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EVALUATION OF TWO RISK ANALYSIS TOOLS FOR PLANNING OF OFFSHORE WELL CONSTRUCTIONS IN D&W EQUINOR WITH FOCUS ON UNCERTAINTY AND REUSABILITY

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Abstract

The Petroleum Safety Authority (PSA) recently introduced a new definition of risk that emphasizes uncertainty as a main component of risk. Offshore well construction carry major accident potential and risk analyses in line with the new definition are expected. Equinor (former Statoil) is a company that annually drill about 150 offshore wells. This stresses the need for consistent reuse of applicable parts of previous risk analyses. Drilling & Well (D&W) is responsible for planning and construction of wells in Equinor.

The purpose of the work presented in this thesis is to discuss and evaluate selected well construction risk analysis tools used by D&W Equinor. Familiarization with Equinor's management system and well construction process DW600 was necessary to properly conduct the evaluation. Among the tools in DW600, focus was on the *Concept Risk Analysis Checklist* and *Risk Analysis Logsheet*. The evaluation was based on a discussion of pros and cons of selected elements. Finally, the tools were compared with respect to a set of criteria and improvements was suggested.

The evaluation showed that both tools are easy to use, efficient and tailored for use by engineers. Both tools provide a detailed risk picture that, if presented correctly, allow for description of the major accident potential in offshore well constructions. In terms of uncertainty, both tools contain elements that indirectly reflect parts of the uncertainty dimension but they lack direct measures. When reflecting uncertainty, it is important to specify: uncertainty about what? The checklist manages to reflect uncertainties about activities by describing a term called manageability for all risk conditions. The risk description format used in the logsheet reflects uncertainties about the risk picture by including causes, consequences, and existing safeguards for all risks elements.

In terms of reusability, the checklist tool uses a field specific template to ensure applicable reuse of main features in the risk picture for specific wells in a field perspective. The logsheet tool is designed for a more detailed analysis context, starting from scratch with "blank sheets". It is therefore unfortunate that, despite the numerous downsides of reusing risk analyses in this tool, experience shows that previously conducted risk analyses are uncritically reused.

Based on the evaluation, two important suggestions are to include more direct measures of uncertainty such as strength of knowledge (SoK) and to create a generic risk template to allow proper reuse in the logsheet. Looking at recent changes, the tools are developing in the right direction.

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1 Introduction

1.1 Background

Imagine that you are standing on top of the Empire State Building in New York. Located below on the pavement is a half-filled plastic bottle. You start putting together straws with the goal of landing the 381-meter-long string into the bottle. It's a challenging task as winds are changing and you can't physically see the target. After a detailed planning phase and several risk analyses, the string is landed into the bottle. This scenario is comparable to the lengths and sizes of drilling an offshore well into a reservoir.

Modern wells start out vertical but enters the reservoir horizontally. Wells are drilled through several thousand meters of rock with only partly known geology. Planning and executing well construction includes complex activities with large uncertainties. Consequences range from jamming a finger when making up drill pipe to fatal blowouts when escaped hydrocarbons ignite on surface. Combining complex operations and large uncertainties with this potential for major accidents makes well construction a high-risk activity. Describing and managing this major accident potential call for high quality risk analyses.

Recent literature on risk management emphasize the importance of representing uncertainties in risk analyses (e.g. Flage et al. (2014)). This work has resulted in the risk concept changing from a narrow focus on probabilities to a broad focus on uncertainties (see e.g. Aven (2011)). Experience in the industry shows that well construction risk analyses maintain a narrow focus on probabilities. Existing work processes and tools for risk analysis in the industry have not yet adapted to this new risk concept. This difference results in a gap between best practice in risk management literature and best practice in well construction risk analysis methods. Existing risk analysis tools in the petroleum industry are modified and new tools are designed in an attempt to close this gap.

Equinor (former Statoil) is an international energy company operating in the petroleum industry by planning and drilling offshore wells. Drilling and Well (D&W) is the discipline in Equinor responsible for planning offshore wells. D&W Equinor have developed work processes and tools specifically for single well construction risk analyses. Planning and constructing about 150 wells every year require consistent, efficient and reusable risk analyses. Every new well project cannot start from scratch.

The Petroleum Safety Authority (PSA) is an independent regulator that is responsible for safety in the Norwegian petroleum industry. Supported by modern risk management literature, the PSA have recently introduced a definition of risk that emphasize uncertainties about future activities as a main component of risk. D&W Equinor is adapting to this focus by changing internal work processes and tools to better reflect uncertainties. Changing work processes and tools is time consuming and require additional resources. There is clearly a need to justify the spending of resources to improve well construction risk analysis process and tools. Evaluating the current state of the risk analysis process in D&W Equinor can contribute to this justification.

1.2 Purpose

This work evaluates the risk analysis tools used when planning and construction of a single well in D&W Equinor, with focus on the uncertainty dimension and reusability. Based on this evaluation, the purpose is to provide and demonstrate a set of practical suggestions for how to reflect uncertainties and how to reuse risk analyses. The current state of the tools is evaluated by discussing pros and cons with respect to a set of criteria for sound well construction risk analyses. Evaluating the work processes and tools for risk analysis of a well-established organization like Equinor can motivate discussions, ideas and practical improvements for others in similar industry.

