical considerations being faced, and the decisions typically taken in well engineering. It reflects on the author's judgments solely, that underlie the methodology development part of the suggested framework. This includes the arguments for selecting between existing methods and tools for decision support, or the development of new ones.

3.2 Decision-making context

The types of decisions and their related decision-making processes vary a lot between different sectors and levels in business organizations. One should consider the whole decision cycle including the various decision activities to understand this problem area [30].

[1] Spud ~ Initiation of the drilling operation

The five typical decision elements are:

1. Goals
2. Relevant alternatives
3. Ranking of alternatives
4. Decision environment
5. Decision makers

The first two elements contain the basic elements of a decision situation. In addition to the clearly stated goals the alternatives or decision options are being limited and defined to a comparable level. The following sections deal with the last three elements in the above list. The description has been prepared on a general basis.

3.2.1 Ranking alternatives

A sequential decision process model, or a decision loop, is illustrated in Figure 11. The decision process typically consists of seven basic steps [30]:

1. Define the problem
2. Decide who should decide
3. Collect information
4. Identify and evaluate alternatives
5. Decide
6. Implement
7. Follow-up and assess

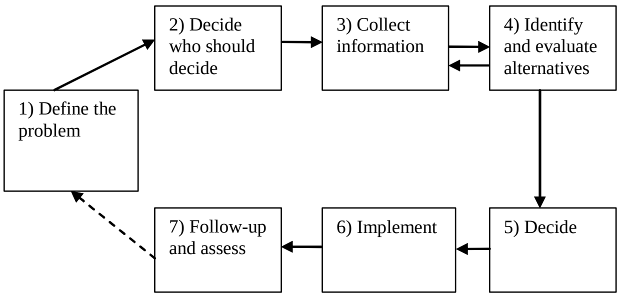

Figure 11 A general decision process model (adapted from [30])

1. Define the problem

A well-defined problem is of great importance for the quality[2] of decisions. If the problem is wrongly or not thoroughly defined, it may be impossible to make a decision. The complexity of many organizations sometimes makes it hard to identify the "real" problem. A typical confusion is not to distinguish between the symptoms of the problem and the problem itself. A symptom is evidence of a problem but not necessarily the problem itself [2].

A number of tools and actions may assist in problem identification. Different information systems, technical standards and means to secure a clear and regular communication with key people in the organization are examples. Continuous up-dating and awareness of technological advances is also important. Here, close contact and interaction with the responsible managers is of major importance in solving technology-design problems.

Decision diagnosis

(Stable) as cited by [2] argues that the diagnosis of current decision-making and the specification of changes in decision processes are the activities that provide the key input to the design of a new/revised DSS. Diagnosis is the identification of problems or opportunities for improvement in the current decision-making behaviour. Diagnosis involves determining how decisions are currently made, specifying how decisions should be made, and understanding why decisions are not made as they should be. According to (Stable) diagnosis of problems in a decision process involves completing the following three activities:

1. Collect data on current decision-making using techniques such as interviews, observations, questionnaires, and historical records
2. Establish a coherent description of the current decision process
3. Specify a norm for how decisions should be made to improve decision-making in the future

[2] Assuring the correct problem interpretations as the basis for decisions

A more comprehensive, but still related diagnostic activity is conducting a "decision process audit". This is a somewhat formal approach which requires more information than the above. The basis may be a review of the decision process in form of data flow diagrams that specify all the participants, data acquisition, decisions criteria, etc. The review should then prepare a list of recommendations in a written report.

2. *Decide who should decide*

A decision process can be categorised according to the degree of involvement and engagement of individuals. The three categories are an autocratic, a consultative, or a group decision process. Individual decision makers make decisions by themselves in an autocratic way with the available information. By consulting with colleagues to gather information and/or opinions an individual decision maker takes part in a consultative process and may come to other conclusions thereafter. Finally, a group decision process is characterised as participative by involving members of the group in the decision-making itself. (Vroom and Yetton), as cited by [30], developed a decision tree to help managers decide who should decide in a given decision situation. Their criteria for choosing an autocratic, consultative, or group decision process were:

- The need for acceptance of the decision
- The adequacy of available information
- The subordinate acceptance of organizational goals
- The likelihood of a conflict situation regarding a preferred solution

3. *Collect information*

Information is collected based on a definition of the factors that affect the problem together with the viable alternatives. The cost of collecting data must always be weighed against the expected benefits. The information systems available may provide the relevant information for decision-making in an effective manner at an acceptable cost.

4. Identify and evaluate alternatives

The most creative part of decision-making is the identification of the set of alternatives and determining what criteria should be used in the evaluation of options.

5. Decide

Making a decision is to commit to a course of action or inaction. In some situations, a decision must be made if it is required or demanded by circumstances, customers, or stakeholders. Decisions are then sometimes made with less information than one would like, and with some feasible alternatives not properly evaluated or considered. In these situations no decision may be taken pending on more information to be collected. A DSS may potentially reduce procrastination and indecision by helping to structure the decision situation and to gather the necessary information more easily. DSS may help to weight and structure "soft" qualitative criteria, like company impact, reaction of competitors, and general reputation. Most of the focus in this section deals with topics related to the decision-step in the general decision process model, as shown in Figure 11.

6. Implement

A decision or choice among alternatives is the culmination of one specific decision process. DSS may help communicate decisions, monitor plans and actions, and track performance.

7. Follow-up and assess

Because situations do not remain the same for a very long time, managers are often dealing with problems that grew out of solutions chosen for previous problems. The completion of one decision loop may lead to consciousness about new problems based on the original problem definition. DSS helps in monitoring, following-up, and assessing such consequences as well.

3.2.2 Decision environment

The decision environment may be both internal and external. Factors in the internal environment influencing decisions include:

1) People, and their goals, experience, capabilities, and commitments
2) Functional units, including the technological characteristics, independence, interdependence, and conflict among units
3) Organization factors, including goal and objectives, processes and procedures, and the nature of the product or service

External decision environmental factors may be laws and regulations, and demands from external stakeholders.

3.2.3 Decision makers

Different types of decision makers need support that is adapted to their problem contexts. The following classification of decision makers has been utilised [2]:

- Individual decision maker
- Multiple decision maker
- Group decision maker
- Team decision maker

The individual decision maker stands alone in the final decision process. The decision rests on his/her unique characteristics with regard to knowledge, skill set, experience, etc., and individual biases come to bear in the decision process.

A multiple decision maker comprises several people interacting to reach a decision. Each member may come with unique motivation or goals and may approach the decision process from different angles. Multiple decision makers seldom possess equal authority to make a particular decision, or enough authority to make a decision alone. They do not necessarily meet in a formalised manner to conduct discussions as a unit. Multiple decision makers are more regarded as an institutionalised pattern of communication, rather than a unit. Given different authority levels and individual motivation, the participants interact in a way so that the decision is reached, and an implementation can begin.

In contrast, a group decision maker is characterised by membership in a more formal structure where members of the group share similar interests in the decision outcome. Each member is involved in the making of a decision based on consensus of the group, but none possesses any more input or authority to make the decision than any of the others.

The team decision maker is a combination of the individual and group classification. The team produces the final decision, but the formalization of that decision and authority makes it rest with an individual decision maker. The decision support may come from several individuals empowered by the key individual decision maker to collect information. In this context the team produces the final decision, but the authority to make it rests with the individual team leader.

Organizational decision levels

An organization, when viewed from a decision-making perspective, may be considered as a hierarchy with three discrete levels [2]:

1. Strategic
2. Tactical
3. Operational

Decisions made in an organization may be categorised within one of these three levels. The strategic decision-making level includes the senior executives of companies and the society, those who make the decisions concerning principles.

The tactical (or planning) level implements decisions made at the highest level of the organization as well as decisions to acquire the resources necessary to maintain desired capacities and output at the operational level. Most decisions related to internal administration of the organization are made at this level.

At the foundational or operational level, the line personnel make decisions regarding day-to-day activities related to production or services while supervisors deploy available resources and make the decisions that are necessary to meet the assigned quotas or schedules.

The level of decision-making must be considered thoroughly when designing and implementing DSS. In the petroleum industry, and field development projects in particular, the decision of project initiation is regarded as a strategic decision. Decisions about what type of technology that ought to be utilised mainly belong to the tactical level. The final decisions and approvals of principles are taken at a strategic level of decision makers. Decisions within the WDP belong to a tactical level of decision-making. Implementation of plans, through the necessary operations and follow-up activities (e.g., preparations, drilling and completion) belongs to the operational level of decision-making.

3.3 Categorization of decisions

Decision may be categorised according to the level of certainty of each decision outcome. The following categories may be used:

- Decision under certainty
- Decision under risk
- Decision under uncertainty

Decisions under certainty means that the decision maker has perfect knowledge about the alternatives and their typical outcome [35]. Such decisions are the simplest for a manager to make, but are quite rare. There is perfect knowledge. This category is of minor relevance to the current problem context because most of the decisions in well engineering are taken under risk or uncertainty. Thus, these two categories are described in the following.

3.3.1 Decisions under risk

In decisions under risk the decision maker estimates the probability of several possible outcomes. The outcomes have different probabilities and expected values [35].

Some events or operational hazards of an activity may be difficult to evaluate in a quantitative way. Hazards may be related to occupational risk or risk to the environment. In those cases a qualitative risk assessment may be useful to highlight the effects of decisions of a technical or operational character. Examples of such methods are PHA, FMECA, Fault tree and HAZOP [1]. Probability estimates are often based on subjective judgements of the analysts.

Risk acceptance criteria

Risk acceptance criteria are important in quantitative risk assessments to decide upon risk level and risk reduction measures. An example of operation specific risk acceptance criteria (RAC) is the MIRA concept [36] given in Table 4.

Table 4 Operation specific environmental RAC (copied from [36])

MIRA Consequence Categories	**Recovery time**	**Intolerable probability/ operation**	**ALARP* Probability/ operation**	**Negligible Probability/ operation**
Minor	< 1year	$1 \cdot 10^{-3}$	$1 \cdot 10^{-3}$-$1x10^{-4}$	$1 \cdot 10^{-4}$
Moderate	1-3 years	$2.5 \cdot 10^{-4}$	$2.5 \cdot 10^{-4} – 2.5 \cdot 10^{-5}$	$2.5 \cdot 10^{-5}$
Significant	3-10 years	$1 \cdot 10^{-4}$	$1 \cdot 10^{-4} – 1 \cdot 10^{-5}$	$1 \cdot 10^{-5}$
Serious	>10 years	$2.5 \cdot 10^{-4}$	$2.5 \cdot 10^{-5} – 2.5 \cdot 10^{-6}$	$2.5 \cdot 10^{-6}$

*ALARP - As Low As Reasonably Practicable

The consequence of environmental damage from a hydrocarbon spill is usually measured by the natural recovery time of the environment in years. The consequence is divided into four classes from minor, via moderate, significant to serious consequences. Then, the three probability classes specify an upper and lower probability per operation to determine whether an operation is tolerable or not for each of the consequence categories. Finally, the interval between is specified as the ALARP region (as low as reasonable practicable) [37, 38]. In addition to the recovery time there are economic and consequential losses to local business and society as result of the spill.

When it comes to personnel risk of the employees and contractors the potential loss of life (PLL) the individual group risk (GIR) and the fatal accidental rate (FAR) may be used. These criteria are useful for both the drilling operations, as well as the production phase of the field. PLL is defined as the statistically expected number of fatalities within a population over a specific period of time [36]. The GIR criterion is a measure of risk to a job position within a defined homogeneous group of people. For the drilling operations, the personnel located on deck may be defined as such a group. As an example: a GIR of 10^{-3} per year for a group of 10 people would indicate that the group experience a fatality every 100 years. The intension is to ensure that no group of people is exposed to a risk that is higher than the GIR. The FAR criterion expresses the number of fatalities per 100 million exposed hours for a defined group of personnel [36]. Several variants of FAR are used mainly reflecting how the averaging of the risk level is done. Examples are the group FAR and area FAR.

Reference is made to textbooks for details about risk assessment, methods and tools, e.g., [1]. See also the web-site in [39].

3.3.2 Well integrity

Well blowouts are considered as major risk potentials. Thus, the well integrity and the availability of barriers require special attention, both during well operations and in the production and abandonment phases of wells. According to the facility regulation of the Petroleum Safety Authority (PSA) [38], well barriers are to be designed so that unintentional influx, cross flow to shallow formation layers, and outflow to the environment are prevented. The following definitions are valid according to NORSOK D-010 [40]:

> *Well integrity is defined as the application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the entire lifecycle of the well.*

> *A well barrier is defined as an envelope of one or several dependent well barrier elements (WBE) preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface.*

A well barrier element (WBE) is defined as an object in a well barrier that alone cannot prevent flow from one side to the other side of the object.

Barrier requirements

According to [40], at least two well barriers must be available during all well activities and operations, including suspended or abandoned wells, where a pressure differential exists that may cause uncontrolled outflow from the borehole/well to the environment. A well barrier is to be designed, selected and/or constructed so that

- it can withstand the maximum anticipated differential pressure,
- it can be leak tested and function tested or verified by other methods,
- no single failure of a well barrier or barrier element leads to uncontrolled outflow from the borehole/well to the environment,
- re-establishment of a lost well barrier or another alternative well barrier can be done,
- it can operate competently and withstand the environment for which it may be exposed to over time,
- its physical location and integrity status is known at all times when monitoring is possible.

The well design process should ensure that the final well design complies with the above requirements, or acceptance criteria throughout the defined lifecycle of the well.

NORSOK D-010 refers to the standard NORSOK Z-013 [36] for the risk evaluations to take place when planning the drilling and well activities. Risk assessment is to be performed such that the effect of the activities is determined as part of the total risk on the installation. It applies to the detailed analyses of well activities for specific wells or groups of wells, and can only be carried out when detailed programmes, equipment specifications and procedures have been proposed. The risk assessment is to provide the basis for:

- Operational planning

- Planning of well control activities
- Selection of and requirements to barriers
- Requirements for training and organization of the activities
- Restrictions (if any) applicable to simultaneous operations

The detailed risk assessment of well activities should usually include:

- Probability of blowout and its consequence in terms of appropriate categories according to what is relevant and what is required according to the risk acceptance criteria
- Probabilities of occupational accidents and their consequences
- Probabilities of different amounts of oil spilled, as input to the environmental risk assessment

3.3.3 Decisions under uncertainty

Decisions made under conditions of risk are the most common types for managers. However, sometimes there is not enough information to estimate the probability of the potential outcomes. Then it is termed as a decision under uncertainty. In well engineering the potential outcomes from main decisions are typically known, but the probabilities are not. Uncertainty is then related to the restricted information or lack of information on which to base the analyses or to reliably estimate the probabilities of known outcomes [35].

Another interpretation of uncertainty also involves the utility as a measure of the desirability of outcomes or otherwise the consequences of decisions. The decision elements: probability and utility are related dually. In a sense they are both subjective. The probability element since it is a function of our information at any given time, and utility element since it is an expression of our preferences [41]. Here, the theory of uncertainty is behavioural, because it is motivated by the need to make decisions and it is therefore linked to the demands of practical life, engineering and decision-making.

Decisions made under uncertainty are perhaps the most difficult of all decision situations.

Non-probabilistic methods

Non-probabilistic methods are considered in a setting where probabilities of any particular state do not exist, but there are still a set of stated outcomes which are comparable. Such criteria may depend on characteristics of the outcomes and/or attitude of the decision maker.

The following criteria have been proposed [32]:

Dominance: By comparing the different outcomes, one might choose the alternative which generally has the best consequence in all, or most of the possible outcomes.

Maximin criterion (pessimism): For each alternative the worst possible outcome among the different states is identified. Then the alternative for which the minimum payoff is highest is chosen. If we are dealing with loss (costs) so that smaller payoffs are preferred to larger payoffs, an equivalent criterion is *minimax*.

Maximax (optimism): For each decision, the best possible outcome is identified. Then the alternative with the maximum payoff is chosen like decision D_3 in Table 5. If the payoffs are costs so that smaller payoffs are preferred to larger ones, the criterion that is analogous to *maximax* is *minimin*.

Table 5 Payoff matrix

Decision / Payoff	*P*
D_1	6
D_2	3
D_3	7

Minimax regret criterion: The objective of the criterion is to choose the action that minimises the maximum opportunity loss after the state has been revealed. A regret matrix specifies the opportunity loss for each decision-state pair. In a (m x n) regret (R) matrix the entry in i^{th} row and j^{th} column corresponds to the regret in state S_j when action D_i was actually taken and is the difference between the maximum possible payoff in column j and the entry in the i^{th} row of column j. The minimax regret criterion chooses the alternative for which the maximum regret associated with each alternative is the smallest. For the example matrix given in Table 6, the alternative D_1 is chosen with the smallest maximum regret of 2.

Table 6 Payoff and regret (R) for decision (D)-state (S) combinations

Decision (D) / State (S)	S_1	S_2	S_3	R_1	R_2	R_3
D_1	6	8	28	1	(2)	0
D_2	3	10	18	(4)	0	10
D_3	7	7	9	0	3	(19)

Probabilistic methods

When introducing probabilistic methods the decision maker either knows, or is able to specify the probability occurrence of each state. Uncertainty related to decisions is then reflected in terms of probabilities.

Building a stochastic model, at least one of the variables is uncertain and must be described by a probability function. Such types of models are referred to as probabilistic models because they explicitly incorporate uncertainty into their structure. The sample space of outcomes may take the form of a probability distribution more than a discrete set of values. In general, a stochastic model with the same number of elements as a deterministic model is more difficult to manage and becomes more complicated to solve. Common stochastic modelling techniques include game theory, queuing theory, linear regression, time series analysis, path analysis and logistical regression [2].

Very often the specification of probabilities represents intuition or the best guess. In any event, one important objective of an analysis is to determine how these probabilities influence the ultimate decisions [32].

Expected value criterion

The most commonly used criterion in decision analysis is that of maximising the *expected value* of the payoff. An example of a payoff matrix and probability distribution is given in Table 7.

Table 7 Payoff matrix with a probability distribution

Decision (D) / State (S)	S_1	S_2	S_3
D_1	6	8	28
D_2	3	10	18
D_3	7	7	9
Probability (P[3])	0.1	0.7	0.2

Let r_{ij} be the payoff the decision maker receives when decision D_i is taken and state S_j occurs. Then the expected value of alternative D_i is

$$E\left[D_i\right] = \sum_{j=1}^{n} r_{ij} P_j \qquad \text{for } i = 1,\ldots, m$$

The modal outcome criterion

The modal criterion specifies that the optimal decision alternative is the one which gives highest payoff in the state (outcome) that occurs with the highest probability. In Table 7, state 2 occurs with the highest probability. Thus, D_2 is the optimal choice under the modal criterion since the highest payoff in state 2 is associated with the D_2 alternative.

Expected regret criterion

The expected regret criterion specifies that the alternative with the smallest expected regret (expected loss) should be chosen. Given a (m x n) regret matrix as in Table 6, with i = 1,....., m and j = 1,....., n, let L_i be the opportunity loss (or regret) with the probability of P_j when alternative D_i is taken. L_{ij} is here all the values the opportunity loss can take for the D_i alternative. P_j is the probability of state S_j to occur leading to the specific loss of $L_{ij} = L_i$. The minimised expected loss, $E[L_i]$ then denotes the expected minimised regret for decision D_i that is calculated as

$$Min\,(E\left[L_i\right]) = Min\,(\sum_{j=1}^{n} L_{ij} P_j) \qquad \text{for i} = 1,\ldots, m$$

[3] To differentiate from “decisions under risk” the given probability distribution here expresses the uncertainty related to specific outcome probabilities.

Note that the criteria of maximising expected payoff and minimising expected regret are identical [32].

3.3.4 Economic analysis

LCC

Lifecycle cost (LCC) is a collective term (or concept) comprising analyses such as reliability, availability and maintainability analysis (RAM), economic analysis, and risk assessment [42]. The main objective of the LCC analysis is to quantify the total cost of ownership of a product throughout its lifecycle, which includes research and development, construction, operation and maintenance, and disposal. The predicted LCC provides useful information for decision-making in purchasing a product, in optimising design, in scheduling maintenance, or in planning major changes. LCC analysis may be applied for the following purposes:

- Evaluation and comparison of alternative design
- Assessment of economic viability of projects/products
- Identification of cost drivers
- Evaluation and comparison of alternative product strategies
- Long-term financial planning

LCC analysis may be carried out in any phases of a product's lifecycle to provide input to decision makers. However, early identification of acquisition and ownership costs provides the decision makers with more opportunity of balancing performance, reliability, maintenance support, and other goals against lifecycle costs. Figure 12 illustrates an iterative LCC concept developed from six basic processes (hexagons). Each basic process is further broken down into sub-activities listed in each sub-area.

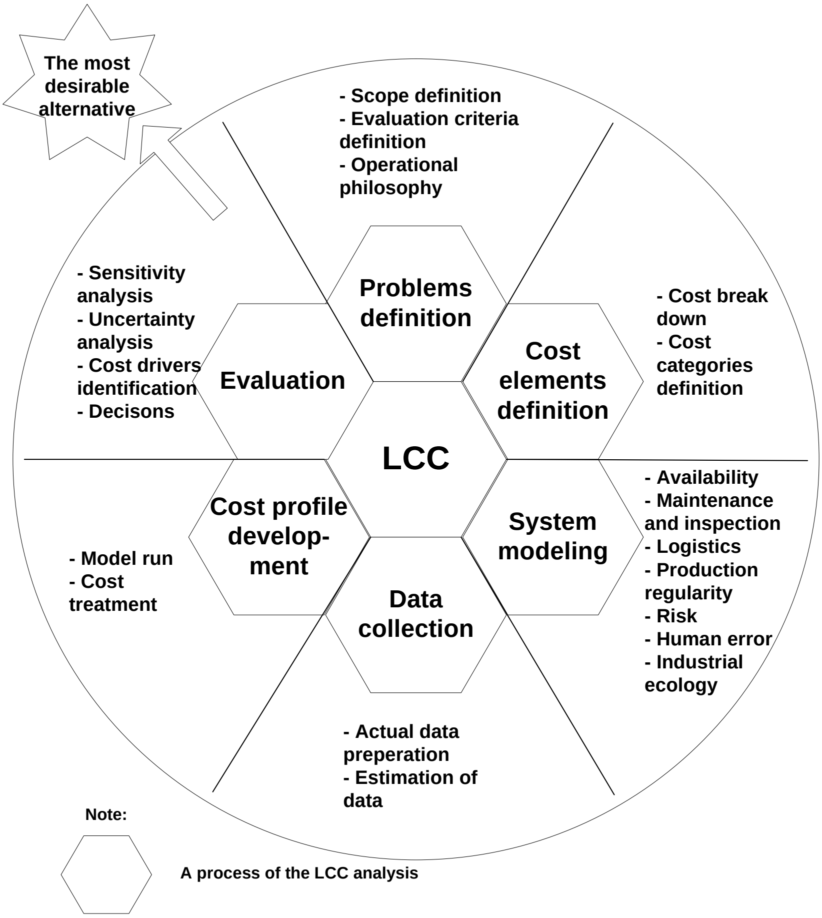

Figure 12 LCC concept (adapted from [42])

Several approaches to LCC analysis are given in the literature [43-46], each typically related to a specific system or application. However, there are some common process steps that appear essential to almost every approach [42]:

1. Problem definition
2. Cost element definition
3. System modelling
4. Data collection
5. Cost profile development
6. Evaluation

Beside an accurate problem definition defining the scope of the study, the cost element definitions are the most critical part of the LCC analysis. It is accordingly recommended to define the cost elements in a systematic manner to avoid ignoring significant cost elements. The international standard IEC 60300-3-3 suggests a cost breakdown structure (CBS) as a basis for the definition of the cost elements [45]. The CBS concept defines items along three independent axes that are the: lifecycle phases, product/work breakdown structures, and cost categories. Commonly used cost categories on the highest level in many LCC analyses are “acquisition cost” and “ownership cost”. They may preferably be called “capital expenditure” (CAPEX) and “operation expenditure” (OPEX). An additional category is the cost of “loss”, or deferred production. Such cost elements are mainly linked to the unavailability performance of the system.

Cost-benefit analysis

Net present value (NPV) is a discounting approach used in capital budgeting where the present value of cash inflow from a system or product is subtracted from the present value of cash outflows. If the NPV of a prospective project is positive, then it should be accepted. However, if it is negative, then the project probably should be rejected because cash flows are negative.

Discounting takes account of the changing value of money. Since some of the costs and expected income from an investment will occur in the future, it is necessary to discount the cost and income figures to a specific point of time that is actually the decision point. A commonly used equation for calculating the NPV is:

$$NPV = \sum_{n=0}^{t} C_n \cdot (1+r)^{-n}$$

where,

NPV	-	Net present value of future cash flows
C_n	-	Nominal cash flow in the n^{th} year
n	-	Specific year in the lifecycle
r	-	Discount rate
t	-	Length of the time period in years

3.4 Decision support systems (DSS)

DSS is broadly defined by (Power) [30] as an interactive computer-based system that helps people to utilize computer communications, data, documents, knowledge, and models to solve problems and make decisions. A more precise and correct definition, not necessarily focusing on the computer aspect of the DSS, is the one given by (Marakas) [2] .

> *A DSS is a system under the control of one or more decision makers that assists in the activity of decision-making by providing an organized set of tools intended to impose structure on portions of the decision-making situation and to improve the ultimate effectiveness of the decisions outcome.*

A DSS is, however, and should only be regarded as an auxiliary system. It is not intended to replace skilled decision makers, but to support them. The DSS expands the decision maker's capacity in processing information of relevance to decision-making. Many elements in a decision situation are highly complex and time-consuming. The DSS may here solve those portions of the problem, and save cognitive resources, and more importantly, time for the decision maker. As a result, the time involved in reaching a complex, unstructured decision may be reduced significantly by using a DSS. Some general benefits and limitations to DSS are [2]:

Benefits

- Extend the decision maker's ability to process information and knowledge
- Extend the decision maker's ability to tackle large-scale, time-consuming, complex problems
- Shorten the time associated with decision-making
- Improve the reliability of a decision process or outcome
- Encourage exploration and discovery on the part of the decision maker

- Reveal new approaches to thinking about a problem space or decision context
- Generate new evidence in support of a decision or confirmation of existing assumptions
- Create a strategic or competitive advantage over competing organizations

Limitations

- A DSS cannot be designed to contain distinctly human decision-making talents such as creativity, imagination, or intuition
- The power of a DSS is limited by the computer system on which it is running, its design and the knowledge it possesses at the time of use
- A DSS is normally designed to be narrow in scope of application, thus inhibiting its appliance to multiple decision-making contexts.

A way of categorising DSS is in terms of the intended users, its purpose, and the enabling technology. The term “driven” is used as a common or shared adjective to name the different categories of DSS. "Driven" here refers to the tool or component that is providing the dominant functionality in the DSS. The major five categories of DSS [30] are:

1. Data-driven DSS
2. Model-driven DSS
3. Knowledge-driven DSS
4. Document-driven DSS
5. Communication-driven and Group DSS

Data-driven DSS is most appropriate where managers need frequent access to conduct ad hoc analyses of large data sets.

Model-driven DSS are appropriate in recurring decision situations that are semi structured and where a quantitative model or models can support analyses and choices.

Knowledge-driven DSS are appropriate where a narrow domain of expertise can be defined, where one or more experts can be identified, or where knowledge can be coded to help a less expert decision maker.

A *Document-driven DSS* should be build when a very large set of documents has been, is or will be created that needs to be filtered, sorted, searched, and analysed.

A *Communication-driven DSS* is most appropriate where several people need to be involved in an ad hoc or ongoing decision-making process, and if somebody either cannot meet or finds it costly to meet, but wants to use technology tools to communicate, collaborate, evaluate, and support decision analysis or evaluation.

Risk and uncertainty characterize many decision situations. Computerised tools may then help to elicit and analyse large amounts and rapidly changing information.

The following sections describe these DSS categories more in detail.

3.4.1 Data-driven DSS

Data-driven DSS emphasises the analysis of large amounts of structured data. These systems include file drawer and management reporting systems, data warehousing with analytical systems, and executive information systems. Simple file systems accessed by query and retrieval tools provide the most elementary level of functionality, including aggregation and simple calculations. Data warehouse systems that allow the manipulation of data by computerised tools tailored to a specific task provide additional functionality. (Dhar and Stein) as cited by [30] indicate that on-line analytical processing provides the highest level of functionality and decision support that is linked to analysis of large collections of historical data.

3.4.2 Model-driven DSS

Decision situations that involve a finite- and usually small number of alternatives may be evaluated with decision analysis models. Model-driven DSS includes systems such as accounting and financial models. Simple statistical and analytical tools provide the most elementary level of functionality [30]. Model-driven DSS use data and parameters provided by the decision makers to aid in analysing a situation, but they are usually not data intensive. Large databases are usually not needed, but data for a specific analysis may be extracted from several data sources.

The modelling process begins with identification of the problem and analysis of the requirements of the situation. It is advisable to analyse the scope of the problem domain and the forces and dynamics of the environment. The next step is to identify the decision variables and their relationships. One should always ask if using a model is appropriate. An influence diagram may be used to examine the variables and relationships. Single goal situations are approached by the use of a decision table or decision trees. Multiple goal situations may be analysed by several techniques including multi-attribute utility analysis and the analytical hierarchy process (AHP) [47].

Assumptions are important in building models because one is projecting or anticipating results. An analyst needs to make assumptions about the time and risk dimension of a situation, and whether there is a static or a dynamic analysis. A test of the assumptions may be a "what if" or sensitivity analysis before accepting the results of the model. A static analysis is based on a "single snapshot" of a situation. Everything occurs in a single interval, which can be very short, or of long duration. During a static analysis, it is assumed that there is stability in the decision situation. Dynamic analysis is used for situations that change over time. Dynamic models are time dependent. The assumptions limit or constrain the types of models that can be used to build a DSS for the situation.

Models may be developed in different programming languages like Java and C++ and in wide spectra of software packages. However, simple spreadsheet software is the most commonly used for desktop model-driven DSS.

The following describes some typical examples of model approaches utilised by many industrial decision makers.

Multi-criteria decision-making

Given a set of alternatives and a set of decision criteria (more than one), what is the best alternative? This is called a multi-criteria decision problem and may come in many different forms. For instance, the alternatives or the criteria may not be well defined, or even more commonly, the related data may not be well defined.

It is often difficult to conceptualize all the different elements that make up a decision. It is easy to fail by not including one or more important elements, or to include elements that are not important at all in the decision. If the decision elements are incommensurable it makes it even more difficult to measure or compare them in any values.

In addition, the cognitive energy necessary to prioritise decision elements may make it difficult to keep track of previous priority rankings and may lead to inconsistent priority judgements [2]. (Saaty) as cited by [2] indicates that the analytical hierarchy process method (AHP) is an attempt to solve these problems. AHP can be characterised as a multi-criteria decision technique that may combine qualitative and quantitative factors in the overall evaluation of alternatives. It is based on a theory of measurement for dealing with quantifiable and intangible criteria that have been applied to numerous areas. Common examples are decision theory and conflict resolution [48]. AHP is basically a problem-solving method, and a systematic procedure for representing the elements of a decision problem. AHP is based on the following three principles:

1. Decomposition
2. Comparative judgements
3. Synthesis of priorities

AHP starts by decomposing a complex, multi-criteria problem into a hierarchy where each level consists of a few manageable elements which are decomposed into another set of elements (see example in Figure 13). The second step is to use a measurement methodology to establish priorities among the elements within each level of the hierarchy. The third step is to synthesise the priorities of the elements to establish the overall ranking of the decision alternatives.

AHP differs from conventional decision analysis methodologies by not requiring decision makers to make numerical guesses as subjective judgements are easily included in the process, and the judgements may be made entirely verbally.

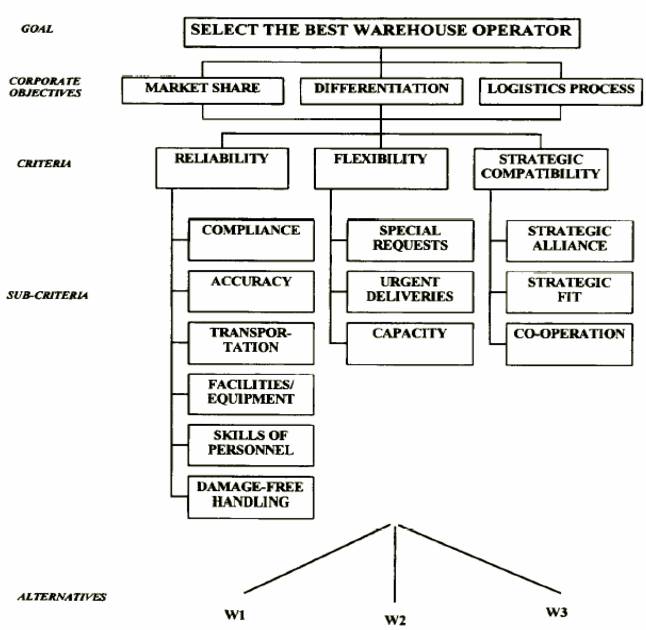

Figure 13 Example of an AHP-hierarchy (copied from [48])

As shown in Figure 13 the overall goal for the analysis is written on the top of the hierarchy with corporate level objectives on the second level. The main criteria are then linked to the corporate level objectives. Each of the main criteria is divided into sub-criteria on which the actual analysis of the potential selection alternatives is based. The different alternatives to select between are located on the lowest level of the hierarchy. The hierarchy forms a logical representation of the complex, multiple-criteria decision process and it effectively describes the relationships between the elements involved. The hierarchy fosters understanding and consensus among the decision makers about the decision process they are facing.

The first step in the AHP-supported qualitative analysis is to identify the criteria on which the evaluations of the alternatives are based. An AHP-hierarchy is structured to represent the relationships between the elements after having identified the relevant factors to be considered regarding the alternatives. (Foreman) as cited by [49] provides a list of typical hierarchical structures:

- Goal, criteria, alternatives
- Goal, criteria, sub-criteria, alternatives
- Goal, scenarios, criteria, alternatives
- Goal, actors, criteria, alternatives
- Goal, sub-criteria, levels of intensities (many alternatives)

An AHP hierarchy may also represent the different decision levels in an organization [2]. The respective levels of criteria are then an illustration of the distributed roles and responsibilities in the organization.

The next step of the AHP analysis is to assign priorities for each element in the hierarchy. The priorities are set by comparing each set of elements in a pairwise fashion with respect to each of the elements on the next higher level. A verbal or a corresponding nine-point numerical scale is used for the comparisons. It may be based on objective, quantitative data or on subjective, qualitative judgements. In a group setting, there are several ways of including the views and judgements of each person in the priority setting process. In a common objectives context, there are four ways that can be used for setting the priorities:

- Consensus
- Vote or compromise
- Geometric mean of the individuals’ judgements
- Separate models or players

If consensus cannot be established, the geometric mean of the group member’s judgements is used as it is the uniquely appropriate rule for combining judgements since it preserves the mutual property of the judgement matrix. The priority setting procedure is started by comparing the corporate level objectives in a pairwise fashion with respect to the goal (what is the importance of each corporate level objective). Then the importance of the main criteria is evaluated with regard to each corporate level objective and the importance of each sub-criterion is assessed with regard to the main criterion they are linked to. The last step in the priority setting procedure is to compare the alternatives in a pairwise fashion with respect to each sub-criterion (what is the preference of each alternative).

(Saaty) [35] discusses the basic differences between AHP and other conventional techniques. One alternative is the Delphi technique that is used to obtain expert opinions and consensus on a topic through the use of a series of anonymous written questionnaires. (Saaty) [35] concluded that while both techniques improve the quality of judgements, the AHP hierarchy better fits the human cognitive style of thinking in the way it decomposes the problem and synthesises the results [47].

AHP helps to structure a group decision so that discussion centres on objectives rather than on alternatives. Since an AHP analysis involves structured discussion, every topic or factor relevant to the decision is addressed in turn. The contrast to this is drifting from topic to topic causing a situation of addressing the same factors several times, and others not at all. Because the analysis is structured, discussion continues until all available and pertinent information has been considered, or the need for additional information becomes apparent. A consensus choice of an alternative which most likely meet the goals are taken in contrast to not knowing when enough discussion has taken place and arbitrarily terminating at some scheduled adjourning time [49].

Another technique used in multi-participant problem-solving contexts is the nominal group technique (NGT) [2]. Nominal grouping is a combination of decision-making techniques in which the group members meet face to face to generate and vote on ideas concerning a particular problem [35]. The purpose is to eliminate social and psychological dynamics of group behaviour that tend to inhibit individual creativity and participation in a group. While the group uses the technique they avoid the normal problems of a few individuals doing all the talking and the rest are listening. Individuals may be more creative, and everyone is given the opportunity to participate. The different steps of NGT include:

1. Silent generation of ideas from individuals and writing them down

2. Recording of ideas that have been generated on a chart
3. Discussion and clarification of each idea on the chart
4. Preliminary vote on priorities by the individuals
5. Discussion of preliminary voting in the group
6. Final vote on priorities by the group

One of the difficulties in applying the analytical hierarchy process (AHP) in a group setting is that some decision makers are frequently reluctant to reveal their true opinions. They may distort their pairwise comparisons in order to enhance the likelihood of a preferred outcome. By using a multi-dimensional scaling technique, known as the "Sammon map" [50], the judgements are visualised to the decision makers, in order to discourage this sort of behaviour. Considering all members of the group as decision makers, the Sammon map displays clusters of decision makers, as well as decision makers who are outliners. By this visualization each participant is encouraged to generate pairwise comparison entries that reflect true opinions that are not distorted.

For any (m x m) pairwise comparison matrix connected to a AHP hierarchy, there are n priority vectors that correspond to the n decision makers, and an additional vector that corresponds to a composite priority vector generated by the geometric mean (a total of $n + 1$ priority vectors). The priority vectors can be thought of as ($n + 1$) points in m-dimensional space. From these points a ($n + 1$) x ($n + 1$) distance matrix, $D = (d_{ij})$, where d_{ij} represents the distance between decision maker i and decision maker j, is derived. Given the distance matrix D as input, the two-dimensional Sammon map is created through an iterative calculation process.

Decision tree

A decision process may involve decision-making over several time periods under conditions of uncertainty. Opportunities for decision-making distributed in time indicate a decision problem of "dynamic" nature. This kind of decision process may be analysed by use of decision trees [32]. A decision tree model shows the timing of decisions along with the necessary decision information. It also illustrates the relevant outcomes that are generated by the decisions. In a dynamic decision process decisions made in one time period may have consequences for decisions in the future as well.

A decision tree uses three types of nodes: choice (decision) nodes, represented by a square, and chance (event) nodes, represented by a circle. Finally, the terminal nodes have shape of a short vertical line representing the end of the decision process. For the chance nodes, the probabilities along each outgoing branch must sum to one. The expected payoffs may then be calculated for each branch of the tree.

An example of parts of a decision tree is shown in Figure 14. Mainly, it illustrates graphically the sequence of decisions and the possible events that may occur. The event probabilities are indicated above the arc and the payoffs are given below the arc. It clearly shows that decisions are distributed over time and depend on available information at the point in time the decision is made. Figure 14[4] shows that information from the hired consultant (likelihood of competitor) turns the decision at node XXXII to be “introduce the new product now” (the “1” given in the decision box). A complex problem may be broken down into a series of sequential decisions and possible events in a similar way [35].

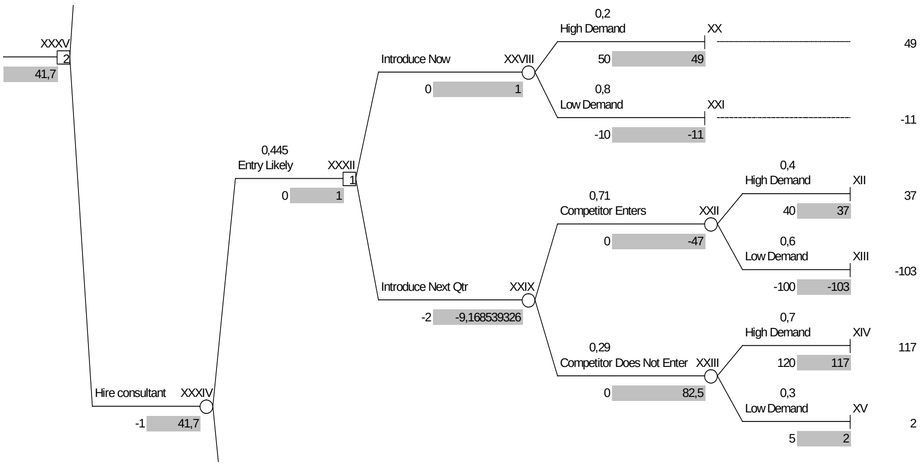

Figure 14 Example of a decision tree (adapted from [32])

[4] The decision tree is prepared in the Excel-based “TreePlan” software.

A critical element in the construction of a decision tree is the timing of the decisions relative to the resolution of the uncertainties. The following procedure is useful in determining the timing [32]:

1. List all the different types of decisions that must be made
2. List each of the uncertainties that must be accounted for
3. For each decision determine if the uncertainties occur before or after the decision is made. In other words, determine the uncertainties that have been resolved at the time a particular decision is made, and which have not.

The dynamics in an optimal decision process is revealed by the tree through a contingency plan. An optimal decision strategy specifies what the optimal action is at every decision node in the tree, no matter how one get to that node. This is a much deeper and flexible tool than a deterministic approach (as, e,g., linear programming). A deterministic approach to a decision problem only specifies one set of values at the time for the decision variables. Hence, there is no notion of contingency. Through the decision tree approach, a plan that responds optimally to every realization of uncertain events may be developed.

However, there are sacrifices that must be made. In the world of linear programming, a rich set of potential solutions are available to select the optimal solution. An infinite of possible values may then suit the existing decision variables. In a “decision tree world”, however, we can only evaluate a finite number of possible actions at each decision node, which must be small in number to limit the model. Otherwise, number of nodes in a tree increases exponentially as more decision options are added at decision nodes, and/or outcomes are added to event nodes.

Benefits

A decision tree has two major advantages. First, a decision tree graphically shows the relationships among the problem elements. Second, it may deal with more complex situations in a compact form. Thus, it may improve the managerial planning a lot. The decision tree makes the timing of decisions and the manner in which "nature" enters the decision process explicit. Other benefits are that it is possible to estimate the expected value of information in the decision process by help of the parameters in the tree and available data. It provides easy measures for sensitivity analysis, e.g., by varying the likelihood probabilities of events.