The uncertainty dimension is evaluated by discussing elements in the tools which directly measures or indirectly reflects uncertainty. The uncertainty dimension is divided into three categories: unknown quantities, the future and phenomena. This categorization makes the evaluation more specific. Reusability in the tools is evaluated by addressing elements that motivate direct reuse of risk analyses and elements that motivate the use of standardized templates when conducting consecutive risk analyses.

The management structure and relevant work processes in Equinor are described to provide the knowledge necessary to properly evaluate the risk analysis tools. Insight into these methods, tools and procedures can also benefit similar industries. The purpose of this work is summarized in the following five goals:

1. Describe requirements and expectations for risk analyses in well construction.
2. Describe the risk management process in Equinor and D&W.
3. Evaluate the uncertainty dimension in two risk analysis tools used in well construction.
4. Evaluate the reusability in two risk analysis tools used in well construction.
5. Suggest and demonstrate improvements to the uncertainty dimension and reusability.

1.3 Structure

Chapter 1 introduces the work by describing its background and purpose. The purpose is summarized as five essential goals. Chapter 2 addresses the first goal by describing how governmental regulations and risk management literature can influence processes and methods for risk analyses. Expectations for risk analyses by the PSA is described before briefly motivating the need for a complete uncertainty dimension and reusability in well construction risk analyses. Chapter 3 addresses the second goal by describing Equinor's corporate view on risk and elaborating on D&W's interpretation of this view. Chapter 4 also addresses the second goal by describing the work procedure for well construction DW600, with emphasis on the methods and tools used in risk analyses. Two well construction risk analysis tools from DW600 are described. Chapter 5 addresses the remaining goals by evaluating interesting elements in the two risk analysis tools with focus on the uncertainty dimension and reusability. Practical improvements are suggested and demonstrated based on this evaluation. The chapter ends with a comparison of the tools based on a set of criteria for sound risk analyses. Chapter 6 concludes the work by addressing the five goals and listing the findings.

2 Requirements and Expectations for Risk Management in Petroleum Activities in Norway

This chapter familiarizes the petroleum industry. The purpose is to describe how risk management in a well project is associated with governmental laws and regulations. The goal is to answer questions like: Why does a company have to conduct risk analyses when constructing offshore wells? Who enforce the law and how do they define risk for the petroleum industry?

First the hierarchy of governing documents are presented and described. Then some expectations for risk analyses and the definition of risk by the PSA is presented. Finally, the uncertainty dimension and reusability in risk analyses are described.

2.1 Governing hierarchy for risk management

This section describes how internal work processes and guidelines in Equinor is based on laws and regulations by the government in Norway. Figure 1 shows an illustration of this hierarchy.

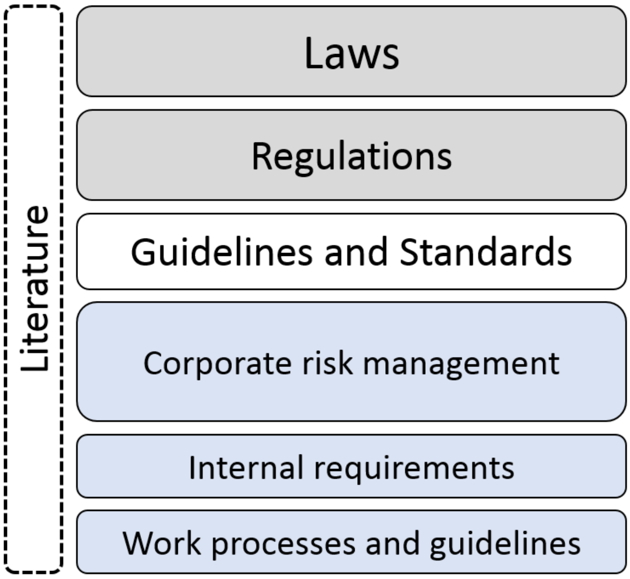

Figure 1: Hierarchy showing how internal work processes and guidelines are associated with laws and regulations. Lower levels depend on upper levels. The literature influences all parts of the hierarchy.

- **Laws** are made by the Norwegian government and are on top of the hierarchy. All petroleum activities must comply with these laws. Important is the petroleum law.
- **Regulations** are specific supplements pursuant to the laws. Complying to the regulations ensure compliance to the laws. PSA is responsible for the petroleum regulations in Norway.
- **Guidelines and standards** demonstrate how the regulations can be met. External organizations have developed certified standards that complies with the regulations. Guidelines or standards are not legally binding and must be used together with regulations.
- **Literature** on risk management is a standalone field that contributes through discussion, ideas and research to sound risk management. Literature affects how companies manage risk and how the government define the regulations.
- **Corporate risk management** includes internal requirements, work processes and guidelines. These are designed based on the standards and regulations and influenced by the literature. This ensures that risk management within the organization complies with the regulations and laws of the government. Example of a work process in Equinor is DW600 for well construction and RM100 for risk management (see Figure 3 for details).

This hierarchy ensures that planning and conducting risk analyses according to internal work processes in Equinor (bottom) will comply with governmental laws and regulations (top). The PSA enforce the laws and regulations on the Norwegian Continental Shelf (NCS). To properly manage risk on the NCS it is therefore necessary to understand the expectations and definition of risk by the PSA.

2.2 Expectations for risk analyses by the PSA

This section presents the general expectations for risk analyses by the PSA and specify what this means for well construction projects. For risk analyses during well construction, the regulations refer to the Norwegian certified NORSOK Z-013 standard. The PSA (2017, p. 8) has summarized some of the elements necessary in risk analyses. Risk analyses should:

a) identify hazard and accident situations,
b) identify initiating incidents and ascertain the causes of such incidents,
c) analyse accident sequences and potential consequences, and
d) identify and analyse risk-reducing measures

for well construction projects, this means that risk analyses should, as a minimum:

A. identify hazards that can occur in the executing phase of a well construction
B. discuss these events to determine causes and consequences
C. analyse the risk elements by rating the consequences in terms of impacts and probabilities
D. risk reducing measure should be identified and analysed for significant risk elements

These expectations are used as criteria when evaluating how Equinor conducts risk analyses in chapter 5. How to manage risk and conduct risk analyses depends on the accepted definition of risk.

2.3 Definition of risk by PSA

This section describes how the PSA defines risk. Implementing this definition into the risk analyses can provide better compliance to governmental views, regulations and laws. The PSA (2016) defines risk as the consequences of activities and associated uncertainty.

Elaborating on this definition, some key points are that:

I. Risk should not be limited to downside risk.
II. The consequences are limited to our activities.
III. The consequences can have any value, monetary or not.
IV. Uncertainty about activities is a main component of risk

Most important for coming chapters is point IV, the focus on uncertainties when describing risk in risk analyses. Interesting is also that point II is limited to our activities and therefore unable to capture the risk in phenomena such as a change in oil price.

2.4 Uncertainty and reusability in well construction risk analyses

Uncertainty and reusability are terms with many applications and different interpretations. This section describes uncertainty and reusability from a risk analysis point of view.

2.4.1 The uncertainty dimension in risk analyses

This section addresses two questions:

- Why is there uncertainty in well construction?
- Uncertainty about what?

The purpose of this section is to motivate why the uncertainty dimension is necessary in risk analyses. Literature with details are referenced.

Why is there uncertainty in well construction?

Well construction projects include simultaneous operations planned by multidisciplinary teams on limited budgets. Wells are drilled thousands of meters into rock with unknown geology. Most of the drilling is blind and based only on seismic interpretations. This high complexity will often cause large uncertainties. Unknown geology is the root cause in terms of uncertainty in a well construction. According to Aven (2014, p. 51), we distinguish between uncertainties about an unknown quantity, uncertainties regarding what the consequences of an activity will be, and uncertainty related to a phenomenon, for example in relation to cause-effect relationships. In other words, there are three main sources of uncertainty:

- Unknown quantities
- The future
- Phenomena

The uncertainty dimension is used when referring to all three sources of uncertainty. The remaining chapters demonstrate the uncertainty dimension in risk analyses but first it is necessary to specify uncertainty.

Uncertainty about what?

When measuring and describing uncertainties in risk analyses it is necessary to specify: uncertainty about what? Uncertainty in general is too broad to be applicable or measurable. Addressing the uncertainty dimension above, examples in a well construction are:

- Unknown quantities – Failure rate of safety valves, pore pressure in the reservoir, reservoir depth, etc.
- The future – Running casing, drilling into the reservoir, cementing, drilling past hard stringers, pressure testing the well, etc.
- Phenomena – There are conflicting elements in the risk picture, the number of risk elements cause a confusing risk picture, the oil price changes, etc.

A well construction risk analysis addresses all these sources of uncertainty. Probability is and unknown quantity commonly used to describe failure frequencies and the distribution of outcomes. As shown in section 2.3, the risk definition by the PSA emphasize on uncertainties about future activities. In well construction risk analyses it is difficult to directly measure the uncertainty about future activities. However, uncertainty about the future can be reduced by properly identifying and describing causes and consequences of the identified hazards. Well construction risk analyses also include uncertainty about phenomena. Most relevant is the uncertainty related to conflicting risk elements (one risk element increasing or reducing the effect of another) and the distribution of risks in the risk picture. This uncertainty can be reduced by improving the presentation of the risk picture.

Strength of knowledge

Probability is a common unknown quantity in well construction risk analyses and the description is therefore extended. Probability estimations are uncertain and depends on the strength of knowledge (SoK). The following example is based on the die example in Aven (2014) and shows the imperfection of probabilities and why SoK is a necessary addition to the risk characterization.