When it comes to the scenario descriptions incorporated in the model, the following advantages are relevant [51]:

- The focus is on capturing the broad range of uncertainty
- The computational effort is limited
- Provides a straightforward extension of deterministic thinking

Drawbacks

Common mistakes are that decision and chance nodes are placed in the wrong order. Note that only chance nodes whose results are known can precede a decision node. Incorrect derivation of chance probabilities are common because chance probabilities may depend on each other and the earlier decisions made. Some specific disadvantages of the scenario approach are:

- The need for subjective estimations of scenario probabilities (often)
- The residual uncertainty within each scenario might be ignored
- It is required that every decision represents a discrete set of alternatives

Influence diagram

An *influence diagram* depicts the relationships between the various elements in a decision problem [32]. The diagram consists of nodes connected by arrows or directed arcs. There are three types of nodes. *Circle nodes* represent events (chance), an activity that results in an outcome that is not necessarily known at the start of the decision process (see Figure 15). In the special case where the event is deterministic, so that the value of the node never changes, the oval node is represented by a heavy line. *Rectangular nodes* represent decisions. *Rounded-corner rectangular nodes* represent final or intermediate values (values of cost, profit, or some other quantity to be optimized). Arrows connect nodes and indicate the direction of influence that the value of the node at the tail of the arrow has on the value of the node that is the head of the arrow. The direction of the arrow conveys important information about the logic of the problem.

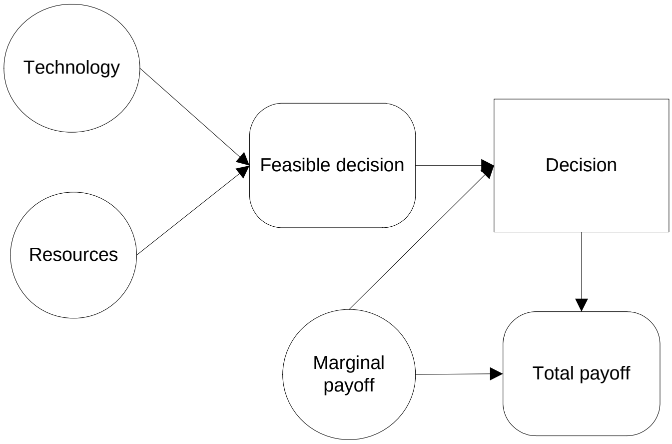

Figure 15 Example of an influence diagram (adapted from [32]

Influence diagrams are snapshots of a decision process at a particular point in time. They may be used as a simple method for graphically modelling a decision. As such, influence diagrams represent what the decision maker knows or does not know at the particular instant of time. In light of this it follows that influence diagrams cannot contain loops, a sequence of nodes and arrows that form a path leading back to a node that appears earlier in the path. In addition, it is important to be aware of the following limitations:

- The influence diagram is not a flow chart used to depict a sequence of activities in a decision process that leads to the determination of some decision
- The influence diagram is not a precedence diagram that depicts the order in which activities must be executed
- The influence diagram is not a decision tree that depicts the timing of decisions and their consequence in a decision process (see part II of [32]).

Simulation

Simulation is a specialised type of modelling tool. Unfortunately for most decision makers, problem structures do not often readily fall into either a strictly deterministic or probabilistic realm. A simulation tests various outcomes that results from combining modelled subsystems in a dynamic environment [2]. Another issue is that most quantitative models are simplifications of the reality, while simulation models try to imitate reality with some fewer simplifications.

Simulation is a technique for performing "What-if" analysis over multiple time periods or events by testing of specific values of the decision or uncontrollable variables in the model and observing the impact on the output. The most common tool in modelling phenomena through parameter changes is probably Monte Carlo Simulations.

Benefits

Simulation is usually needed when the problem under investigation is too complex to be evaluated using optimization models. Simulation theory is relatively easy for managers to understand. A typical simulation model contains a collection of many elementary relationships. It allows managers to ask "what-if" questions.

Drawbacks

By simulation, an optimal or "best" solution cannot be guaranteed. Constructing a simulation model is frequently a slow and costly process (which makes it impractical to solve small and narrow problems). Solutions and inferences from a specific simulation study are usually not transferable to other situations.

3.4.3 Knowledge-driven DSS

The terminology for knowledge-driven DSS is still evolving [30]. Other related terms are “suggestion DSS” and the “management expert systems”.

A knowledge base may be defined as a collection of organized facts, rules, and procedures. It may describe elements contained in the decision process along with their characteristics, functions, and relationships.

Knowledge-driven DSS suggest or recommend actions to managers. They use business rules and knowledge bases including specialised problem-solving expertise. The expertise consists of knowledge about a particular domain, understanding of problems within that domain, and “skill” at solving some of these problems. A related concept is “data mining”. This term refers to a class of analytical applications that search for hidden patterns in a database. Data mining is the process of sifting through large amounts of data to produce data content relationships.

Benefits and drawbacks

A knowledge-driven DSS differs from a more conventional model-driven DSS in the way knowledge is presented and processed. An expert system attempts to simulate human reasoning processes. Such a decision environment often makes use of heuristic methods to obtain a recommendation. A model-driven DSS has a sequence of predefined instructions for responding to an event and uses mathematical and statistical methods to obtain more precise solutions.

3.4.4 Document-driven DSS

A document-driven DSS helps managers gather, retrieve, classify and manage unstructured documents, including Web pages. A variety of storage and processing technologies to provide document retrieval and analysis is provided. Examples of documents that would be accessed by a document-driven DSS are policies and procedures, product specifications and historical documents. A search engine may be a powerful decision aiding tool associated with a document-driven DSS. Some may call this type of system a knowledge management system.

3.4.5 Communication-driven and group DSS

Group Decision Support Systems (GDSS) and groupware came first, but now a broader category of communication-driven DSS may be identified. This type of DSS includes communication, collaboration, and decision support technologies. A GDSS is an interactive computer-based system intended to facilitate the solution of problems by decision makers working together in a group. Groupware supports electronic communication, scheduling, document sharing, and other group productivity and decision support activities. Examples are session rooms, two-way interactive video, white board, chat and e-mail system (e-room).

3.4.6 Developing a decision support system (DSS)

A number of analysis and design approaches may be applied to the process of developing a decision support system (DSS) [2]. Three of the most common approaches are the system development lifecycle (SDLC), representation operations memory aids and control (ROMC), and the functional category analysis (FCA). Each of these approaches focus on special features of the decision-making process as described in the following.

System development lifecycle

The SDLC portrays the process as a series of repeated phases, each with its own set of required inputs, activities, and outputs. During system analysis, the analysts focus in the determination, collection, and documentation of specific requirements for the new system. Based on these requirements the design phase begins with a detailed model of the various system component processes and data elements as well as their interactions and interrelationships. The primary advantage of the SDLC approach in DSS development is that it brings a necessary structure and discipline to the DSS development process. The major complaint associated with it is its rigidity. If the requirements in a DSS system change rapidly, the SDLC structure may force too much structure on the end-user requirements too early in the development process.

Representation operations memory aids and control

An alternative to the SDLC approach is a ROMC analysis [52]. Here, the analysis focuses on developing understandings of representations (R), operations (O), memory aids (M), and controls (C). The analyst characterises the various representations available for use as methods of communication between the DSS user and the DSS application. Examples of representations are graphical displays, charts, tables, among others. Memory aid components provide support to the user of various identified representations and operations. Examples of memory aids include databases, work spaces or blackboard systems. Finally, control mechanisms help the DSS extract or synthesise a particular decision-making process from the available representations, operations, and memory aids. Examples of a control mechanism are modules that assist the DSS user in learning to use specific elements within the DSS via examples rather than trial- and error discovery.

Functional category analysis

The functional category analysis [53] identifies the specific functions necessary for the development of a particular DSS from a broad list of functions as selection, aggregation, estimation, simulation, equalization, and optimization. Functional category analysis organizes the key functions of the proposed DSS into a useful arrangement, thus allowing the DSS designer to perform a more focused and detailed analysis.

Development process

Very often the specific information needs of decision managers in a given problem context are not clear in the early stages of DSS design, and thus they are not easily identified. To facilitate the collection of DSS requirements and functions, a process that emphasises prototyping is suggested by (Marakas) [2]. A generalised process of system development, as shown in Figure 16, is tailored to the special needs and challenges of the DSS design. The process shows a set of activities and phases of development that are typically associated with DSS design.

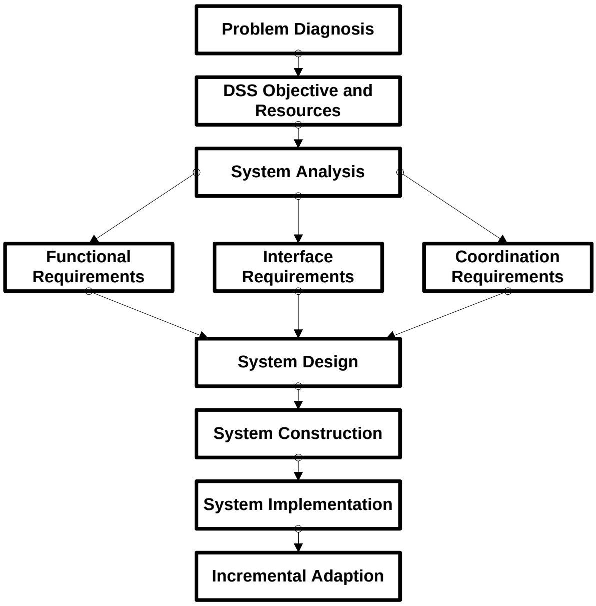

Figure 16 DSS development process (adapted from [2])

Opportunities for decision support may present themselves in many ways. In addition to providing support for identified problems within an organization, the DSS assists in the discovery of new knowledge as well. The specific objectives and the key decisions to be supported by the DSS must be described early in the process. The objectives should clarify the function of the proposed DSS with regard to the various types of knowledge to be managed. Also of importance are the methods or approaches by which the success of these objectives is evaluated.

The system analysis should result in a detailed set of requirements for the DSS. According to [54] three primary categories of system requirements for the DSS are essential: 1) Functional requirements (FRs), 2) Interface requirements, and 3) Coordination requirements.

In a system design phase, one of the primary activities is the selection of development tools to be used in the construction of the DSS. This tool should facilitate the development platform and being basis for the system structuring.

During the system construction phase, the designer may use an interactive prototyping approach in which small, yet constant, refinements are made based on feedback received from testing and the user environment.

The goal of the system implementation phase is to test, evaluate, and deploy a fully functional and documented DSS. Modifications may be necessary to fully realize the potential of the DSS and to fully implement the objectives of the decision makers.

Through incremental adaptation, the continual revisiting of the activities of the earlier stages is an effort to enhance the capabilities if the DSS based on knowledge gained as a result of its use.

3.5 A case from the petroleum industry

3.5.1 Management system

The Ormen Lange well delivery project, conducted by Shell is used as a case example to illustrate the different decision levels and processes taking part in well engineering. The Shell management system, that is mandatory for all the exploration and production (E&P) activities, is illustrated in Figure 17 below. It shows the direct linkage of the WDP to the value chain.

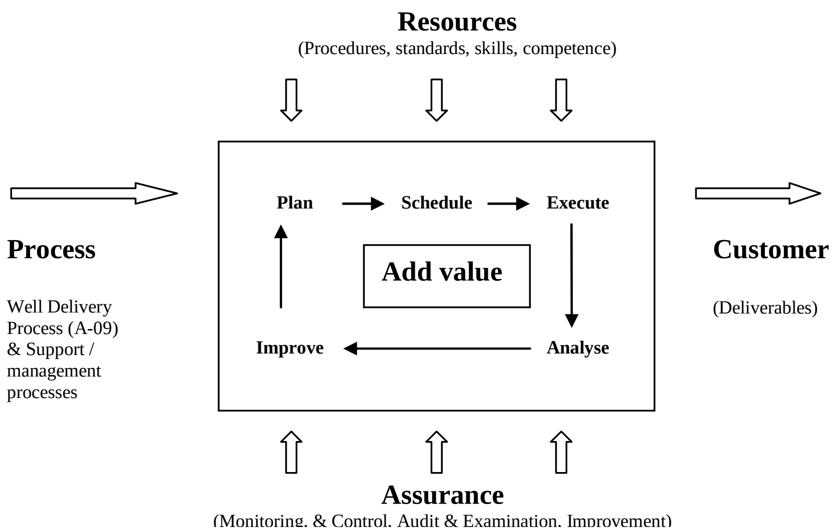

Figure 17 Shell E&P management system (adapted from [29])

Shell E&P has the document: “opportunity and project management guide” (OPMG) at the highest strategic level of management. This is an overall procedure for business realization within Shell E&P. The document describes the opportunity realization process (ORP) by the following steps:

- Identification of business opportunities
- Definition of objectives and how to prove viability
- Decide ways the opportunities may be exploited
- Implementing the strategy
- Make plans for accomplishment
- Provide tools to facilitate planning and implementation

In this context the project management is defined as: "an application of knowledge, skills, tools and techniques to project activities in order to meet the stake holder's needs and expectations". And of cause it implies the fulfilment of all authority regulations to such activities[5]. The structure of (OPMG) is shown in Figure 18.

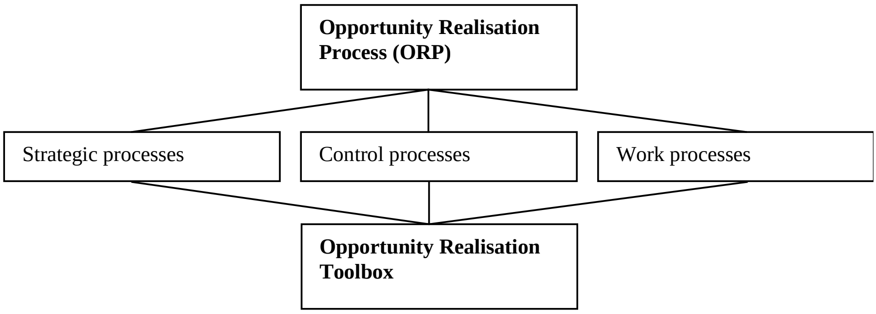

Figure 18 Structure of opportunity and project management guide [29]

The most interesting part of Figure 18 is the main work processes (or phases) where the different project sub-activities are linked. Some important decision gates (milestones) will be attached to a set of primary activities. Sub-activities, like well engineering, are attached to the main work process where they are relevant. An example model with five main work processes and connected sub-activities are shown in Table 8. The effectuation of such a model involves a full multidisciplinary approach to project accomplishment.

[5] Notes based on the QA-Manual of Shell E&P

Table 8 Work processes in the development project

Phase 1	Phase 2	Phase 3	Phase 4	Phase 5
Identify & assess	Select	Define	Execute	Operate
Portfolio management			Detailed design	Start-up
Venture generation			Procurement	Production
Exploration	Appraisal		Construction	Maintenance
Concept Id.	Concept selection	Concept definition	Commissioning	Inspection
Well engineering	Well engineering	Well engineering	Prepare for operation	Reservoir management
Material management	Material management	Material management	Well engineering	Well engineering
Logistical management	Logistical management	Logistical management	Material management	Material management
			Logistical management	Logistical management

Some important definitions and terms related to Table 8 are the following:

- Front end engineering (FFE): Related to the opportunity inspection that leads to the major project specification
- Concept selection: Part of FEE, a concept selection report (CSR)
- Concept definition: Part of FEE, stretching from the completion of CSR until completion of the project specification
- Detailed design: All design work carried out after the final project specification at a detail level as needed to produce a commercial asset
- Follow-up engineering: Response to site quarries, etc.

The selection phase and the following well engineering and field engineering activities imply carrying out activities such as:

- Estimation of well expenditure (CAPEX)
- Estimation of facility capital expenditure (CAPEX)

- Estimation of operating expenditure (OPEX)
- Other economic analyses

Shell utilize a toolbox for these activities is named the “STEP 99-5500”- exploration play and prospect evaluation methodology”. The reference is framework EP 97 for the well engineering activities.

3.5.2 Ormen Lange well engineering

Decisions regarding field development and the choice of main development concept and technology may be seen at two levels of detail when related to exploration and development. The two decision levels are:

1) Field exploration and development strategies. There is a need for integrated and interdisciplinary decision support methods and tools that may address field development feasibility studies and link those to the decisions regarding the concept (strategic decision-making).
2) Selection and definition of technology options and conducting detailed design. There is need for additional tools to evaluate the different solutions/opportunities available on market or even immature alternatives at more detail level including their risks (comparing pros and cons in a tactical decision-making context).

The objective of a feasibility study is basically to clear out options. As an example, the following aims were defined ahead of the evaluations prior to the selection of well configuration for the Ormen Lange field[6]:

1. To assess the overall mechanical feasibility of drilling 2.5 km and 5 km step-out wells from the main production area at Ormen Lange
2. To identify key surface and down-hole equipment that will be required
3. To evaluate sensitivity to the major design assumptions
4. To establish well designs with “typical available” rig packages

[6] Notes based on the feasibility study (AS Norske Shell and Norsk Hydro).

A feasibility study at this level provides a workable preliminary well design, forming the basis for further detailed planning, contracting and purchasing of services and equipment. Rig tendering is also initiated at this phase. Information about facts and feasibilities of the field is documented in the "well engineering design basis".

Decision basis

In the following a brief description of the decision basis for the Ormen Lange predrilled wells is given. Exploration wells were drilled at Ormen Lange to determine both the geological and the operational aspects of the reservoir as input to the planning work of the wells to be predrilled. Five exploration wells[7] were drilled in the time period between 1997 and 2002. A considerable amount of data including relevant geological and operational information was collected. Useful experience and knowledge for the later well engineering activities were gained in that period. Important geological and operational aspects are as listed in Table 9.

Table 9 Geological an operational aspects of the Ormen Lange wells

Geological aspects	**Operational aspects**
Lithology	Casing sizes and setting depths
Pore and fracture pressure data	Hole sizes
Mud weights	Mud types
Losses (mud enters into fractured formation)	Cementing
Shallow hazards (boulders, gas or water)	ROP data
	Hole condition issues

When it came to the well construction, the hole-sizes along with the casing sizes and shoe setting depths determined the well basic design. As an example the most important issues when drilling the conductor and surface casing sections were to maintain minor well inclination and good hole-conditions. The issue of avoiding inclination is here mainly to prevent any BOP latching problems later on in the drilling phase.

[7] According to the "Ormen Lange Exploration Wells Review"

Well engineering design basis

The design basis for the wells reflects the well objectives[8]. The most important for the Ormen Lange wells is to start-up production in October 2007. A minimum of 6 predrilled wells should be ready by the start-up of production enabling a production take-off of 30 MSm^3/day in the first year, 50 MSm^3/day in the second year and maximum production of 70 MSm^3/day in the third and subsequent years[9]. Two additional wells will be drilled in phase one to a total of eight wells. In phase two another 16 production wells may be drilled starting in 2009 and onwards. Then a total of 24 production wells are planned drilled. Four templates will be installed in water depths varying from 848 to 1065 metres. Templates A and B located in the main production area will be installed in 2005, while templates C and D in the northern and southern part of the field, respectively, will be installed at a later date. Templates A and B will be used for the eight predrilled wells, four wells on each template. These first eight wells will be drilled with 9 5/8” tubing. The remaining 16 wells in phase two will be completed with 7” or 9 5/8” tubing. Due to the high flow rates of 10 MSm^3/day for the 9 5/8” wells and 5 MSm^3/day for the 7” wells, open hole gravel packs are used. The well inclinations are increased following a planned “deviation learning” process. The first wells will have a maximum step-out of 1500 metres while the later wells will have a maximum step-out of 2500 metres. The basis for the completion is nearly intervention free wells, only limited by the necessary reservoir management requirements.

The highly prolific reservoir capacity of the Ormen Lange reservoir, in terms of *permeability, size and pressure* present the opportunity to consider *big-bore, high flow rate wells* during the initial design. The chosen design concept for the 9 5/8” wells is based upon the big-bore well design of Woodside Energy Ltd. used in Australia at the Goodwyn and Rankin gas fields [25]. The basic well concept was chosen based on the following:

- The design fits the FRs as stated for the wells.

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[8] Notes from the “Ormen Lange well engineering design basis”

[9] Notes from the “Ormen Lange design premises”

- By applying a 7” well design, instead of 9 5/8”, would mean 15 more wells to be drilled to satisfy 30 MSm^3/day requirements for October 2007 and the 50 MSm^3/day for October 2008.
- As the approximately 240 MNOK cost per well is similar for 7” or 9 5/8” wells, the CAPEX savings possible with the big-bore concept are huge as fewer wells are needed.
- The concept is expected to be robust over the whole lifetime of the wells at the planned production rates. The wells are intended to have minimal intervention requirements, apart from straightforward wireline activities such as locked open failed subsurface safety valves, etc.

The formation between the seabed and the planned surface casing setting depth comprises medium soft clay with possible boulders, at approximately 1600 metres true vertical depth (TVD). Due to the anticipated boulders it is decided to drill the surface hole rather than jetting. No well bore stability problems are, however, expected when drilling this section. Below the surface casing setting depth, the Hordaland formation is described by ooze, which may lead to severe losses if too high mud weights are used. This ooze extends to approximately 2100 metres TVD. It will therefore be required to set an intermediate casing before drilling into the next formation, which is the Rogaland formation. The Rogaland formation comprises mechanically weak shale. It is important here to have a high enough mud weight to support the formation. If severe losses or drilling related problems arise in the intermediate hole below the surface casing, then a drilling liner may be considered as contingency. An expandable casing liner may also be used to not sacrifice tubing size.

To summarise, the most relevant design topics to reflect upon when conducting well design for the Ormen Lange wells are the following:

1. Risk and opportunity register
2. Well trajectory
3. Bottom hole assembly design (BHA)
4. Conductor and casing

5. Drilling fluids
6. Cementing and zone isolation
7. Formation evaluation
8. Well suspension
9. Well intervention technique
10. Lower completion
11. Upper completion
12. Well control and blowout contingency
13. Extended out-step aspiration “plug-in”
14. System integration

Reservoir properties

The basic reservoir properties of Ormen Lange are described in the following [4]. The main production field is at a water depth of 850 metres, and encompass a single reservoir at 2705 metres TVD. The reservoir pressure is 289 bar while the reservoir temperature is 96 degrees C. The depth reference to initial reservoir condition is 2913 metres TVD. The temperature at the seabed is -2 degree C. The net reservoir height is 37.5 metres with around 500 mDarcy permeability and 27% porosity. The gas condensate ratio is 10 600 Sm^3/Sm^3 while the water gas ratio is 2.89 10^{-6}. The net gross ration is found to be 0.92.

Completion design basis

The overall objective of the completion design, including sand control, is to maximize production, utilising a robust completion solution that will be able to withstand high gas production rates, 10 MSm^3/day for a design life of more than 30 years.

The completion installation is planned by using a subsea test tree (SSTT). In case a well intervention is emerged, a BOP will be needed in combination with the SSTT. The completion design consists of:

- Lower completion with sand screens and fluid loss control device suspended from a 9 5/8” gravel packer

- Upper completion with production packer, down-hole gauge carriers, dual TRSSSVs, tubing and tubing hanger

The window between the lower and upper completion is not entirely closed. The packer tailpipe consists of a mule-shoe guide that will ease entry into the 9 5/8”x13 5/8” liner hanger without rotating the string. This should allow a wireline tool-string to be guided back into the upper completion. There will not be a closed annular volume between the upper and lower completion.

Due to the low well bore temperature there is risk of hydrates forming. The TRSSSVs is set at about 750 metres below the seabed for that reason. This setting depth is assumed being below the hydrate forming temperature. In case of closing the TRSSSV, MEG will be pumped on the valves to prevent hydrates forming.

“Bull heading” of gas into formation is the method planned for in case well killing is required. “Bull heading” means to kill a well in one single mud displacement operation. A pump output of 25 bpm will be required for these big-bore wells. Following a well kill, the full bore isolation valve is closed, or a 7” bridge plug is set on top of the lower completion in case of a workover.

Well intervention strategy

The Ormen Lange wells are based on high quality design, with minimum intervention requirements[10]. It is anticipated that a major workover, requiring tubular replacement, will be infrequent with a MTTF of 20 years per completion[11]. However, future interventions cannot be completely ruled out. Shell Technology Norway is therefore involved in a project where the objective is maturation of light well intervention (LWI) equipment for particularly deep-water applications, and with a global use perspective in mind. The system that is closest to the Ormen Lange requirements is the FMC Technology’s riserless light well intervention system (RWLI). This system currently satisfies the big-bore requirement for Ormen Lange,

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[10] Notes based on “Ormen Lange – well intervention strategy”

[11] Notes based on the “Well intervention-HXT report”

but is still not rated for the actual water depth. Therefore, FMC is conducting a study into development of their RLWI system, to meet the 1100 metres water depth requirement for Ormen Lange. Deliverables from this study will describe the cost, schedule, HSE, risk impact of modifying the system, including proposals for interfacing with a range of vessels, and finally the possible commercial proposals.

3.5.3 Process based decision-making

Process thinking in development projects is mandatory in Shell E&P, and provides an alternative strategy to the more comprehensive and restrictive procedures approach [29]. Being process oriented, this requires a continuous high focus and involvement from project members and connected experts during the project period. One needs to define what to do, and how to do it all through, compared to the situation of having detailed procedures and guidelines. The processes must be prepared and suit every single project. Compared to a procedure regime the process-way of thinking provides less documentation at the managerial level. However, when it comes to the detailed plans and work instructions offshore the situation is the opposite. The amount of such documentation may become huge.

From the author's point of view, the biggest advantage of a process orientated approach is the opportunity of self verification of activities as they pursuit. Through a multidisciplinary involvement the focus is continuously on the problem, both during the planning and execution phase of tasks. However, a major drawback may be time consumption and the need for qualified evaluations and decisions all the time during the project execution, compared to the more lined-up approach of procedures. The necessary skills and qualification of personnel may here be a critical resource.

Activities described in clear procedures may be easier and quicker to deal with, both through their special preference, but also in the way they are documented. However, an unfavourable effect is the tendency of a copy/paste practice from earlier projects. This is an easy approach to exchange experience from one finalized project to the next. Anyway, one needs to evaluate all relevant aspects of the new project with respect to differences from previous comparable projects.

It was an expressed feeling that links between the planning process and Shell's management system sometimes were lacking. This might introduce uncertainty among the actors involved. However, the positive elements in both Shell's and Norsk Hydro's management systems provide a good basis for improvements to the management system. A revised system was expected to be better than each of the individual systems, both in quality and effectiveness.

The different type of management system structure is not critical for the ability of the authorities to carry out inspections and audits. The main challenge is however to handle the different types of management systems simultaneously for the same project[12]. This is highly relevant for Ormen Lange since both companies must undertake work simultaneously, in accordance with their respective management systems. In order to maintain its responsibility as operator, Norsk Hydro therefore needs to undertake reviews and system audits related to the work undertaken by Shell.

3.5.4 Ormen Lange well delivery process (WDP)

The Ormen Lange wells are prepared by applying Shell E&P's framework called the well delivery process (WDP). An illustration of this framework is given in Figure 19 [3]. The main intention of the WDP is to improve wells and the business performance. This framework guides in selecting, planning and execution of wells and well services projects. The WDP framework has been constructed from proven, successful practices drawn from the Shell regions and the industry as a whole. When the WDP is applied it serves to:

- Create leadership accountability through decision gates at key milestones when decision makers must accept or reject the value and risk balance proposed by the project team
- Promote effective multidisciplinary teamwork through the intent and design of the process activities, and through effective integration with the opportunity realization process

[12] Notes based on the "AS Norske Shell/Norsk Hydro production agreement"

- Reduce the occurrence of HSE incidents by implementing risk management throughout and specifying quality assurance through formal review activities
- Create value using the technical limit (TL) approach that emphasises the pursuit of perfect execution, and other similar techniques that facilitate divergent creative thinking in the early planning stages

A key aspect of the WDP is that it must be scaled or tailored to address both the requirements of each project and the governance framework of the region in which it is applied. The WDP map of Figure 19 shows the activities as a sequence of discrete steps.

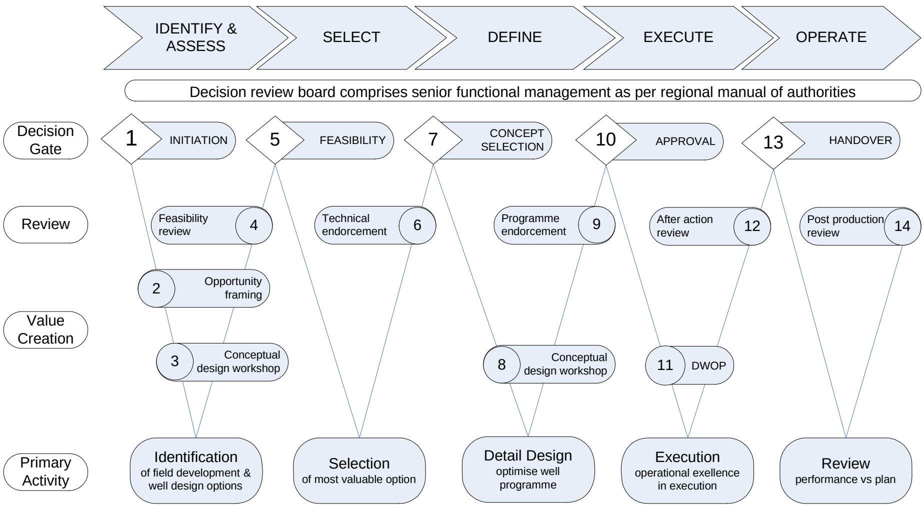


Figure 19 Shell's WDP (adapted from [3])

The WDP has five phases, listed in order: identify and assess, select, define, execute and, operate. Within each of the five phases of the WDP, four generic activity types are employed as building blocks. These are indicated in Figure 20. The focus and structure of each building block varies from phase to phase as the project matures. However, the basic structure remains the same throughout.

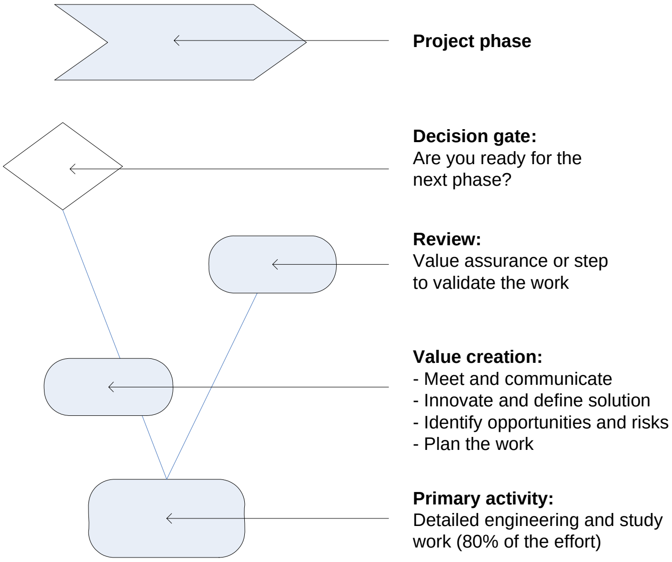


Figure 20 The main building blocks of the WDP (adapted from [3])

A value creation activity is scheduled at the beginning of a phase to create a work plan and performance goals for the primary activity. The review takes place at the end of the phase, to assure the work, before the decision to go forward to the next phase. The value creation activities are normally structured to engage multidisciplinary teams working in a cooperative, creative and challenging spirit. The main intention is to set high performance goals against shared objectives for the project. The value creation activities prior to execution are defined as opportunity framing, concept design, value challenge and drill the well on paper (DWOP). They vary in focus with increasing attention to detail as the project matures. The generic goals are, however, the same for each one, namely as follows:

- Invest in building the team and align it to common clear goals
- Use the diversity and experience of the team to create well-defined improvement opportunities
- Formulate the opportunities into a high performance goal and an action plan that the team owns

The technical limit goal that results from the value challenge activity describes how all of the feasible technical and operational opportunities would ideally be combined to create the optimum aspired well design for the project.

The intention of reviews is to ensure that the work done throughout the project phases is sound. Depending on the project, some elements of the work may be reviewed by the project team, others might need contractor input or require external assistance.

Implementation of the WDP may differ in two important ways from the above idealised schematic. Firstly, it may be necessary to repeat or iterate certain activities. Secondly, work for the value creation and review activities may be integrated into the primary activity for that phase.

Although the structuralised approach of WDP, the project involves dynamic decision processes especially when it comes to the detailed design activities. (See Section 3.4.2 for the meaning of dynamic decision processes). Uncertainties connected to decisions are, and will be present in almost all the life phases of the wells (engineering/design, construction, operation, maintenance, modification, and abandonment). The perspective of a phase model, as indicated at the top of Figure 19, is then to work from an abstract problem formulation to more concrete solutions and splitting problems into sub-problems [5]. Iterations here take place. In connection with the WDP framework, decision quality may be described as the results of providing information on the following six key attributes [3]:

1. Appropriate frame (objectives and scope)
2. Meaningful information (right information, reflect uncertainties)
3. Alternatives (creative, do-able, comprehensive, compelling)
4. Values and trade-offs (values of alternatives, risks, constraints)
5. Logical reasoning (analysis oriented, understanding of outcomes)
6. Commitment to action (motivation, commitment from individuals)

The well delivery team of Ormen Lange was aware of the uncertainties connected to the selected well design from the early project start-up on, throughout the project. Therefore, the team worked continuously at revealing, or obtaining control over the uncertainty as long as it influenced on the decisions. Much of the uncertainties were revealed during the engineering phase as more information was confronted and processed. Such information was related to both, the reservoir and geological phenomena as well as technological aspects of the development. Information was provided by real-time production simulations, equipment testing or verification studies.

The WDP is the basis for all activities taking place through the preparation of, implementation and execution of the chosen well concept. Experience from Shell also tells that an engagement of a wider group of stakeholders delivers great value to the process.

A DWOP involves a structured review of the “hole section guidelines”, generating opportunities and risks. Optimization and risk mitigation are key themes, together with target setting. Each event uses well delivery value drivers in the ranking and assessment of actions. A similar approach and terminology are applied to the completion and testing preparation sessions. These are titled: “completion the well on paper” and “testing the well on paper” (CWOP, and TWOP). The main roles of the technical limit sessions are to:

- Provide multidiscipline input to the detailed drilling guidelines
- Identify risks as input to the operational risk register
- Identify opportunities for improvements in HSE, quality, schedule (performance), and cost including target setting.
- Generate other meaningful actions that may deliver value from risks and opportunities.

The workshops facilitate an environment where the vendors and project team members combine and coordinate skills and experience to deliver opportunities and detail input. The shared ownership of actions, risks and opportunities is obtained within the frame of the project value drivers, objectives and key performance indicators. The DWOP events build upon the technical limit objectives but fall closer to execution in time. The DWOP’s involve the operational rig personnel who will carry out the work. As the technical limit sessions feed input to the drilling programme documentation, the additional role for the DWOP is to:

- Deliver any certain actions and issues that are managed before execution
- Identify risks and opportunities, with a more operational impact or relevance
- Deliver detailed performance targets. These targets should be more realistic that decided in previous technical limit sessions, and are performance targets shared by both the crew's supervisors and the Well Project Management.

The detailed drilling guidelines, which have been through a DWOP with updated actions, will form input to the generation of detailed work instructions offshore. Technical limit sessions are being conducted in an integrated manner, combined with the DWOP programme. Within the WDP the DWOPs are held after the Decision gate "Approval", and typical focus is on the well-matured drilling programme and its guidelines.

A successful DWOP is only achieved with the right people present. It has been recognised some deviated group compositions and that different stakeholders are invited to the different Ormen Lange sessions. However, the overall strategy for the review and feedback activities is shown in Figure 21.

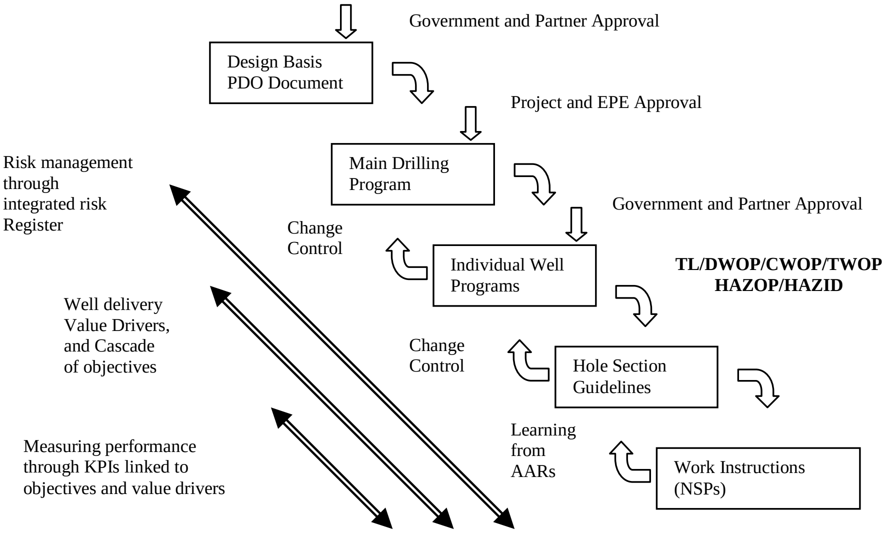


Figure 21 Document cascade, role of the DWOP's (adapted from [29])

The technical limit, DWOP, CWOP and TWOP sessions all together play important roles in providing a check out of the detailed drilling guide lines. Combined with coordinated the after action reviews (AAR) the feedback loops are actively used to enhance performance. Pivotal in this approach is an effective knowledge management philosophy.

The management system for the WDP is of course within the framework of Shell's management system. The interface between the Ormen Lange project's management system and the Shell's management system has therefore been defined in detail. All the project requirements, as specified in the Ormen Lange project manual, are reviewed in that respect.

3.5.5 Qualification of technology

The qualification of technology is supposed to be included as part of the main work process: "Execution". The Ormen Lange project needs to demonstrate: "Why do we need to qualify equipment" and next "How to actually carry out such qualification". The basis for the qualification is the defined capability of equipment and the actual loads it will be exposed to at the field. Two internal Shell qualification processes are mentioned. These are the "completion equipment review team" (CERT) and the "intervention equipment review team" (IERT). A common interpretation is that a well system, or elements of the system, will require qualification if it cannot be shown that it has earlier functioned satisfactorily in similar well operating conditions as Shell defines at Ormen Lange. Most of these procedures are again based on the recommended practice procedure, notified as DNV-RP-A203 [55].

DNV's recommended practice

DNV-RP-A203 outlines the work processes needed to ensure that new technology is qualified in a systematic and well documented way. Focus is on technologies related to the exploitation and exploration of hydrocarbons where the reliability of the new technology is crucial in order to sustain economically valid field development. The procedure proposes to use 1) documented margins to failure, and 2) reliability proven by tests/analysis as the neutral benchmarking between technologies.

BP Reliability strategy

As another reference, BP has made a reliability strategy with basis in good practice from industries where high reliability is already taken for granted. The method has been adapted in conjunction with the Cranfield University to suit the petroleum industry using feedback from benchmarking projects in the North Sea and Gulf of Mexico [56].

Implementation of the BP reliability improvement strategy in BP projects means introducing reliability into subsea system requirements. Through this procedure BP demands greater assurance from suppliers that a known level of reliability is managed during design and manufacture in the subsea industry. It will influence the way systems are selected with increased emphasis placed on the supplier’s reliability management capability.

The reliability strategy targets three groups of processes that are being essential elements to a well defined reliability engineering and risk management capability. In all, these three groups of processes account for thirteen key processes.

1) Identify	• Definition and Reliability Requirements • Risk and Reliability Analysis in Design • Reliability Assurance
2) Implement	• Reliability Verification, Validation and Benchmarking • Project Risk Management • Reliability and Qualification Testing • Performance Tracking and Analysis • Supply Chain Management • Management of Change • Reliability Improvements and Risk Reduction
3) Invest	• Organisational Learning and Knowledge Management • Education and Training in reliability • Reliability Research and Development

Figure 22 Key reliability processes (adapted from [56])

The first group of processes is used to develop a project specific strategy. System reliability requirements are defined here. Specific reliability tasks and activities are identified to meet these requirements and form part of an overall reliability plan to deliver against strategy expectations.

The project specific reliability plan is executed in the second group of processes. These processes specifically relate to the management of risks during the project lifecycle and assurance that these risks are being either eliminated or reduced.

The third and final group of processes is used to continually improve the success of the reliability strategy on current and future projects. It is worth mentioning that BP has made a long-term commitment to support reliability research and development at Cranfield University's Centre for Risk and Reliability Engineering.

A similar approach has been prepared by FMC technology [57].

3.5.6 Risk-based selection of concept

A risk-based methodology has been adapted by Shell to support the concept selection process for the Ormen Lange wells [4]. The main purpose of using such an approach is to select the most optimal technology among available solutions in well engineering, given a set of specified field data.

Methodology description

A need for more effective decision processes in the Ormen Lange well delivery project encourages the production of a useful and easy decision tool. The adapted method has its background from earlier experience and practice in Norsk Hydro. It has proved being a successful aid into improving the discussions and the decision-making conducted in a setting looking at options to select. It forces more structure into the work sessions than earlier. The methodology has been formally used, and documented for approximately 10 cases, constituting the well design. The important evaluation criteria in use were based on the Ormen Lange well requirements, as documented in the well engineering design basis.

Using a big-bore well concept should result in a significant well-cost reduction compared to a conventional well design due to the fact that fewer wells are needed, and that the individual well cost is minor size-dependent. The major question is what big-bore concept would be the best for the Ormen Lange development, adding most value while taking into account the associated "risk elements". The method is based on a risk and penalty matrix approach with some clearly defined probability and consequence classes (see the example in Figure 23. The risk matrix approach has been widely used by the petroleum industry to rank criticality in early project phases, especially in connection with Preliminary Hazard Analysis (PHA) [1].