New drill bit technology example:

> A decision maker is considering investing in a new drill bit technology that increases the steering precision. For simplicity, the expected cost of failure, i.e. adjusting a wrong drill path, is 1 million NOK and the new bit technology costs 0.15 million NOK. Based on simulations by the vendor, the following information is available to the decision maker:
>
> Probability of deviating from drill path (failure) with a conventional bit: $p_{conv} = 0.3$
>
> Probability of deviating from drill path (failure) with new bit technology: $p_{new} = 0.1$
>
> The expected cost for both cases becomes:
>
> Expected cost with conventional bit:
>
> $$C_{conv} = 0.3 * 1\, million\ NOK = 0.3\, million\ NOK$$
>
> Expected cost with new bit technology bit:
>
> $$C_{new} = 0.1 * 1\, million\ NOK + 0.15\, million\ NOK = 0.25\, million\ NOK$$
>
> The decision maker decides to invest as the expected cost with the new bit is lower than the expected cost with the conventional bit. The drilling starts and after a couple of hours the new drill bit deviates from planned path (it fails). After consulting with the vendor, it turns out that the simulations used to determine p_{new} was not based on the correct geology for this specific operation. Correcting for geology, the new simulations show a new bit failure, $p_{new} = 0.4$. Invalid assumptions corrupted the probability estimate. The SoK behind the probability estimates was weak and the decision maker didn't know.

Flage and Aven (2009) presented a scoring method to identify significant uncertainty like in the example. Later this scoring has been used to measure the SoK in probability estimates. Flage and Aven (2009) suggested that the SoK in our probability estimates is **weak** if one or more of the following conditions are met:

1. The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.
2. The assumptions made represent strong simplifications.
3. Data are not available, or are unreliable.
4. There is lack of agreement/consensus among experts.

Conditions 1 – 4 are modified to a well construction risk analysis context in Table 4. Motivated by the observation that uncertainty about probabilities can be directly measured while it is difficult for uncertainty about the future and phenomena, uncertainty in well construction risk analyses is described in two ways:

- Directly:
    - Measures exist that qualitatively or semi-quantitatively can provide a description of the uncertainties.
- Indirectly:
    - Simple measures do not exist. Uncertainties are instead indirectly reflected in the setup and structure of risk analyses.

Direct and indirect measures and reflections of uncertainty is presented and discussed throughout chapter 5.

2.4.2 Reusability in risk analyses

The purpose of this section is to describe reusability in risk analyses and motivate why reusability is necessary when planning a well construction.

Understanding reusability in risk analyses

Reusability in risk management can be direct or indirect:

- Direct:
    - Reusability as the ability to reuse information and knowledge from previously conducted risk analyses. Identified risks, risk reducing measures and risk ratings from previously conducted risk analyses are reused in the new analysis.
- Indirect:
    - Reusability as the ability to conduct risk analyses based on a standardized concept or template. An example is how single well risk analyses are based on a standardized field specific concept risk analysis (section 4.4).

Generally, information can be considered as treated data and includes equations, concepts, experiences, decisions, ideas, questions, etc. Knowledge can be considered as organized information and includes understanding, evaluations, frameworks, beliefs, safety culture, etc.

Motivation for reusability in well construction risk analyses

Managing risk when constructing wells are challenged by a need for high quality risk analyses and a need for resource efficient risk analyses. High quality risk analyses are motivated by the major accident potential in well construction. Resource efficient risk analyses in Equinor are motivated by annually drilling more than 100 wells. In the petroleum industry, inefficient resources in risk analyses will be used more efficiently in other parts of the planning process.

Well construction risk analyses are conducted by the same engineers responsible for the entire well planning. There are no dedicated risk analysis experts. Tools for risk analyses must therefore be intuitive and easy to use as the risk management expertise among the engineers is limited and of practical nature. Reusability is necessary to increase the efficiency of resources and ensure that risk analyses are intuitive, easy to use and of practical nature. The main motivation is therefore to avoid reinventing the wheel for every single well construction. The more similar wells and homogeneity in a field, the larger the potential is for reusability.

3 Drilling and Well Activities in Equinor

Equinor is an international energy company with a value chain primarily influenced by oil and gas. Constructing wells is an important part of this chain and is performed by D&W. Wells are constructed for exploring or development (production or injection) purposes. Development wells are constructed as part of field development and includes a planning part and an execution part. The planning phase starts when receiving a well target and the execution phase ends after completing the well.

Risk assessments are important when planning a well to ensure a safe, economic and efficient execution phase. DW600 is the work process used by D&W to plan and execute the construction of development wells. The scope of this work is limited to the risk analyses in the planning part of well construction. The purpose of this chapter is to describe how Equinor as a company defines risk and then to elaborate on how D&W perceive risk based on this definition. The latter is necessary to understand the purpose and mindset of systems and people within D&W.

3.1 Approach to risk and risk management in Equinor

Risk exists because we are uncertain about future outcomes. Uncertain events can have positive impact (upside risk) or negative impact (downside risk) relative to some reference value. Equinor believes that reducing the downside risk will increase the company deliverables and reduce costs. Minimizing the exposure to risk is therefore an important goal for all activities in Equinor. Unfortunately, there is no complete description of risk. Based on the international standard ISO31000, Statoil (2018c) has defined risk as the deviation from a specified reference value and the uncertainty around the magnitude of the deviation.