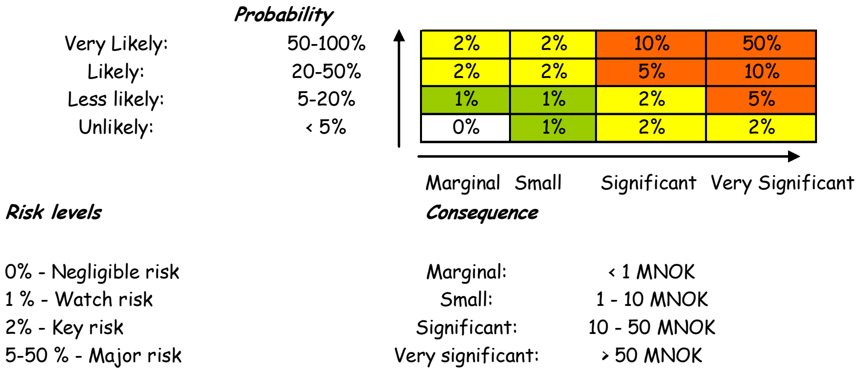


Figure 23 Risk and penalty matrix (adapted from [4])

By adopting a risk and penalty matrix like in Figure 23, the selection of an optimum concept is derived by carrying out the following steps: One needs to

1. Identify the relevant concept
2. Identify and agree on the main *functional requirements* (FR). Rank them by use of the maximum obtainable score.
3. Define the risk and penalty matrix to be used for the review. A penalty system as indicated in Figure 23 is used to help in quantifying risk value. A higher risk gives a higher penalty. The matrix is not seen as acceptance or non-acceptance of an option. The project risk acceptance criteria are then to be used.
4. Identify *risk elements* associated with the main differences. Risk areas are *HSE, technology, execution, operation, and authority.*

5. Review each risk element against the main FR as defined in point 2. The probability and consequences for not fulfilling the FR are identified by use of the risk and penalty matrix. The risk is defined as the perceived risk as of today, i.e. the current knowledge of plans and manageability of actions is taken into considerations only (static analysis).
6. The risk value is defined and any comments are added to it in the comment column.
7. For each concept, the penalty is summarized for each FR and weighted against the importance (scoring).
8. Each concept ends up with a score, drawing conclusions and making recommendations. Risk items with high penalty will be highlighted together with a statement on HSE.

The FRs of importance for the casing design of the big-bore, pre-drilled Ormen Lange wells in order of priority are:

1. Capable of producing 10 MSm^3/day – *max score 10*
2. Well deviation, allowing horizontal step-outs of min. 1.5 km, preferable 2.5 km – *max score 8*
3. Use of monitoring (pressure and temperature) device – *max score 6*
4. Use of standard and qualified well equipment – *max score 4*.

Thus, a well that meets all FRs fully scores 10+8+6+4=28. Examples of risk elements are casing wear, kick tolerance and blowout contingency.

By the use of the risk elements, the risk and penalty matrix and links to the FRs, the penalty of each concept is derived by assessing the severity of the risk elements to each concept. For each concept the total penalty connected to the FRs is obtained by multiplying the number of risk elements falling into each penalty class with its related penalty percentage and then summing all the penalties. The resulting score for each FR is obtained by reducing the maximum score of the FR with this sum penalty percentage. Finally, a total score for the competing alternative is derived by summing all the resulting FR scores.

The probability and consequence figures are derived from separate studies, available information/databases, or from common understanding and knowledge in a group of experts. However, the method may be used to perform sensitivity analysis of certain risk elements. It allows seeing whether the overall score or order will change by changing elements that affect the probability and/or consequence estimates.

Follow-up risk assessments

The selected well concept is subject to more detailed risk assessments and studies. The following detail studies, among others, are initiated for the selected well concept:

1. Blow-out contingency planning and risk assessment for the drilling, production, and work-over situations
2. Hole size contingencies studies
3. Study of barriers and possible leak paths to surface
4. Well bore stability and well deviation design evaluations
5. Decide upon sand control and cementing
6. Decide upon drilling fluid and cementing
7. Completion design and qualification testing

The risk-based decisions supplied with these additional studies should lead to the final Ormen Lange big-bore, high flow-rate, and deep-water well design.

As mentioned above, the risk-based comparison analysis is an important starting point for the detailed risk review of the chosen option. Several assumptions are made as the basis for determining the risk value i.e. like high quality deliverables from contractors, knowledge about equipment, and so on. A detailed review of these assumptions is necessary to ensure that they still are valid, and that the assessment is carried out efficiently and with sufficient quality. In addition, the risk value will indicate where further focus is needed to reduce the risk. Actions are then defined in order to follow-up such important issues.

The Ormen Lange risk acceptance criteria are used to ensure that all risks are acceptable according to the ALARP principle.

Experience from use

Shell's experience from conducting detailed well design at Ormen Lange (Phase 4) indicates that technical meetings had a tendency to end up in discussions with too broad a scope. Then it was unable to conclude upon a decision due to the lack of focus. To manage complex and sometimes distracting discussions between team members is certainly a challenging task in such settings. It is not, however, always wanted or even natural to constrain discussions prior to meeting start-up. Hence, one often learns to live with discussions tending to drift-off in topics. Problems may then end up being too complex at the actual stage in the process. Some technical sessions at Ormen Lange were terminated, and further discussions were held in wait for more detailed information to be collected. Usually, that meant further study to be carried out by the disciplines, and/or more accurate information to be collected prior to the scheduling of next meeting.

Individual aspects of the group members as deviated competence/experience may have introduced additional problems. In a "group decision setting" a single member or several members of the group might try to front their own personal opinions as precedence for reaching consensus. Such behaviour may distract the discussions within the group. However, the other extreme variant seems no better. If decision makers are reluctant to reveal their true opinions they may actively distort their own statements in order to enhance a preferred outcome of a discussion [50]. Some suggestions to solve the above problems are to:

- Provide accurate problem definitions prior to session start-up, both to narrow scope, and to lead discussions in the direction of the main topics of interest.
- Improve the ability to translate knowledge, personal experience and project experience of the group in decision-making by use of relevant tools and methods.

Discussion

A risk-based decision method as described above provides a transparent approach that enables the linking of important *FRs* in the field development, as they are defined in the design basis, to significant *risk elements*. It allows prioritising the FRs by assigning a score to each of them. Next, the method is open to sensitivity analysis through manipulation of the input data. The method is easy facilitated in an Excel spreadsheet, and is easy to use and follow up. However, the given results are not meant to, and should not be seen as a full risk assessment of the selected concept, but rather a starting point for more in-depth risk assessment after the selection is made. Assumptions are made prior to estimation of the probability and consequence scores. The prioritising of FRs, however, is seen more as a direct consequence of the importance of certain properties as they are presented in the design basis or the design premises.

The FRs are essential as the basis for giving (risk) score to the competing concepts. Both geological and operational aspects of the reservoir provide information of importance for the preparation of FRs to the wells. These requirements, as far as can be seen, focus mainly on aspects and parameters that contribute to fulfilment of a cost-effective development (completion). Challenging aspects to the production phase of the wells, affecting on dependability, operational cost and occupational risk are only minor focused in the design basis. Thus, these aspects are not treated explicitly by the FRs. Neither, are the differences related to the major cost elements of drilling and completion included in the decision basis. If there are elements that influence the availability and safety of the well in a longer term these elements should be part of the decision basis as well. It is of major importance in the early project phases to catch these elements if they have the potential to interrupt the expected outcome from a planned field investment.

In that respect, it is recommended to extend the decision basis of basic well configuration to include FRs describing cost elements and safety aspects of relevance for the future production phase of the wells.

Revealing such information might be a demanding task that increases the work load of the project team above accepted limits (cost/benefit). Thus, one needs to balance the work of bringing forward such information against the value of the expected results in terms of an improved decision basis. One should be aware of the uncertainties connected to the estimates carried out in early project phases. Such uncertainties are connected to the expected operational cost, the amount of interventions, maintenance or unexpected events, operational obstacles, etc. Here, the experience and the existence of historical failure and maintenance data, collected in different databases such as "OREDA Subsea" and the "WellMaster" should provide an important decision basis. Failure and maintenance data (from interventions) on similar equipment may be reviewed to select between certain concepts. Interesting historical data is subsequent operational expenditures of the installed equipment. In this context the OREDA Subsea database covers equipment located above the wellhead and up to the sea level, whereas the Wellmaster database covers the equipment attached to the well downhole.

In the way the existing method is presented for the Ormen Lange case one needs to identify and agree upon FRs prior to each new analysis. An improvement may be to define a set of "generic" requirements, e.g. as part of a guideline, to accomplish this part. Such a list may be described for the different subsets of completion equipment or systems (concepts). Effective decision support may be provided by applying such a guideline. In that case the decision group may focus more of their time on the evaluation part, i.e. reflecting on the influence of different risk elements on the FRs.

An important part in this discussion is the amount of risk elements needed to be part of the evaluation. Those identified for the casing design, or the well concept decision, look mainly like operational and technical constraints. They also seem closely connected to the chosen FRs. It is observed that the same combination of risk elements and FR are relevant for all the alternatives under consideration. This might not be the case if the FRs are extended to include operational and safety aspects in addition. Then it may be necessary to develop individual combinations of "Risk element - FR" to fit each alternative as a means to intercept operational aspects into the final score. The risk elements are regarded as a list of characteristics that are both based on the exploration data from the current field, but also based on information from earlier risk assessments and experience from applications of similar technologies or solutions at other fields. However, it should only be needed to identify them once for each project, and then be used throughout the study.

In addition to fulfilling the requirements of wells being capable of producing the expected volume, one is also interested in identifying expected acquisition and ownership costs (CAPEX/OPEX) of a solution. This should provide the decision makers with an opportunity of balancing performance, reliability, maintenance support and other goals against *lifecycle costs* (LCC). A sort of economic analysis applied for evaluation and comparison of alternatives is therefore recommended (see Section 3.3.4 for a description of the LCC method). It may be a full LCC analysis, but it is assumed that only a few cost elements contribute significantly to the total cost.

In drilling and completion of deep-water subsea wells the major cost elements are connected to casing and drilling time related costs. The time related cost elements are for the most manifested in rig rate costs, and focus will be to reduce rig time as far as possible by applying effective operations. Casing acquisition and drilling/completion time related costs accumulate during the development phase of the wells only. The relative short time it takes compared to the total life time of the operational phase of the field indicates that a net present value (NPV) approach is not so relevant for the comparison of these major cost elements. It may be sufficient to compare the cost elements directly (present cost) for the different alternatives. When it comes to the operational expediencies and costs related to availability and safety loss the situation is different. Unwanted events and obstacles may occur during the whole life time of the field. For such cost elements, a NPV approach is recommendable. Of challenging topics, however, are the uncertainties connected to these evaluations, mainly related to estimating the frequency of events.

4 Decision Methodology

This chapter presents a new decision methodology accommodating the framework. It is adapted to the generic well delivery process that supports the most common decision processes of well engineering.

4.1 Introduction

Structured and qualified decision processes are important throughout a well engineering project. Effective planning and execution of these work processes require well-qualified and traceable decision processes. The original Shell E&P framework, called the well delivery process (WDP), guides in selecting, planning and executing wells, and in carrying out later well service projects. In short, the WDP supports the main well engineering project phases and activities. A brief introduction to the WDP is given in Section 3.5.4. However, the WDP, like any other similar approaches suffers from ineffective decision processes. Improved decision-making in the WDP is expected by using risk and uncertainty assessments in connection with the WDP evaluations.

The new decision methodology presented in this chapter builds on the ideas of Shell's WDP framework and may be seen as a reinforcement of it. The main intention is to support the well planning activities and related decision processes by use of alternative methods and tools. The methodology has been developed as a sequential process following the decision activities in a typical well engineering project. A conceptual model of the methodology is shown in Figure 25.

The methodology comes into use when entering the identification phase of the major project plan (see Figure 24), i.e., the identification of alternative well concepts for a desired field development. It facilitates decision-making through its procedures, mainly when comparing and evaluating options. The following main activities in a typical WDP are of relevance:

1. Identifying and assessing alternative well concepts
2. Selecting the most valuable option among the alternatives
3. Carrying out "detailed design" in order to optimise the selected basic well concept as endorsement to a final well programme

It is assumed that exploration drilling is completed, and the owners, including the relevant stakeholders, have decided to develop the field for production. Geological characteristics and operational aspects have been extracted from the exploration drilling review. This is important information for the assessments taking place of technical and operational character concerning the basic well concept. The feasibility study provides the basis for detailed time and cost evaluations when comparing the alternative well concepts.

The second main activity above is selecting among alternative well concepts. This is characterised as a "static" decision. The decision is typically based on the scarce information available in this phase, at the time the decision needs to be taken. Basically, the information appears from the exploration review and the feasibility studies, as subsequently documented in the well engineering design basis. At the other end, the decision progress is influenced by demands from the stakeholders (operator, society, market, and customers) who might stress the progress of the field development. It is always important from a business point of view to put the field into production according to the planned schedule. Hence, any postponing of the concept selection might seriously slow down the project with a delayed start-up of the detailed design phase.

The detailed design phase is more dynamic with regards to decision-making. Not all the necessary information is available at the time decisions need to be taken. Instead it may be generated during the period of the detailed design phase. Many of the subsequent decisions also depend on previous decisions. Uncertainties are connected to many of the options and should be treated carefully. Qualification studies, as according to [55], may be initiated if there is a lack of information or experience with the current technology. This may be necessary to confirm that the suggested technology meets the requirements for the intended use.

Most of the value generation in well engineering is made during the detailed design phase. For that reason, the current methodology focuses on qualified work processes, including the decision-making procedures.

4.2 Problem structuring

Problem structuring is important in order to assess a decision problem. A general definition of a problem may be stated in terms of the current situation, the desired situation, and an objective [2]. This definition fits well with the current methodology. A path towards the best solution is discovered by an accurate definition of the decision problem. The current state is identified and described together with the desired state, towards a fully formed problem statement. The problem definition is then completed by stating the central objectives that distinguish the current situation from the desired situation.

A “problem”, like any other structural entity, should be structured in a way that makes a simultaneous analysis of the “problem” possible with regard to 1) final appearance, 2) elemental details, and 3) the relationship between these elements. As suggested by (Marakas) [2] a problem structure is described in terms of the following three basic components, regardless of the decision context:

1. Choices
2. Uncertainties
3. Objectives

A similar notation of (Narayanan) [31] defines a “decision view” with the following components: 1) Objective, 2) State parameters, 3) Decision variables, and 4) Constraints. Compared to (Marakas) [2], the state parameters are defined as variables that cannot be controlled and are subject to uncertainty. Constraints are boundary conditions that restrict the values available for the decision variables. A practical example is the maximum number of wells that it is possible to drill, which may be constrained by the number of slots available on the template.

One of the most common methods to model a problem structure is the influence diagram. By this method, the three components of a problem structure (not constraints) are represented by specific shapes that are combined and connected to represent the problem structure. Another common method is the decision tree method which focuses on a limited set of choices and expected outcomes. These two modelling approaches are further described in Section 4.5 and are used to model different aspects of the current problem. The three basic components of a problem structure are described in the following sections.

4.2.1 Choices

Implicit in the concept of choice is the existence of a set of alternatives. In case there is only one alternative, the concept of choice is not relevant and thus no such decision is actually required.

4.2.2 Uncertainties

Uncertainty is similar to uncontrollable events in a decision context. If all the events in a problem context are determined with absolute certainty, then “complex” decisions would have been simple. The process of decision-making would not need to be focused. This is seldom the case because nearby all problem structures contain uncertainties that must be accounted for by the decision maker. The primary difference between choices and uncertainties is the probability of the occurrence of events and decision outcomes. With a choice the specific outcomes of all the decision alternatives are known. The optimal alternative may then be based on a deterministic approach[13]. In a “decision context” the probability of selecting one specific alternative is regarded as equal to any of the other alternatives (i.e., no uncertainty connected to the alternatives). It is only the known specific outcomes of

[13] Here, the possibility of selecting none of the options is disregarded

the alternatives that matter. This supposition is also true if the viable alternatives have been identified after being accounted for in their project uncertainties (e.g., through testing and pre-qualification of the equipment). Thus, by making a choice the selection of one alternative is under the complete control of the decision maker, and uncertainty plays no role at the point in time when the decision is made. With uncertainties involved in one, or more of the alternatives this is no longer the situation.

In addition, any outcomes that are subject to uncertainty may require a complete restructuring of future activities that makes the problem even more complex. Here, the real value of problem structuring is seen. By mapping the uncertainties and their probabilities of occurrence, the decision maker cab visualise the various scenarios of future decisions and events. Then it is possible to compare one possible scenario with another. This approach may also prepare a basis for complex computer-based simulation models.

4.2.3 Decision objectives

Within a decision problem context the objectives describe the desired situation after the decision is made. The objectives also provide the means of establishing criteria at lower levels that may be used to measure the value, or desirability of a particular outcome. Examples of objectives are specific increases in revenue, or specific reductions in the cost of a well development. An objective should allow for quantitative comparisons. Decision makers might have multiple objectives to evaluate the decision outcomes. To model a decision problem appropriately, at least one measurable objective must be relevant.

4.3 Decision scope in well engineering

The main focus in well engineering is on solutions that contribute to the final revenue of an investment. One decision criterion is then the accumulated cost of the development project. Through an LCC analysis, both the capital expenditure (CAPEX) and the operational expenditure (OPEX) contributors may be estimated and compared according to a net present value. It is, however, not possible to express all factors in cost element debits. Typical examples are criteria such as occupational safety and risk to the environment, e.g., emissions to sea.

When a decision problem has been clearly formed and stated, one needs to examine the scope of the problem. The whole decision problem faced in well engineering might instantly become a complex task that is beyond the capacity of available resources, cognitive abilities, or the time constraints of the decision maker. Therefore, the scope needs to be structured and divided into reasonable parts. This should again allow for an instant and successful deployment of the available resources toward a given solution set. Thus, the scope must, somehow, be determined according to the project opportunities and structured in a way that enable the relevant decision maker to make the right priorities in time. Thus, the current decision methodology relates to a phase model of the value chain [58]. A phase model like in Figure 24 is typical for any documented "well engineering project plan". Similar models are found in [5, 56].

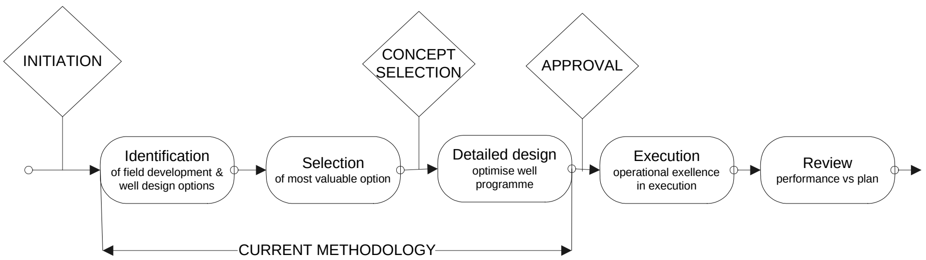


Figure 24 Decisions related to phases in a well engineering project

4.4 Methodology development

The development of the current decision methodology has been a sequential process. It may be looked at as a description of how the elements of decision-making are handled in a WDP.

4.4.1 Assumptions and limitations

The new methodology covers comprehensive and complex technical decisions in well engineering. Complex decision-making has a tradition within the oil industry to rely on experts with detailed insight into specific problems. Thus, it requires simultaneous effort from key personnel or groups of experts. This is nearly the case, both in the planning and execution of activities constituting phases of the WDP. Therefore, it is required that decision points are thoroughly mapped and described prior to project start-up. If not, one might run into unexpected problems that are too complex and difficult to handle in a way that satisfies all the quality demands. The risk of losing valuable project time and/or sacrificing decision quality is also of vital concern. This could happen if complex decision-making is carried out on an individual basis, or by a temporary group of experts found to have the relevant competence. Thus, it is important to be ahead of the problem, by acting proactively and with sufficient planning. If problems pop-up unexpectedly and need immediate intervention, it may be too late to handle them, or to reach any of the planned objectives.

An examination of the WDP is necessary to identify important milestones, uncertainties and decision points throughout the project. Thus, for the current methodology it is assumed that an activity plan, including a decision map, has been prepared based on such a review. Additionally, decision-making in a project organization may be divided into three levels:

1. Strategic
2. Tactical
3. Operational

As described in Section 3.2.2 all decisions made in an organization are positioned within one of these three levels. In Table 10 the major project activities and decisions connected to well engineering have been sorted according to the respective organizational decision levels.

Table 10 Organizational decision levels

Strategic decisions	**Tactical decisions**	**Operational decisions**
Feasibility approval	Identification of design options	Detailed drilling plans
Basic concept selection	Design approval	Planning for field activities
	Detailed design	Daily operations
	Selection between design	Follow up activities

Strategic decisions	Tactical decisions	Operational decisions
	options Equipment testing Assessments/simulations	

As indicated by Figure 24 the current methodology has been adapted to phases and project activities that follow the project milestone "initiation" and proceeds into the "approval" of the final well design. According to Table 10, decision-making in the project phases of "identification", "selection", and "detailed design" is defined to be within the strategic and tactical decision levels of an organization.

4.4.2 Description of the WDP

Table 11 lists project activities for a general WDP as it is interpreted in the current methodology. The different activities are linked to decision milestones of a typical well engineering project plan.

Table 11 Milestones and activities of the WDP

➢ **START:** ***Owners and stakeholders have decided to develop a field***

♦ **Identification**

- Review of reference documentation, e.g., the well engineering design basis
  - Review of technology scan, feasibility studies and exploration review
- Problem structuring related to technical decision-making:
  - Apply the influence diagram method to illustrate relationships between elements of the basic decision problem (events/chances, values/objectives and decisions) as they typically appear at initiation of the WDP
- Preliminary analysis of alternatives:
  - Clear out options (concepts) by use of results from the feasibility study, etc.
  - Carry out a coarse cost/benefit screening (LCC/NPV) [59]
  - Carry out a preliminary hazard analysis (PHA) or a hazard identification / hazard and operability analysis (HAZOP) to identify major hazards related to the planned operations

♦ **Selection of "basic well concept"**

- Select the most valuable solution based on the results of the above activities:
  - Carry out an AHP-session to merge criteria such as CAPEX, OPEX, occupational risk and risk to environment. The result is a qualified prioritising of concepts

♦ **Detailed well design**

- Define functional requirements (FRs) to the chosen basic concept
- Describe alternative casing designs that may constitute the basic concept
- Describe drilling and completion alternatives
- Define different design options within the limits of the basic concept
- Compare the different design options by invoking the following procedure:
  - Confirm the FRs and related importance of the FRs upon each decision taken in the detailed design phase
  - Define risk elements and uncertainties connected to the options
  - Define the risk and penalty matrix to be used for the review, e.g., by applying the

existing risk and penalty matrix developed by Shell [4])
- Specify alternative decision scenarios (including decision sequences and consequences of previous choices, future choices, etc.)
- Model the decision scenarios with the uncertainties involved, distributed in time, by use of the decision tree method (e.g., use the "treeplan"-software [32])
- Identify each real FR and risk element (criteria) combination out of the scenario analysis and assign the risk penalties
- Carry out comparison studies of options based on the preliminary analysis and results from the uncertainty studies by use of a "revised risk and penalty matrix" methodology
- Establish priority scores to the different options
- Select between the options to complete the final well design

- Verify the integrity of safety barriers concerning the final well design

♦ **Approval**

➢ **STOP**

Decision trees are suggested as the approach to model dynamic aspects and uncertainties. Qualitatively, they visualise the sequences of decisions, and quantitatively, they estimate the expected value of the outcome from a decision scenario. The use of qualitative models vs. quantitative models depends on the amount of data or background information that is available, and the complexity of the decision problem. As a summary, the adaptations of methods presented in Table 12 illustrate the use of qualitative vs. quantitative modelling tools.

Table 12 Employment of modelling tools

Qualitative models	Quantitative models
• Influence diagram method to structure the overall problem • PHA method to identify hazards, environmental risks and mitigating actions • AHP method to support knowledge driven decisions and to structure group decisions	• Development of Shell's current risk-based comparison methodology for selection between technology options • Cost/benefit, LCC/LCP for lifecycle cost/revenue comparisons, or a simple cost comparison of alternative basic designs • Multi-criteria decision-making (AHP) by assigning numerical priorities to alternatives by two-way comparisons of alternatives and criteria, and thereafter synthesising of priorities • Quantitative decision trees to model decisions in time and assigning uncertainties and consequences to decision scenarios. The purpose is to estimate the expected value of outcomes in detailed design.

4.5 Methodology description

This section describes the methodology in more detail through the methods and tools being applied. It outlines the sequence of decisions in the WDP and relates these activities to the suggested methodology. Methods and tools are adapted to the decision problems as they turn up in each phase of the engineering project. The models should reflect the most important characteristics of the decisions. Different models cover the whole decision context, and specific parts of it.

4.5.1 Conceptual model

A complex decision problem can be thought of as a set of sub-problems that are functionally decomposable by the decision maker. Each sub-problem is then modelled to form a representation of specific part of the problem context. Despite a variety of available decision methods and modelling techniques for different applications, an abstraction or a formal model may not always be the most appropriate one. Sometimes, one needs to simplify the structure of a model, because the problem tends to be too complex, or time-consuming and costly to model. A conceptual model is then suggested [2].

The conceptual model in Figure 25 shows an analogue to the total problem context in well engineering. Using this model, the decision makers may recall and combine a variety of past experience and contexts to create an accurate model of the decision problem. The current situation is described, and a forecast of the decision outcome with the various choices is outlined. One criticism of conceptual models is, however, that they represent subjective and individual beliefs of decision makers. In that respect it is obvious that also abstract models are affected by subjective beliefs with regard to modelling techniques. Abstract models depend on the decision maker's expertise within the chosen technique. It is, however, important for decision makers to evaluate the appropriateness of different techniques for the given problem.

Decision problems connected to well engineering are regarded as complex and time consuming. Thus, a conceptual model is found appropriate to map the decision process and to forecast the outcomes in an early project phase. Therefore, the methodology description starts with a conceptual model, followed by more specific models. According to a “generic” WDP, the conceptual model in Figure 25 visually describes the total problem by the way it structures information. The formal approaches or methods to apply are easily identified. The conceptual model is prepared on basis of the author’s experience, as gathered from the sources of information mentioned in Chapter 3.

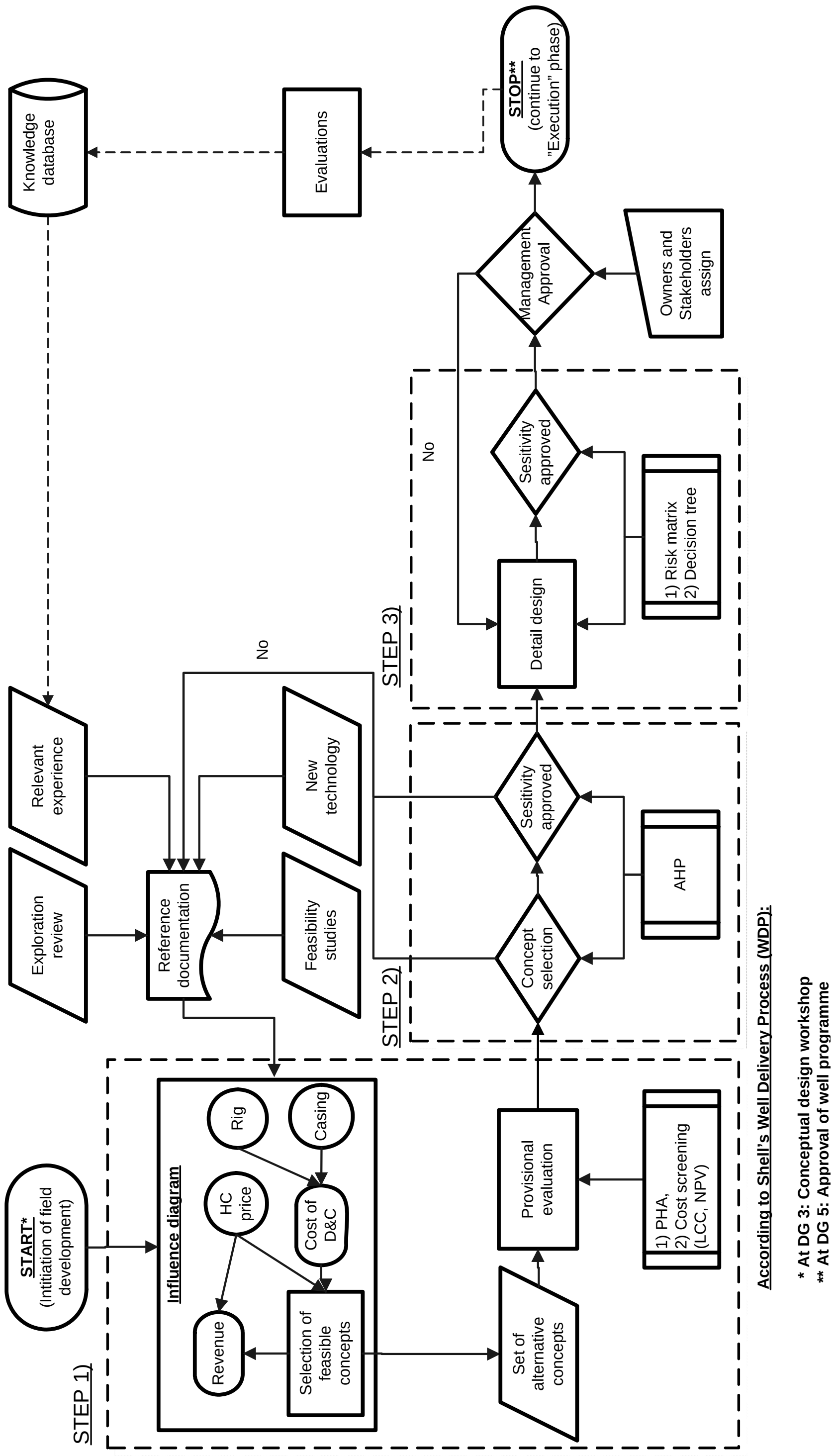
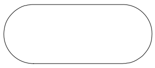
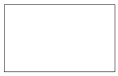
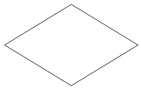
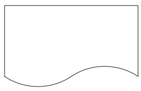
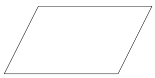
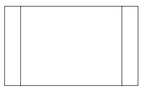
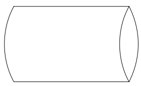
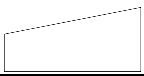


Figure 25 Conceptual model of the whole decision problem context

Table 13 describes the specific symbols applied in the model with their interpretation. These symbols are the most common ones in typical business flowcharts [60].

Table 13 Description of conceptual model symbols

Symbol name	Sign	Description
Start/termination of a process		This symbol indicates the START and STOP in the model
Process		The process symbol represents the main activity within a step of the methodology
Decision		The decision symbol represents principal selection or approvals
Document		The document symbol indicates a set of structured documentation, either utilised, or generated in the model
Data		The data symbol indicates specific type of information, either utilised, or generated in the model
Predefined process or method		The predefined process symbol represents the existing, formal methods being adapted to the methodology
Information in a database		The database symbol represents generated data, or information intended for a certain purpose
Manual input to a process		The manual input symbol represents process interaction with external stakeholders

The conceptual model in Figure 25 describes a step-by-step process. It starts by structuring the total decision problem of the WDP. A total of three modelling steps are linked together in a sequence. In addition, there is a feedback loop starting from the management approval box. This is to take care of gained project experience to benefit future projects. As seen, it will be a part of the reference documentation in future projects along with information from exploration reviews and feasibility studies of new fields and technologies.

An input and an output are connected to each step in addition to the preconditions and assumptions. The input to the subsequent step is similar to the deliverable from the former step. The following describes the three basic steps of the methodology, including their main deliverable. The enlarged boxes in Figure 26 to Figure 28 highlight the deliverable, from each step.

1. *Definition of technical decision scope and structure of the WDP*
   - Deliverable: Set of alternative concepts
2. *Selection of basic well concept*
   - Deliverable: Most promising concept
3. *Conducting detailed design and approval*
   - Deliverable: Approved final design

Definition of decision scope and structure

The objective of the first step is to define the decision scope and structure the total decision problem. Based on demands at the current time, it ends up with an identification of alternative well design options as indicated in Figure 26. These options are brought into the selection step.

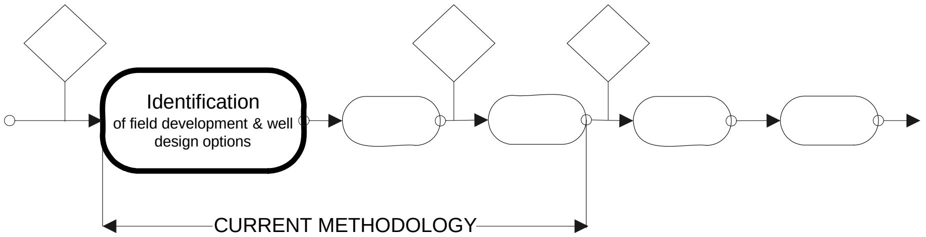


Figure 26 Identification phase of a well engineering project plan

The identified well concepts are subject to provisional[14] evaluations. The provisional evaluations are based on the reference documentation that was established for the project. Such early evaluations should consider:

- What constitutes the final result of the decision?
- What elements influence it?

[14]Coarse level, carried out there and then based on available information

- What are the relationships between these elements?

The feasibility study "normally" focuses on one single option at a time and concludes upon its feasibility for the present application. A set of alternative well concepts have been provided for comparative evaluations in the current step. The restructuring of information then concerns earlier well engineering experience, the current exploration review and early feasibility studies of different options.

The restructuring of information is suggested to be carried out by the use of the influence diagram method. An influence diagram approach helps to identify the most relevant information, to sort things out, and restructure information so it is applicable within the defined context. Such a restructuring visualises the relationships between elements of importance. As mentioned earlier, the most important symbols in an influence diagram are events (or chances), objectives (values) and planned decisions (choices).

The provisional evaluation of alternative well concepts is either carried out as a cost/benefit screening followed by a preliminary hazard analysis (PHA) or a hazard and operability analysis (HAZOP). The adaptation of methods for the hazard identification and review must be seen in relation to the type of events found relevant and the risk potential of these events or scenarios. For each concept, the main costs must be identified. Cost/benefit may be assessed by comparing the main costs with the expected production income. If the expected production level (field dependent) and rates (well dependent) are approximately the same during the period of time, then only the direct cost needs to be compared, e.g., by the lifecycle cost (LCC). On the other hand, if the production curves and rates differ significantly in time, this effect should be considered with regard to the rate of return on capital. A net present value (NPV) approach is suggested in these cases.

Any unexpected events in connection with the operations are identified and assessed through the preliminary hazard analysis. Events are assessed with respect to the direct causes, including rough estimates of the probabilities and consequences [1]. Both the occupational risks and risks to the environment are evaluated. These effects are not easy to quantify. Thus, the PHA analysis should at least provide some qualitative information to highlight criticality for the purposes of comparison.

Selection of basic "well concept"

The most valuable option among the options identified in the previous step is now selected as indicated in Figure 27. The main intention is to prepare a thorough decision basis and a recommendation to management. By documenting the decision basis in a way that is easily verified and traced, the decision milestone of concept selection nearly becomes a formality.

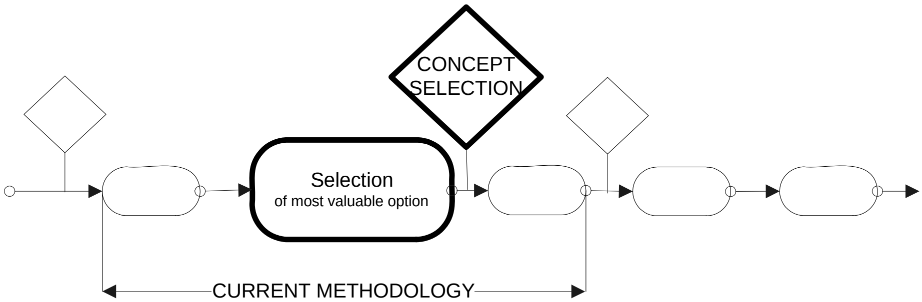


Figure 27 Selection phase of a well engineering project plan

The decision-making process within this phase is typically based on detailed knowledge and expert judgements by members in the project team. It is believed that improved decisions are obtained by conducting decision-making in structured group/team sessions. Less information is missed, or overseen when all the relevant disciplines are involved in common sessions. The different options are discussed and compared based on a set of criteria, of which the team members have agreed upon in beforehand. Thus, a multi-criteria approach is highly relevant for this type of decision-making.

The analytical hierarchy process (AHP) is suggested as an appropriate method to address multi-criteria decision-making such as selecting the main concept. AHP is recommended because of its features of guiding "principal" team/group decisions in a systematic and structured way. The ability to reach consensus in the team or group, where members share common objectives is believed to be much easier [49]. The main reason is that the AHP method can balance the different decision criteria and thus contribute to reaching consensus more easily.

All the consequences of a decision at this level are not straightforward to quantify in cost or income. Typical examples are criteria related to personnel safety and the environment. The AHP approach treats such evaluations in the same process.

All relevant objective or subjective information possessed by the team members is made available to the entire group through the comprehensive sessions. The AHP hierarchy of criteria fits well to the human cognitive style and improves the quality of judgements. It effectively utilises the human capacity of treating information by the way it decomposes the problem into main goal, criteria, sub-criteria and decision alternatives. A weighting process is carried out through a pairwise comparison of criteria and alternatives. Finally, and by applying appropriate software, the synthesis of results emerges. It is then easy to carry out sensitivity analysis of the priority ranking of alternatives against changes to the input data.

Reaching consensus is desirable in a well delivery team. To a certain degree members of the team need to feel “ownership” of the basic decisions. Accordingly, they will make their best efforts to assure successful implementation. To arrive at consensus in the early phases of well engineering, may be more important than the selection of a specific alternative itself. This is especially the case if the alternatives do not significantly differ from one another [49]. The success of the decision depends more on the subsequent implementation phase. In that respect, factors like the quality of detailed design work and the planning/preparation of the construction and commissioning activities are thus regarded to be more important to the project success.

Conducting detailed design

The comprehensive process of detailed design starts after the selection of the basic well concept. The detailed design should then be based on the most promising well concept. The main objective is to provide a final well design that optimises the final well programme for the field development, as indicated by the respective box in Figure 28.

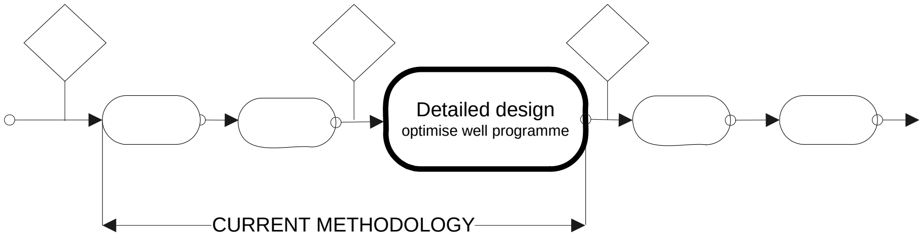


Figure 28 Detailed design phase of a well engineering project plan

The main information carried into this step includes detailed operational and geological data about the field in addition to the features of the selected concept. It requires a lot of work in the detailed design phase before the final well design is completely fit for the challenges of the current field. In addition to the geological requirements, the well design should fit the operational demands for the drilling and completion phases. In addition there are important demands for the production and abandonment phases of the field. Thus, comprehensive assessments and equipment testing need to be carried out. Only in this way can the technical and operational uncertainties related to the chosen concept be eliminated, or reduced to acceptable levels.

There may be final solutions or immature solutions that might satisfy the expected FRs of the current well concept. Then the most straightforward and cost-effective approach may be to select between these existing solutions. A risk-based comparison methodology is suggested to deal with the uncertainty connected to these decisions. Comparison is here based on the best available information about every option.

Shell applied their risk-based comparison methodology for technical decision-making in the WDP of Ormen Lange. To a certain degree, detailed design was actually about the selection between a number of non-ideal options. Shell utilises the term “risk element” as descriptions of common criteria applied in the comparison [4]. In addition, they defined FRs to the total well system. The risk elements were linked to the FRs as the basis for comparison of the options. The

Shell methodology was developed for the specific needs of the well delivery team responsible for the Ormen Lange well engineering. An extension of Shell's methodology is suggested in this thesis to fit more general applications. The revised risk-based comparison methodology is presented in Section 4.5.3. The main intention is to develop a more scientifically based approach, and still maintain its appropriateness for the industry.

Risk assessments, as any other analytical approaches, are characterised by the static view of the decision situation and the risks associated with it. In detailed design, however, the opportunities for decision-making may change during time, both because of the comprehensive nature of the process, the available information, and the time and resources required to carry out decisions. Decisions in detailed design typically are distributed in time. One decision might have direct consequences on future decisions and are therefore characterised as dynamic. The "decision tree" method is suggested as a supplementary tool to the risk and penalty matrix approach to capture any dynamic effects. By identifying those "critical" decision scenarios and relating uncertainties to event branches of the decision tree, estimates of the possible outcome from the scenarios, i.e. the risk consequences are derived. By comparing the different outcomes from the scenarios, the ability for improved decision-making is significant.

The suggested approach provides additional information to the risk and penalty matrix through the details about the expected outcomes from the alternatives. Two levels of actions are then suggested. In case major risk is revealed, the first level of actions is first to update the probability and consequence classification of the original risk and penalty matrix if this is found to be necessary. Next, one carries out assessments according to this new matrix. In most cases, however, only minor effects are expected towards the original risk picture. The second level action is then to adjust the related probability and consequence scores given to risk elements. Here, the original risk and penalty matrix is used. The revised risk and penalty matrix method in combination with the decision trees, should for the current decision contexts improve the ability for handling dynamic decision situations in detailed design. The traceability of the assessments is secured through the systematic approach. Sensitivity analyses are easily obtained by looking at the effects of changing the input parameters.

At the end, the final well design is submitted for approval by management before entering the execution phase. The documented decisions made during the well engineering are made available for management. The step-by-step procedure in the current methodology makes it possible to trace decisions throughout the process in detail. It also documents the consistency of the decisions made for the approval management.

At the end of the decision process a feedback loop is attached, as seen in Figure 25. The value of learning by doing should encourage collecting experience data, e.g., by evaluating finalized projects. By convenience, the engineering companies should establish knowledge databases to improve the availability of specific information and experience gathered from the projects. This information should be traceable, both for fast learning purposes and for decision support in forthcoming projects. Important keywords are: “knowledge management” and “learning by experience”.

4.5.2 Specific models

Descriptions of the specific models are given in the following. The application of methods and tools in the current methodology is based on the procedure described in Section 4.4.2. References are made to Chapter 3 in the thesis, or to any recognised literature/textbooks for detailed description of generic methods. Method descriptions have been included to parts of the methodology when considered necessary to better explain the specific adaptations.

Influence diagram

As mentioned in Section 4.4.2, the influence diagram method is used to depict relationships between elements of the total decision problem. To illustrate a model, the structure of information toward selection of the “basic well concept” is presented in the following. The model is built in three stages, the basic, the main and the detailed stages.

The first stage is shown in Figure 29 and illustrates the relationships between the intermediate and final values to the well concept selection. Emphasis is on the important role of identification and "evaluation of well configurations" as an intermediate decision.

The final values of the concept selection are revenue (major), personnel safety, and risk to the environment. These values directly affect the selection, thus the influences are indicated both ways in Figure 29. Intermediate values included in the model are the CAPEX and OPEX. Another intermediate value may be the regularity expenditure (REGEX) that describes the cost of lost, or deferred production due to downtime [61]. REGEX is relevant for the current example as a value to visualise the production capability of the well concepts. However, only the CAPEX and OPEX are treated explicitly in the current model, but elements of REGEX are regarded as being included in the OPEX. Similar, other values may be the reliability, availability and maintainability expenditure (RAMEX), and the risk expenditure (RISKEX), but these are not considered here.

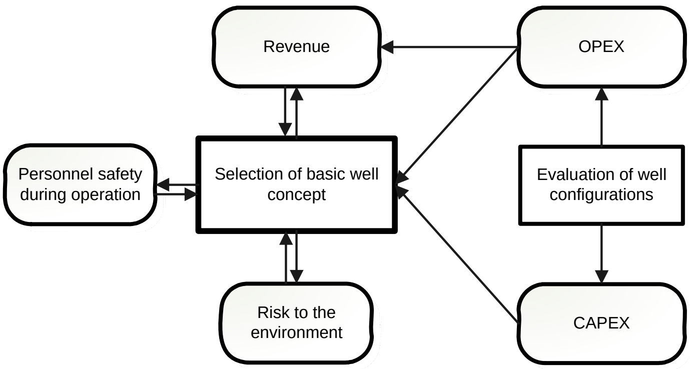


Figure 29 Basic stage influence diagram of well concept selection

The second stage shown in Figure 30 includes a number of intermediate decisions in addition to major uncertainties. The intermediate decisions are connected to the final decision, either directly or indirectly through the other elements of the model. A number of five major uncertainty categories (or chances/events) influence on the final decision:

- Oil and gas (HC) price

- Field geology
- Well constraints
- Intervention requirements
- X-mas tree design

The x-mas tree design is the interface between the well system and the down-stream production systems.

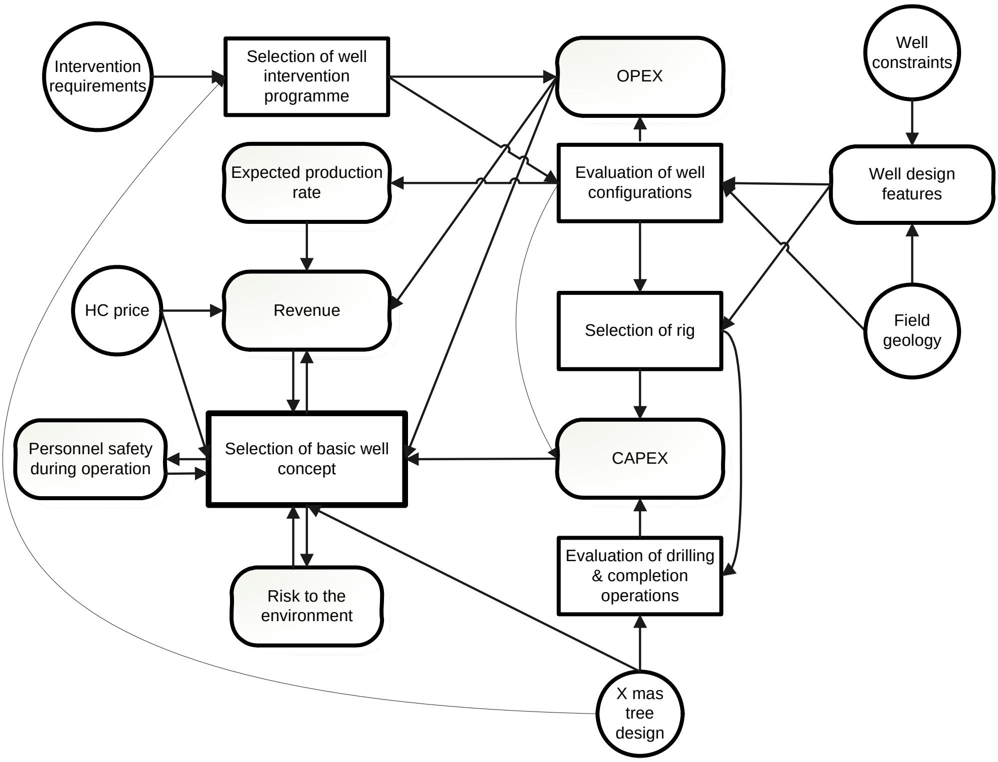


Figure 30 Main stage influence diagram of well concept selection

The following intermediate or final values are leading to the decision objectives:

- Well design features
- CAPEX
- OPEX
- Expected production rate
- Revenue

- Personnel safety
- Risk to the environment

The following four intermediate decisions are made prior to the selection of basic well concept:

- Evaluation of well configurations
- Evaluation of drilling and completion operations
- Selection of rig
- Selection of well intervention programme

In the third and last stage, shown in Figure 31, the evaluation of well configuration is divided into main parts. Then all the known details about uncertainties are included in the model. The field geology, well constraints and intervention requirements are subdivided into different underlying phenomena or uncertainties. Even though Figure 31 is the most detailed, this model should not be regarded as all-embracing.

Influence diagrams become huge and complex as more details are incorporated as easily seen by Figure 31. It may therefore be convenient to sort out information of minor relevance and group information in the same category. As far as possible, this has been done in Figure 31.

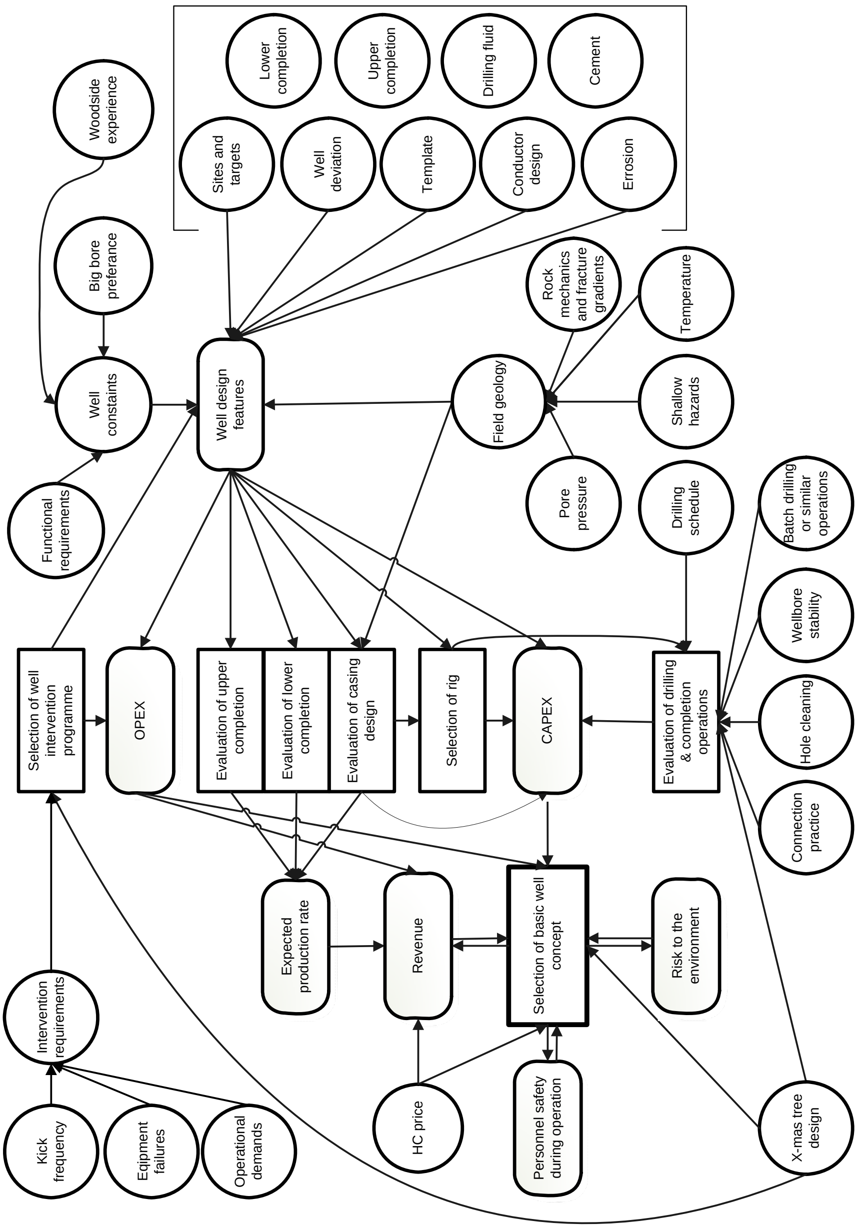


Figure 31 Detailed stage influence diagram of well concept selection

Many of the uncertainties are subject to detail assessments in the engineering project prior to the decisions upon their effect. In that light, the intention of the influence diagram models has been to draw an overview of the decision scope at a project management level, and not go into details of every aspect. However, details about the geology, well design features, and intervention requirements must be brought to the decision arena prior to the selection of the basic well concept, due to their significance.

LCC

The lifecycle cost (LCC) method is used to conduct preliminary assessments of the alternative well concepts. Normally, a LCC analysis is preferred in the early design phases of any production system [42]. The early identification of acquisition and ownership costs (CAPEX and OPEX) provides the decision makers with the opportunity of balancing the lifecycle costs against the decision objectives, or values. These relations were indicated in Figure 29.

Figure 32 is an example of typical cost profiles of commitment and expenditure related to activities in well engineering [42]. The curves proceed into the field operation and disposal phases. It shows the range of uncertainty in cost prediction [46]. The opportunity of minimising LCC in the early project phases is significant by conducting an LCC analysis. As seen, the "cost profile of commitment" rapidly increases in the early development phases. It is generally believed that 80% of the LCC is allocated by decisions that are made within the first 20% of the project life time.

The uncertainty of an LCC analysis depends on where in the process the LCC is predicted. Earlier predictions of LCC have more uncertainty connected with them than predictions later in the project. The uncertainties of the commitment and expenditure cost may be between 2.5 and 0.5 times the cost estimates at the time of project initiation [42]. When reaching time of abandonment, this uncertainty becomes insignificant (~1.0). Thus, the timing of the LCC analysis is always a trade-off between the cost commitment curve and the uncertainty profile.

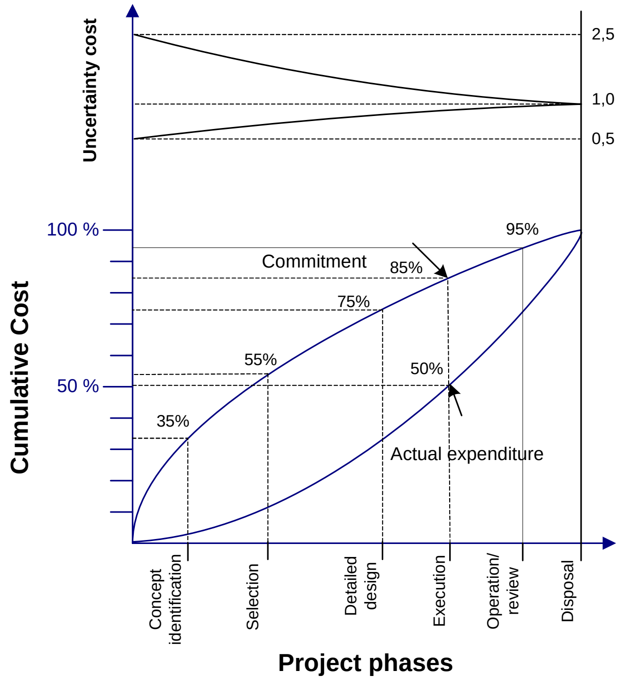


Figure 32 LCC related to project phases (adapted from [42])

Cost-benefit analysis

In a lifecycle perspective there may be cost- and income variations in time between the well concepts. By calculating the net present value (NPV), any such variation is taken account of. The alternative with the highest NPV should then achieve priority. A basis for estimating the expected revenue during time for the different concepts is, thus, provided.

The time related costs of rig rent may differ significantly between the concepts, especially when it comes to the big-bore concepts applied in deep waters. This affects the CAPEX estimates. Alternatives that apply slimmer casing programmes, compared to the conventional design, save time all through the drilling operation, and thus reduce the total rig time. Among the most time consuming operations are the running and pulling of the riser with BOP and the drill string in deep waters. Next, the time for drilling the big holes and installing the casings [59].

Another consequence of a slimmer well design is the reduced total weight of casing material, equipment and drilling mud that need to be stored on the rig deck. This further encourages the usage of lighter and cheaper rigs.

Although, the CAPEX differs significantly between well concepts, it plays a minor role when comparing concepts in a NPV perspective. The CAPEX occurs mainly in the initiating phases of the lifecycle, and the present value effect is minor. On the other hand, the OPEX and production income occur over the whole subsequent production period. Thus, the “return on capital” effect is significant in a NPV context. Therefore, it is easy to confirm the benefits of big-bore well designs compared to conventional designs. This is mainly because of the increased well efficiency through higher production volumes. Despite slightly increased CAPEX, the big-bore well concepts have proved their precedence as great opportunities wherever applicable for field developments.

PHA/HAZOP

Some hazards connected to the drilling and completion activities are more relevant in deep water. The impacts of these hazards need to be evaluated as long as they affect the selection of the basic well concept.

Hazards are related to the final values: “risk to environment” and “risk to personnel” as indicated in Figure 29 to Figure 31. These evaluations are additional to the pure revenue contributing factors of CAPEX, OPEX, production rate of wells, and the oil and gas price. A preliminary hazard analysis (PHA) sheet is suggested for these assessments. A simple example of a PHA-sheet with one hazard filled in is shown in Table 14. This sheet layout is based on the failure mode and effect analysis (FMEA) method [1].

Table 14 PHA Sheet

Operational Sequence	**Events/ Hazard**	**Cause**	**Probability Class (1-4)**	**Consequence Class (1-4)**	**Risk (PxC)**
Running drill string	Falling objects on drill deck	Mechanical failure	2	4	8
-	-	-	-	-	-

It might be demanding to estimate the probability and consequence of any hazardous event related to these specific well concepts. This is mostly due to the coarse information available that covers the big-bore well concepts. This is especially a problem at the early stages in the design process when the uncertainties are still high. The available generic databases are mostly expected to cover the conventional well designs.

Thus, it is much more convenient to rely on expert judgements and to presume intervals for the classification of event probabilities and consequences. Then it will be easy for the experts to assign scores given the distinctive alternatives or intervals to choose between. As a general recommendation, one should apply the consequence categories and the respective probability and consequence classifications as found in the risk management system of the operator. These documents should be referred to when applied in the assessments.

Analytical hierarchy processes (AHP)

As discussed above there is a need to evaluate the alternatives prior to selection on the basis of several criteria. The consequences of the selection related to the economy require cost and revenue estimates, such as those derived from the LCC analysis. However, the consequences with respect to safety or the environment are not so easily quantifiable in cost, although these criteria should count in the comparison as well. As explained above, the current methodology then assesses the risk by applying the PHA.

Thus, when it comes to the selection of the most promising well concept the decision makers are facing a multi-criteria decision. The AHP methodology is the suggested method for selecting the basic well concept based on multi-criteria. AHP enables the decision makers to structure complex multi-criteria decisions into hierarchies [49] of goal, criteria and alternatives. The criteria and alternatives (elements) are compared pairwise at each level of the hierarchy as the basis for synthesis of the priorities. The judgement is about the relative importance or preference of each element with respect to the element (criterion) on the level above. The ability to structure a complex decision in a hierarchy, and then focus attention on single elements at the time amplifies a group's decision-making capability. The comparative judgements are used to derive ratio scale priorities for both the decision criteria and the alternatives.

The AHP-procedure was described in Section 3.4.2 and an example application is given in the paper in Appendix A.4. However, in Figure 33, an AHP hierarchy is shown for the example mentioned above. The main decision objective is "selecting the most promising well concept" and it is placed on the top of the hierarchy. The decision alternatives, consisting of two big-bore alternatives and a conventional alternative, are attached to the lowest level. Above these are the two levels of decision criteria indicated.

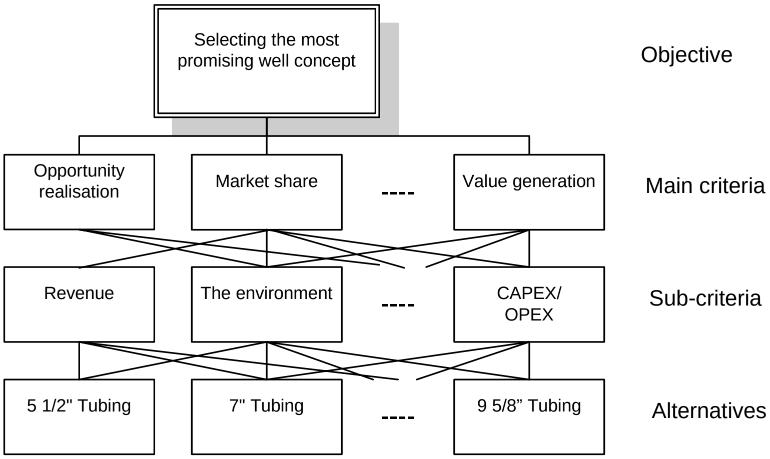


Figure 33 AHP hierarchy: Selecting the basic well concept

Risk matrix method

After selection of the basic well concept, the project enters the detailed design phase. Until now, decisions have been concentrated on selecting the well concept. From now on, decisions concern the detailed design of elements that should constitute the final design. Of prior importance is fulfilling the FRs to the selected well concept (big bore). The concept is further developed to fit the geology and operational aspects of drilling and completion in the specific area. Also the demands given through regulations and acts in the geographic area are of relevance. Examples are the HSE requirements of national authorities, international agreements, company agreements, etc. The existing risk-based comparison method of Shell was actually developed for this purpose [4]. According to Shell the objectives of their approach were to:

- Get a structured and transparent approach to decision-making
- Define the FRs of desired options that constitute every part of the basic design
- Highlight the main risks for the different options
- Link the FRs with the main risks identified
- Review possibilities of managing risks associated with design options
- Conduct sensitivity analyses
- Get stakeholders to buy in and to focus on the main issues
- Implement risk-based management to engineering in line with national regulations and company requirements
- Arrive at decisions that are in line with the given company requirements
- Prepare a basis for more detailed assessments of the chosen design

As clearly indicated by the last point, the methodology is meant to be a basis for planning the further work concerning assessments of the chosen design. Thus, an important question is:

> *Does the current risk-based comparison methodology of Shell provide an appropriate and well-founded decision basis within detailed design where it was meant to come into use?*

Answer:

> *Not all relevant factors of economic- and non-economic relevance have been considered. An example is the accumulated costs of operation and maintenance of the wells.*

Based on the above statement the following discusses elements of the Shell-approach and suggests some improvements. According to the Shell methodology description in Section 3.5, it is believed that certain parts of the methodology may be improved or extended from a scientific point of view. This mainly concerns the complexity of the decision problem and the general decision quality. From a scientific point of view the methodology should cover the total criteria. In addition it should handle uncertainties and consequences of decisions more accurately. The following forms the basis for refining the current Shell methodology:

1. ***Decision process:*** The methodology is arranged so that it is easily integrated with the decision process of WDP and the discussions taking place in detailed design. Important arenas and decision points are identified in the detailed project plans and are subject to evaluations.
2. ***Functional requirements (FR):*** The relevant FR and risk elements include requirements concerning future operation like the expected availability of equipment and HSE objectives in addition to the economic requirements and design features.
3. ***Risk classification:*** The risk and penalty matrix, FR scores and the probability and consequence classes are to be reviewed in light of the official safety management system(s) and recognised safety knowledge. If necessary, the risk classification may be updated based on the severity of decision scenarios as identified by use of the event tree method.
4. ***Guideline:*** Lists of “FR-risk element/criteria” combinations fitted to subsets of typical well systems are prepared. Such guidelines may help the decision makers and speed up the decision processes. Such guidelines might be useful for the specification of FRs and risk elements close to the execution phase. The decision team may then focus their time more on the evaluation part.
5. ***Implementation aspects:*** The implementation strategy of the entire new methodology of this thesis is linked to the DSS, as it has been interpreted in Chapter 5. Evaluating what type of interface, facilities and/or procedures that best fit a given well engineering organization are essential. Important concerns are how to lead and act in a group setting.

The main features of a DSS are here to:

1. Facilitate session leadership of discussions towards consensus
2. Improve the visualization and structuring of the decision problem
3. Prevent distracting argumentation in the discussions
4. Secure decision quality by focusing on effective decision support all through (procedures)
5. Develop a procedure for site implementation and a basis for a software applications

The first four features are discussed in this chapter, and statement No. 5 is treated in Chapter 5.

4.5.3 Revised risk-based comparison methodology

The revised risk-based comparison methodology is suggested in the following. The existing procedure of Shell is described in Section 3.5.2. The risk and penalty matrix in Figure 23 captures the probability and consequence classification as adopted in the Ormen Lange "risk acceptance criteria" document. Finally, the penalties, as a basis for assigning scores to each FR, are given as combinations of the probability and consequence of events.

Decision tree

Before conducting the risk-based comparison studies of options as indicated above, the alternatives to select between have been identified and evaluated to a certain degree in beforehand. However, the selection of a design alternative for given field conditions are affected by uncertainties due to an unknown impact or the influence of its features. Thus, the effect of the different risk elements on the FRs might not be straightforward to predict if there is a lack of information. This could seriously affect the selection. One might select the most "believed" or "secured" option, to be on the safe side and avoid any later unexpected consequence of the selection. However, the advantages of known innovative solutions might be missed by following the latter strategy.

Other uncertainties are related to external conditions like severe sea and weather conditions, increased water depths, rough seafloor conditions, and such natural phenomena. Uncertainties related to unproved technology are normally severe. If the technology has neither been tested for the specific application or similar, nor been qualified for it, qualification work needs to be carried out before it can be regarded as a serious option. Comprehensive testing or qualification then needs to be conducted as part of the project. However, it is much a question of cost/benefit or trade-off, whether or not, such activities are being considered. An improved evaluation of uncertainties concerning their effects and outcome may actually reveal new opportunities. It might turn out that the decision made earlier was not as critical to the outcome as first imagined. A study of the different decision scenarios and their uncertainties may show that the selection made earlier only had a minor effect on the final result, compared to what was expected in the first place.

A decision tree analysis is suggested for the evaluation of dynamic decision scenarios influenced by uncertainty like those indicated above. Through this approach the dynamics of the decisions are revealed as important information to the decision makers. Updated information about the selected technology may then initiate reviews of the consequence- and probability estimations carried out in the risk-based comparison. An example of a decision tree to assess such scenarios is shown in Figure 34. In the following, explanations are given to the symbols and to the numbers that are encircled.

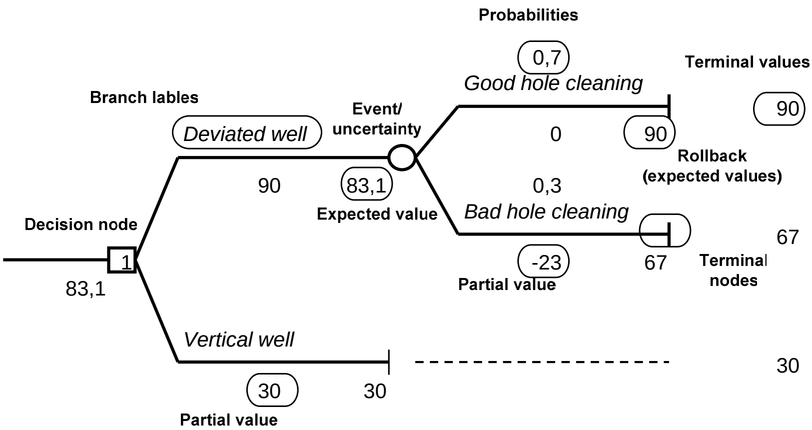


Figure 34 Decision tree model developed in the Treeplan software [32]

Numbers are attached to the figure only to illustrate an example. The decision tree indicates a simplified model of a decision as a function of the expected daily production (*terminal values* in the figure). This example is further developed in the case study in Chapter 6. It is about the principal decision of selecting deviated wells or not. The model is developed by use of the software: “Treeplan” [32] which is running in Microsoft Excel. The model consists of *decision nodes*, *event nodes* and *terminal nodes* connected by *branches*. Each branch is surrounded by Excel-cells containing formulas, cell references, or labels pertaining to that branch. The tree is "solved" using formulas embedded in the spreadsheet. The *terminal values* sum all the partial values along the path leading to that terminal node. The tree is then "rolled back" by computing expected maximum values at event nodes by the use of *probabilities* and *partial values* that are attached to each branch. The *rollback values* appear next to each node and show the expected value at that point in the tree. The numbers in the *decision node* indicate which alternative is the optimal decision at that point. In the current example the "1" indicates that it is optimal to drill deviated wells. As seen in the figure, this decision provides the highest expected value of daily production of 90, given the uncertainty connected to hole-cleaning capability while drilling.

Risk and penalty matrix

The risk levels identified in the risk and penalty matrix are the basis for addressing penalty to the original FRs. The score of each FR is summed and used to rank design options. The following nine-step procedure is applied:

1. Identify the relevant solutions or options that may constitute the desired functions of the selected basic well concept
2. Identify and agree on the main FRs to be used in the evaluation. Requirements regarding future operation like the expected availability and HSE requirements are included in addition to the existing operational-, and efficiency requirements. Examples of the additional requirements are:
    - Documented availability and safety of the drilling facility, either a production rig or a hired rig given some assumptions

- Documented availability and safety connected to operation and maintenance of the final well system
- Intervention requirements/frequency of the wells
- Safety integrity of barriers, in every well phase

3. Assign the maximum score to each FR and rank them
4. Define the risk and penalty matrix to be used to assign penalties. A higher risk level implies a higher penalty. The matrix is not seen as any acceptance or non-acceptance criteria of options. Specific project risks may, however, be used to decide upon the probability and consequence classes of the risk and penalty matrix.
5. Identify the *risk elements* (or risk criteria) associated with the main differences. The original risk areas of concern are *HSE, technology, execution, operation, and authority.*
6. Review each risk element against the main FRs, as defined in point 2. If a "Risk element-FR" combination is relevant the probability and consequence for not fulfilling the FR are identified by use of the probability- and consequence interval classifications.
7. Estimate the risk levels by use of the risk and penalty matrix and comment on the "Risk element-FR" combination in the column to the right. The risk should be defined as the perceived risk as of today, i.e. only the current knowledge of plans and the manageability of actions are considered (static analysis).
8. Summarise the penalty (%) for each FR and weighting it against the importance of the FR (maximum score).
9. Summarise the score of every FR to a total score for the option. This total score is used to rank the options. The selection is based on the ranking.

Guidelines to assist in point 6 are considered because the risk element-FR combinations are not always obvious, or easy to predict. These guidelines may be developed as a set of generic tables presenting the relevant "Risk element - FR" combinations for typical equipment configurations. The guidelines are prepared either company specific or generic to serve general applications. Industry standards based on the latter may be prepared in a longer time perspective. A standardised approach may improve traceability of assessments if they become independent of application. Below is the suggested list of FR categories adopted to big-bore casing designs [4]:

FR 1. Well production capacity in MSm^3/day

FR 2. Well deviation

FR 3. Well monitoring devices downhole

FR 4. HSE requirements

FR 5. Minimum operating cost (OPEX)

FR 6. Qualification of equipment

Based on these FRs a "risk element - FR" combination matrix for the big-bore casing design is prepared, as shown in Table 15.

Table 15 "Risk element-FR" combinations related to casing design

Casing design		**Functional requirements (FRs)**					
No.	**Risk element**	**FR1**	**FR2**	**FR3**	**FR4**	**FR5**	**FR6**
1	New technology such as packers, liner hangers						x
2	Deviation vs. hole size		x				x
3	Down-hole monitoring			x			
4	Casing wear	x		x			x
5	Kick tolerance	x			x	x	
6	Cementing of long casing strings	x			x		
7	Hole size contingencies	x			x		
8	Well access and work-over requirements				x		x
9	Blowout contingency	x				x	
10	Unit technical costs	x					x

The probability and consequence estimates may derive from separate studies, available information databases, or from expert judgements directly. The current method may also be used to perform sensitivity analyses of certain risk elements. It enables changes to be observed to the overall score or to each option's order of priority by changing the input data that affect the given probability and consequence estimates.

The final well concept may subsequently be the subject of more detailed risk assessments and studies. The basis is then the risk elements that have been given higher penalties. These are subject to further analyses with regard to causal mechanisms and/or phenomena. The following studies may be initiated to confirm the final well design:

1. Blow-out contingency planning and risk assessment for the drilling, production, and work-over situations
2. Hole size contingency studies
3. Study of safety barriers and possible leak paths to surroundings
4. Well bore stability and well deviation design evaluations
5. Sand control and cementing evaluations
6. Evaluation of drilling fluid and cementing
7. Fulfilling completion design and qualification testing

Integrity of safety barriers

The study of safety barriers must be given attention due to its importance to personnel safety and the environment. Thus, each design needs to fulfil the safety requirements of the authorities [37], and at the same time the requirements for cost-effective well design.

By preparing a well barrier schematic adapted to the specific well design, the status of the well barriers is systematically evaluated. According to the NORSOK D-010 standard [40], a well schematic is to illustrate the primary and secondary well barriers with their barrier elements in blue and red, respectively. Potential leak paths from the reservoir to the surroundings are then easily drawn in a barrier block diagram. This block diagram shows the leak paths, as the fluid comes from the reservoir leaking through the different barrier elements that contain the primary and secondary barriers. The reservoir is indicated at the bottom of the diagram. Finally, the leak ends up as a hydrocarbon outflow, either to the formation, the sea (environment) or to the surface (personnel safety). An illustration of a well schematic and a barrier diagram has been prepared in connection with the case study in Chapter 6.

4.6 Sensitivity analyses

The particular direction or course of action indicated by the decision tree model does not necessarily make it the only choice. Even if the underlying assumptions in the model appear reasonable, other sets of assumptions might be equally reasonable. Sensitivity analyses provide methods for testing the degree to which alteration of underlying assumptions affect the results obtained from a given model. Another name is "What-if" analyses because the decision maker is interested in outcomes if changes to the input are introduced. The sensitivity of the model to changes is as important to the quality of a decision as the accuracy of the construction of the model. Sensitivity analyses of the event probabilities are carried out in Treeplan [32].

The new methodology presented in this thesis applies different decision analysis methods to well engineering. The decisions made from each step are distributed in time and may depend on each other. Thus, the accomplishment of one step leads into the next step. Sensitivity analyses should then be related to the specific assessments, and the assumptions made in each step. There is no point in carrying out sensitive analyses only at the end of the whole decision process (before approval of final design). After each of the intermediate decisions, the decision process continues into the next step. The decision process therefore turns irreversible because the forthcoming decisions/selections depend on the choices made earlier in the process. A sensitivity analysis is thus to be incorporated into each step of the current methodology and be related to the respective models.

4.7 Reporting of results

The reporting of results from the decision processes should be carried out continuously throughout the assessments. A short introduction of the problem context including description of the alternatives, uncertainties and objectives are made prior to every step of the decision process. A brief model description with the valid assumptions should thereafter be described at a level found necessary to trace the results. Finally, the decisions from each step are briefly described and commented upon.

4.8 Verification and validation

Verification of specific procedures is carried out by testing on a real case, and comparing each step of the methodology with existing methods. In addition to this, the sensitivity analysis should provide information about its quality. Through validation the methodology should prove its accuracy and usefulness by supporting dedicated decision processes. Thus, a case example is presented in Chapter 6.

A discussion has been prepared in Chapter 8 based on the main results and the experience gained from the case study. In this discussion the results are compared to what might be achieved by other methodologies or approaches. The operational and scientific contributions are described in Chapter 7. Operational, here means the practical contribution in the way the industry may be lifted a step forward. All together this should prove the features or excellence of the decision methodology within the current framework.

4.9 Continuous improvement

It is of the utmost importance in companies that are responsible for well engineering to formalise learning-by-doing (experience) from accomplished projects. The concept model shown in Figure 25 indicates the topic as a feedback loop of experience at the end of the detail well design phase. To utilize such information, the evaluation of experience and collection of information should be formalised. The recommended strategy, as indicated in the concept model, is to carry out such work as part of an ongoing project. Then it may be identified as an activity and milestone that is assigned resources to in the project plan. It may be appropriate to collect information into a knowledge database. This database should be accessible for an easy scanning when found relevant in future projects.

4.10 Conclusion and remarks

In this chapter a new decision methodology has been developed. The main body of the methodology contains three basic steps including their deliverables:

1. *Definition of technical decision scope and structure of the WDP*
   Deliverable: Set of alternative concepts
2. *Selection of basic well concept"*
   Deliverable: Most promising concept
3. *Conducting detailed design and approval*
   Deliverable: Approved final design

During the first step, influence diagrams are applied to visualise the connection between factors and decisions at an operational level, and the main decisions taken at the managerial level (tactical and strategic levels). The models should be at a detail level that makes it possible to aggregate main contributing factors to the managerial decisions. Such models should reflect uncertainties as far as possible. The benefit of investing in measures is then revealed, e.g., through cost-benefit assessments.

The AHP assessment used in the second step makes a prioritization between the most valuable well configurations among the set of possible alternatives. Through the AHP discussions it is expected that preferences and objectives of all stakeholders are evaluated in order to arrive at a consistent prioritization. The comprehensive detailed design of the selected concept is thereafter conducted in the third step by applying the revised risk-based methodology. Most of the information needed to evaluate risks connected to the detailed design is revealed through the previous activities. However, because of the time dynamics of decisions throughout the detailed design phase there is still some uncertainty. Decision trees are utilised to highlight uncertainty connected to events and to the decision outcomes.

As mentioned earlier, the risk-based comparison analysis is meant as an important starting point for more detailed risk reviews. Several assumptions were made as a basis for determining the probability and consequence classes of different risk elements. Examples of assumptions are expected high-quality deliverables from contractors and sufficient knowledge about equipment availability. A review of these assumptions is necessary after the selection of the basic well concept to ensure that they still are valid. Then the detailed assessments may be carried out with sufficient quality. It is important that detailed risk assessments conclude with risk reduction measures. Finally, an action list should be defined in order to follow up important issues.

5 Implementation - Decision Support System

This chapter describes a strategy of implementing the results from the current research work. The term decision support system is applied to describe the implementation part of the framework.

5.1 Introduction

The intention of this chapter is to develop a procedure for implementing the main results from the current research work to the industry. Process oriented well engineering organizations are intended users of the new decision methodology. The implementation part of the framework has been linked to the preparation of a decision support system (DSS). From the literature, a DSS is typically referred to as the system itself, or the software application that deals with information in a decision-making context [2]. In the current approach, however, the DSS is linked to a somewhat superior level. Actually, DSS is been associated with the preparations in prior to a development of a software application. Thus, the current procedure is regarded independent of specific system applications or configurations.

A two-step procedure is suggested. The first step evaluates the relevance of the current approach to a given organization. The evaluation is about, whether or not, the organization manages the information needed for comprehensive decision-making. For those organizations passing the first step the current decision methodology is recommended, and the second step suggests a plan of action for the implementation.

The first step evaluation is based on a specification of quality requirements to the project information, Section 5.2. A list of nine important characteristics of the organization is applied to evaluate the organization's potential for fulfilling the quality requirements. In other words, the evaluation is about to what degree the *means* of fulfilling quality requirements to information exists in the organization, or may be prepared for. The interpretation is whether or not the methodology is found appropriate for the organization under study.

The organization's compliance with the requirements is evaluated in a matrix. Scores are assigned to each requirement according to the importance and conformity of the organization characteristics. An expression of the organization's ability to utilize the methodology is then obtained by summing the score of all the requirements.

The second step of the procedure presents a plan of action for the final implementation of the decision methodology. Section 5.3 specifies the main activities, prior to, and during the implementation. A guideline identifies the most important processes and dataflow for the organization under study. This should support the preparation of a design specification of the final DSS application that fits the organization. As part of the guideline, a flow-chart model is prepared that links the decision information to relevant processes and data flow in a DSS application.

5.2 Specification of quality requirements

The intention of the first step is to evaluate whether or not the methodology fits the organization under study. The evaluation is based on the list of quality factors and requirements presented in Table 16. These quality factors were used by (Marakas) [2] to determine both the level of information required and the quality of the information available in a DSS context. Information is considered a form of service to the end user [2]. Thus, information quality may then be associated with the service level that is offered to a decision maker. This interpretation of quality is most relevant, and is applied to the current decision framework.

Quality is about how closely the information matches its intended purpose, i.e. forms the basis for appropriate decision-making in the given context. Thus, factors like in Table 16, that determine the quality of information, may be defined in a way that a wide variety of information quality and service levels can be realized. However, the suggested nine factors are found appropriate for the current service level (as related to well engineering).

Table 16 Quality factors and requirements [2]

No.	Quality factors	Requirements
1	Relevance	The information must be relevant to the tasks at hand, or the decision under study
2	Correctness	The information should represent the reality
3	Accuracy	The information should be as close to the real world as possible and within acceptable error tolerances
4	Precision	The information should represent the maximum accuracy
5	Timeliness	The information must be available in time for its intended use
6	Usability	The information should be easily understandable for the user, or users to utilize it
7	Consistency	Similar information should be stored and presented in a similar and predictable way
8	Conformity	The information must conform to the expected meaning of the end user, or users
9	Cost	The cost of obtaining information and translating it into something usable must be predictable for trade-off purposes

The different elements in the evaluation part are described in the following sections given the above quality factors. It starts by listing important characteristics of an organization regarding its ability to handle the information as needed. Then, the method to carry out the assessment within is described, including an example-matrix. Finally, some acceptance levels of scores to base the evaluation on are given as an illustration.

5.2.1 Characteristics

In order to assign scores to the quality factors and requirements given an organization, a linkage to the organization under study should be established. The list of generic characteristics of the organization presented below constitutes such a linkage. These nine characteristics with explanations have been identified based on the discussions with Shell, and the author's own judgements:

A. *Size* of a typical well engineering project (duration and/or cost)
B. Availability of *skilled personnel* (internal/external)
C. Availability of *administrative personnel*
D. Access to *relevant decision information*
E. Available *methods and tools* to handle relevant decision information
F. *Accessibility to tools* in “decision locations”
G. Uncertainties connected to the exploration of *immature technology*
H. *Number of stakeholders* involved in decision processes
I. The degree of *safety and environmental concerns*

Appropriate size of a well engineering project means the size and complexity that favour an investment in more advanced computerised information system(s). Only those organizations dealing with these kinds of information systems are expected to be recipients of the current methodology.

Availability of skilled personnel means the necessary competence, either internal or external, is available at a reasonably short notice in connection with a project.

The same interpretation regards the availability of administrative personnel. But here, the administrative tasks like follow-up of document revisions, meeting organising, software system support, etc., are of concern.

Regarding the access to relevant decision information, it characterises the organization with respect to its ability of providing the necessary project information in time. This is both with respect to the internal resources, external contact net, different company licences and other agreements. This might be a critical point when dealing with immature technology due to the degree of uncertainty.

Available methods and tools to handle the decision information focus on the existing decision methods and tools within the organization. The topic of interest is to what degree this is appropriate and interacts with the current decision methodology.

Accessibility of tools in “decision locations” leads attention to the existing system architecture and infrastructure, and how it is built in terms of networks, personal computer systems, hand-hold systems, etc.

Uncertainties connected to immature technology characterises the organization’s policy with respect to the opportunities found in new technology. Is it a typical wait and see attitude, or are uncertainties presumed to reveal during the projects accomplishment?

The number of stakeholders involved in the decision processes lead attention to multiple goal organizations, thus, a multiple criteria decision approach may be appropriate.

The degree of safety and environmental concerns in well engineering projects increases the amount of early investigations and preparation. Thus, an increased utilization of risk and reliability assessment tools is expected in the early project phases. That is something the current methodology leads up to.

5.2.2 Evaluation of applicability

The evaluation is conducted by giving scores to each quality factor according to the characteristics. A score is given in the interval 1-5, where “1” indicates “none” effect, and “5” indicates a “most significant” effect. The scores in-between are “small”, “some” and “good” effect, respectively. Only one score is assigned to each quality factor - characteristic combination. Finally, the organization is given a total score according to the sum of all the nine requirements[15]. Thus, using this sum the quality factors are given equal weights (1.0). It is however, possible in this method to differentiate the importance of each quality factor by assigning specific weights.

In Table 17 the quality factors, in terms of the related quality requirements, are lined up with the characteristics in a matrix. The purpose is to illustrate the method of assessment and the way of calculating the total score. Only the first two requirements are given scores in Table 17, just to illustrate the approach.

[15] It is the project information as a whole that is evaluated.

Table 17 Evaluation of quality factors against characteristics

No.	Quality factors	Weights (0.0-1.0)	Characteristics									Sum score
			A	B	C	D	E	F	G	H	I	
1	Relevance	1.0	5	4	3	5	1	2	3	3	3	30
2	Correctness	1.0	1	2	3	4	4	3	3	3	3	27
3	Accuracy	-	-	-	-	-	-	-	-	-	-	-
4	Precision	-										
5	Timeliness	-										
6	Usability	-	-	-	-	-	-	-	-	-	-	-
7	Consistency	-										
8	Conformity	-										
9	Cost	-	-	-	-	-	-	-	-	-	-	-
								Total score:				Max (405)

5.2.3 Acceptance scores

The maximum achievable total score is 405 [5 (max score) x 9 (number of characteristics) x 9 (number of requirements)]. This is for the case all the nine quality factors are equal important (weight = 1.0) and are given max score according to all the characteristics. To indicate an application, the following acceptance levels of total scores are suggested:

- A total score below 100 indicates that an implementation to the organization under study is not recommended.
- A total score between 100 and 300 is acceptable. However, measures should be considered regarding those quality factors that are given low scores according to specific characteristics.
- A total score above 300 reveals no doubts with regard to an implementation.

The above acceptance levels are meant as an illustration only. However, they are reasonable in sense of disqualifying organizations with a very low potential, i.e. the probability to succeed with an implementation is assumed to be low. Thus, if an organization is given less than 100 in score the implementation process should be put on hold (or cancelled). Then, maybe other means might be more relevant to consider than the current methodology.

5.3 Plan of action

A plan of action has been prepared for the detailed implementation part. If the above evaluation was passed, these activities, with reference to Chapters 3, 4 and 6 should implement the different steps of the new decision methodology.