Elaborating on this definition, some key points are that:

i. Risk is not limited to only upside or downside consequences.
ii. A reference value can be related to unknown quantities, the future or phenomena.
iii. No value is specified for the consequences, i.e. it can be monetary or not.
iv. Focus is on uncertainty about the unknown magnitude quantity
v. The reference value is considered the expected value used as a starting point for the risk analysis.

Compared to the definition of risk by the PSA in section 2.3, both definitions have introduced a focus on uncertainties instead of probabilities. However, the PSA focus on uncertainties about activities (the future) while Equinor focus on uncertainties about unknown quantities. It is also interesting that Equinor refers to risk as deviation from a reference value. This reference value can also capture risk about phenomena such as change in the oil price. Next section describes how D&W perceives risk based on the definition and aspects above.

3.2 Risk and risk management in D&W Equinor

Most daily activities include uncertainty we can live with, surprises that have limited impact and causes of events that are relatively predictable. In this respect, drilling a well is not a daily activity. Drilling wells include high risk with potential for major accidents. According to Statoil et al. (2013), complexity and uncertainty are to main contributors to risk when planning well construction. Well planning is complex due to many moving parts, across multiple disciplines, in dynamic work processes. Major contributors to uncertainties are:

- Personnel: Human mistakes and inconsistencies cause uncertainties.
- Technology: Equipment fails and techniques, simulations and models produce uncertain results.
- Organization: Ineffective systems, work processes and a poor safety culture produce uncertainty.
- Underground conditions: Interpretation of the geology, pressures and hydrocarbon volumes are uncertain properties.

Combining these uncertainties and mentioned complexity with our failure to predict can result in major negative consequences. Consequences in D&W affects people, the environment and the economy. Impacts are therefore grouped in three categories:

- Health Safety Environment (HSE)
- Well Objective (OBJ)
- Time and Cost (TC)

HSE impacts can range from jamming a finger when tightening a drill pipe to several fatalities from an explosion when escaped gas ignites on surface. Monetary impacts (OBJ and TC) range from a few thousand NOK in new equipment to a few hundred million NOK when the well must be re-drilled or abandoned. These examples are all undesirable events with different values for consequence and probability. As mentioned, the risk level in D&W is considered to depend on two factors:

- Uncertainty
- Complexity

D&W consider the risk level to be proportional to the product of uncertainty and complexity. The risk related to an activity could be described as a combination of one consequence and one probability. However, due to large uncertainties and complexity in drilling operations, one value of risk for one activity is not enough. Instead, risk in D&W is described as a range of consequences (measured by impacts) and probabilities for all undesirable events in an activity (see Figure 2).

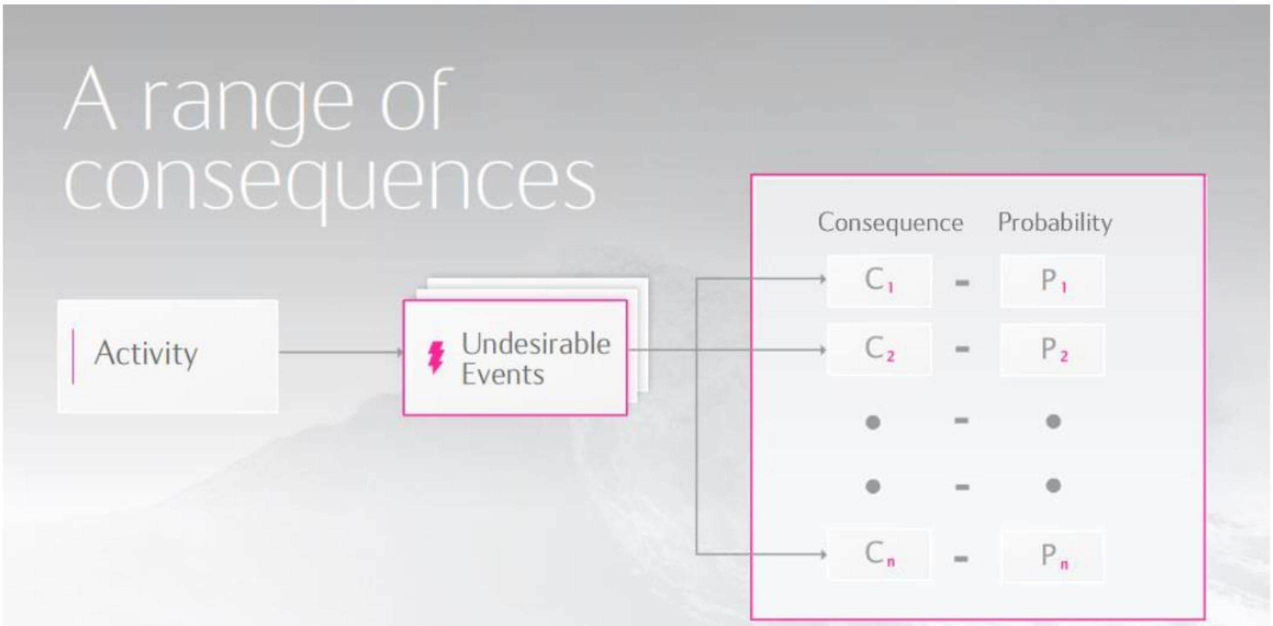

Figure 2: Risk related to an activity is described as the range (1, 2, …, n) of consequences and probabilities for all undesirable events identified in that activity. From: Statoil et al. (2013)

While risk in D&W is generally measured based on the impact and probability of all consequences, the description of risk in the different risk analysis tools vary. These tools are designed to support the risk analysis process by identifying hazards, rating risks and visualizing the risk picture. These tools are presented in the following chapter.

4 Risk Analyses When Planning Single Well Constructions in D&W Equinor

The purpose of this chapter is to describe the risk management system for planning single well constructions and specifically the risk analysis tools used by D&W. First the governing management structure in Equinor is presented to describe the origin for D&W specific work processes. Then, the work process for well construction DW600 is described with focus on risk analyses. Finally, two common risk analysis tools in DW600 are described.

4.1 Management structure in Equinor

The management system in Equinor is structured as a three-level hierarchy consisting of fundamentals, requirements and recommendations. The fundamentals apply for all areas and disciplines in Equinor. The requirements are designed for specific activities and disciplines to ensure compliance with the fundamentals. The recommendations are tailored as guidelines to help meet the requirements as efficiently as possible and contribute to a common practice. Figure 3 shows how the management system (blue) is documented at corporate level (grey) and in a selection of specific areas and disciplines (pink).

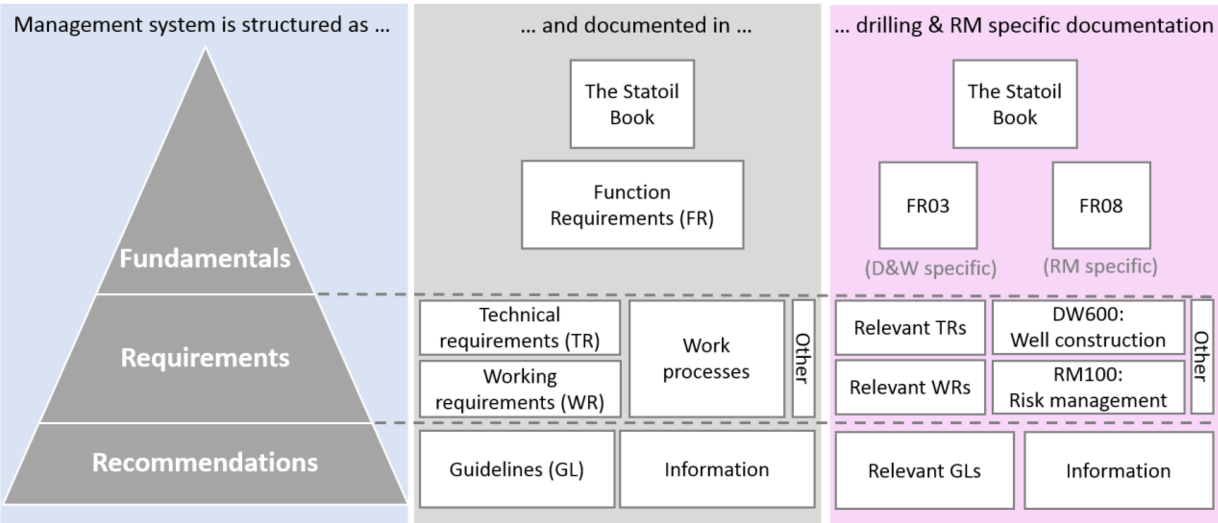

Figure 3: The management system is structured as fundamentals, requirements and recommendations, it is documented at corporate level and in specific areas such as D&W and risk management (RM). Only elements relevant for D&W and RM is illustrated.

DW600 for well construction is one of the work processes used in D&W. Other work processes exist, examples are DW500 for field development and DW400 for well interventions. RM100 is a work process for how to manage risk in all of Equinor. Activities in DW600 are designed to always comply with the requirements in RM100. All work processes are designed to comply with governing function requirements (FR03 for D&W and FR08 for RM). RM100 is shown in Figure 4.