There may still be open questions concerning the information quality within the second and third acceptance levels in Section 5.2.3. The respective quality factors or the characteristics of the organization must then be given special attention in the preparation for implementation. The plan of action constitutes a total of 14 activities. The first 9 activities are regarded as being project independent and may be incorporated as general procedures to the steering documentation of the company.

1. Draw a typical project plan with a timeline, the primary activities, sub-activities and decisions included. As guidance, Table 11 in Section 4.4 lists activities of relevance.
2. Identify typical value creation activities and review activities according to WDP, prior to, and after each primary activity, respectively (see Figure 19 and Figure 20)
3. Develop a conceptual model of how the organization typically structures a decision problem (see Figure 25) including the activities above
4. Specify the decision processes (technical decision tasks) that typically take place in the three project phases covered by the methodology (see Section 4.5.1)
5. Specify the required interoperability of information. This is interpreted as the decision locations (organization level or responsible bodies) where the information is being utilised
6. Decide upon specific software requirements to carry out influence diagram modelling and AHP modelling. The Microsoft Office Visio and the EC11-decision software of Expert Choice Inc. [62], are recommended sub-applications
7. Specify requirements for the computer- and software systems to mitigate interoperability

8. Review the interface and compatibility with other existing information system architecture(s)
9. Specify the new information system in terms of functional requirements and system architecture to constitute the whole DSS application

As indicated above, different software applications are required to accommodate the main purposes of the new decision methodology. It may be a single DSS application or several embedded applications serving different parts of the decision process.

A guideline in terms of some basic questions is suggested to support in activity No. 9. The DSS application depends upon answers to the following questions regarding its intended purpose, and information treatment [2]:

- What are the *objectives of the DSS application* as a whole in terms of the decisions to be made and the required outputs?
- What are the *external sources and recipients* for the DSS application under design, and under what conditions will the DSS application communicate with each?
- What is the exact *nature of the data flow* between the DSS application and each of the previously identified external sources and recipients?
- What *data will reside within the boundary* of the DSS application?
- What are the detailed *temporal processes* contained within the DSS application?
- What are the *data needs* for each of these processes?

A flow-chart model of processes and dataflow in a generic DSS application is shown in Figure 35.

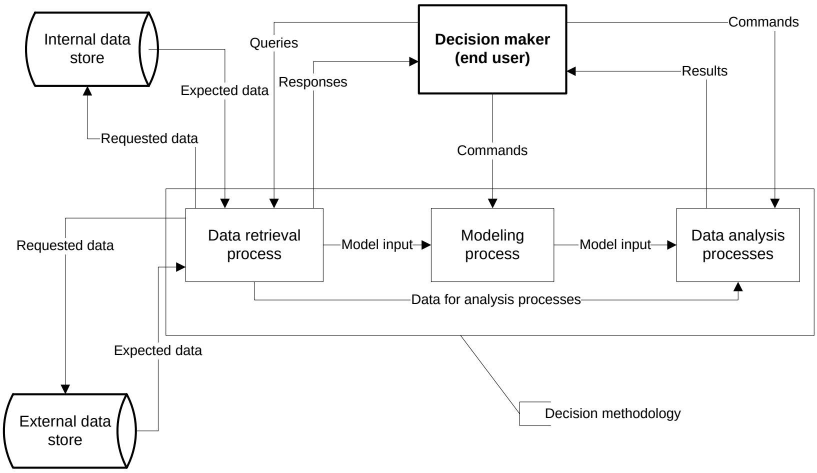


Figure 35 Processes & dataflow in a DSS application (adapted from [2])

A flow-chart similar to the above should be prepared by the organization, both to get an overview of the information flow and processes, and as means to structure the specific content of the intended DSS application.

Responsible party: Project manager with input from supporting staff
Resources: Except from activity No. 6, no specific requirements to application software beyond a word processor, spreadsheet software, and graphical presentation software similar to the Microsoft Office package are required.

Activities Nos. 10-14 below are project dependent, and are specific for every new engineering project. It is assumed here that a new DSS application has been prepared based on activity No. 9, and that it is ready for use.

10. Identify the relevant decision elements in the conceptual phase, to accommodate the information in step No. 4 of the methodology
11. Draw connections between the decisions and the decision elements towards a well concept selection by the use of the influence diagram method
12. Carry out specific assessments of decision elements, including the uncertainties (see Section 4.5.2)

13. Carry out multi-criteria assessment of concept alternatives by use of AHP method in a group session, with a session leader (see Section 4.5.2)
14. Carry out detailed design and decision-making with help of the revised risk-based comparison methodology and by applying decision trees (see Section 4.5.3)

Responsible party: Well delivery team leader
Resources: The well delivery team with external actors. To be supported by the new DSS application at office locations and in session rooms.

5.4 Conclusion

This chapter has described a two-step procedure for implementation of the new decision methodology to the industry.

The first step is given as a specification of information quality related to engineering projects. The specification is applied as a means to evaluate whether or not the decision methodology fits to the organization under study. The basis is a coarse evaluation of the quality requirements to decision information against main characteristics of the organization.

The second step presents a plan of action for the detailed implementation provided that the organization has passed the evaluation given in the first step. A total of 14 activities have been described. The first nine activities are general, whereas the last five activities are project specific regarding their implementation.

Following activity No. 9, a guideline to assist in design of a specific DSS application is attached. The guideline lists important questions regarding the intended purpose of a new DSS application. As part of the guideline a flow-chart model of a general DSS application indicates the basic processes and dataflow that it should contain. A specific model building on the general one is prepared by the responsible organization. This is to link the basic processes identified in activity No. 4 to the new DSS application. An overview of the complex information flow and processes, within, and outside the organization is then obtained. It will also function as a means to structure the specific content of the new DSS application.

Project activities like qualification of technology through component testing and simulation of drilling and completion scenarios are important in well engineering. However, such detail evaluations may be affected or even be rendered superfluous by applying the proposed decision methodology. Thus, a review of existing procedures in the project organization under study may be necessary in connection with an implementation to detect if there are any information overlaps.

6 Case Study - Deep-water Drilling

This chapter presents a case study for which the new decision methodology has been applied. Specific procedures are tested, and the methodology as a whole is validated. The introduction part defines the objectives, assumptions and limitations of the case study.

6.1 Introduction

The proposed decision methodology, described in Chapter 4, incorporates decision theory and uses analytical methods that have been developed to fit the context of well engineering. The research basis has been knowledge within technical systems of deep-water drilling and completion as described in Chapter 2, and the survey of decision support documented in Chapter 3. Among important references, was the experience from Shell regarding their risk-based comparison methodology used to select between technical options for the Ormen Lange wells [4]. Also of relevance was Shell's experience with their global framework, the well delivery process (WPD) [3]. Altogether, this information was merged with knowledge within risk analysis and mechanical engineering and formed the basis for the methodology development in Chapter 4.

However, discussions with Shell have not been on a day-to-day basis. Thus, it is not expected that every aspect or details of the decision processes conducted for the Ormen Lange well engineering are known. Shell shared experience through short meetings with their key personnel and by giving access to specific project information through the project's intranet site. In addition to this, participation in a few technical sessions was offered where important discussions of relevance took place.

Based on this background information, and the assumptions and limitations listed in Section 6.1.2, a somewhat pragmatic approach to modelling has been followed to ensure the applicability of the proposed decision methodology. Thus, the methodology needs to be tested to ensure that it fulfils its intended purpose and that it delivers the expected results.

In this case study the proposed decision methodology is applied on a hypothetical well engineering project. After the introduction part with the objectives and limitations described, the detailed case description follows in Section 6.2. A brief discussion of the decision problem is given in Section 6.2.1. Then, the specific drilling scenario is described in Section 6.2.2. Finally, in Section 6.3, the description of the potential technical solutions to apply completes the well engineering basis for the current case.

6.1.1 Objective

The main objective of the case study is testing and validating the proposed methodology. Specific procedures of the methodology are verified, and the methodology as a whole is validated according to demands given by the concrete well engineering project. Through the validation, the practical implications to the industry are revealed and discussed. The main objective of the case study is achieved by the following tasks:

- Identify and assess the potential drilling and completion technology candidates to the specific drilling scenario
- Carry out and document the assessments concerning the selection of the basic well concept given the main criteria and alternatives to select between
- Carry out and document the assessments in detailed design given the requirements and preconditions of the current drilling scenario
- Validate the associated procedures of the current methodology against the objectives of the current drilling scenario

6.1.2 Assumptions and limitations

The following assumptions and limitations have been defined to the case study in order to limit the scenario and to focus on a selection of the decision tasks:

- The case study enters the WDP at the beginning of the project phase: “selection of well concept”
- The drilling scenario is defined on a coarse level
- Deep water is assumed
- Drilling is carried out from a floating drilling rig
- A big-bore completion design is assumed for all the well alternatives under consideration (an I.D. similar to, or above 7”)
- A managed pressure drilling process (MPD) is assumed to be required to handle the deep-water drilling challenges as faced through the given reservoir conditions
- Five potential technologies for the required MPD process have been identified prior to the case study

Decisions are related to the phase model as earlier presented in Figure 24. Based on experience from the Ormen Lange project [29], the set of decision options, or the action space typically are limited within each phase of the well engineering project. The set of available options within a project phase might depend on external and internal conditions such as national regulations, weather conditions, and the availability of personal resources or technological skills. Such limitations must be considered when dealing with the current drilling scenario. However, no sacrifice to quality of the well engineering is expected due to such limitations.

6.2 Case description

6.2.1 Decision problem overview

Whether or not to apply comprehensive decision-making approaches to well engineering is seen as a trade-off between the feasibility of such approaches measured against the norms and business rules of the industry. Cultural aspects should be reflected thoroughly in connection with implementation of methodologies as the one been proposed. However, it is believed that given general knowledge, and a good understanding of the relevant decision processes, one should be capable of improving decision-making. For the current case study the Ormen Lange WDP is seen as an important preference for decision making [63]. Decision processes from the early identification phases, through the concept selection and detailed design phases of well engineering are of main interest here.

The decision problem is briefly described to sort out the information basis, to identify the most relevant well concepts, and to carry out decision-making through the well engineering project accordingly. In that respect, the basis for the evaluations taking place is mainly assessments of possibilities and limitations connected to the options being considered.

As an example of the context, Figure 36 and Figure 37 give an overview. Figure 36 shows the activity plan or the WDP along with a timeline like it was organized for the Ormen Lange project. Figure 37 shows the processing of information into the detailed drilling programmes.

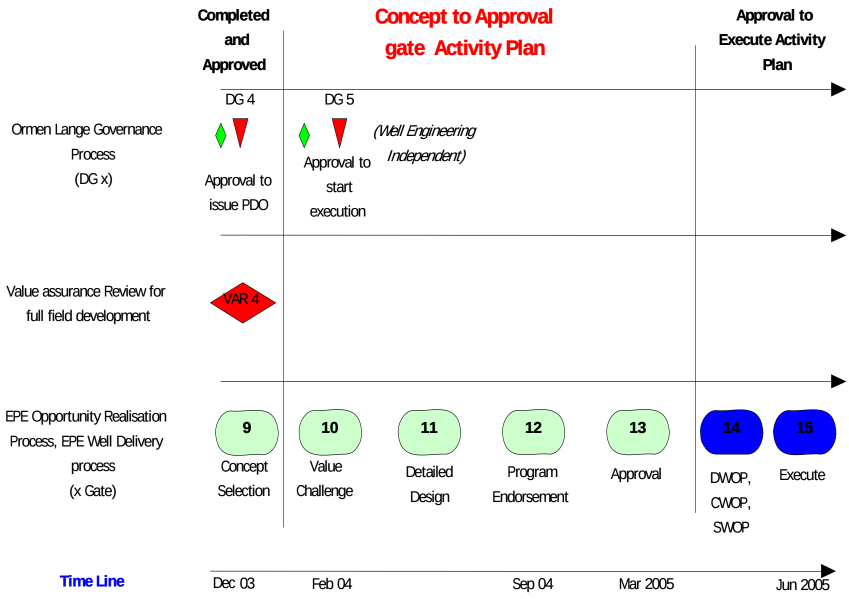


Figure 36 Timeline, and the WDP (copied from [63])

As seen from Figure 36, the basic concept selection was carried out prior to issuing the plan for development and operation (PDO). This is noted as decision gate 4 (DG4) in Figure 36. DG5 is concerning the decision to start execution of the detailed design phase upon approval of the PDO. Prior to approval of the development concept, it is required to make a flexible well execution plan. This plan should also take account of any reservoir and drilling uncertainties[16]. The individual well programmes and section guidelines prepared for Ormen Lange handled these matters, as indicated in Figure 37.

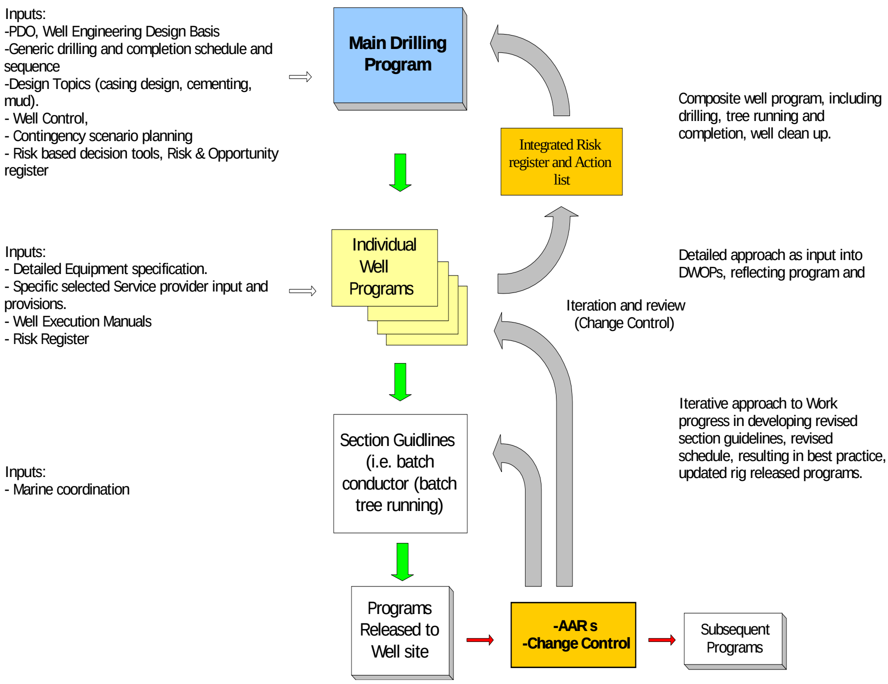


Figure 37 Information carried into a drilling programme (copied from [63])

Important criteria in the evaluations to take place in the case study are the overall project reliability, project cost, general reliability of equipment, and the HSE concerns related to the operations being planned. Information is collected prior to, and during the evaluations that are connected with uncertainty. For the most, this is

16 Ormen Lange: Activity plan: Concept selection to approval gate

site specific data about the geological and operational aspects of the field reservoir, but also about external factors like the weather conditions and the amount of ship traffic in the area.

6.2.2 The drilling scenario

The hypothetical drilling scenario defined for the current case study is related to a deep-water, high permeable gas field, located on the Norwegian Continental Self. The overall objective of the well design is thus, to maximize production within acceptable costs, and to minimize risks to personnel and the environment.

The water depth is 1000 metres and the well target is located 2800 metres below the seabed with a horizontal displacement of at least 1500 metres from the drilling facility. Some shallow hazards have been detected during the exploration drilling as zones of possible high pressure gas and/or water. There are depleted zones deeper in the formation that need to be drilled under conditions of narrow pressure margins. In these depleted zones, the pore pressure has dropped significantly causing the overlying layers to become unstable. The fracture pressure has been reduced while the pore pressure remains virgin in the overlying and sealed sand pockets. However, the mud weight must be kept within the limitations of the pore pressure and the fracture pressure. Finally, the risk of hitting small intermediate and permeable gas zones deeper into the well is imminent. Hence, the ability to recognise and cope with a possible kick should be considered carefully when planning the drilling process. The field development is based on subsea wells tied-in to a process platform offshore, or to a subsea manifold. However, the maximum tolerable height of the subsea facilities is restricted due to trawler fishing in the area and for maintaining the general seabed environment.

The narrowed margins between pore pressure and fracture pressure of the current scenario calls for new drilling and completion methods. Managed pressure drilling (MPD) is a method to reduce the above-mentioned problems. In the following section a general description of MPD technologies is given. Another MPD scenario is given in [64]).

6.3 MPD technology

6.3.1 General description

The current case study focuses on challenges met in deep-water drilling. Normally, in such areas the interval between pore pressure and fraction pressure gradients is quite narrow compared to more shallow waters. That means the drilling operator is forced to run a larger number of casings in order to reach the target. These operations become time consuming and expensive. The high rig rates and amount of equipment and casing steel needed on deck are other contributors of significance to the increasing operational costs.

The use of MPD technology may handle many of the drilling problems listed in the drilling scenario. MPD processes are mainly regarded as enhancers to conventional drilling. However, separate alternatives to conventional drilling may be more relevant by applying MPD technology. It may be possible to drill longer open-hole sections with a reduced number of casing strings compared to conventional drilling. Basically, the application of MPD technology helps to realize the promising potential of deep-water fields more cost effectively. By controlling the bottom hole pressure and/or the annular hydraulic pressure profiles accurately throughout the well bore, the operational conditions become predictable. For example, it may be possible to operate between the narrow pressure margins without fracturing the formation. Conventional drilling, on the other hand, has the drilling fluid return to open atmospheric pressure with no means of annulus pressure control, except from the surface choke.

The unique MPD functionality may be achieved by using different technical and operational solutions. Different categories of equipment are considered. More or less, the relevant MPD technologies to select between are depending on the drilling challenges found in each case. Challenges are related to the geographical characteristics of the field and conditions of the reservoir (geological data). Hence, we talk about a "toolbox" of advanced drilling. The toolbox of MPD technologies covers a variety of drilling problems. An example of a challenge is drilling through heavily depleted zones, or zones of significant higher pressure than the major pay zone. Another problem is the difficulty of reaching the planned total well depth with a sufficient production tubing I.D. by solely utilising conventional drilling. Contingency plans may be prepared to face a problem zone while drilling. One contingency may imply setting a new casing or a liner tie-back through the problem zone before drilling any deeper. However, this strategy increases the costs and limits the desired I.D. of the well. By applying an MPD process in such a case may generate a more cost-effective solution. By managing the bottom-hole pressure according to the pressure regime, as it is immediately faced, one is able to drill the problem zones more effectively.

6.3.2 Riser margin

The pressure generated from the mud column should at all times be within the pressure window between the formation pore pressure and the fracture pressure. Thus, normal operating practices have required a mud weight in excess of the formation pressure such that in the event of an emergency disconnect, the mud weight remaining in the hole should balance the formation pressure of the well [65]. This added mud weight should compensate for the loss of hydrostatic pressure of the mud column from the wellhead back to the rig when the BOPs are closed and the riser is disconnected. This added differential pressure is referred to as the *riser margin* (RM). With increasing water depths and use of heavier mud weights, also the riser margin will increase. In deep-water drilling, where the difference between formation and fracture pressure typically is very small, the riser margin approach becomes difficult as formation pressure often can exceed the saltwater pressure gradient [65]. When drilling in deep water, it is rarely possible to drill with a riser margin and the fluid column is therefore disqualified as a barrier during disconnection of the riser. In such situation, operators on the Norwegian Continental Shelf have to apply to the Norwegian Petroleum Safety Authority for dispensation from the regulations in order to drill without a riser margin.

The riser margin capability of the different MPD technologies applied to deep-water drilling varies. Mainly, it is connected to the actual mud weight that is normally used, and the possibility of immediate adjustments of the mud weight as needed in connection with an emergency disconnection. Normally, an emergency disconnection of the riser takes place in a very short period of time and a replacement of drilling fluid in the borehole is thus very unlikely.

6.3.3 MPD technology

A total of five different MPD technologies or MPD processes are described in connection with this case. These MPDs are all defined within the category of proactive MPD processes [21, 23]. A *proactive MPD* means that the well's casing and fluid programmes are designed for the purpose from the beginning. Then the casing, fluids, and open-hole programme takes full advantage of the MPD process. This "walk the line" approach is expected to offer the greatest benefits to offshore drilling [21] in the way they generate more cost-effective and safe operations. The five MPD technologies being relevant are listed in Table 18. Indications of their RM capabilities are included to the right in the table.

Table 18 MPD technologies

MPD technology	Riser margin (RM)
Continuous circulation system (CCS)	-
Gas lift in riser (GLIR)	+
ECD reduction tool (ECD RT)	+
Dynamic annular pressure control (DAPC)	-
Low riser return system (LRRS)	+

Further descriptions of the MPD technologies, along with typical applications and benefits are given in Appendix A.3.

6.4 Modelling

6.4.1 Structure of the decision problem

The decision processes of well engineering were divided into three basic steps, as presented in Chapter 4, and illustrated by the concept model in Figure 25. As pointed out in this figure and described in Section 4.5.1 the three basic steps are:

1. Definition of the technical decision scope as to be conducted in the WDP. Deliverable: A set of alternative concepts and pre-conditions

2. Selection of the basic well concept; Deliverable: Basic well concept
3. Conducting detailed design; Deliverable: Final well design

In the first step the basis information, including information related to the specific drilling scenario, is identified and structured. The information is structured by using influence diagrams to depict the relationship between the various factors and elements within the decision context. The elements are connected with arrows indicating the direction of influence. The diagrams are also used to identify provisional concepts and to highlight what decision elements to focus on in the more detailed evaluations coming up.

Next, the basic information concerning the provisional well concepts is utilised in a preliminary hazard analysis and a cost screening. For the current methodology an LCC analysis is recommended at this level giving a coarse estimate of CAPEX and OPEX for the preliminary alternatives.

Based on the above information, selection of the most promising concept takes part in stage two by applying the AHP approach.

Finally, the detailed design is carried out by applying the revised risk-based comparison methodology including the risk and penalty matrix for selecting between the detailed options. This is supplied with decision trees to evaluate uncertainties connected to the information utilised in detailed design.

6.4.2 Decision criteria

The main decision criteria are divided into levels of sub-criteria. For the current case study two levels of criteria are given. The main criteria are:

- Operational profit
- Project reliability
- Working environment
- Personnel safety
- Risk to the environment
- Total project cost

The main decision criteria are divided into sub-criteria according to Table 19.

Table 19 Decision criteria

Main criteria	Sub-criteria
Operational profit	• Operational cost, or operational expenditure (OPEX) • Production revenue
Project reliability	• Reliability of well drilling system • Maintainability of rig and equipment • Maintenance support
Working environment	• Amount of manual operations • Competence and training
Personnel safety	• Well integrity • Well control
Risk to the environment	• Geographical area • Emergency preparedness
Project cost (CAPEX)	• Rig and equipment cost • Material cost (casing, drilling mud, chemicals, etc.) • Drilling cost (hole cleaning, hole stability, drilling contingencies, etc.)

6.5 Assessments

6.5.1 Definition of the technical decision scope

The first step of the methodology suggests a three stage influence model to carefully reveal the decision scope (the basic, main, and detailed stage). All three model stages may not be required. It depends on the premises of the actual project, knowledge of the technology and the accuracy of available information.

The first basic stage may be regarded as a review of the feasibility studies. At this level the focus is on cost and revenue potentials in addition to major safety concerns and risks to the environment. The main stage model includes intermediate decisions connected to the final decision. Also included here are uncertainties of concern to the intermediate decisions and the final concept decision. Finally, the detailed stage model incorporates even more information about the uncertainties. For the current case study, decisions under uncertainty are introduced to the main stage level.

Given the above information, an influence model at the main stage level is developed. The model illustrates the action space faced at this level. What are the major drivers behind the choices of principal character, and what restrictions are connected to the different alternatives? Of importance to notify is that some of the intermediate decisions follow different timelines that are not synchronised from a planner’s point of view. This effect is assumed most significant for principal decisions and conditions under direct influence of the major stakeholders [58, 63].

Detailed assessments

Based on the above definition, the following influence diagram is adapted to the present drilling scenario:

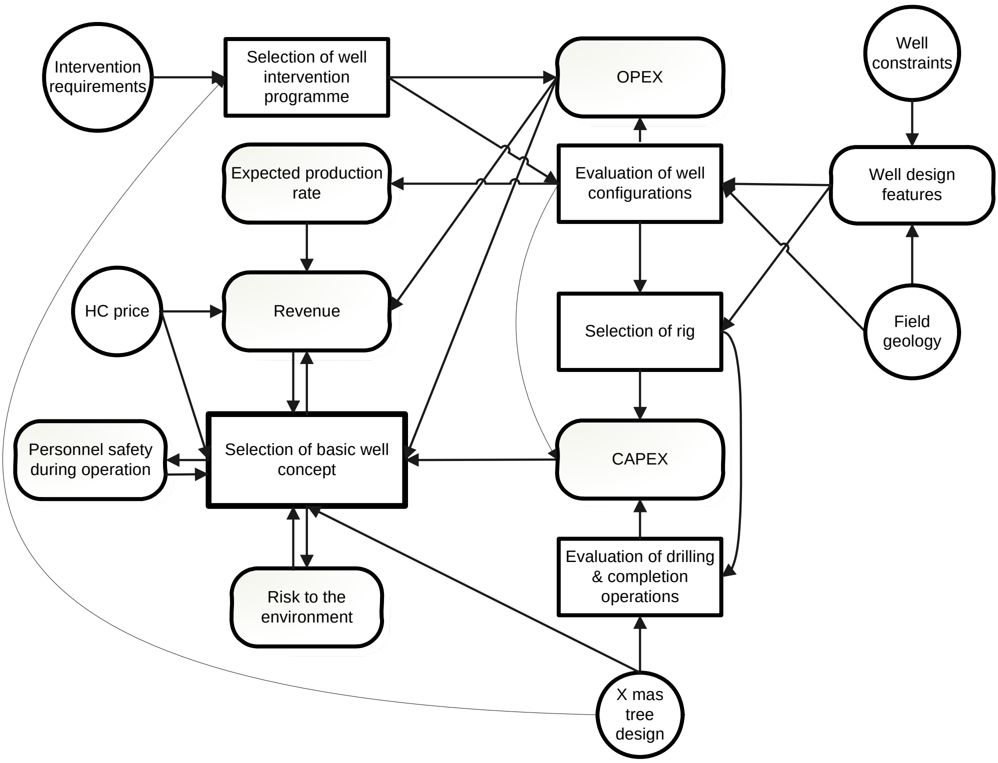


Figure 38 Main stage of basic well concept selection

According to Figure 38, the main decision is the selection of basic well concept. Prior to the main decision a set of four intermediate decisions are identified, namely the:

- Evaluation of well configurations
- Evaluation of drilling and completion operations
- Selection of rig
- Selection of well intervention programme

This is not a complete list of intermediate decisions. Other intermediate decisions may be relevant, but are not included in the current study to limit the amount of work.

Each of the intermediate decisions is affected by uncertainty, or they depend on events, as indicated by the circle-elements in the figure. An example of such is the prevailing conditions for selecting the X-mas tree design. The scenario description tells that there is a restriction to the overall height of the subsea constructions at the seabed. It is a fact that horizontal X-mas trees are building less in height than vertical trees. A demand from the stakeholders may then be to utilize a horizontal X-mas tree design as far as possible. The event element: “selected X-mas tree design” is then more regarded as a precondition to the decision maker responsible for the detailed well design.

The pre-evaluation of alternative well configurations identifies well concepts with features that meet the basic requirements of the field. Next, some drilling requirements, that are assumed relevant, are listed below and draw attention to specific MPD processes:

1. Possibility of uninterrupted circulation while drilling long sections of a highly deviated hole
2. Ability to drill hazardous shallow water formations safely
3. Reduced kick frequency while making connections
4. To drill a formation of unfavourable characteristics in the upper sections of the hole which cannot withstand ECD of conventional drilling
5. Minor investment in “dual gradient” technology is needed

6. To handle narrow pore/fracture pressure margins in deepwater environment
7. Reducing formation damages of depleted zones by lowering the dynamic overbalance
8. To maintain the bottom hole pressure within required limits
9. To maintain hydrostatic pressure control in annulus when circulating, without needing to change the initial mud weight so often

Coarse evaluations of MPD systems, including notes, are given in Table 20. These evaluations are based on objective interpretations of the MPD descriptions given in Appendix A.3.2[17]. A plus sign in Table 20 indicates a clear relation between system properties and the specific requirement. A minus sign indicate only minor, or no such relation. Suggestions of MPD technology realisations are given in the column to the far right. This is not based on an in-depth evaluation of system properties. Thus, the suggestions must be looked at as examples of realisations only, and do not exclude the other options at this level of the assessment.

Table 20 MPD system ability to fulfil drilling requirements

Requirement	CCS	GLIR	ECDRT	DAPC	LRRS	System
1.	+	-	-	+	+	CCS
2.	+	-	-	+	+	CCS
3.	+[1]	-	-	-	-	CCS
4.	-	+[2]	-	-	+	GLIR
5.	-	+[3]	-	-	-	GLIR
6.	+	+	+[4]	+	+	ECD RT
7.	+	+	+	+	+	ECD RT
8.	+	-	+	+[5]	+	DAPC
9.	-	-	-	-	+[6]	LRRS

Note 1: Circulation is not interrupted while making a connection
Note 2: The gas lift may eliminate 2 or 3 strings of casing for the upper sections
Note 3: Much of the equipment are regarded as standard tool for under-balanced drilling
Note 4: Reduced impact of uncertainty on casing setting depth
Note: 5: Maintains the bottom hole pressure mostly constant
Note 6: Dynamic pressure control by adjusting the fluid level in annulus

Accordingly, the five MPD technologies that were listed in Table 18 are identified from the overview in Table 20.

[17] MPD descriptions are taken from SPE articles that may be subjective in nature.

Comparison of alternative designs

To further facilitate the selection process, a rough identification of acquisition and ownership costs (CAPEX/OPEX) of the alternatives is conducted that provides the decision makers with the overall opportunity of balancing costs against the goals. Any other effects of the decisions that are not directly quantifiable in cost such as safety aspects, working environment, and risk to the environment are evaluated thereafter.

An LCC analysis is recommended for conducting the early cost estimates. If the cost profile, or the income of the investment, is distributed in time, a cost-benefit analysis is recommended. Calculation of the net present value would then take account of cash flow variations in time. The safety aspects and the risk to the environment are identified in a preliminary hazard analysis or a hazard and operability analysis (PHA/HAZOP).

It is not possible within the scope of the current thesis to collect detailed information on every detailed cost element of the current drilling operations and well configurations. An identification of the major cost elements is thus, limited to a brief overview of the main contributors as they might occur in connection with the MPD processes associated with the well concept. Apart from some differences regarding the equipment required on deck, the major contributors to acquisition cost of well construction are connected to the operational time of drilling, and the final casing design. Normally, a 5th generation rig is necessary for deep-water drilling. However, requirements to the drilling rig also depend on whether, or not, a 21" marine riser is applied for the drilling, either for the whole length of the hole, or for the lower sections only. In some cases it may be convenient to drill only the upper sections with a marine riser, and turning to a slimmer, high-pressure riser after a while. Then, a surface blowout preventer is utilised in addition to a subsea BOP. A simpler 3rd or a 4th generation rig, with a significant lower rate, may then be applied for the lower sections. Table 21 presents an overview of the cost contributors emerged from the specific features of the MPD alternatives being identified for the given drilling scenario. According to the given scores, three plusses are most beneficial, whereas two plusses are medium and one plus is the less beneficial.

Qualitative evaluation of the major cost elements, and the other non-quantifiable elements, are conducted for the current case. If sufficient data had been available, an LCC analysis should be conducted at this level as described in Section 4.5.2. Anyway, the current evaluation ends with a pre-ranking of the different MPD concepts. It is used to direct attention to the most relevant topics prior to a selection taking part in the next step of the methodology. Based on engineering judgments, Table 21 identifies and evaluates the major cost elements, whereas Table 22 identifies and evaluates the non-quantifiable elements of significance. These evaluations are documented for the convenience of the next step of the methodology.

Table 21 Cost elements used in pre-ranking

MPD concept	Rig cost[1]	Operational downtime	Equipment and materials	Casing design	SUM
CCS	++	+++	+[2]	+	7
GLIR	++	+[3]	+++[4]	+	7
ECD RT	++	+	+++[5]	++	8
DAPC	++	++	+[2]	++	7
LRRS	++	+++[6]	+[2]	+++[7]	9

Note 1: No difference between the five MPDs with respect to rig size
Note 2: Requires additional systems and equipment on the rig
Note 3: Early kick detection might be a major concern due to the additional gas in the drill string
Note 4: Assuming a rig already equipped for under-balanced drilling
Note 5: Relative small and low cost equipment integrated in the drill string
Note 6: Assuming a redundant subsea mud-lift pump
Note 7: Longer sections are possible to drill with less changes of the original mud weight

Rig cost depends on the rig size requirement for the systems. Operational downtime is due to possible equipment failures or any other obstacles during the drilling operations. Equipment and materials are those expected to be beyond standard rig equipment. Casing design also incorporates required amount of mud and cement. The above cost evaluations may be verified quantifiably by applying rough estimates of the cost elements for a concrete drilling scenario. However, this has not been done because it is not the main focus of the methodology.

Table 22 Non-quantifiable elements used in pre-ranking

MPD concept	**Kick frequency**	**Well control**	**RM**	**Working environ-ment**	**Project reliability**	**Risk to environ-ment**[1]	**SUM**
CCS	+++[2]	++	+	+++[3]	++	+	12
GLIR	+	+	+++[4]	+	++	+	9
ECD RT	++	++	+++	+++[3]	++	+	13
DAPC	+++	+++[5]	+	++	+[6]	+	11
LRRS	++	++	+++[4]	++	+[6]	+	11

Note 1: No information available that differentiates the concepts with regards to the environment risk.
Note 2: Reduced kick frequency due to continuously circulation while making connections
Note 3: No need for manually interference during operation
Note 4: Dual gradient ability makes it possible with a heavier mud weight deeper into the well, securing the RM
Note 5: Facilitates an accurate pressure control and a rapid pressure recovery
Note 6: Assumed more comprehensive testing on site is required than for the other MPDs

Project reliability in Table 22 is related to the efficiency of project accomplishment, testing and commissioning. Finally, we remain with the pre-ranking of alternatives as given in Table 23 that is the sum of the scores given in Table 21 and Table 22, respectively.

Table 23 A preliminary coarse-ranking of MPD concepts

MPD concept	**SUM total**
ECD RT	21
LRRS	20
CCS	19
DAPC	18
GLIR	16

Results and implications

The main stage influence model is not regarded as all-embracing, but it is found appropriate to structuralise the elements of interest as far as the available information allows for. The diagram depicts the relationships between the important decision elements according to the given decision context. It also highlights elements of importance for the more detailed assessments.

To summarise results of this first step, a structured decision problem has been prepared. A pre-ranking of the MPD technologies is made according to major cost and risk elements, as they are revealed in connection with the current drilling scenario. These major elements are evaluated in more detail during the selection phase, described in the following section.

6.5.2 Selection of the basic well concept

According to the exploration review and the subsequent well engineering design basis, a set of requirements for the well design are registered. Among these are the functional requirements (FRs) of casing design and completion design the most important ones with respect to the total well concept. Examples of such requirements are presented in the following:

Well general

To maximize production the well design should allow for a 7” or 9 5/8” production tubing. Due to a high permeability and an expected high flowrate from the reservoir, a 9 5/8” production tubing is found most beneficial to maximize production. Because no 9 5/8” tubing retrievable sub-surface safety valve (TRSSSV) and X-mas tree are approved for subsea applications, a hybrid design, including a 7” X-mas tree and a 7” TRSSSV is applied for the 9 5/8” production tubing.

The wells are assumed pre-drilled to above the reservoir section. Then the production casing is set and the wells are temporary abandoned. Batch drilling takes place to optimise the logistics, and thus, sensitive operations during the winter season may be avoided. The completion operations are all planned to take place during the summer period.

Conductor design

Maximum allowable conductor inclination is typically 1.5 degree to the vertical, to ensure necessary alignment with the template. Especially, the inclination is important to accommodate for the first conductor joint. Then it will be easier to align the whole conductor. An appropriate setting depth of the conductor is around 80 metres, depending on the soil conditions.

Casing design

The pore pressure and fracture gradients are quite normal down to the lower depleted parts of the formation. These depleted zones imply more narrow pressure margins while drilling. A standard casing design, comprising a surface casing, an intermediate casing and a production casing is applied. The annular space in the production casing then allows for installing the TRSSSV.

To compensate for the narrow pressure margins in the lower parts some compensating measures are required. One option is to apply a contingency liner that may be set if serious mud losses or drilling related problems arise. An example is setting a 16” liner below the 20” surface casing shoe. However, this option can also introduce some other problems, such as a too narrow circulation space between the liner and the open hole to maintain circulation properly. The resulting narrow space leads to an increased ECD while drilling the 17 1/2” hole for the 13 3/8” casing. This might cause problems in reaching the total depth within the required tubing size. Hence, other measures may be more appropriate, like giving the possibility of controlling the bottom hole pressure more accurately while drilling. Different MPD processes may handle this sort of problem, hence the MPD technologies have been considered in connection with the casing design and the completion design.

Deviation design

The well deviation design is assumed standard with a dog-leg (knee) of 1 degree per 30 metres in the top hole, and 2.5 degrees per 30 metres in the intermediate hole section.

Completion components

Completion components for the 7" and 9 5/8" well designs are readily available, except from the deep-set (TRSSSV). As an example, Halliburton has developed a complete 9 5/8" system comprising of tubing hanger, production packer, bridge plugs, liner hanger, wellhead plugs and multiple cycle tubing plugs[18].

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[18] The Halliburton's “Peak system”

Tubing retrievable sub-surface safety valves

It is advised to set the TRSSSV below the depth of the hydrate forming temperature, e.g. as low as 1500 metres TVD. The maximum setting depth for a 7" is currently regarded as 1500 metres TVD and for a 9 5/8", approximately 700 metres TVD[19]. The restrictions are mainly due to the long control lines implying slower response time of the hydraulic activated valves. Until lately no 7” sub-surface safety valve design was available to be set so deep. A qualification programme for the 7” and 9 5/8” valves has been initiated lately, and valves of both sizes is planned to be tested and qualified [29]. A tubing retrievable subsurface safety valve is preferred compared to a wireline retrievable safety valve because it is more reliable.

Well intervention

The chosen well design may incorporate two sub-surface safety valves to reduce the well intervention frequency. Otherwise, the well should allow for minimum intervention. No regular wireline operation is planned other than the required barrier testing as per PSA regulations, and for ordinary well monitoring purposes.

MPD alternative

There is obviously a need to compare different well concepts based on a set of criteria, including the identified MPD technologies from the previous step. Several criteria might be considered in order to select the most promising concept. These criteria may reflect different interests and objectives of the project team members and important stakeholders. Thus, a multi-criteria decision approach is suggested to support the decision process. It is assumed that most of the decisions at this step are taken in a group/team setting. Utilising the AHP method is a recommended approach in such environments. It has important features that help to structure the decision criteria, and to facilitate the project group/team through planned sessions, towards a decision. It might well be the situation that important information for an accurate decision-making is lacking. The AHP approach may then reveal an option

[19] Notes from the “Ormen Lange - Concept Selection Report”.

to hold the session in wait for more accurate information. Spending valuable time on subjects that are not yet ready for decision-making is then avoided.

Detailed assessments

The process of selecting an MPD technology to constitute a part of the basic well concept has been carried out. The detailed assessment is documented in a conference article submitted to the PSAM8[20] conference. This article is attached to the current thesis in Appendix A.4. The article consists of an introduction part and a description of the decision approach applied to the current phase of the WDP. The case example in the article describes the assessments taking part for the current drilling scenario, and leads through the different steps of the AHP procedure. The assessment was carried out by help of the software programme: Criterium DecisionPlus [66]. The selected MPD technology from the AHP assessment turned out to be the CCS concept. Note, that after the pre-ranking carried out in the first step it was the ECD RT concept that attained the highest score.

Results and implications

The final basic well concept now constitutes a subsea well with 9 5/8” production tubing and a 7” X-mas tree. It has a 7” TRSSSV located 600 metres below the seabed. A horizontal step out at 1500 metres is being anticipated. The well design requires minimum of intervention. Thus, no regular wireline operation is planned other than the required barrier testing as per PSA regulations, and for ordinary monitoring purposes.

The result from the AHP assessment of MPD technologies is a ranking of the alternatives according to how well each of them meets the decision criteria. The CSS comes out as the preferred MPD alternative, mainly based on its safety features. Additionally, the following pros and cons of applying the AHP method were experienced:

[20] PSAM: The International Conference on Probabilistic Safety Assessment and Management

- The AHP approach structuralises the decision process to reach an improved decision quality
- The decision makers are able to organize and evaluate the relative importance of the decision criteria and the alternatives in an effective way
- The consistency of the judgments is easily measured, and it is straightforward to re-evaluate the judgments that are found inconsistent
- Strong leadership throughout the decision process is found to be important

It is noted that a continuous focus and loyalty to the AHP approach throughout the decision process is a success criterion.

6.5.3 Conducting detailed design

The majority of well engineering and planning work is taking place in the detailed design phase. The main objective is to deliver a final well design that fulfils the FRs[21] and is as close to the technical limit aspiration as the economy and other constraints allow for.

Detailed design incorporates updated information about the operational and geological aspects of the field. This information is most important to the detailed planning and execution of the wells. Information regarding the future operation and maintenance of the well installation is also of relevance to this phase.

Within the boundaries of the chosen well concept there are several design tasks to be conducted, where one is considered in this case study. The procedures are applied on the design task of “casing design”. Within the total scope of work, other detailed design tasks may include the following:

- Conductor installation method
- Production packer
- Lower completion including a sand screen or a gravel pack
- A single or dual TRSSSV, with, or without lockup capability
- Well monitoring equipment

[21] Functional requirements are given by the “well engineering design basis”.

- Testing facility of pre-drilled wells
- Intervention equipment

Detailed assessments

A big-bore well design is selected, including a hybrid 9 5/8” completion design as described in Section 6.5.2. Now, we would like to develop the casing design further by incorporating detailed knowledge about the geology and operational demands to the drilling and completion activities. The later production and abandonment phases are also, to some extent, considered in this phase.