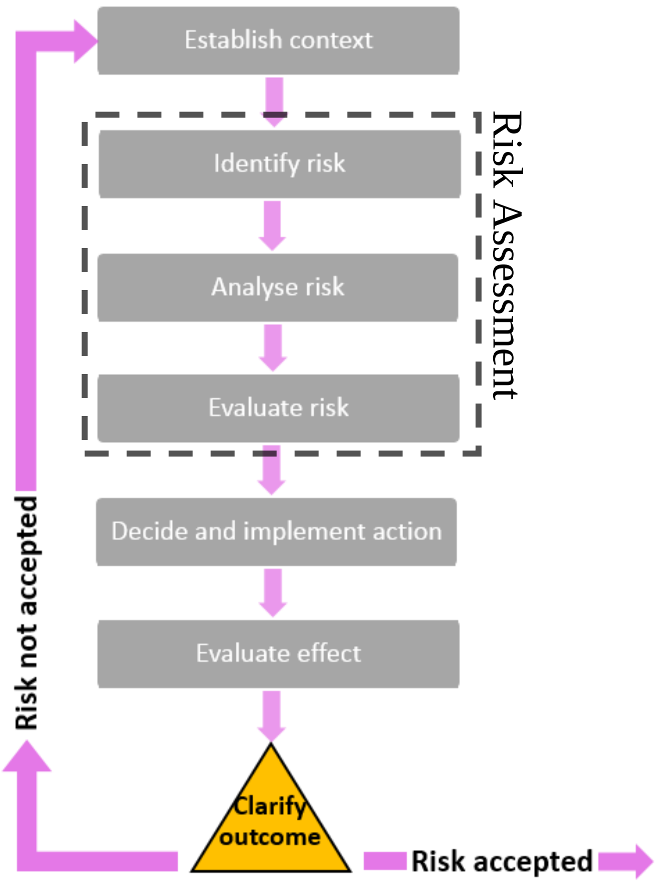

Figure 4: RM100: Work process for risk management in Equinor. The risk assessment process is indicated. Redraw from ARIS (2017b)

The RM100 work process is based on the NORSOK Z-013 standard and describes how to manage risk in all of Equinor, i.e. it is not D&W specific. However, all work processes in D&W are designed based on RM100. RM100 is a general and overarching process that provides common approaches and principles for RM in Equinor. All RM activities in work processes on a specific level in Equinor should be in line with RM100. This is to ensure that all activities comply with NORSOK Z-013 and PSA regulations. As the next section shows, risk assessments and risk analyses (the box in Figure 4) are important parts of well construction RM.

4.2 DW600: Construction of Development Wells

The work process DW600 chronologically describes all activities necessary to plan and execute a well construction, in compliance with relevant fundamentals and requirements. The work process starts by assessing the feasibility of the well project and ends by executing the planned operations. The level of detail in each phase increase accordingly. Figure 5 shows DW600.

Figure 5: Summary of DW600: Construction of Development Wells. The four main phases are feasibility, concept selection, detailed planning and execution. First three phases include risk assessments (purple boxes). Blue boxes are additional RM activities but which are not covered in this work. From: (Statoil et al., 2013)

As indicated in Figure 5, DW600 is divided into four phases:

1. Feasibility phase: Assess if a feasible well design exists.
2. Concept phase: Develop well concepts and select and mature the best one.
3. Detailed planning phase: Plan the selected concept in detail.
4. Execution phase: Execute the planned operations.

Each of the four phases include structured flowchart activities to ensure an efficient and streamlined development process.

Risk management is integrated as part of the activities in the work process DW600, i.e. there is no stand-alone RM process. Risk assessments (purple boxes) are included as part of the feasibility, concept selection and detailed planning phases. Additional risk management activities (blue boxes) exist but are not discussed in this work. After each phase there is a decision gate (DG) for the management to determine if the well project can move to the next phase.

The risk assessment result is used as decision support at these DGs. Having multiple layers of phases and decision gates ensures that the risk assessment is used for decision support rather than for verification. See Appendix A for more details about DW600, flow charts and decision gates. The next section describes the risk assessment activities in DW600 with focus on risk analyses.

4.3 Main risk analyses in the work process DW600

Figure 6 shows the risk assessment part of DW600. According to this process, risk assessments are iterative processes that starts by conducting a risk analysis. After the risk analysis, the potential for detailed studies are decided before eventually updating the project risk register. The risk register summarizes all relevant risks for the management to use as decision support.

Risk assessments are part of the feasibility, concept and the detailed planning phases as shown in Figure 5. The common purpose of risk assessments is to provide decision support. However, the purpose varies across project phases:

- Feasibility risk assessment: Assess feasibility risks with focus on potential show-stoppers to justify a feasible project. Will this well project be feasible?
- Concept risk assessment: Assess the risks related to well design and concept. Should the well concept be moved to the detailed planning phase?
- Operational risk assessment: Assess operational risks related to the detailed planning of the project. Are the planned activities within accepted risks in the execution phase?

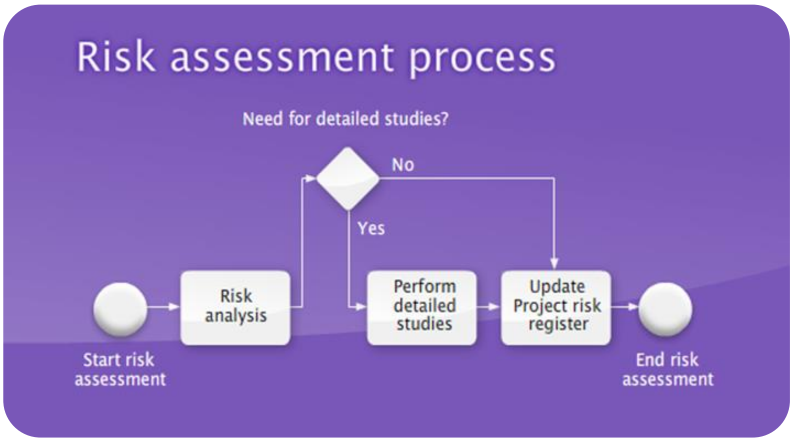

Figure 6: The risk assessment process in DW600. From Statoil et al. (2013)