As earlier pointed out, a big-bore well design is highly relevant for a cost-effective development of deep-water gas fields. In this case two specific big-bore design options [25] are found relevant, in addition to a straight conventional casing design. The two big-bore designs, shown in Figure 39, are:

1. Variant big bore (VBB)
2. Variant slick big bore (VSBB)

These two big-bore alternatives have their origin from the well designs developed by Woodside Energy Ltd. for the Perseus field outside Australia [25]. There, they were referred to as the VBB, and the VSBB concepts. The term “variant” refers to using a 9 5/8” tubing with a 7” TRSSSV and a 7” X-mas tree. The term “slick” refers to setting the production packer high, near the top of the 9 5/8” liner. Note that the 7” safety valve for the time being is the largest acceptable TRSSSV option for big-bore designs on the Norwegian Continental Shelf.

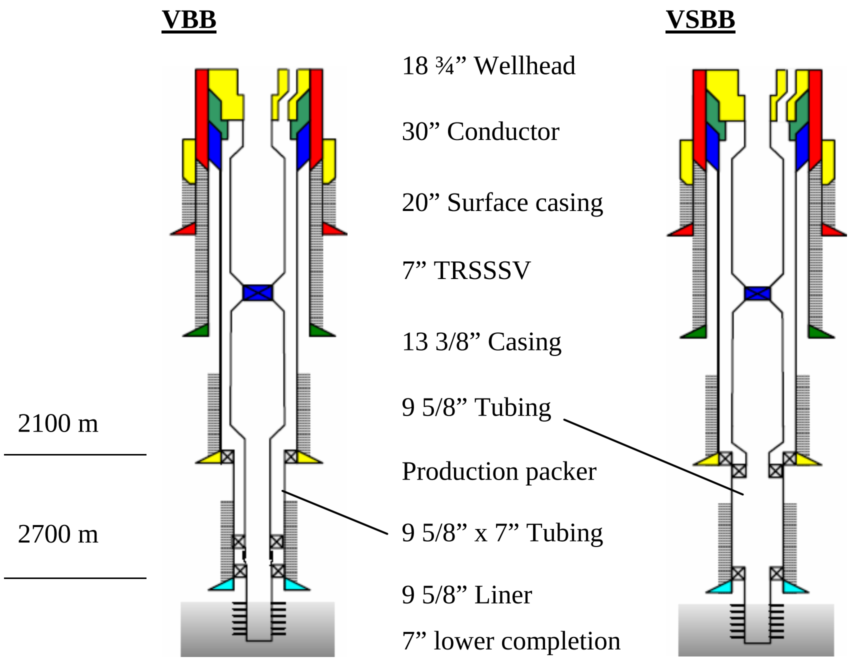


Figure 39 Two big-bore casing designs (adapted from [25])

By applying the slick design, the formation outside the 9 5/8” production liner in combination with the 13 3/8” casing shoe cementation, is relied upon to be the second barrier to the well surroundings.

Drilling- and completion-summary for the VBB

After having the conductor installed, the surface casing is drilled and set. Then the 13 3/8" intermediate casing is drilled and set approximately at 2100 metres TVD. Next, one continues to drill a 12 ¼” hole down to the top reservoir at approximately 2700 metres TVD, to set the 9 5/8" production liner. Then, a 8 1/2" hole is drilled for the 7" lower completion. Finally, the 9 5/8" x 7" tubing is run down to the 13 3/8" casing shoe.

Drilling- and completion-summary for the VSBB

The same procedure as above is followed including the 7" lower completion. But instead of the 9 5/8" x 7" tubing for the VBB, a short 9 5/8" tubing is run down and set below the 13 3/8" casing shoe.

Decision tree

To model the dynamic decision process together with uncertainties, the decision tree method is applied. A decision tree model presents simplified decision scenarios of relevance to the current design case. The decision scenario that maximises the expected daily production rate may be identified and quantified. Any uncertainties connected to the operational aspects of drilling are included in the assessment. It is here assumed a near correlation between the final casing design and the expected production rate. The major difference between the two big-bore options looked at is that the "variant slick big bore" has 60% increased capacity compared to a conventional well, whereas the "variant big bore" has only 40% increased capacity [25]. The conventional well implies a 7 5/8" production tubing all the way up. The VBB has 9 5/8" production tubing above- and below the safety valve, and a 7 5/8" tubing inside a 9 5/8" liner below the 13 3/8" shoe. The VSBB utilises a 9 5/8" production liner below the 13 3/8" casing shoe as by way of comparison. Both well designs utilize a 7" lower completion. Thus, for the current reservoir it is assumed a production rate per well of 10 MSm^3/day for the VSBB, and 5 MSm^3/day for the VBB [29], compared to 3 MSm^3/day capacity of a conventional well design. Due to the relative long section of 7 5/8" tubing needed for the VBB design, it is considered more like a 7" completion. The expected production rate is thus only the half compared to the VSBB design.

The decision tree model presented in Figure 40 incorporates demands like *maximum production capacity, hole cleaning ability,* and the *borehole stability*. However, a full scale model would have been too complex within the boundaries of the current thesis. Thus, for this case example the model includes uncertainties and intermediate decisions related to well deviation only. Nevertheless, the usefulness of a decision tree approach to this kind of a decision problem is truly proved. The model has been prepared in the software programme “Treeplan” [32] running in Microsoft-Excel. Uncertainties are modelled as “events” that are assigned subjective estimates of event probabilities.

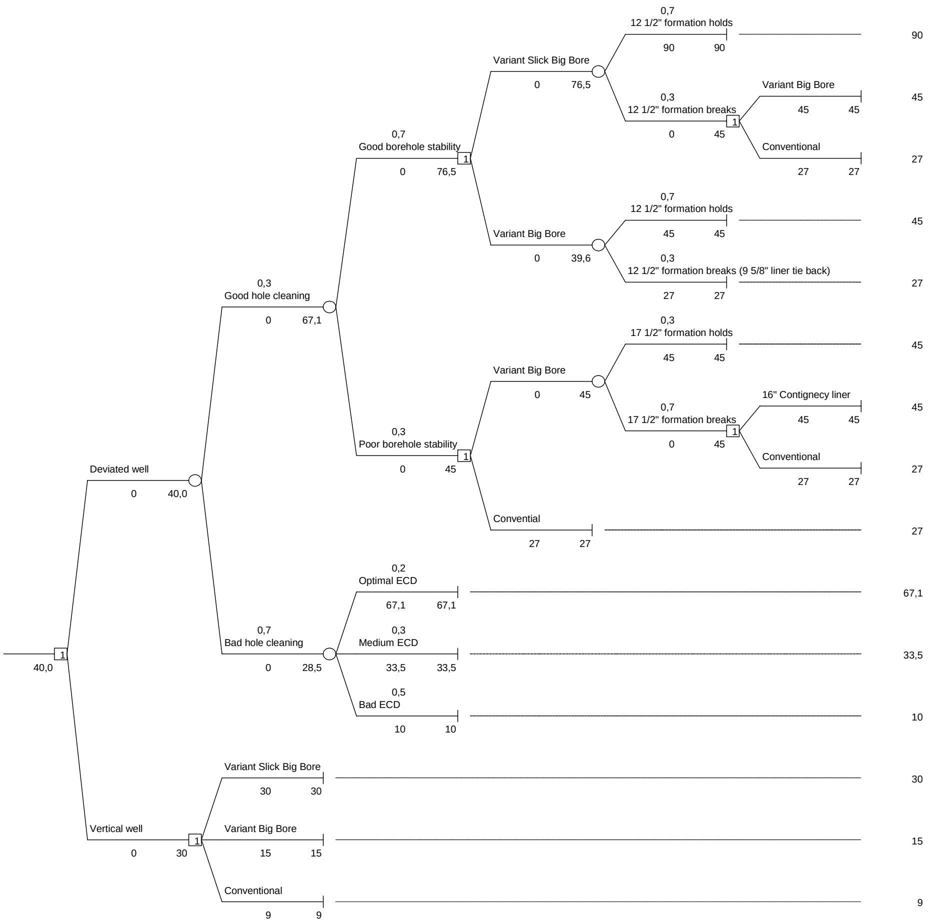


Figure 40 Decision tree for a big-bore casing design

The basic decision, shown to the far left in the figure, is whether to prepare for templates with deviated wells, or to go for clusters of distributed vertical wells. Something in-between may be an alternative, but is not considered in this example. Note that the alternative of distributed vertical wells is becoming less relevant after the introduction of the deviated drilling technology. Experience has shown that deviated wells in most cases are the most cost-effective alternative. The major reason is the ability to utilize a drilling facility in place to extend the area of reservoir drainage.

It is assumed that templates, with a total of 8 deviated wells, are able to reach 3 times more of the oil reserves contained in the reservoir during the production lifetime of the field, compared to the case of having 8 vertical wells drilled from the area near the centre of the reservoir. The maximum daily production, Q_{Max} with the vertical VSBB wells is estimated to 90 MSm^3/day the first production year, compared to 30 MSm^3/day for the case of vertical wells. It is here assumed that three out of eight wells on average are in production during the first year. The terminal values in the decision tree, to the far right, indicate these adjusted daily production rates. Q_{Max} for the deviated VSBB wells is calculated as follows:

$$Q_{Max} = 10(MSm^3 / day) \cdot 3(wells) \cdot 3(factor) = 90(MSm^3 / day)$$

As seen, the daily production rate of three wells is multiplied by a factor of 3 to compensate for the extended reach of deviated wells. It is here taken into account the same lifetime of the field as for the case of vertical wells. Similar calculations for the VBB and conventional designs give a Q_{Max} of 45 MSm^3/day, and 27 MSm^3/day, respectively.

Deviated big-bore wells typically imply two major challenges to overcome:

- Keeping the borehole cleaned during drilling
- Handling problems with borehole in-stabilities (formation hazards)

Uncertainty is connected to these aspects even after the drilling has started. Thus, contingency plans must be prepared to overcome these problems if they should arise.

It is assumed that proper hole-cleaning to a certain degree depends on the well inclination. The mud weight and circulation rate in combination with the amounts of cuttings determine the equivalent circulation density (ECD) that is a critical parameter in drilling operations. The hydrodynamic effect of a too high ECD (bad) might cause fracturing of the formation. This is a problem in combination with deviated wells due to the increasing well length. As a simplification, the model captures this effect by simply introducing an uncertainty branch to the decision of selecting deviated wells or not. The uncertainty is modelled as probabilities for reductions in the expected outcome of 67.1 MSm^3/day given the case of good hole-cleaning (optimal or low ECD). A reduction factor of 50% is used for the case of medium ECD. Finally, the production is reduced down to the volume of only 10 MSm^3/day for the case of high ECD. These expected production rates derive from the different contingencies to the casing design in case of well plugging, stuck pipe or lost circulation. These scenarios are, however, not modelled in detail.

Depending on where in the drilling sequence the problem arises, the model suggests different contingencies to cope with formation stability problems[22]. For example when drilling the 12 ½" hole for the 9 5/8" liner for the VSBB design, one might expect running into formation problems if formation stability problems were explored. Then the driller is faced with a decision of whether to complete with a VBB or to drill and set a 9 5/8" conventional casing. The model shows the different outcomes of the decision scenario depending on the actual casing design that was selected. As seen, if the VBB is selected at the first place there is no other option than a conventional completion if running into formation problems. This solution implies running a 9 5/8" liner tie-back to obtain the new 9 5/8 production casing.

Revised risk-based comparison method

The revised risk-based comparison method including the risk and penalty matrix is used for the ranking of the alternative casing designs. According to Section 4.5.3, the recommended FRs to the big-bore well design, are listed in Table 24.

Table 24 FRs to the well concept

Functional requirements (FR)		**Max score**
FR 1.	Capable of producing 10 MSm^3/day	12
FR 2.	Well deviation, allowing horizontal step-outs	10
FR 3.	Use of well monitoring devices downhole	8
FR 4.	Safety integrity of barriers in all phases	6
FR 5.	Minimum operating cost (OPEX)	4
FR 6.	Use of qualified well equipment	2

[22] Note: Formation stability problems and hole cleaning problems are in this model assumed totally independent of each other that is actually minor realistic.

Each FR is given a maximum score. In case no penalty is given, a maximum total score of 42 is obtained for the option.

Table 24 includes the same FRs as for the Ormen Lange wells [4], but with two new ones added. They are the “safety integrity of barriers” and the “minimum operating cost”. These two new FRs are both ranked above the former FR 4 “use of qualified well equipment” as it was applied for Ormen Lange. The main reason is that the two new FRs might reveal more information regarding safety concerns at earlier stages of the design process. Similar concerns are related to the operating cost requirement that may be linked to the expected production availability of the wells. An enforcement of this requirement may reduce the uncertainty connected to immature technology, accordingly.

The utilised risk and penalty matrix is shown in Figure 23, in Chapter 3. It includes a penalty system to be used in the review of risk elements against the current FRs.

A “Risk element - FR” combination matrix for the big-bore casing design is presented in Table 25. The actual combinations of risk element - FR that have been found relevant for the current case are based on the Ormen Lange experience, in addition to pure engineering judgements.

Table 25 Risk element - FR combinations related to casing design

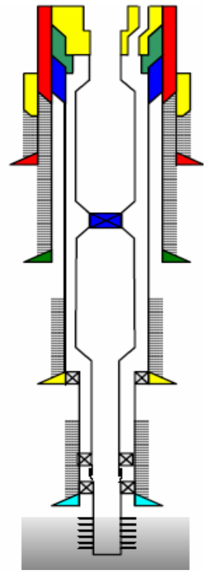
Casing design		**Functional requirements (FRs)**					
No.	**Risk element**	**FR1**	**FR2**	**FR3**	**FR4**	**FR5**	**FR6**
1	New technology					x	x
2	Deviation vs. hole size		x				
3	Down-hole monitoring			x		x	
4	Casing wear	x		x	x		
5	Kick tolerance	x			x		x
6	Cementing of long casing strings	x					x
7	Hole size contingencies	x			x		x
8	Well access and workover requirements				x	x	x
9	Blowout contingency	x				x	
10	Unit technical costs	x					x

Figure 41 shows the score calculations for the VBB casing design, whereas Figure 42 shows the similar for the VSBB casing design. The basis for the score calculations is the sum penalty given to each FR that is calculated by use of the risk and penalty matrix in Figure 23. Given the sum penalty in percentage for each FR, this value is subtracted from the max score of the respective FR. These final figures are summed up to arrive at the total scores.

According to the purpose of the revised risk-based comparison method, presented in Section 4.5.3, the decision tree reveals more information about uncertainty. For the current case this has been realized concerning the 12 ½” open hole contingencies of the VSBB design. With the opportunity of making a VBB design in case the 12 ½” formations breaks it reduces the consequence of a 12 ½” formations breakage. This opportunity is compared to the alternative of completing the well with a 9 5/8” liner tie back. Thus, the uncertainty is reduced, and the score given to risk item No. 7 (hole size contingencies) in Figure 40 is reduced from “very significant” to “marginal” in the assessment found in Figure 42. This revision affects on FR 1, FR 4 and FR 6. With a probability score of “less likely”, the risk and penalty score of these FRs is reduced from 5 %, to only 1 %.

As seen by the Figure 41 and Figure 42, the VSBB design finally comes out with the highest score of 40.1, and is selected. Compared to the score of 32.5 for the VBB design, this is a significant better result. The maximum score for the current case is 42.

VBB design



Score tables

Summary					
FR (Max score)	Red 50%	Red 10%	Red 5%	Yellow 2%	Green 1%
FR1 (12)	1	0	1	2	1
FR2 (10)	0	0	0	1	0
FR3 (8)	0	0	0	1	0
FR4 (6)	0	0	1	2	1
FR5 (4)	0	0	0	2	0
FR6 (2)	1	0	1	1	1

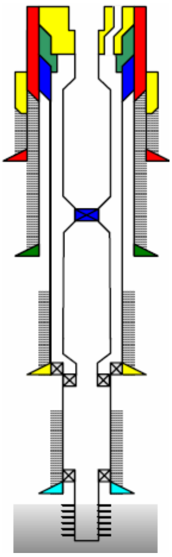
Penalty	FR1	FR2	FR3	FR4	FR5	FR6	
	60%	2%	2%	10%	4%	58%	
Sum score for FR	4,8	9,8	7,8	5,4	3,8	0,8	Total 32,5

Assessments

No.	Risk item	Probability	Consequence	FR 1	FR2	FR3	FR4	FR5	FR6	Risk
1	New technology as i.e. packers, liner hangers	Unlikely < 5%	Marginal	☐	☐	☐	☐	☑	☑	0
2	Deviation vs. hole size	Unlikely < 5%	Significant	☐	☑	☐	☐	☐	☐	2
3	Down hole monitoring	Unlikely < 5%	Marginal	☐	☐	☑	☐	☑	☐	0
4	Casing wear	Unlikely < 5%	Significant	☑	☐	☑	☑	☐	☐	2
5	Kick tolerance	Less Likely 5% - 20%	Small	☑	☐	☐	☑	☐	☑	1
6	Cementing of long casing strings	Unlikely < 5%	Marginal	☑	☐	☐	☐	☐	☑	0
7	Hole size contingencies	Less Likely 5% - 20%	Very significant	☑	☐	☐	☑	☐	☑	5
8	Well access and work-over requirements	Very Likely > 50%	Marginal	☐	☐	☐	☑	☑	☑	2
9	Blow-out contingency	Unlikely < 5%	Very significant	☑	☐	☐	☐	☑	☐	2
10	Unit technical costs	Very Likely > 50%	Very significant	☑	☐	☐	☐	☐	☑	50

Figure 41 Score for the VBB design

VSBB design



Score tables

Summary FR (Max score)	Red 50%	Red 10%	Red 5%	Yellow 2%	Green 1%
FR1 (12)	0	0	1	2	2
FR2 (10)	0	0	0	1	0
FR3 (8)	0	0	0	2	0
FR4 (6)	0	0	1	2	1
FR5 (4)	0	0	0	3	0
FR6 (2)	0	0	1	1	2

Penalty	FR1	FR2	FR3	FR4	FR5	FR6	
	11%	2%	4%	10%	6%	9%	
Sum score for FR	10,7	9,8	7,7	5,4	3,8	2,7	Total 40,1

Assessments

No.	Risk item	Probability	Consequence	FR 1	FR2	FR3	FR4	FR5	FR6	Risk
1	New technology as i.e. packers, liner hangers	Unlikely < 5%	Marginal	☐	☐	☐	☐	☑	☑	0
2	Deviation vs. hole size	Unlikely < 5%	Significant	☐	☑	☐	☐	☐	☐	2
3	Down hole monitoring	Very Likely > 50%	Small	☐	☐	☑	☐	☑	☐	2
4	Casing wear	Unlikely < 5%	Very significant	☑	☐	☑	☑	☐	☐	2
5	Kick tolerance	Less Likely 5% - 20%	Very significant	☑	☐	☐	☑	☐	☑	5
6	Cementing of long casing strings	Unlikely < 5%	Marginal	☑	☐	☐	☐	☐	☑	0
7	Hole size contingencies	Less Likely 5% - 20%	Marginal	☑	☐	☐	☑	☐	☑	1
8	Well access and work-over requirements	Very Likely > 50%	Marginal	☐	☐	☐	☑	☑	☑	2
9	Blow-out contingency	Unlikely < 5%	Very significant	☑	☐	☐	☐	☑	☐	2
10	Unit technical costs	Unlikely < 5%	Small	☑	☐	☐	☐	☐	☑	1

Figure 42 Score for the VSBB design

6.5.4 Verification of safety integrity of barriers

To verify the safety integrity of the final VSBB casing design, the safety barriers are identified and evaluated according to the NORSOK D-010 standard [40].

In Table 26, all the barriers connected to the VSBB design are listed.

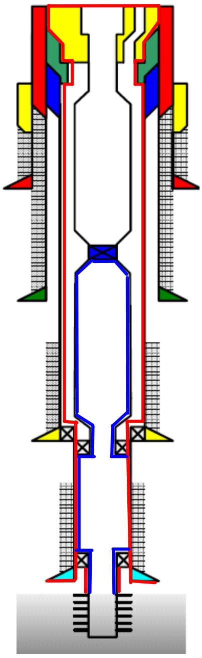
Table 26 Primary and secondary barriers for the well design

Primary barrier	Secondary barrier
• 7” reservoir liner • 7” x 9 5/8” reservoir liner seal • 9 5/8” liner shoe • 9 5/8” production liner between shoe and production packer • 7” x 9 5/8” production packer • 9 5/8” tubing below TRSSSV • TRSSSV	• 7” formation • 9 5/8” liner cement and formation, • 9 5/8” x 13 3/8” liner packer • 13 3/8” casing and shoe • 13 3/8” casing hanger/wellhead seals • wellhead/X-mas tree seals • tubing hanger/X-mas tree seals • 9 5/8” tubing above TRSSSV

In Figure 43, a simplified well schematics and a barrier diagram are shown. The primary and secondary barrier elements are indicated by blue and red lines, respectively. This is an effective way to visualise and describe the barriers, both for the purpose of design verification and for control and follow-up purposes during the operations. A further discussion of this approach is given in the paper, attached in Appendix A.5.

Well schematics **Barrier diagram**

Note: Primary elements are blue, secondary elements are red



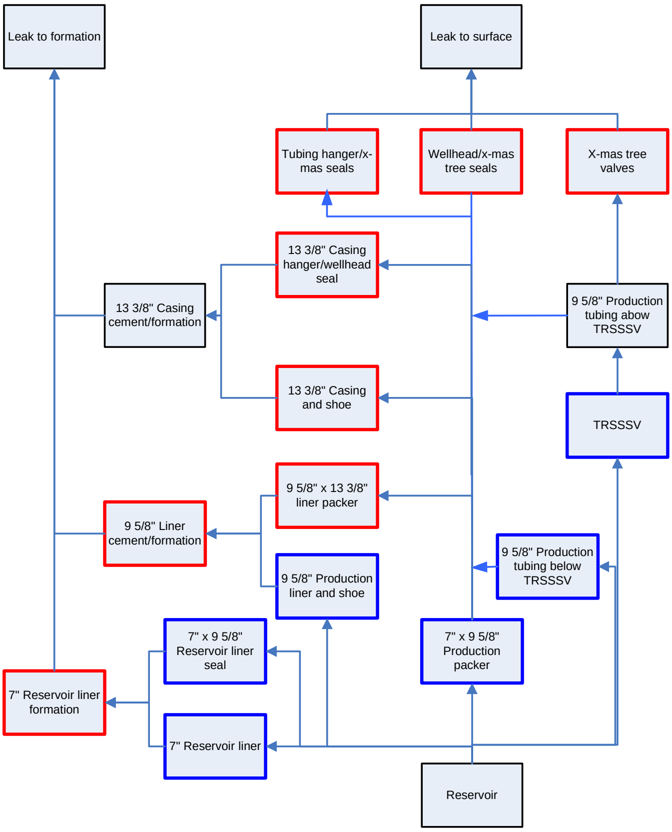


Figure 43 Well schematics and barrier diagram

As seen in the barrier diagram the primary barrier elements are in blue boxes. Primary barrier elements are exposed to the reservoir pressure, and are always followed by secondary barrier elements drawn in red boxes. Thus, the formal requirements to the well barrier design, according to NORSOK D-010, are fulfilled. As required in NORSOK Z-013 [36], detailed risk assessment of well activities should include probability estimates of a blowout with the presumed consequences. A quantitative analysis of the barrier availability then needs to be carried out. Based on the barrier diagram in Figure 43 it is quite straightforward to generate a fault tree model, with a blowout as the top event.

The complete assessment model of the final VSBB design needed for availability assessment of the safety barriers has not been included here. The intention has been to illustrate the approach as part of the decision methodology only, and not to carry out any detailed risk assessment. However, a documented assessment of safety barriers as indicated here, among other detailed studies, should confirm the final well design.

If deviations to the barrier requirements are revealed through these assessments, the final VSBB design might need to be redesigned. If such a redesign interrupts with the original basic assumptions one might need to go one step further back in the design process. Then, questions concerning the selection of basic well concept might be raised. Anyway, this should be looked at as an iteration process until all the safety integrity requirements are fulfilled.

6.5.5 Results and implications of the assessments

The VSBB big-bore well design is the preferred concept with the highest score of 40.1. Thus, the current casing design is similar to the original VSBB [25]. The well concept appears as a big-bore subsea well constituting a 9 5/8” production tubing. It is further equipped with a 7” X-mas tree, and a 7” tubing retrievable sub-surface safety valve (TRSSSV) located 600 metres below the seabed. A horizontal step-out of 1500 metres is anticipated. This design is characterised by having the packer mounted high, near the top of the 9 5/8” production liner. It is here anticipated that the formation outside the 9 5/8” production liner, in combination with the 13 3/8” casing shoe cementation, can be relied upon as the second barrier to the well surroundings. Finally, the well concept utilises the continuous circulation system (CCS) [67] to drill the deep sections efficiently and safely.

6.6 Discussion and conclusion

A case study has been performed where the proposed decision methodology was tested out. Specific procedures were verified and the methodology as a whole was validated.

By following the decision steps of the methodology, a final well design appeared for the given drilling scenario. Modules of the methodology including the specific procedures were selected according to their relevance, and applied to the specific drilling scenario. Limitations and assumptions of the drilling scenario were here taken into account. All the assessments carried out with the generated results, have been documented throughout each step of the methodology, and should form an appropriate basis for decision-making through the main phases of the well delivery process (WDP) [3].

The case study was based on a hypothetical well engineering project. The case description consisted of a specific drilling scenario and some descriptions of technical options that were related to deep-water drilling. The technologies were potential realizations of the expected MPD process and formed an important part of the engineering basis for the current case. The evaluations carried out ended up with a well concept that is based on the former big-bore subsea well concept of VSBB. The actual design consists of a 9 5/8" production tubing, with a 7" X-mas tree, and a 7" TRSSSV located 600 metres below the seabed. To drill the deeper sections efficiently and safely, the continuous circulation system (CCS) [67] has been recommended applied as the MPD.

The final well design should be subject to further assessments in order to confirm its appropriateness. As an example of such detailed assessments, an approach for evaluating the safety barriers of the final subsea production well has been described in the current case study. This approach was based on the NORSOK D-010 standard.

It was early recognised that an intention to cover every detail and aspect of the drilling scenario would have been too extensive within the boundary of the current case study. Thus, an even more pragmatic approach to modelling was conducted in the case study compared to the methodology description (Section 4.5).

The validity of the methodology has been evaluated qualitatively only, thus, no empirical evidence of the usefulness has been provided. However, it is believed that the systematic approach to operational problems, as described through the methodology description and the case study together, is sufficient proof of accuracy and usefulness in the suggested decision methodology. The assessments carried out have been largely “desk analyses”. Thus, when in comes to verification, no sensitivity assessments have been carried out. Measuring sensitivity would have had no meaning as long as input to the models only is given through illustrative examples. The verification that took place was based on qualitative discussions such as the comparison with other existing methods. Much of this discussion is left to Chapter 7 and Chapter 8. Given the above discussion, the need for more comprehensive case studies of the current approach in a real engineering environment seems evident.

To summarise, the new decision methodology was validated and found appropriate for the intended use through the case study and the following discussion. The assessments and evaluations taking place when applying the methodology were found traceable through the detailed method descriptions and in the way the assessments were documented in the case study. Thus, improved confidence was gained with regard to improved decision processes in well engineering. For the most, it is the systematic approach to well engineering, and the way of treating uncertainty connected to relevant decision information.

7 Contributions of the Thesis

This chapter outlines the main contributions of the thesis, both from a scientific and from an operational point of view. It also includes an evaluation of the research process being a part of the current PhD project.

7.1 Scientific contribution

It is a clear opinion within the industry that complicated decision processes in well engineering suffer from insufficient decision quality. The main objective of the current PhD project was thus, formulated:

> *To develop a decision framework adapted to the needs of decision makers responsible for well delivery processes (WDP)*

The main objective of the PhD project has been fulfilled and as part of the framework a new decision methodology has been developed. By applying this methodology, the operators responsible for well engineering should be able to improve their decision-making. The methodology development was based on a structured literature review of petroleum technology and decision support. As they were parts of the total framework, the suggested strategy for an industry implementation and the case study fulfils the PhD project.

The main intention has been to improve confidence among decision makers, and thus, stimulate the utilization of new and alternative technology in deep-water drilling and completion. From a scientific point of view, the following sub-objectives were defined to arrive at the main objective:

1. Review recent technology in drilling, completion and intervention of subsea, deep-water wells
2. Review decision-support literature as the basis for the decision framework
3. Identify steps, activities and important decision milestones of a typical well engineering project
4. Make accurate adaptations of existing methods and tools, and develop a new decision methodology
5. Apply the new decision methodology in a case study and validate it according to the objectives of a hypothetical case scenario
6. Verify the dedicated procedures through the case study
7. Incorporate learning from the case study into the final methodology
8. Specify a strategy for industrial implementation
9. Discuss and draw up conclusions of the main results and suggest subjects for further work

The outcomes from the first three sub-objectives are discussed in Section 7.3, regarding evaluation of the research process. Sub-objective 8 is discussed in Section 7.2, and sub-objective 9 is discussed in Chapter 8. All the others are discussed in this section.

The overall decision methodology has some similarities to traditional risk assessments. The use of risk analysis methods is not new to the well engineering field of the petroleum industry. Inductive methods like the FMECA and HAZOP are typically carried out in the early project phases. An FMECA analysis is used to reveal possible component failures of systems and their possible effects. The intention of a HAZOP is typically to reveal hazards or serious risks connected to a suggested design. Risk assessments are carried out as part of the design verification before the finalisation of a development phase, and/or before any operations can take place.

Given the above similarities, the use of risk analysis methods in combination with methods for decision analysis is somewhat new. Instead of independent risk assessments, the current approach links such assessments directly to the decision processes of well engineering, like the WDP.

An additional point is the appropriate handling of information and the way the methodology directs discussions between parties involved towards common goals (making appropriate decisions). The application of the multi-criteria decision method of AHP is the basic contribution here. The whole framework deals with the information of relevance to assessments, how the assessments are planned and accomplished, and how the results are implemented. There is always a linkage to the decision process in well engineering, i.e. to the value chain. Compared to ordinary risk assessments, these usually serve as one of several types of information that either is used for design verification, or documents the fulfilment of safety requirements. Another aspect is that the current methodology is developed to handle levels of information that can be expected at a specific point of time in the project. This is a somewhat new assumption compared to traditional risk assessments in early design.

The AHP method is a rather new approach to concept selection in well engineering. Another is the combination of the risk-based comparison methodology of Shell and uncertainty analysis by use of the decision tree method. By this approach, dynamical aspects of decisions, as well as uncertainty are modelled.

A well engineering project is challenging both with respect to the evaluations taking part, and to the amount of information required, especially when dealing with decisions under uncertainty. Uncertainty is both modelled by the use of influence diagrams (concept selection) and decision trees (detailed design). What was learned from the case study was that the decision tree models easily grow huge if the intention is to include every intermediate decision and uncertain factors in detailed design. The amount of required information follows the same trend if intending to cover every aspect of the models. Thus, one needs to clearly define the main objectives and expected deliverables in order to limit the number of branches in the model. Thus, one should only focus on the most important elements.

Another important thing that was learned from the case study was that applications of different methods and tools should be flexible and it should be possible to adjust according to the decision scope in each case, or project. Thus, for the implementation part, a module-based software package is recommended. This should be considered as a functional requirement for the new DSS application.

7.2 Operational contribution

Generally told, the practical contribution of the framework is proactive support to well engineering organizations responsible for carrying out decision processes. Among the important decision processes are the identification of alternative well concepts, the selection of the basic well concept and the subsequent detailed design. The current decision methodology increases the quality, and the efficiency of these decision processes. The operational tasks that are most affected are collecting, structuring and analysing of the relevant decision information, and conducting decision-making in project teams based on it. The decision processes are thoroughly documented and made traceable all through the engineering project. Then, it may be possible to track decisions and to re-evaluate decisions if found necessary based on new, updated information.

As a special feedback from Shell, they mentioned the usefulness of applying influence diagrams during the early identification phase of potential well concepts. By applying this method, the linkage between the detailed factors at an operational level and the values aggregated at a higher decision level is identified. This may be done straight up to the highest managerial decision levels. However, the influence diagram modelling approach of the current methodology contains only qualitative models. A possible extension is to develop quantitative models based on the present models. This requires additional information regarding the detailed relations that must be possible to collect at a sufficient quality. The influences are then modelled by the use of accurate algorithms and detailed assumptions. This is a highly relevant approach to consider, improving the basis for top-management decisions.

A two-step implementation procedure for the methodology part of the framework has been suggested. Basically, it accommodates two needs of the engineering organization. Through the first step, the organization could find out by itself, whether or not, the methodology suits their needs, without consulting any external parties. If it fits their needs, the second step guides through the detailed implementation. If not, a lot of work is saved before going into detail. In those cases, the implementation process may be put on hold to wait for more information, or stopped permanently after the self-evaluation. Such a strategy is rather new in the way it involves the intended user from the start. It is not dependent on a consultant or an external adviser to convince the organization with respect to the excellence of the suggested methodology. It fully depends on the organization itself, and how it intents to behave based on its own conviction.

7.3 Evaluation of the research process

The current area of research concerns well engineering and related decision processes. Even though well engineering is known as a rather technical-, and hardware field of knowledge it also deals with human interaction and behaviour in project teams that are important aspects of a project in order to succeed.

My scientific background is that of a natural scientist with basic education as a mechanical engineer, and specialisation within safety and reliability analysis. This background has to a certain point formed the scientific approach of the current PhD project. The work must be seen in a developmental and explorative context. It is mainly about the development of concepts and methods for practical applications. The purpose has been to apply knowledge within existing risk analysis methods and tools to an application area where the lack of such knowledge and utilization has been recognised. Well engineering is much about development and evaluation of technology with the intention of designing for an optimal well efficiency, given the technical, operational and geological aspects of the field. Technical and operational properties and well efficiency of alternative solutions are thus, balanced against lifecycle costs and different risk and uncertainty factors.

The research area of decision support might become huge if the aim is to get a full overview of it. Decision processes also appears somewhat different by comparing different branches. However, the role of expert judgements has been prominent in evolutions of the different approaches. This is a clear opinion based on experience of other researchers and scientists who have worked within the field [30, 31, 33, 34]. In well engineering, major decisions are traditionally taken by experts in team. Thus, one intention of the current research has been to stimulate to a better cooperation between the experts, to arrive at better decisions. The structured literature review of decision support, that also includes the WDP information from Shell, reflects the role of expert judgements. As a consequence, the literature review has been focused on sources that mainly cover decision-making influenced by expert judgements. The sources were textbooks, journal- and conference articles in addition to the industry experience of Shell E&P (see Section 3.1). Actually, the selection of decision-support literature was done based on what was seen most relevant for the current research problem (WDP). Decision support in a more generic perspective might require a more thorough survey of information. The technical part of the literature survey was mainly based on conference articles describing the recent technological evolutions. Information from NTNU and my supervisor was also provided regarding the recent innovations within big-bore concepts and applications of MPD technology [8, 23, 64, 68].

A systematic methodology development was emphasised by the utilization of knowledge within generic risk analysis methods and mechanical engineering. Still, a somewhat pragmatic approach to modelling was followed to ensure applicability of the suggested methodology. Verification of procedures and validation of the methodology as a whole has to a certain degree been conducted through the case study. A full verification of the framework is, however, unrealistic due to the large number of influencing factors that make a precise repetition of a design process virtually impossible. Further verification and development of the current framework must, therefore, be seen in conjunction with a client implementation. Through such, it may be possible to carry out detailed verifications and adaptations of the framework in order to fulfil objectives of a client.

8 Discussion and Conclusions

This chapter discusses the main results of the PhD project and draw some conclusions regarding application of the framework. Finally, recommendations for further work are outlined.

8.1 Discussion of main results

Well drilling and completion in deep-water areas are normally complex and expensive operations to conduct for the operating companies. Thus, development of these oil and gas fields urge for cost-effective, big-bore well designs that may involve new, immature drilling and well technology. Utilization of new technology should increase both the operational efficiency and the production revenue from the fields. However, it also involves uncertainty with respect to well operations, the availability of future installations as well as risks to personnel and the environment. Thus, the responsible decision makers in well engineering need methods and tools, or a focused decision methodology, to support in their decision processes. Important premises are appropriate collecting, structuring and analysing of decision information in order to make the best decisions at any time during a well engineering project.

A new decision methodology has been developed as part of the current decision framework to overcome the above challenges. A conceptual model of the methodology is shown in Figure 25 that provides a visualisation of the procedures and information flow. The arena of application is project-team decision processes of technical matters in deep-water well engineering. The ability of linking decision criteria to properties and characteristics of decision alternatives is a basic expectation for the decision methodology. An important concern prior to developing the methodology was whether it should be adapted to a process oriented, or a procedurally oriented engineering organization (discussed in Section 3.5.3). Process oriented means focusing on the quality of work processes more than detailed procedures. Therefore, the process orientation requires a continuous high focus and involvement from the project members and other experts during the whole project period. The greatest advantage of a process orientated approach is the opportunity of self verification of activities as they are done. Through a multidisciplinary involvement of team members the focus is continuously on the problem, both during the planning and the execution phases of a project. However, a considerable challenge is the time efficiency of the related work processes. There is always need for qualified evaluations and discussions all through the project period. The availability of personnel resources with the right skills might be a critical factor.

With reference to the discussions with Shell, a process orientated approach was selected due to its major relevance. Shell E&P’s global framework, the well delivery process (WDP) has thus, been the industrial link as it is presented in Chapter 4. In addition to the methodology itself, the suggested strategy for implementation presented in Chapter 5, together with the case study in Chapter 6, constitute the main results from this PhD project. Each part is briefly discussed in the following sections.

8.1.1 Methodology

The influence diagram method is applied to visualise the connection between factors and decisions from the detailed operational level, and up to the main decisions taken at the managerial level (tactical and strategic levels). The models should be prepared at a detailed level that makes it possible to aggregate the main contributing factors to the manageable decisions. The models should also reflect uncertainty. The benefits of reducing uncertainty may then be revealed, e.g., through cost-benefit assessments.

The AHP method is used to prioritise between the most valuable well configurations among a set of possible alternatives. Through the AHP assessments it is expected that preferences and objectives of all the stakeholders are evaluated in order to arrive at a consistent prioritization.

The revised risk-based comparison method is used during the comprehensive detailed design of the selected well concept. Most of the information needed to evaluate risks has earlier been revealed through the previous assessments. However, because of the time dynamics of decisions throughout the detailed design phase there is still some uncertainty. Decision trees are therefore regarded as an appropriate approach to highlight the dynamics and uncertainties connected to both, specific events and to the known decision outcomes.

8.1.2 Implementation

Implementation of the new decision methodology in the industry is described by a two-step procedure. The first step describes a specification of information quality related to well engineering projects. The specification is applied in an evaluation of whether, or not the decision methodology fits the given organization. More specifically, the information-quality requirements are evaluated against the main characteristics of the organization under study.

The second step presents a plan of action, containing 14 basic activities for the detailed implementation. These are followed provided that the organization has passed the evaluation carried out in the first step. A guideline to assist in designing of a specific DSS application is here included. The guideline lists the important questions regarding the intended purpose of a DSS application. As part of the guideline a flow-chart model of a generic DSS application indicates the basic processes and dataflow that it should contain. A more specific model is prepared based on the generic model. This model links the basic processes identified in activity No. 4, described in Section 5.3, to the new DSS application. Thus, an updated overview of the information flow and processes, within, and outside the organization is obtained. The flow-chart model also functions as a means to structure the specific content of the proposed DSS application.

A review of the existing procedures in the project organization under study might be necessary in connection with the implementation to avoid any information overlap with existing information systems.

8.1.3 Case study

The dedicated procedures in the new decision methodology were tested out during the case study in this PhD project. The case study also served as a validation of the methodology according to its intended use. By following the decision steps of the methodology, a final well design appeared for a given drilling scenario. The relevant procedures (or modules) were picked from the methodology and applied to the scenario according to their relevance. Also of concern, were the limitations and assumptions connected to the scenario itself. The assessments were documented throughout each step of the methodology corresponding to the main phases of Shell E&P's well delivery process (WDP) [3].

The new decision methodology was found appropriate through the assessments that took place. The decisions were made traceable by the method descriptions and the assessments. Thus, improved confidence with regard to decision-making was proved by the systematic approach, not least in the way the uncertainties connected to the decision information were treated.

8.2 Conclusions

A new decision methodology has been developed. It forms the main part of the decision framework in addition to the technical descriptions of deep-water drilling and completion technology, the suggested strategy for implementation and the case study with an application example.

For the purpose of decision support, the proposed methodology applies risk analysis methods in combination with methods for decision analysis. This combination is somewhat new compared to traditional risk assessments that normally apply to design verification studies in well engineering. The current approach links the use of analytical methods, directly to the value chain, i.e. the decision processes of well engineering, or the WDP. The decision methodology consists of the following three basic steps, included their main deliverables:

1. *Definition of technical decision scope and structure of the WDP*
   - Deliverable: Set of alternative concepts
2. *Selection of basic well concept"*
   - Deliverable: Most promising concept
3. *Conducting detailed design and approval*
   - Deliverable: Approved final design

Main features of the framework are given below with respect to its application:

Detailed technical and geological factors at an operational level are linked to the important decision values aggregated at a higher decision level. The linkages are fitted to the available information at the time by using adaptive influence diagram models.

Discussions between different parties in well concept-selection processes are directed towards common goals. Here, the application of the multi-criteria decision method of AHP is the basic contribution.

The dynamic aspects of decisions in the detailed design phase, and uncertainty connected to events are modelled by use of the decision tree method. These assessments provide additional input to the technical selection process when using the revised risk-based comparison methodology of Shell.

An industrial implementation of the decision methodology is based on participation of the intended user from the start, throughout the implementation process. Some basic characteristics of the organisation should exist. However, the usefulness of the methodology should always depend on the user's own conviction.

8.3 Recommendations for further work

It is always possible to improve models and methods, and that is also the case for the current framework. Decision support is a wide area of science. The conducted literature survey was adapted to the specific research problem of the current PhD project. In this connection, it may be of interest to contact one or several research communities that recently have been in front of the research area. The current methodology should then be verified against approaches and experiences of those communities. Apart from this, the following recommendation for further work is suggested:

8.3.1 Implementation

Several assessments and tasks are carried out in an engineering organization, of which not all are defined within the current framework. Examples are the simulation studies of drilling and completion scenarios involving the different technological solutions, and qualification testing of components according to the conditions of the field. Thus, the current methodology needs to be verified thoroughly in a real engineering environment. The intention is twofold:

- To make boundaries between contributions from the current approach and existing approaches and information systems
- To verify the detailed procedures against the objectives of a real project

8.3.2 Models

A possible extension of the methodology is to develop quantitative influence diagram models out of the current qualitative models. These models should link technical and geological factors at the operational level to the manageable-level decision values. Prior to such an extension, an information survey among a selection of operator companies is recommended. The important topic for the survey is to find out, whether or not, there is available information at appropriate quality and cost, and capabilities in “typical” engineering organizations that could defend, and support such an extension. There is also a need for more focused case studies within the framework, both by applying the whole set of procedures, or only single methods at the time. Decision tree models easily become huge and the need for information follows. One suggested case study is, thus, to test out what the practical size and composition of decision tree models actually are. The main intention is to contribute with additional information to the risk-based comparison assessments, as given by the revised Shell-method described in Section 4.5.3.

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Appendix

Appendix A.1 Acronyms

Acronym		Full text
AAR	-	After Action Review
AHP	-	Analytical Hierarchy Process
ALARP	-	As Low As Reasonable Practical
BHA	-	Bottom Hole Assembly
BHP	-	Bottom Hole Pressure
BOP	-	Blowout Preventer
CAPEX	-	Capital Expenditure
CCS	-	Continuous Circulation System
CERT/IERT	-	Completion/Intervention Equipment Review Team
CSR	-	Concept Selection Report
CWOP	-	Completion the Well on Paper
DAPC	-	Dynamic Annular Pressure Control
DE	-	Diametric Efficiency
DP	-	Dynamic Positioning
DSS	-	Decision Support System
DtL	-	Drilling the Limit
DWOP	-	Drill the Well on Paper
ECD	-	Equivalent Circulation Density
ECD RT	-	Equivalent Circulation Density Reduction Tool
FCA	-	Functional Category Analysis
FEE	-	Front End Engineering
FMECA	-	Failure Modes Effects and Criticality Analysis
FR	-	Functional Requirement
FTA	-	Fault Tree Analysis
GDSS	-	Group Decision Support System
GIR	-	Group Individual Risk
GLIR	-	Gas Lift In Riser
GOM	-	Gulf Of Mexico
HAZOP	-	Hazard and Operability Analysis
HSE	-	Health, Safety and Environment
LCC	-	Lifecycle Cost
LRRS	-	Low Riser Return System
MAASP	-	Max Allowable Annular Surface Pressure
MPD	-	Managed Pressure Drilling
MTTF	-	Mean Time To Failure
MWD	-	Measurement While Drilling
NCS	-	Norwegian Continental Shelf
NPV	-	Net Present Value
OPEX	-	Operational Expenditure
OPMG	-	Opportunity and Project Management Guide
ORP	-	Opportunity Realization Process

Acronym		Full text
PHA	-	Preliminary Hazard Analysis
PLL	-	Potential Loss of Life
PSA	-	Petroleum Safety Directorate
RAM	-	Reliability Availability and Maintainability analysis
RLWI	-	Riser Less Well Intervention
RM	-	Riser Margin
ROMC	-	Representation Operations Memory aids and Control
SCSSSV	-	Surface Controlled Sub-Surface Safety Valve
SDLC	-	System Development Lifecycle
TD	-	Total Depth
TRSSSV	-	Tubing Retrievable Sub-Surface Safety Valve
TTRD	-	Through Tubing Rotary Drilling
TVD	-	True Vertical Depth
TWOP	-	Testing the Well On Paper
VBB	-	Variant Big Bore
VSBB	-	Variant Slick Big Bore
WDP	-	Well Delivery Process

Appendix A.2 Glossary

Terms		Explanations
Annulus	-	Space between the tubing and the production casing [40]
Abandonment	-	Well status, where the well or part of the well, will be plugged and abandoned permanently, and with the intention of never being used or re-entered again [40]
Analytical Hierarchy Process (AHP)	-	An approach to decision-making that involves structuring multiple choice criteria into a hierarchy, assessing the relative importance of these criteria, comparing alternatives for each criterion, and ranking of the alternatives [30]
Big-bore well concept	-	Well designs with a completion that utilises a 7” or larger production tubular [69]
Critical	-	Activity or operation that potentially can cause serious injury or death to people, or significant pollution of the environment or substantial financial losses [40]
Completion	-	Equipment installed in a well after it is drilled to allow hydrocarbons to be produced [69]
Cost/Benefit Analysis (CBA)	-	A systematic, quantitative method for assessing the lifecycle cost and benefits of competing alternatives. Typical measures in CBA are return on investment (ROI), net present value (NPV), and discounted cash flow [30]
Data Flow Diagram (DFD)	-	A modelling method used for process modelling that graphically depicts business processes and the logical flow of data through a process [30]
Decision information	-	Information that is provided as service to an end user, being a decision maker (adaptation of [2])
Decision quality	-	Quality decisions are the result of providing sufficient information on key attributes of the decision [3]
Decision Support System (DSS)	-	A system under the control of one or more decision makers that assists in the activity of decision making by providing an organized set of tools intended to impose structure on portions of decision-making situations and to improve the ultimate effectiveness of the decisions outcome [2]

Terms		Explanations
Deep water	-	Deep water applies to greater than 600 metres water depth. Ultra deepwater refers to deeper than 1500 metres [28]
Framework	-	A skeleton of technologies, methodologies and procedures that are integrated for a specific solution to a problem. The intention may be software development [70]
HTHP well	-	High-pressure and high-temperature well with expected shut-in pressure exceeding 69 MPa, or a static bottom hole temperature above 150 degrees C [40]
Information system architecture	-	The manner in which the various pieces of the system are laid out with respect to location, connectivity, hierarchy, and internal and external interactions [2]
Kick tolerance	-	Maximum influx to equal MAASP [40] Note: MAASP - Maximum Allowable Annulus Surface Pressure MAASP is based on the weakest zone in the well bore, normally assumed to be at the casing shoe
Managed Pressure Drilling (MPD)	-	An adaptive drilling process used to precisely control the annular pressure profile throughout the well bore and to assert down-hole pressure environment limits [21]
Methodology	-	A collection of methods and tools adapted to a defined problem. It refers to the rationale and the assumptions that underlie a particular study [70]
Operation	-	Sequence of planning and execution tasks that are carried out to complete a specific activity [40]
Plugging	-	Operation of securing a well by installing the required well barriers [40]
Primary barrier	-	First object that prevents flow from a source [40]
Pumping	-	Injection or flow of a fluid from a surface reservoir and into the well [40]
Regularity	-	A term used to describe how a system is capable of meeting demand for deliverables or performance [61]
Reservoir	-	Permeable formation or group of formation zones originally within the same pressure regime, with a flow potential and/or hydrocarbons present or likely to be present in the future [40]

Terms		Explanations
Riser margin	-	Additional fluid density added to the hole below the mudline to compensate for the differential pressure between the fluid in the riser and seawater in the event of a riser disconnect [40]
Risk element	-	Risk factor used to differentiate comparable options in detailed design, applying the risk-based comparison methodology [4]
Secondary barrier	-	Second object that prevents flow from a source [40]
Shallow gas	-	Free gas or gas in solution that exists in permeable formation which is penetrated before the surface casing and BOP are installed [40]
Simultaneous activities	-	Activities that are executed concurrently on a platform or unit, such as production activities, drilling and well activities, maintenance, modification and other critical activities [40]
Spud	-	The point in time the drilling is started [29]
Surface casing	-	The last casing installed prior to drilling into an abnormally pressured formation or the reservoir formation [40]
Temporary abandonment	-	Well status, when the well is abandoned and/or the well control equipment is removed, with the intention that the operation will be resumed within a specified time frame [40]
Trip margin	-	Incremental increase in drilling fluid density to provide an increment of overbalance in order to compensate for effects of swabbing [40]
Under balanced drilling (UBD)	-	Drilling operation where the dynamic bottom-hole pressure in the well bore is intentionally lower than the pore pressure of the formation being drilled [40]
Well barrier	-	Envelope of one or several dependent barrier elements preventing fluids or gases from flowing unintentionally from the formation, into another formation or to surface [40]
Well barrier element	-	An object of a well barrier that alone can not prevent flow from one side to the other side of it self [40]
Well control	-	Collective expression for all measures that may be applied to prevent uncontrolled release of well bore effluents to the environment, or uncontrolled underground flow [40]

Terms		Explanations
Well delivery process	-	A common framework to guide the way operators select, plan and execute well and well service projects [3]
Well delivery team	-	A multidisciplinary project team responsible for carrying out the well delivery process [3]
Well engineering	-	The selection, planning and accomplishing of wells and well services [3]
Well influx	-	Unintentional inflow of formation fluid from the formation into the well bore [40]
Well integrity	-	Application of technical, operational and organizational solutions to reduce risk of uncontrolled release of formation fluids throughout the lifecycle of a well [40]
Well intervention	-	Collective expression for deployment of tools and equipment in a completed well [40]

Appendix A.3 Technical descriptions

Appendix A.3.1 Big bore well - the improved Arun design

This appendix describes the improved Arun design [26]. Both the original and the improved Arun design are shown in Figure 44. This design preserves the true mono-bore concept and reduces the possibility of any gas turbulence from the landing nipples and tubing restrictions of the original Arun design. For this reason, two elements were focused on in the development of the new Arun design:

1. A 9-5/8” tubing retrievable sub-surface safety valve (TRSSSV)
2. A new high-load permanent packer.

The latter was to eliminate a potential leak path to the completion in the area of the previous upper polished bore receptacle (PBR), while requiring a third trip to finalize the completion. It was seen that the elimination of this feature would have several benefits. First, the system complexity was reduced. Second, a potential leak path was eliminated, and third, the completion operation was reduced from a three-trip completion to a two-trip completion. The targeted configuration and benefits were accomplished by a new high-load permanent packer that was designed to handle all the tubing movement loads, and thereby eliminated the existing upper PBR of the original Arun concept.

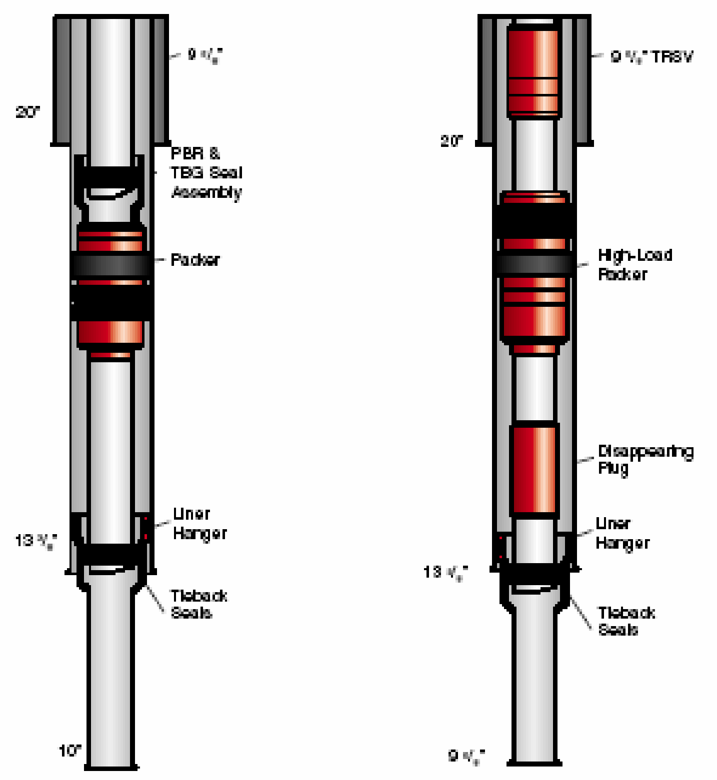

Figure 44 The original and improved Arun design (copied from [24])

Tubing retrievable sub-surface safety valve (TRSSSV)

A TRSSSV for a 9 5/8” tubular was developed, as shown in Figure 45. When it was first given serious thought, it was generally accepted that a 16” casing at the valve would be required to accommodate the large outer diameter. But, it was soon realized that the capability to run the TRSSSV inside a 13 3/8” casing would provide enormous benefit [24]. The goal, therefore, was to achieve an outer diameter that would be compatible with a 13 3/8” casing and be capable of accommodating a cable bypass. In keeping with a true mono-bore completion design, the desire was to have an I.D. approaching tubing drift. A no-go system that allows the valve-insert equipment to locate without the reduction in internal diameter, that a conventional no-go shoulder requires, was developed.

Knowing that these valves most likely would be used exclusively in high flow rate gas completions, the capability of the TRSSSV to slam shut against high flow rates was a critical parameter in the validation testing. However, slam testing was by no means the only criteria. A rigorous test programme was carried out according to API 14A. It included a combined load testing of all connections and an endurance testing to simulate a 20-year lifecycle.

High-load permanent packer

In order to increase the reliability and running efficiency of the new large-bore mono-bore completion system, the elimination of the upper PBR of the original Arun design was needed [24]. To support this elimination, a new production packer was developed being capable of absorbing loads created by the expected tubing movement (see Figure 45).

In contrast to the conventional segmented slips commonly used on packers, the new packer was developed with a one-piece circumferential slip, evenly distributing the load over a wide area. This resulted in a lower stress imparted to the casing. In addition, multiple ramps were used to energize the slip, again ensuring a more even load distribution than a conventional segment. Instead of applying the typical “squeeze” to energize the elements, the package is expanded radially on a ramp to provide the contact with the casing and form an annular seal. The control of burst impact is then higher than compared to the conventional “squeeze” technique used for most packers. Permanent packer features and reliability are provided while allowing equipment retrieval.

Validation testing plays an important role in the overall reliability of the completion system including the packer. Exposing the packer to the expected loading and gas environment is critical. The regulatory standard ISO14310 [71] addresses many aspects of packer validation and is the chosen test programme for this packer design as well.

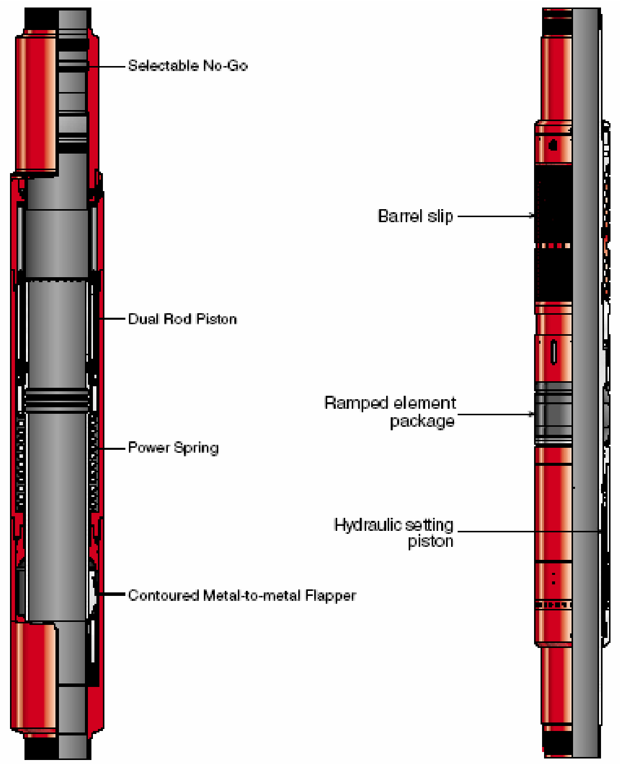

Figure 45 TRSSSV and hydraulic set packer (copied from [24])

Disappearing plug technology

The "Disappearing plug" technology [72] eliminates the need for the completion riser and drilling rig during subsea tree installation. It allows the testing of the tubing string and setting of the packer without intervention because it acts as a well barrier. The disappearing plug performs the same function as the tubing hanger plug, until it is opened remotely from the host facility. The running of the completion system is reduced from three trips to two trips [24]. Installation of a subsea tree from a floating drilling rig is a complex and time-consuming operation. Removing the subsea tree installation from the "critical path" of rig time would yield a step-change reduction in the time and cost to complete a subsea well.

A down-hole "Disappearing plug" would allow the packer to be set, and the well suspended, without any usual slick-line intervention.

Wellhead plug

In keeping up with efficiency and a reduction of complexity, a 9-5/8” wellhead plug was developed [24]. The plug is compact through the inclusion of a non-bearing no-go feature. This allows the plug to have a much smaller O.D. than conventional plugs that again reduces the valve and riser size.

A back-pressure valve has been designed that uses the same plug body but incorporates a one-way check valve to allow pump-through capability. Both plugs are easily set and retrieved by wireline methods. Both the wellhead plug and back-pressure valve use the same running and pulling tools.

Liner hanger

If the well construction requires the use of a liner hanger to reach total depth, a highly reliable hanger can be deployed that is the same type as that used on the original Arun completions [24]. The liner hanger uses unique slip technology that, much like the high load permanent packer, distributes the load over a wide area, thus reducing the stress imparted to the casing. The slips can be designed to accommodate any expected loading scenario.

Wireline retrievable plug

Without landing nipples, a means for landing and setting a temporary barrier or intervention device becomes necessary. A field-proven 9-5/8” wireline retrievable bridge plug has already been developed [24]. This device allows the setting of flow-control devices (such as gauges or plugs) anywhere within the tubing string. The retrievable bridge plug is not restricted to predetermined and limited landing nipple locations and gives the operator maximum flexibility.

The plug uses circumferential slips similar to those found in the high-load packer. The placement of the slips below the packing element has been proven to increase retrieval reliability. This plug has been in use for several years and has a commendable field history. It has been used mainly in the Southeast Asia, North Sea, and South America regions.

Expandable screen

An expandable screen design was developed for the Marlim Sul Field, located in Campos Basin, Brazil [73]. Due to the presence of unconsolidated sandstone, sand control was mandatory. Open-hole gravel pack was used to avoid sand production. The application of new technologies such as a rotary steerable tool, expandable screens and synthetic oil base drilling and completion fluids allowed a new horizontal well design, eliminating one operational phase in well construction. The design uses a 30” conductor casing, 10 3/4” production casing and a combination of conventional 7” liner and 5 1/2” expandable screen inside the 8 1/2” well. The liner and the expandable screen are deployed in one trip.

The expected savings was about 25% of the original well construction cost compared to a standard design. This cost reduction was mainly due to the decreased rig time in operations caused by the following:

- One operation less than for a conventional screen, avoids a BOP run
- Fewer trips needed for bit changes
- Speed-up of penetration rate by use of a rotary steering tool
- Elimination of one change of mud weight

Appendix A.3.2 Description of MPD technology

This appendix gives a technical description of the five MPD technologies that are considered in the case study of the current thesis. Also included in the descriptions are different applications and benefits of each concept.

Appendix A.3.2.1 Continuous circulation system

Drilling with a continuous circulating system (CCS) means drilling without interrupting circulation while new joints of drill pipe are added to the drill string [67]. It was developed over a three-year period by a joint industry project (JIP) managed by Maris International, and introduced in 2003.

The entire system is made up of a coupler as shown in Figure 46. The CCS is actually a pressure chamber located on the rig floor, over the rotary table, through which the drill string passes and seals around the drill pipe pin and box during the connection process.

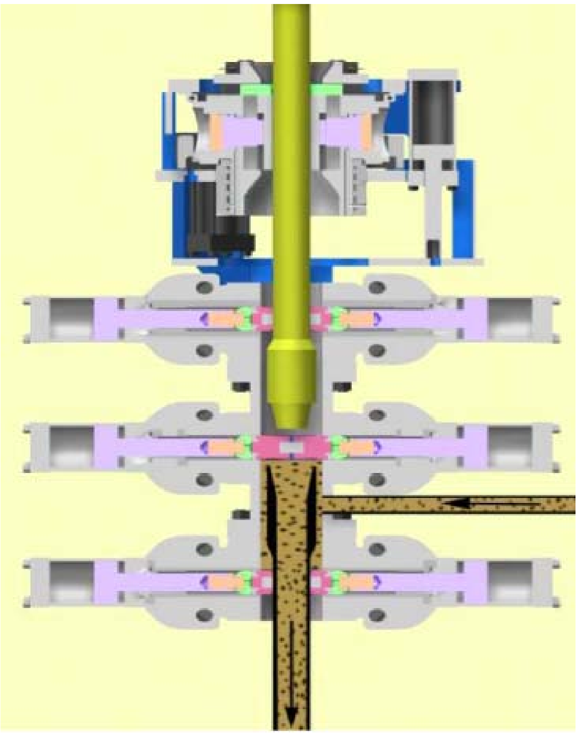

Figure 46 The CCS system (copied from [67])

The CCS system comprises the following sub-systems with their main functions:

- Mud diverter manifold - connected into the discharge line between the mud pumps and the standpipe manifold. The main function is to switch mud between the top drive and the coupler during the connection process.
- Extension/wear sub - attached below the top drive. The main function is to connect to the top of each new stand/joint to position the tool joint within the coupler correctly to make the connection, or break the connection
- Top drive connection tool - allows the extension, or wears sub to be made up to, and broken from the top of a stand in the derrick
- Independent hydraulic power unit (HPU) and electro-hydraulic controls operated by the driller using a touch screen system.

Applications

The following applications can utilize the CCS system:

Long deviated sections: An uninterrupted circulation while drilling *long sections* of a highly deviated hole will allow continuous movement of drilled cuttings, and minimize the risk of cuttings built up in the annulus.

Deep-water Wells: The improved ability to drill shallow water formations immediately below the sea bed is achieved by reducing the likelihood of a hole collapse and/or stuck pipe conditions.

Narrow pore pressure/fracture pressure gradient: By continuous circulation throughout a critical hole section, improved ECD control is achieved by adjusting the circulation rate and the drilling fluid density.

Pressure sensitive wells: Formations that are sensitive to pressure changes, such as shale and salt, may cause problems if circulation is stopped. When circulation is stopped, these formations are allowed to relax and slough or squeeze into the well bore resulting in stuck pipe or loss of the hole.

Circulate/Drill-in liners: The open hole conditions may require the circulation of drill-in liners through parts of, or the entire open hole. This is greatly improved by continuous circulation.

Safety: Improved safety is obtained by elimination of any kick while making a connection and the accompanying stuck pipe possibility while killing the well. Automation of the system removes personnel from the connection process, improving the level of safety around the drill floor.

Benefits of CCS

Potential applications of CCS have been investigated since the system became a real option for the industry. The most basic benefit is the reduced total connection time, i.e., the time from stopping drilling to recommencing drilling. Especially, this is a major contribution in cases of high rig rates. Another benefit is the improved ability to drill pressure sensitive sections without imposing any pressure surges. Below is a list of specific benefits that are linked to the relevant operational and/or geological aspects of drilling:

Long deviated sections:

- Improved hole conditions
- Reduced probability of stuck pipe
- Reduced rotary torque
- Improved directional control of the drill string

Drilling deep-water wells:

- Less hole collapse
- Reduced probability of stuck pipe

Narrow pore pressure/fracture pressure gradients:

- Avoid pressure surge each time the pumps are started after a connection
- Reduced probability of lost circulation and ballooning

Pressure sensitive wells:

- Maintained formation stability

Circulate/drill-in liners:

- Improved annulus cleaning
- Avoidance of stuck liner while keeping circulation

- The liner lap is continuously swept that eliminates any build-up of cuttings blocking an effective placement of cement
- Avoidance of stuck pipe when applying drill-in liners with a tight annular clearance

Safety:

- Reduced kick frequency
- Automation removes personnel from hazardous areas

Appendix A.3.2.2 Gas lift in riser

The gas lift in riser concept (GLIR) is actually an option for dual gradient drilling. By using dual gradient drilling the resulting effective mud weight at the previous casing shoe is less than the effective mud weight at the drilling depth. Building on proven air drilling procedures and under-balanced techniques, nitrogen is used to cut the mud weight back in the riser above the seafloor. As an example, it is maintained through the subsea BOP, as indicated in Figure 47. Alternatively, the injection may be made even deeper by including a separate conduit between the casing strings [74].

Making a connection is similar to the under-balanced drilling by applying a rotating BOP. Nitrogen is supplied by keeping the compressor running while making a connection. A valve shuts in the mud and avoids it from running back into the hole. Again, there is a standard tool from under-balanced drilling that covers this functionality. This “flow stop” is fitted to the drill string. The technology is somewhat new to ultra deepwater, but has been regarded as a standard tool for under-balanced drilling. The valve might be mechanical spring operated, wireline or mud-pulse operated.

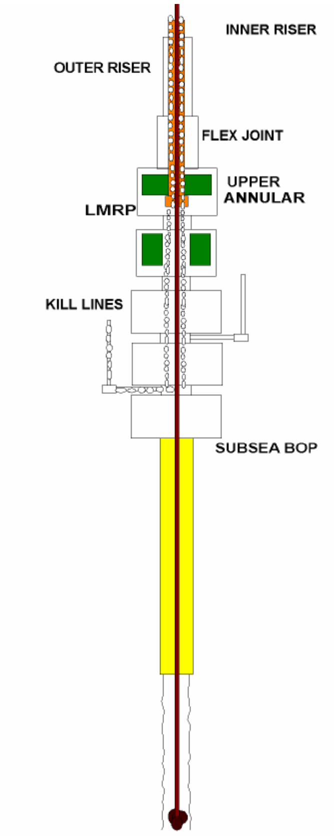

Figure 47 Nitrogen injection through a subsea BOP (copied from [74])

Applications and well control

The nitrogen injection approach is a very dynamic system where kick detection is a major concern. However, the kick probability is reduced if the operation is done prior to encountering the reservoir formation. The dual density is suited for the upper sections of the hole where formation characteristics are found unfavourable. If a gas lift solution here eliminates 2 or 3 strings of casing, the benefits have been achieved prior to reaching the reservoir. The reservoir formation may thereafter be drilled conventionally. While drilling, the kick awareness is normally raised after a drilling break. When a kick is suspected due to a reduced pump pressure (while the nitrogen system is kept constant) the mud pump is stopped and the nitrogen then breaks out. As during a trip, the mud level will fall to an easily estimated point in the riser. If the well is under-balanced, the pressure sensor in the subsea BOP will indicate that the mud level is rising. At that point a kill circulation will be undertaken. While it is not possible to load the well with a “kill” fluid, it would be possible to reduce the nitrogen injection rate - thus, increasing the bottom hole hydrostatic pressure - and to circulate the kick fluid out.

Benefits of gas lift

To achieve the dual gradient effect by gas lift has several attractive features:

- No new equipment is required below the surface
- All moving parts are on the surface
- All the gas lift equipment being used may be maintained without implying a trip to the seafloor
- The nitrogen generators may be temporarily installed if not already part of the rig equipment
- No major investment in “dual gradient” technology is needed
- The equipment may be rental
- Gas lift combines proven technologies of gasification drilling and under-balanced drilling
- The usage of a concentric riser reduces the needed gas volume

Appendix A.3.2.3 Equivalent circulating density reduction tool

The equivalent circulating density reduction tool (ECD RT) is designed to counter down-hole pressure increase due to friction in the annulus by reducing the hydrostatic head [75]. The tool is integrated in the drill string and consists of three section parts. At the top is a turbine motor, which draws energy from the circulating fluid and converts it into mechanical power. In the middle is a multistage mixed pump, part-axial and part-centrifugal, which is driven by the turbine motor and pumps return fluid in the annulus. The lower section consists of bearings and seals. The turbine is matched to the pump duty so that no gearbox is required. Figure 48 illustrates an ECD tool application, as experienced by Weatherford through a field trial [76].

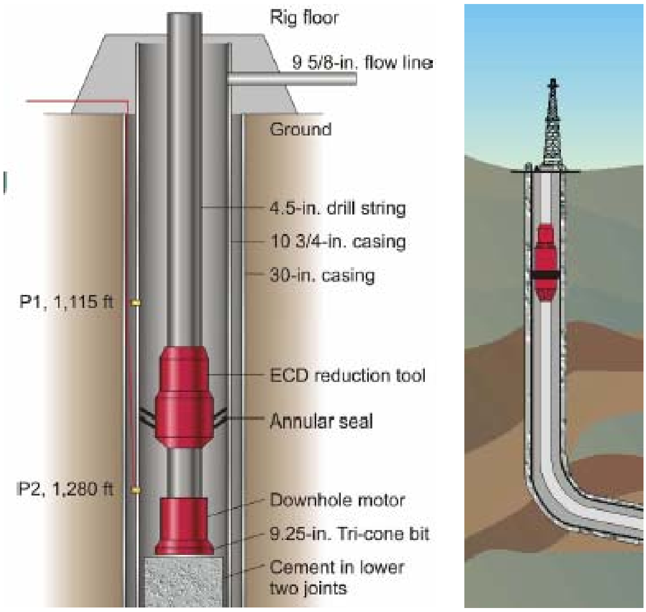

Figure 48 ECD reduction tool from Weatherford (copied from [76])

There is no need for a full trip to add or service the ECD tool since it is designed to be located in the upper section of the well. It is typically installed in the drill string at a depth of 1000 ft at the initiation of a bit run. The tool includes two packer-type seals to seal the pump body inside the casing and to ensure that all returning fluid passes through the pump. It is capable of processing drill cuttings by a grinding mechanism located just below the pump. Tests have shown that 5/16” (8 mm) and smaller cuttings smoothly can pass the pump.

Applications

The ECD RT was designed to be a portable tool, applicable to a wide range of well types, both onshore and offshore. The tool was intended to be a low cost alternative to dual gradient systems for deepwater drilling where the issue is to overcome the significant hydrostatic pressure in the riser. The tool is intended for drilling applications such as:

- Narrow pore/fracture pressure margin in deepwater environment
- Well bores prone to instability
- Pressure depleted reservoirs

- Extended reach wells
- If it is wanted to reduce the impact of uncertainty with respect to casing setting depth (the usable pressure margins)

Benefits of ECD RT

In extended reach drilling, the ECD RT may permit the use of heavier drilling fluid to improve the well bore stability without increasing the risk of fracturing the formation or causing any mud loss. The benefits of applying the ECD RT are then:

- Improved well bore stability by tolerating higher static mud weights
- Extended hole intervals and reduced number of casing strings
- Improved hole cleaning by virtue of higher flow rates
- Reduced impact of uncertainty on casing setting depth by widening the usable pore and fracture pressure gradient margin
- Reduced lost circulation in permeable formations
- Reduced formation damage due to lower dynamic overbalance
- Low cost alternative to dual gradient systems

Appendix A.3.2.4 Dynamic annular pressure control

The aim of the dynamic annular pressure control system (DAPC) is to ensure a constant bottom hole pressure all the time by applying an automatic back pressure control system. An illustration of the system developed by Shell E&P is shown in Figure 49. The system was successfully tested in 2003. A long-term trial on a deep geothermal well was conducted in 2004 proving the robust nature of the design [20].

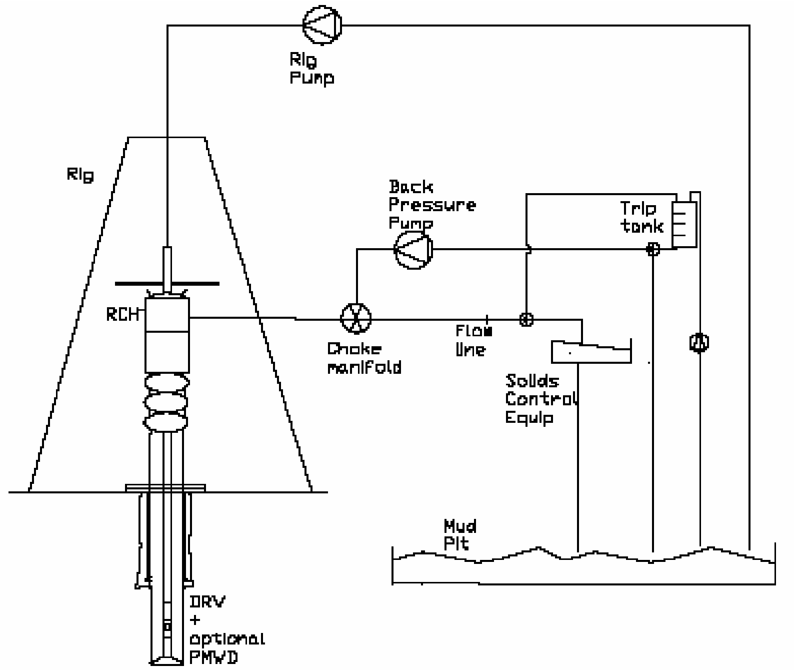

Figure 49 DAPC system (copied from [20])

The main components of the back pressure system are:

1. Control system based on a hydraulic model
2. Choke manifold and a backpressure pump
3. Rotating control device

The rotating control device is needed to maintain a dynamic seal on the annulus, enabling the choke to control the annular pressure at the surface [77]. This seal allows continuous drilling while controlling the influx of formation fluids.

The purpose of the hydraulic model (programme) is to calculate the required $P_{surface}$ set point to obtain the desired $P_{down-hole}$. It is necessary to use a hydraulic model to calculate the pressure set point since feedback from the down-hole pressure sensor is usually too slow or intermittent for the control loop. The reasons for that are connected to the low telemetry speed and different risks of interruptions.

The electric pump in combination with the choke is installed on the annulus discharge, upstream of the choke, to provide pressure to the well when the main drilling pumps operate at a reduced rate, or are stopped.

The choke manifold is usually fitted with a redundant choke in the event that the first one fails or is plugged. The ability to change to the other choke after a failure of the first increases the system availability significantly.

The electro-mechanical equipment is compliant to the European ATEX directives for such equipment used in hazardous areas.

Applications of DAPC

The DAPC system is applied to wells requiring the bottom hole pressure to be maintained constant of bore hole stability reasons. As of 2004, two offshore wells have been successfully drilled with the system [20]. The desired bottom hole pressure during drilling were for those wells successfully maintained.

Benefits

Benefits of using the DAPC are:

- Maintains the bottom hole pressure within required limits
- Quick recovery from a differentially stuck pipe situation may be obtained by momentarily reducing the back pressure, achieving substantial time and cost savings
- In cases of flow interruptions the system is capable of a rapid pressure recovery

Appendix A.3.2.5 Low riser return system

The low riser return system (LRRS) [68], also called controlled mud cap (CMC) [64], consists of a pressurized riser without any kill- and choke lines. The riser is connected to a subsea BOP at the seabed and, and at the other end to a surface BOP located on the drilling vessel. Drilling fluid is pumped down through the drill-string and the mud return is taken in the annulus region between the drill string and the drilling riser. At a certain calculated depth in the riser, the return of the drilling fluid is diverted through an outlet that is connected to a pumping system and pumped up to the platform. An illustration of the system is shown in Figure 50. Also shown in the figure is the sea water pressure gradient, compared to the annulus pressure gradients (both static/dynamic) and the fracture pressure gradient.

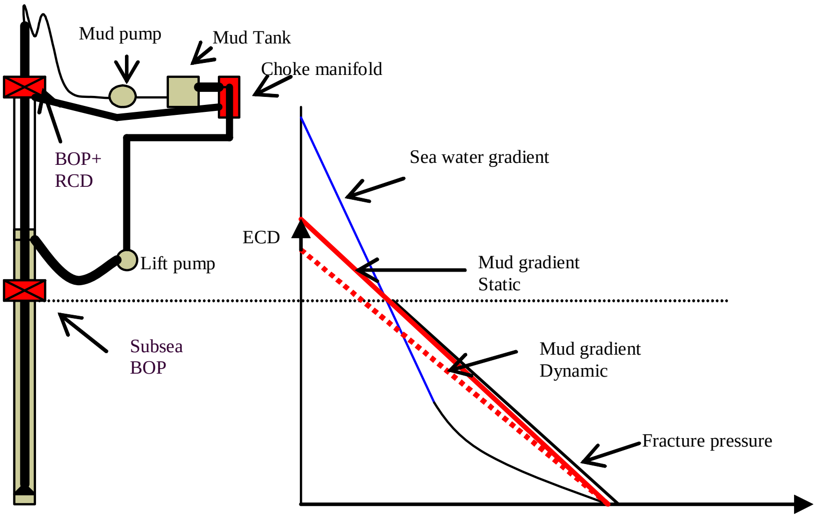

Figure 50 LRRS/CMC with a HP-riser & two BOPs (copied from [64])

The drilling fluid level in the riser may be dropped below sea level and adjusted by the subsea pumping system so that the hydraulic pressure in the bore hole is controlled. Dynamic drilling process requirements appear by measuring and adjusting the liquid level in the riser. Due to the dynamic nature of the drilling process, the liquid level will never remain steady. The liquid level could be anywhere between the normal return level on the drilling vessel above the surface BOP, and the depth of the low riser return section outlet. In this fashion the bottom-hole pressure is controlled by regulating the liquid level in the riser.

Applications

An application of the LRRS is when expecting high-pressure zones both deep in the well, and in the formation higher up. An example is when the surface casing shoe cannot support the expected riser return level or the drilling fluid density that is needed. This can be compensated for, by dropping the fluid level in the riser while increasing the mud weight. The combined effect will be a reduced pressure at the upper casing shoe while keeping a higher pressure at the bottom of the hole. Thus, the pressure is maintained without exceeding the fracture pressure below the casing shoe.

Another application is to drill through severely depleted reservoirs and always stay in-balance. With the LRRS, the bottom-hole pressure exerted by the fluid in the well-bore can be regulated to less than the hydrostatic pressure of water. Alternatively, this should require special drilling fluid systems like gases, air, foam, or similar. Instead, the LRRS can achieve this with a seawater drilling-fluid system.

Benefits of LRRS/CMC

Several advantages arise from the LRRS solution:

- Hydrodynamic overbalance is maintained and ECD is compensated for by adjusting the level in the riser while keeping the same mud weight
- Measure while drilling (MWD) capabilities remain unchanged from normal drilling
- Geo-steering may be performed, and there will be no difference in hole cleaning capabilities
- The drilling riser functions as a first stage gas knock-out separator eliminating or reducing large and costly separation systems topside
- Allows longer sections to be drilled
- Normal well control procedures will apply
- The riser is at atmospheric pressure at the surface

In addition to the above descriptions, reference is made to the MPD-performance overview given by Table 4-1 in the conference paper attached in Appendix A.4. In this table the different MPD concepts were evaluated with respect to some selected deep-water drilling requirements. This evaluation was based on the above listed benefits for each MPD. The paper in Appendix A.4 actually documents the decision analysis carried out by use of the analytical hierarchy process method that was referred to in the case study (Section 6.5). The mentioned drilling requirements were used as main decision criteria when establishing the AHP hierarchy.

Appendix A.4 Conference paper No. 1

Decision-making in Oil/Gas Well Engineering

Eivind Okstad and Marvin Rausand, PSAM8, May 2006

Appendix A.5 Conference paper No. 2

Integrity Assessment of Interrupted or Degraded Well Barriers

Eivind Okstad, Terje Dammen, Arve Nordskag, Sigbjørn Sangesland

DECISION-MAKING IN OIL/GAS WELL ENGINEERING

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0 SUMMARY/ABSTRACT

This paper presents a decision-making approach based on the analytical hierarchy process (AHP). The general AHP approach is outlined and discussed, and applied to important decisions during the engineering phase of oil and gas wells. A case study involving selection among five different system options for managed pressure drilling (MPD) is described and discussed. The most favorable system option is chosen based on decision criteria like: operational profit, project reliability, working environment, personnel safety, risk to environment, and project cost. The decision process is shown in detail and is illustrated by results obtained by using the computer program DecisionPlus.

New drilling technology imposes risk and uncertainty, both regarding the technology itself, and the application of the technology. During the design phase, the project team has to make a high number of decisions and to evaluate the risk and uncertainty related to the various options. In the petroleum industry, these issues are mostly discussed and decided in project meetings with representatives from the technical and geological disciplines. It is, however, a tendency that each topic is handled separately, and only related to the project delivery plan. It is believed that these discussions and decisions could benefit from a more holistic approach.

Decisions should always be based on the most updated information available at that point of time. However, information is often scarce or lacking, and too little time is available to make the decisions. Handling of dynamic decision situations may also be required, that makes it even more challenging. An example is changing conditions during the time span of a well engineering project. Important means in that respect will be to maintain good communication and cooperation in the multidisciplinary project teams throughout the decision process.

The AHP approach is found to improve the structuring of information and the communication between responsible persons in a project team. It leads to a significantly improved decision quality because the decision makers are able to organize and evaluate the relative importance of the decision criteria and the decision options more effectively. The consistency of the judgments is easily measured, and it is straightforward to reevaluate the judgments that are found to be inconsistent. It is, however, important to maintain a strong leadership throughout the decision process. A continuous focus and loyalty to the approach throughout the decision process are required in order to succeed.

1 INTRODUCTION

Offshore oil and gas operators continuously strive to improve project revenue by using new technology. This trend has become even more emphasized in later years. Most of the remaining offshore fields are located in deep waters and in remote areas, far away from available infrastructure. Conventional drilling technologies are less effective in such fields. The drilling becomes time-consuming due to the long running and pulling distances in deep waters, and expensive due to the high rates of the large drilling rigs that are required. This implies an increased focus on alternatives to conventional drilling. The pressure regime in deep-water reservoirs often makes conventional drilling a challenging task. In addition, there are increasing demands for cost-effective developments. These challenges require a development strategy that can reduce the time required to develop and implement new technology. Another issue is that the industry experiences less effective work processes and planning prior to technical decisions in well engineering projects. Important topics are often dealt with separately. In situations of scarce or lacking information and little time available, the quality of decisions might suffer. Poor planning processes and lack of suitable tools are points of concern. Changing conditions during the time span of a well engineering project could increase these problems.

The main objective of this paper is to propose a decision-making approach that can be applied during the engineering phase of offshore oil and gas wells. By using the approach the operator should be able to select the optimal basic well configuration for a specified offshore oil/gas field, subject to a set of decision criteria comprising: operational profit, project reliability, working environment, personnel safety, risk to environment, and total project cost. The decision-making approach should be exemplified in a relevant case study, and the applicability, and the pros and cons of the approach should be evaluated based on this case study.

The decision-making approach described in this paper is limited to the early design phase of oil and gas wells, but will later be implemented as a part of an overall decision framework that covers the concept selection leading into the detailed design phase. The topic for the case study was chosen to be the selection among five different system options for managed pressure drilling (MPD).

A brief description of the five MPD system options considered in the case study is presented in Section 2. This is followed by a description of the decision-making approach in Section 3, as embodiment of the methodology. Section 4 describes the case study of the MPD system options, whereas Section 5 presents the conclusions related to the decision-making approach and the case study.

2 SYSTEM OPTIONS

The managed pressure drilling (MPD) technology is regarded as an enhancement to conventional drilling, especially in deep waters. The potentials of oil/gas fields are considered to be realized more cost-effectively and safer by applying MPD. The basic feature of the MPD technology is the ability to control the annulus pressure during the whole drilling program, and further to ascertain that the bottom-hole pressure remain within set limits. The MPD functionality is achieved through a combination of technology and operational procedures.

In this paper, five different MPD concepts are considered. These system options are selected because of their proactive features [1]. “Proactive” indicates that the well’s casing and fluid programs are designed from the beginning to take full advantage of the ability to manage the pressure profile during the whole drilling program. A brief description of the five systems is given below. Further details and applications are presented in [2-6]. The five proactive MPDs are denoted:

1. Continuous circulation system (CCS)
2. Gas lift in riser (GLIR)
3. Equivalent circulating density reduction tool (ECD RT)
4. Dynamic annular pressure control (DAPC)
5. Low riser return system (LRRS)

Continuous circulation system: The CCS system allows circulation to continue when connecting drill pipes [2]. A coupler, i.e., a pressure chamber is located on the rig floor, above the rotary table, and the drill string passes through this chamber during the pipe connection process. The main benefits of the CCS system are reduced connecting time of drill pipes and the ability to drill through pressure sensitive zones without imposing abnormal pressures to the formation. The kick probability during pipe connection is reduced, and the automated operations remove personnel from the connection task – both of which improve safety.

Gas lift in riser: The GLIR system is actually an option for dual gradient drilling. Dual gradient gives an effective mud weight at the previous casing shoe less than the effective mud weight at the actual drilling depth. The functionality is achieved by injecting Nitrogen gas, cutting the mud weight back in the riser above the seafloor [3]. Injection of gas imposes a dynamic system. Well control is thus a major concern due to the ability to recognize a kick. This problem is avoided by completing the operation prior to encountering the target formation. The biggest potential of the GLIR system is in the upper section of the hole where the formation characteristics are unfavorable. By eliminating two or three strings of casings the benefits are achieved prior to reaching the reservoir. The target formations can then be drilled conventionally. No new subsea equipment is required.

Equivalent circulating density reduction tool: The ECD RT is designed to counter downhole pressure increase due to friction in the annulus by reducing the hydrostatic head [4]. The tool is integrated in the upper drill string and consists of three sections: A turbine motor draws energy from the circulating fluid and converts it into mechanical power. In the middle is a multistage mixed pump, which is driven by the turbine motor and pumps return fluid into the annulus. The lower section consists of bearings and seals. The turbine is matched to the pump duty so that no gearbox is required. The biggest advantage is that in extended reach drilling, the ECD RT can permit the use of heavier drilling fluid to improve well bore stability without imposing abnormal pressure to the formation.

Dynamic annular pressure control: The primary components of the DAPC system are the choke manifold and a backpressure pump connected to a control system which is based on a hydraulic model [5]. The purpose of the hydraulic model (program) is to calculate the required $P_{surface}$ set point to obtain the desired $P_{downhole}$. This is necessary since feedback from the downhole pressure sensor usually is too slow or intermittent for the control loop. It is further equipped with a rotating control device for maintaining a dynamic seal on the annulus. The rotating device enables the choke to control the annular pressure at the surface [7]. The basic application is where a constant bottom-hole pressure is desirable all time.

Low riser return system: The LRRS system consists of a pressurized riser without any kill and choke lines [6]. The riser is connected to a subsea blowout preventer (BOP), and at the other end to a surface BOP on the drilling vessel. Drilling fluid is pumped down through the drill string and the mud return is taken in the annulus region between the drill string and the drilling riser. At a specified, calculated depth the drilling fluid return is diverted through an outlet of the riser that is connected to a pumping system. The mud level can be adjusted with the subsea pumping system. The borehole pressure is then controlled in accordance with the dynamic drilling process requirements. An important application is when unexpected pressure is encountered deep in the well and the formation higher up at the surface casing shoe cannot support a high mud density. This is compensated for, by dropping the level in the riser while increasing the mud weight.

3 DECISION-MAKING APPROACH IN WELL ENGINEERING

The decision-making approach presented in this paper is exemplified through the selection of a basic oil/gas well configuration. These decisions are traditionally related to a phase model, like the well delivery process illustrated in Figure 3-1.

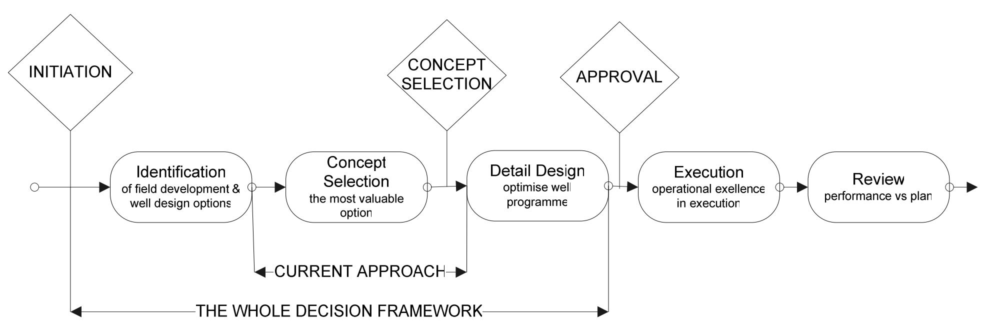

Figure 3-1. Primary processes of well engineering

As indicated in Figure 3-1, the current scope deals with the decisions following the identification phase. It ends with selecting the basic well configuration. Figure 3-1 further indicates that the current approach is a limited part of a more comprehensive decision-making process.

The proposed decision-making approach is based on the analytical hierarchy process (AHP), which was developed by Saaty [8]. Several decision support approaches were evaluated, and we concluded that the AHP approach was the most appropriate approach for ranking the MPD systems.

Before we can apply the decision approach we need to define the drilling scenario and to clarify the opportunities and limitations connected to the field being explored. In this paper the focus is limited to drilling conditions where an MPD technology is regarded as an option.

In well engineering projects it may be difficult to conceptualize the different issues or elements that influence technical decisions at the conceptual stage. It is easy to fail to include one or more important issues, or include issues that are not relevant. One should also recognize the cognitive energy needed to make priorities between the different decision criteria. In case the required information is unwieldy, it may be difficult to keep track of previous priority weighting of criteria, which again may lead to inconsistent priority judgments [9]. The AHP approach is an attempt to solve such problems. The AHP approach can be characterized as a multi-criteria decision support technique that combines subjective and objective criteria in an overall evaluation of options. It deals with quantifiable and intangible criteria at the same time. The AHP approach may be applied to different areas, and is basically a problem-solving framework and a systematic representation of a decision problem.

To select the most promising MPD system, we need to evaluate the options according to a set of criteria. In the current study the following decision criteria were selected: operational profit, project reliability, working environment, personnel safety, risk to environment, and project cost.

Criteria related to economy may be evaluated based on cost and revenue estimates, e.g., from life cycle cost/profit analyses. Other criteria may not be quantifiable, e.g., consequences to occupational health, safety and the environment. Risk assessments of various types are important supplements to cost/revenue analyses (e.g., see [10]). The AHP approach covers all the selected criteria through three main steps: (1) decomposition of decision elements, (2) comparative judgments and rating of criteria, and (3) synthesis of priorities.

The first step of the analysis is to decompose the complex, multi-criteria problem into a hierarchy where each level consists of a few manageable elements. These elements are again decomposed into another set of elements, and so on. The overall objective of the analysis ("selection of the optimal MPD system") is written on the top of the hierarchy with the second level objectives beneath. The main criteria at the third level are linked to the second level objectives. The main criteria may be further divided into several sub-criteria levels. The system options are attached to the lowest level of the hierarchy and they are analyzed based on the sub-criteria nearest above. The constructed hierarchy forms a logical representation of a complex, multi-criteria decision process and it effectively describes the relationships between the elements involved. It also fosters understanding and consensus among the decision makers regarding the decision process. An example of a decision hierarchy is illustrated in Figure 4-3, where the hierarchy is drawn horizontally to save space.

The second step is to establish priorities among the elements within each level of the hierarchy. The AHP approach differs from other decision analysis methodologies by not requiring decision makers to make numerical guesses, as subjective judgments are easily included in the process. The judgments can also be made entirely in a verbal mode. A verbal, or corresponding numerical scale is used for the comparisons. Assigning scores can be based on objective and quantitative data or subjective, qualitative judgments. In a group setting, there are several ways of including the views and judgments of each person in the priority setting process. A common objective context suggests four ways of setting the priorities [11]: (i) consensus, (ii) vote or compromise, (iii) geometric mean of the individuals' judgments, and (iv) separate models or players. If consensus cannot be established, the geometric mean of the group member's judgments is recommended as an appropriate rule for combining judgments.

The third step is to synthesize the priorities of the elements to establish the overall ranking of the decision options. The weighting of decision elements starts by comparing the second level objectives in a pair-wise manner with respect to the overall goal. Then the importance of the main criteria is evaluated with regard to each second level objective, and the importance of the sub-criteria is assessed with regard to the main criterion they are linked to. The last step in the priority setting procedure is to compare the system options in a pair-wise fashion with respect to each sub-criterion at the lowest level (being the preference of each option).

In this study, we tested the free version of the computer program DecisionPlus [12] as an aid of structuring and documenting the analysis.

Saaty [8] discusses the main differences between the AHP approach and approaches based on the "Delphi" technique, and concludes that while both techniques may improve the quality of the decisions, the hierarchical feature of the AHP approach better fits human cognitive style of thinking because of the way it decomposes the problem and synthesizes the results. An even more comprehensive approach to multi-criteria optimization is discussed in [13].

4 CASE STUDY

In this section, the AHP approach is illustrated in a simple case study. The following drilling scenario is chosen for the case study:

A deep water (> 1000 m. water depth) gas well is to be drilled. The well target is located at 3000 m below sea bed with a horizontal displacement of 1500 m from the drilling facility. Some shallow hazards have been detected as zones of possible high pressure gas and/or water. Some sections needs to be drilled under conditions of narrow pressure margins. Finally, the risk of hitting small intermediate and permeable gas zones deeper into the well is imminent. Hence, the ability to recognize and cope with a kick must be considered thoroughly in the planning of the drilling process.

As mentioned above, the decisions are based on criteria arranged in a hierarchical structure. The criteria are identified and used to compare the system options for a basic well configuration. Based on the drilling scenario, the preferences listed in Table 4-1 were established through expert judgment. The following three categories are used to indicate relevance: minor (+), medium (++), and high (+++).

Table 4-1. The relevance of drilling requirements to decision options

Concepts **Drilling requirements**	**CCS**	**GLIR**	**ECD RT**	**DAPC**	**LRRS**
Shallow hazardous formations in deep water	+++	+++	+	+	+++
Narrow pressure gradients	++	+	+++	+++	+++
Long deviated well (torque, hole cleaning)	+++	+	+++	+	++
Drilling safety (kick, well control)	++	++	++	+++	++
Working environment	++	+	++	+	+
Project reliability	+	++	+	+	+
Material cost (well construction, casings)	++	+++	++	++	++
Drilling cost (hole stability, stuck pipe, etc.)	++	+	++	++	++
Rig cost and amount of equipment	+	+++	+++	+	+

A project team brainstorming session was carried out to select and specify criteria and decision elements for the decision process, and how these criteria/elements are connected. The results from the brainstorming session are illustrated in the influence diagram in Figure 4-2. The brainstorming session concluded that the criteria “operational profit” and “external environment” are of minor relevance, and that it is not possible to differentiate the system options based on these criteria. These two criteria were therefore excluded from further analysis, as indicated by the broken connection lines in Figure 4-2.

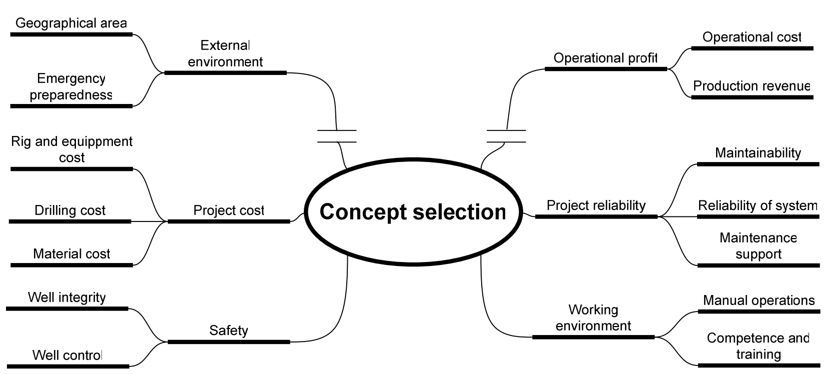

Figure 4-2. Brainstorming decision criteria

A hierarchy model was generated based on the information from the brainstorming, as shown in Figure 4-3. The model is made horizontal with the decision goal at the left and the underlying criteria in levels of importance from left to the right. Decision options are attached to the lowest level, on the right hand side.

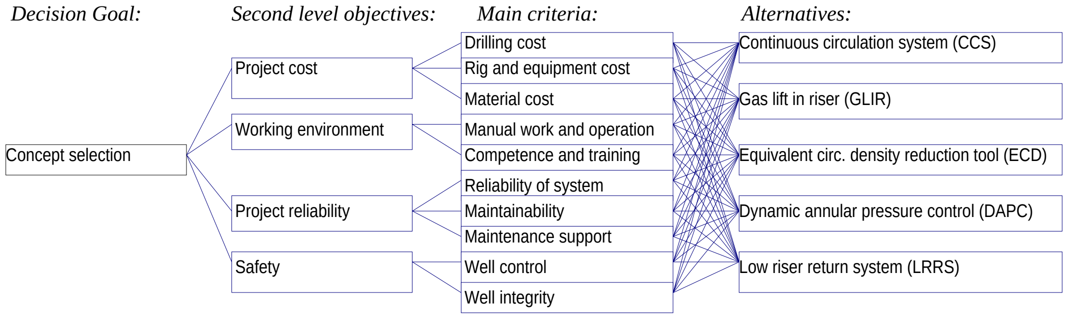

Figure 4-3. A hierarchy of decision criteria (printout from DecisionPlus [12])

The hierarchy model was thoroughly checked and verified, and the computer program DecisionPlus was thereafter used to rate the criteria. In DecisionPlus this task is carried out in three steps: (i) choosing a rating method, (ii) assigning a rating scale, and (iii) entering weights and scores.

Three rating methods are available in DecisionPlus; *direct comparison, full pair-wise comparison*, and *abbreviated pair-wise comparison*. Direct comparison may be used if quantitative data about the criteria exists, either from previous analyses or from experience and detailed understanding of the decision problem. Pair-wise comparison means comparing criteria in pairs. This method is useful if we are lacking quantitative data, or feeling much the same about all the criteria. This method rates a criterion relative to all the other criteria within its ratings set. It is easy to enter weights because all criteria in the set are verbally compared against each other. Subjective judgment or intuition is all what is needed. Abbreviated pair-wise comparison is similar to the full pair-wise comparison except that it allows working in smaller sets. Not all weights are shown. If criterion A is better than criterion B, and B is better than criterion C, then A is also better than C. The comparison of A to C is therefore not shown.

For this case study the abbreviated pair-wise comparison was selected because we can work with smaller sets of criteria, which was considered beneficial for the well configuration case. The set of criteria might be huge in a full scale model. Another argument is that the input information will be more like expert judgments, than quantitative input data.

Assigning a rating scale is closely related to the choice of a pair-wise comparison strategy. Instead of quantitative data, we may estimate ratings as we proceed. It is important to choose a combination of rating method and scale that allows for comfortably weighting of the criteria. In the standard AHP approach, the pair-wise comparison method uses a scale relating nine words with numbers, as shown in Table 4-2. Judging the importance then becomes straightforward in DecisionPlus. The ratings may be viewed numerically, verbally or graphically, or by all three options.

Table 4-2. AHP rating scale

Verbal Scale	Standard AHP
Absolutely Better	9
Critically Better	8
Very Strongly Better	7
Strongly Better	6
Definitely Better	5
Moderately Better	4
Weakly Better	3
Barely Better	2
Equal	1

After finalizing the weighting, the results or the decision scores can be viewed. The score is an aggregate of all the weights for the system options entered into the model. The higher the decision score the closer that option comes to meet the decision criteria. DecisionPlus also measures the inconsistency by a ratio, where the value of 1.0 is considered complete inconsistency, and less than 0.1 is considered acceptable (10% of the time).
Figure 4-4 is a printout of the decision scores for the case study. Absolute uncertainty is indicated as the percentage of the times the option came out best.

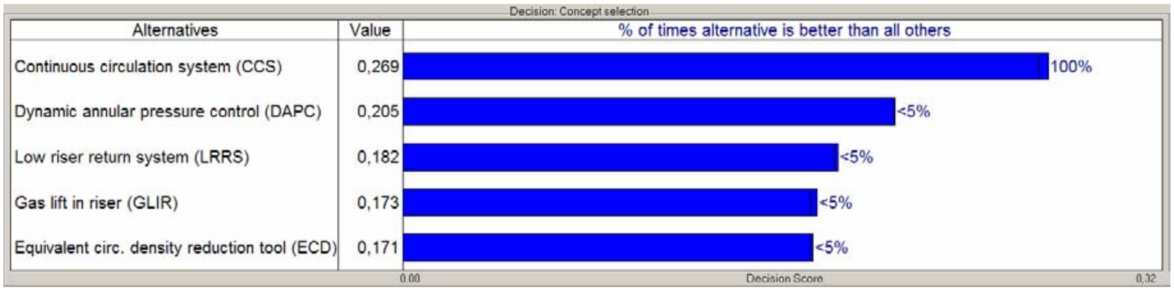

Figure 4-4. Ranking of system options (printout from DecisionPlus [12])

The CSS system is seen to come out as the best option. The underlying data of the decision scores are explained in Table 4-3. The system options are listed across the top of the table, and the lowest level criteria in the left column. The priority value of each system option with respect to a specific criterion is shown in the corresponding cell. Priority values are normalized values of weights. These are used to calculate the decision scores. Next, the model weight of each lowest criterion is given in the last column. The model weight is the effective weight of the lowest level criterion (main criteria) if connected directly to the decision goal. The decision score for each system option is calculated at the bottom of each column, and is the sum of the priorities with respect to each lowest criterion multiplied by the model weight of that criterion.

Table 4-3. AHP results data (results from DecisionPlus [12])

Lowest Level	CCS	GLIR	ECD RT	DAPC	LRRS	Model weights
Drilling cost	0.235	0.059	0.235	0.235	0.235	0.019
Rig and equipment cost	0.068	0.548	0.274	0.055	0.055	0.097
Material cost	0.053	0.211	0.105	0.211	0.421	0.014
Manual work and operation	0.222	0.111	0.333	0.083	0.25	0.209
Competence and training	0.243	0.081	0.027	0.162	0.486	0.052
Reliability of system	0.174	0.522	0.174	0.087	0.043	0.062
Maintainability	0.111	0.444	0.148	0.074	0.222	0.021
Maintenance support	0.286	0.143	0.143	0.286	0.143	0.004
Well control	0.4	0.1	0.1	0.3	0.1	0.391
Well integrity	0.211	0.053	0.105	0.316	0.316	0.13
Results	0.269	0.173	0.171	0.205	0.182	

Figure 4-5 shows the contribution on *Concept selection* by criteria, here from the second level objectives (according to Figure 4-3). Each area of the graph corresponds to its contribution to the final score.

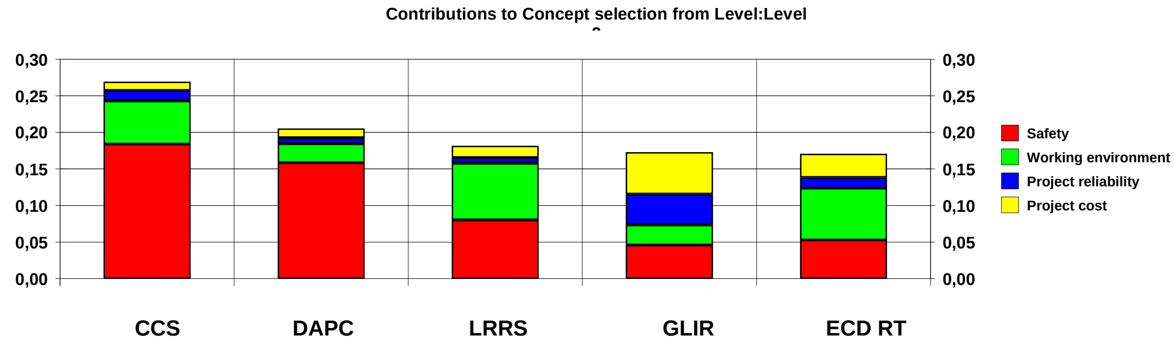

Figure 4-5. Contribution of second level objectives (printout from DecisionPlus [12])

From Figure 4-5 it is seen that "safety" is the overwhelming contribution to the two highest ranked system options. In addition to the contribution by criteria the sensitivity of the preferred option to changes in the input data, i.e., the criterion weights are analyzed. The sensitivity of a criterion is connected to how much the current value of the priority can be changed without changing the preferred options. This is denoted as the minimum change of each priority in percentage of the total priority scale. This percentage is also referred to as the crossover percentage for a given weight. The sensitivity of concept selection to changes in the criteria "Safety" is shown in Figure 4-6. The x-axis represents the range of values over which critical weights vary, and the y-axis represents the decision score. The vertical red line is at the "current value", the priority corresponding to the weight entered for the criteria "safety" against "concept selection. The value of that weight, in its own units, is shown to the right of the graph in parenthesis (black text). The same is repeated just above (red text). By moving the priority slider (the vertical red line) the new priorities and weight value are shown as "temp value" (red text).

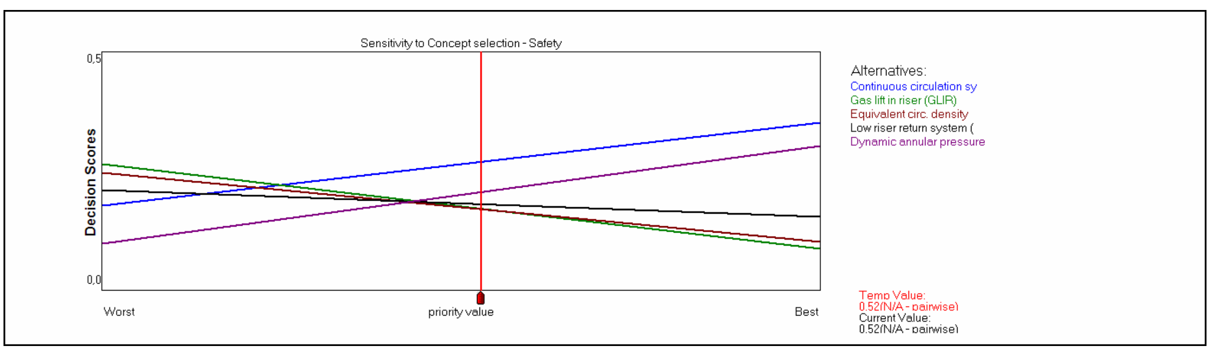

Figure 4-6. How measuring sensitivities (printout from DecisionPlus [12])

The sensitivity analysis and graph in Figure 4-6 indicate that a change in priority of safety corresponding to 27.4% implies that the preferred system option is GLIR instead of CSS.

5 DISCUSSION AND CONCLUSION

The case study shows that the proposed decision-making approach is well suited for selecting a basic well configuration. An important presumption is that the industry believes in a strategy of systematic handling of information and communication during the well engineering process. In that respect the suggested AHP approach contributes to, and forms an important part of a decision framework. An application of the current methodology is shown in a case study, considering which MPD system option to select for a given drilling scenario. The results from the analysis is a ranking of system options according to how well each of them meet the decision criteria agreed about early in the process. The CSS system comes out as the preferred option among the five available system options, mainly based on its safety features.

The following pros and cons are related to the AHP approach:

- The AHP approach leads to a significantly improved decision process quality.
- The decision makers are able to organize and evaluate the relative importance of the decision criteria and the decision options more effectively.
- The consistency of the judgments is easily measured, and it is straightforward to reevaluate the judgments that are found to be inconsistent.
- It is important to maintain a strong leadership throughout the decision process.
- Continuous focus and loyalty to the approach throughout the process are important in order to succeed.

6 ACKNOWLEDGEMENT

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Integrity assessment of interrupted or degraded well barriers

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ABSTRACT: Degradations or interruptions of the original well barrier elements might occur at offshore wells after some time in operation. Experience from the Norwegian Continental Shelf has shown that these problems are not always treated as thoroughly as expected by the parties involved. This paper presents an approach for an efficient visualization and description of interrupted well barriers, basically to increase the well barrier control and management. By mapping the history of operational demands and load picture of the well in combination with the status of well barriers, a consistent basis for evaluations is obtained. The main intention is thus to realize the real well problem and its underlying causes in a controlled and systematic manner. Then, the responsible parties involved can take action more accurately according to the type of failure that has been revealed.

1 INTRODUCTION

Interrupted barrier elements are related to well integrity and are critical from the point of view of safety, but also concerning production regularity and costs. Failure in the well barrier functions caused by degradations or interruptions of barrier elements needs immediate attention from the responsible bodies. During drilling and well activities there are always to be at least two independent and tested well barriers after the surface casing is in place according to the Activities Regulations of the Norwegian Petroleum Safety Authority (PSA) [1].

Experience from (PSA) [2] has shown that barrier failures occur both in newly drilled wells, and in wells that have been in operation for some time. Well integrity failures may be latent in the early constructing phase, or imposed through later maintenance tasks. Shifting between well operational phases can also initiate abnormal load situations causing well integrity failures to occur. Many of these "unexpected" loads are not necessarily taken into account in the design phase. An investigation carried out by the PSA on the Norwegian Continental Shelf showed that 14 % of 309 checked wells currently in operation had problems with, or deviations related to the well integrity [2]. Experience has also shown that integrity problems are not always treated as systematically and thoroughly as expected by the well operators.

The main objective of this paper is to present a visualization methodology for the purpose of evaluating well integrity problems that communicates facts about integrity problems to the responsible bodies. Intended users of the approach are operators, contractors, the authorities, researchers and consultants who have interest in carrying out assessments of well integrity matters. As one possible application, the options regarding future operation of wells may be clarified by the operator, with new preconditions and operational limitations.

A brief introduction to the technical problem area is given in Section 2 from a system perspective. Then a description of the three-step methodology follows in Section 3. Section 4 discusses the implications of the methodology and gives some remarks regarding applications. Finally, a brief conclusion with remarks concerning further work is outlined in Section 5.

2 PROBLEM DESCRIPTION

Well integrity problems need attention and systematic handling both from the operator's and from the safety authority's point of view. In this focused work the parties involved need appropriate tools to communicate and document the problem, both for the purposes of incident investigation, and for the planning and follow up of future well operations.

The problem under study is the apparent lack of a systematic approach to well integrity problems or barrier problems. Well barriers are defined in NORSOK D-010 [3] as envelopes of one or several dependent well barrier elements preventing fluids or gases from flowing unintentionally from the formation into another formation or to the surface.

A casing hanger problem related to a specific wellhead design has been used as a case to illustrate a well integrity problem. An investigation was carried out by the PSA in 2006 [4]. The specific casing hanger is in line with conventional wellheads, with the difference that the load bearing shoulder that supports the casing hanger has an angle (α) of only 8 degrees (see Figure 1). In more conventional designs this angle is typically 45 degrees or more. Due to the low angle and the high axial load (F) on the casing hanger, a very high normal force (Fn) is created between the casing hanger and the casing hanger seat. Figure 1 illustrates the load distribution as it exposes the casing hanger seat. It also illustrates the difference in force distribution (Fn vs. Fn') for the cases of having a load bearing shoulder angle of 8˚ and 45˚. Actually, the Fn component increases to infinity when this angle approaches zero and assuming no friction. Thus, the casing hanger failure occurs when the casing hanger is forced through the load bearing shoulder of the casing hanger seat. The mechanism is the deformation of the casing hanger seat enforced by the high normal force (Fn).

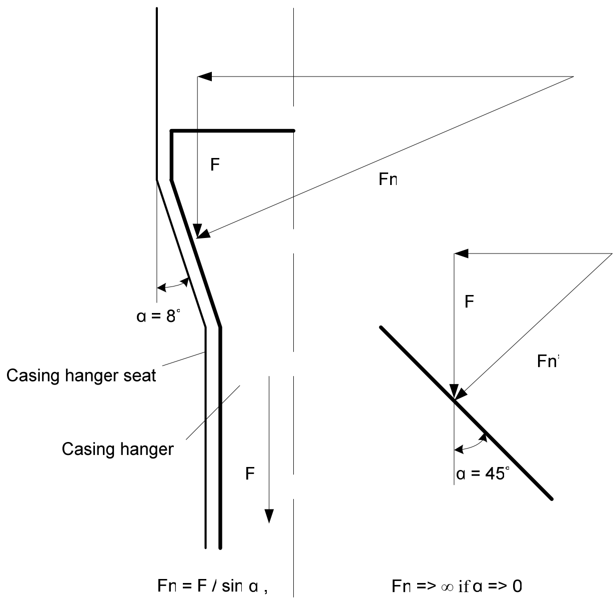

Figure 1. Comparison of the force distribution given a casing hanger seat angle of 8˚ and 45˚

3 METHODOLOGY

A three-step methodology for visualization of well integrity problems has been developed. Indirectly, the well integrity problem is shown by illustrating the historical load picture of the component that fails. More directly, it is visualized by the operational status of well barriers, both before and after the occurrence of the well integrity problem. Thus, the methodology consists of the following three steps:

1. Map the initial loads imposed through the previous operational phases of the well by use of a generic influence diagram [5].
2. Draw the well barrier schematics according to NORSOK-D010 [3] and indicate the status of barrier elements before and after the well incident.
3. Prepare the barrier diagram [6] with leak flow-paths that show the status of barrier elements after the well incident.

Each step of the methodology is explained more in detail in the following:

3.1 *Influence diagram*

The influence diagram is a method to depict relationships between various elements, or influencing factors, and how they affect on the final value or decision (adapted from [5]). An influence diagram approach is utilized here to illustrate the relation between previous operational phases and the possible loads the component under study has been, or will be exposed to. The different operational phases and loads are connected and visualized by the use of lightly and heavily shaded boxes, respectively. For the current case example, the influence diagram in Figure 2, intends to visualize the load picture as it actually affects the probability of the casing hanger failure. A quantitative application of the influence diagram is to calculate the maximum aggregated load in order to compare it with the load capacity of the casing hanger. On the second level from the top, the different well configurations are given that are of relevance to the integrity problem under study. Here, the actual well configuration is indicated by the heavily shaded box.

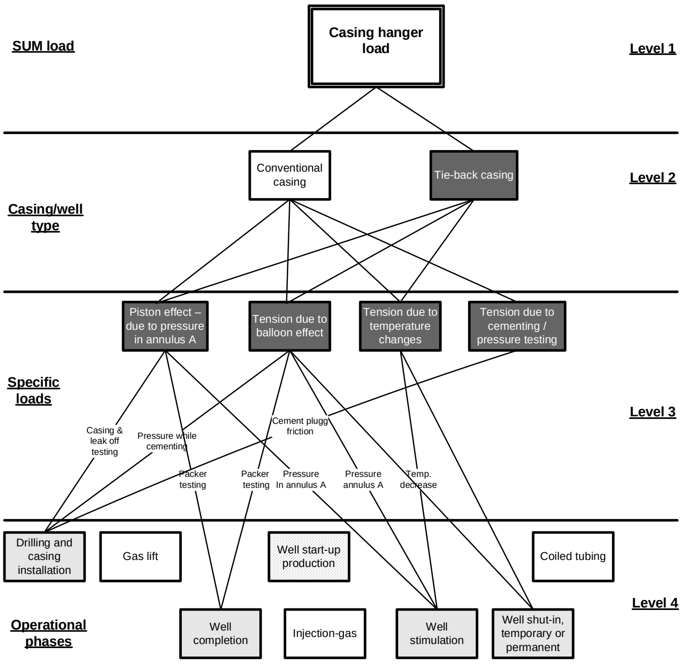

Figure 2. Influence diagram showing the actual operational phases and loads for the well type

The influence diagram has been divided into four levels. The bottom level shows the different (possible) operational phases of the well. The third level from the top identifies the different load contributions that may affect the casing hanger, given the operations. The second level from the top shows the well configurations of relevance to the current well integrity problem. Finally, the load situation for the casing hanger is described in the top level box. This may be the aggregated load, given the worst case scenario of well configuration and loads.

The specific diagram is based on a template that includes all possible operational phases and loads for the well under study. From this template the relevant operational phases are highlighted in lightly shaded boxes. Potential future operations of the well are indicated in hatched boxes. The identified loads types are shown in heavily shaded boxes at level three, similar to the box on the second level representing the well configuration under study. The other white boxes, on levels three and four, are not relevant for the well under study. The text on the connector lines, between the operational phases and loads, indicates load-causes or mechanisms that are enforced by the specific operations. In the highest level box the worst-case load may be aggregated and compared to the load capacity of the specific component. For the current case it is assumed that the calculated load factor for the casing hanger is in direct correlation with the casing hanger failure probability of the well under study.

3.2 *Well barrier schematics*

Well barrier schematics, according to NORSOK D-010 [3], are developed as a practical method to demonstrate and illustrate the presence, or non-presence of the required primary and secondary well barriers. An example of a well barrier schematics of the platform operated well is shown in Figure 3. The schematics indicate the primary and secondary well barriers with their barrier elements as broken lines. The barrier situations with the hanger in position is shown to the left in Figure 3, and the situation after the hanger has failed or dropped is shown to the right. The heavily dashed lines indicate the primary well barrier with its barrier elements. The dashed-dotted lines indicate the secondary well barrier with its barrier elements. The small-dotted lines to the right represent the secondary well barrier elements that have lost their function due to the hanger failure. Finally, the grey dashed lines to the right illustrate the elements that may compensate for the lost barrier elements, and be part of a "new" secondary well barrier. These are possible options only in case these elements can be qualified as the "new" secondary well barrier elements.

Through this kind of illustration it is possible to verify the new status of the barriers and whether it is critical or not. Future operation of the well is greatly dependent on these assessments. Control and monitoring may be planned based on these assessments to maintain the barriers.

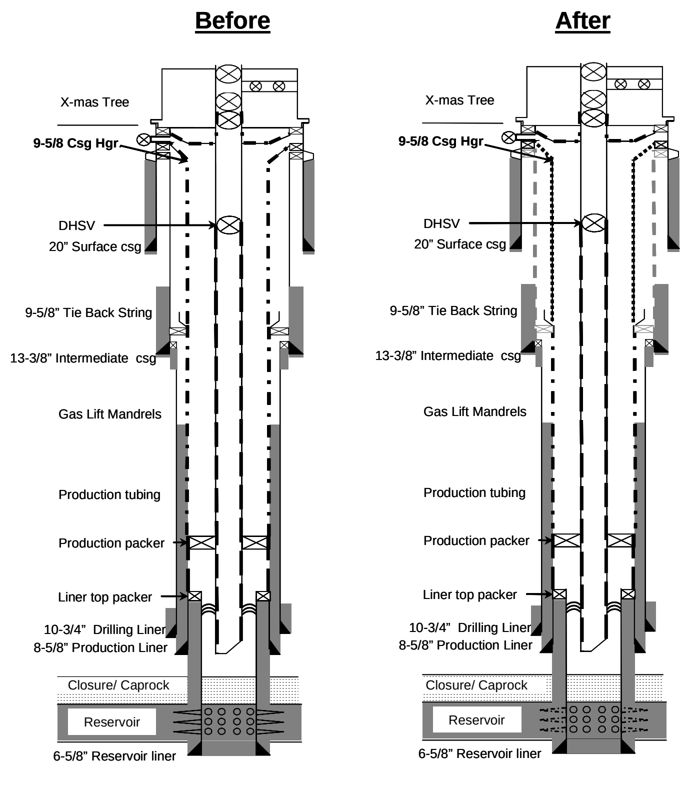

Figure 3. Well schematics, before and after the incident

3.3 *Barrier diagram*

The barrier diagram is developed as a flow-path diagram indicating the possible leak paths from the reservoir to the surroundings. In Figure 4, the barrier diagram for the current case shows the leak paths after the hanger failure has occurred, and taking into account the original well barrier elements. Each of the boxes represents the relevant well barrier element with focus on the casing hanger drop. The line types of the boxes have been given the same meaning as for the well barrier schematics in Figure 3. Thus, the elements of the primary and secondary well barrier are shown as heavily dashed boxes and dashed-dotted boxes, respectively. The arrows connecting the boxes indicate the possible leak directions.

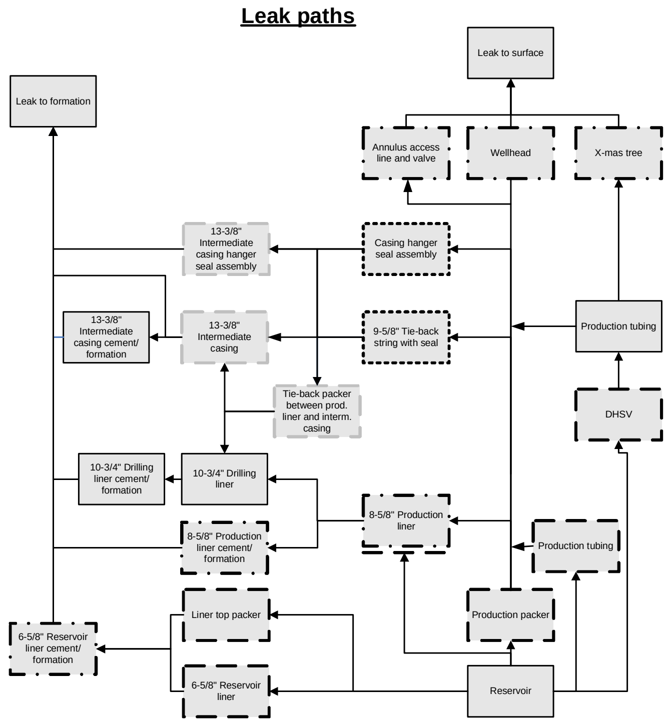

Figure 4. Barrier diagram (leak paths)

4 DISCUSSION

The following discusses implications to the parties involved, who might benefits in their work by applying all, or parts of the methodology, as it is presented in this article. Some key words with respect to different needs and applications are identified and listed below. Applications are further discussed thereafter.

Needs of the authorities

- Communicating well integrity problems, both internally and externally to the authorities
- Planning of audits
- Investigating incidents
- Following up operators after incidents
- Updating regulations

Needs of the operators

- Mapping status and the current load situation for wells under operation
- Documenting need for operational control (monitor and follow up)
- Reviewing operational demands
- Mapping additional loads when changing operational phases

Needs of contractors and suppliers

- Identifying needs of barrier pre-qualifications
- Guiding in design

Needs of researchers and consultants

- Understanding system behaviour
- Preparing basis for operational risk and reliability assessments

4.1 *Needs of the authority*

From the safety viewpoint of the authority, the methodology provides an easy overview of the well situation. It is easy to communicate facts about the actual problem to people outside, even with limited system knowledge. This is useful both internally for the authorities, and externally for to the well operators and other involved parties. At the same time it is easy to update the overview of well situations based on new information.

Both the influence diagrams and the well barrier schematics may be used in planning audits of operators based on updated well information. Another application is investigations of well incidents and following up these operators afterwards. Building knowledge about operational well aspects by the use of the current methodology will over time enforce the authority's ability to update their own regulations. The most important knowledge may be the ability to foresee effects of the ageing well facilities, rapid changes between operational well phases, effects of implementing new technology, etc. The motivation to apply it is the increasing trends of incidents or other unexpected phenomena that are observed on the NCS, and which are not yet covered by existing regulations.

4.2 *Needs of the operators*

Very often there are changes with regard to the operational phase of wells, like going from production to injection. The influence diagram method then provides a structured approach in addressing the changing loads on critical components. The assessment may reveal whether or not, critical components are affected in a negative manner with respect to safety and operation. Through the lifetime of wells this kind of load picture may be continuously updated and used actively by the operator as a means to monitor and control the well conditions. In addition to the load picture, the consequences of failures in any operational phase, such as the casing hanger failure, are easily described by well barrier schematics and well barrier flow diagrams. These are helpful tools in reviewing the operational demands of the wells.

4.3 *Needs of contractors and suppliers*

Contractors should gain access to operational experience data regarding well integrity problems that are connected to aspects of their own well designs. In their struggle to improve the design they should be more capable of identifying vulnerable components, given the updated information of incidents. The original design with its contingencies may then be reviewed with respect to the existing barrier elements, and components that may be pre-qualified to become the "new" barrier elements. Generally, the overview of well experience that the new methodology provides ensures that contractors and suppliers improve their well designs.

4.4 *Needs of researchers and consultants*

The needs from the external parties, like researchers and consultants, may be seen as more peripheral within the current context. However, the application of known methods from risk and reliability analysis into the operational phases of installations is always interesting from a researcher's point of view. Typically, these kinds of methods have been applied in the early concept design. Just as interesting, is the improved understanding of systems and system behavior that is gathered by this kind of system analysis. Knowledge is obtained with respect to the technical and operational aspects of well systems, and how these aspects influence the system integrity and its ability to maintain the safety barriers.

5 CONCLUSION

Barrier failures occur both for newly drilled wells, and for wells that have been in operation for some time. Experience has shown that these kinds of failures are not always treated thoroughly as expected by the well operators. A three-step visualization methodology for evaluating well integrity problems and communicating facts around such problems to the responsible bodies has been developed. The approach was applied to a case example involving a casing hanger problem related to a specific wellhead design. The experience from the case example shows that the methodology provides an easy approach to barrier control and management. The assessments reveal relations between operational demands/operational phases of wells and the critical exposure of components to forces. By the use of well barrier schematics and flow-path diagrams the consequences of critical component failures are defined with respect to failure conditions and well integrity. This is useful information in order to identify measures for maintaining the well barriers. The influence diagrams provide a method for calculating worst case load scenarios that is compared to the capacity of the respective component. This kind of information provides valuable input to operators who are responsible for planning the future operation of the wells. The current methodology has been developed to serve the specific needs of a SINTEF project. However, it has not been thoroughly qualified or verified to fit any general application. Thus, a possible further development of the methodology may focus on the following topics in order to fit more general purposes:

- Identify the requirements of a methodology that is designed to serve general applications
- Identify needs in a system life cycle perspective that should be served by the methodology
- Develop a plan of action for collecting and handling incident data that may be relevant for contractors and suppliers who should carry out well design
- Develop the final methodology
- Specify functional requirements of models and the connections between them in order to develop a software application
- Carry out additional case studies in cooperation with the end users to validate the appropriateness of the methodology in use.

6 ACKNOWLEDGEMENT

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