The remaining parts of this work focus on risk analyses. According to Statoil et al. (2013, p. 15) and shown by the process in Figure 6, a risk analysis should provide a basis for:

- Identifying the need for risk reducing measures if the current risk level is not acceptable (not shown in the figure)
- Deciding the need for detailed studies to elaborate the understanding of the risk
- Updating the final risk register used as decision support for the management

Based on this, the main purpose of a risk analysis can be summarized as providing decision support. More specifically for risk analyses in D&W, the purpose is to provide decision support in terms of:

1. **Deciding if the current risk level is acceptable**
   Identify and analyse risk elements to determine if the well can be constructed within risk acceptance criteria (RAC).
2. **Selecting the best solution among a set of decision solutions**
   In D&W, a risk analysis should be open and transparent enough for decision makers to choose between well concepts. This selection process is outside the scope of this work.
3. **Optimizing the selected solution**
   The risk analysis should identify and analyse risk reducing measures necessary to manage the current risk level.

In D&W, risk analyses are conducted by holding one or more risk analysis meetings. These meetings are led by a risk facilitator who invites the necessary disciplines for a brainstorming and group discussion on relevant risk topics.

The scope, length, level of detail and number of participants in these meetings depend on the project phase, experience, context and complexity. In general, it is common with brainstorming sessions to identify hazards, causes and consequences before rating these risk elements in terms of probability and impacts. In D&W, the terms risk element or risk factor are used to describe the combination of a hazard and its causes and consequences.

Tools are used in the risk meetings to support the risk analysis by collecting identified risk elements and visualizing them to the management. Each project phase in DW600 has a unique risk analysis tool. In the concept phase it can be challenging to specify probabilities and impacts of risks. However, in the detailed planning phase, the level of detail makes it reasonable to specify probability and impact. Such differences are why the tools are tailored to fit the level of detail in the project phase. A checklist approach is used when analyzing concept risks while a logsheet is commonly used when analyzing operational risks in the detailed planning phase. The next sections describe checklist and logsheet.

4.4 The Concept Risk Analysis Checklist in DW600

The Concept Risk Analysis Checklist (referred to as the checklist) is used only in the concept phase. Shown in Figure 5, the concept risk analysis is limited to the chosen well design such as casing design, drilling method, completion solution etc. Unfortunately, experience shows that operational elements are often discussed in concept risk analyses. This results in double-work as operational risks are also covered in the following detailed planning phase. Well constructions are planned with short schedules and limited budgets. A checklist approach was made with the intention to ensure the right level of detail, on schedule and within budget. The checklist has a spreadsheet base and is actively used during risk meetings. The tool consists of two main parts:

1. The first part is a risk analysis of the field specific well concept (see Appendix B.I for as-is example). Developing the field specific concept is a standalone work process called DW916 and is done in advance of the risk analysis for the specific well in question (part 2). This field specific well concept serves as a template for all new development wells in that field. The field specific risk analysis is conducted based on a pre-defined checklist. Shown to the left in Figure 7, the main activities in a risk meeting using the checklist include:
    1. Checking risk factors that are relevant for this field specific well concept.
    2. Describing the concept specific aspects for risk factors that are ticked off.
    3. Rating the manageability of relevant risk conditions.

    It is common to start at the top and work the way down. The resulting risk picture serves as a starting point for the well specific risk analyses in single well projects (part 2).

2. The second part of the tool is used when analyzing the risks related to the selected well concept in DW600; the current well in question. The analysis is conducted by extending and elaborating on the field specific analysis in step 1. Shown to the right in Figure 7, the main activities include:
    1. Reconsidering if unchecked conditions and risk factors should be ticked off for this specific well.
    2. Describing the well specific aspects for risk factors that are ticked off.
    3. Proposing risk reducing measures for same.
    4. Describing the change in risk level relative to the field specific concept for same.
    5. Rating the manageability of risk conditions based on the relevant risk factors.

Based on this risk analysis, the management evaluates the risk conditions (group of risk factors) based on manageability, risk reducing measures and the relative change in risk level. Both parts of the checklist are shown in Figure 7. This work focuses on the well specific (right part) analysis as it is used in DW600.

Field specific concept					**Well specific**				
ID		**Risk Factor**	**Concept specific aspects**	**M**	**Well specific aspects**	**Proposed measures**	**Change**	**M**	**Comment**
1. Operational pressure window									
1.1	X	Pressure margin	Small pressure window in Tor formation due to uncertain pressure conditions	Manageability	Most recent well experienced losses and difficulties predicting the pressure window.	Plan to include pressure points during drilling	⇧	Manageability	Mud weight should be planned according to logging results
1.2	X	Faults	N/S fault with possible migrating gas is present in TOR formation.		Well path for this well avoids the fault.		⇩		
1.3		High ECD							
1.4	X	Depletion	The reservoir is expected to be depleted.		Depletion may have increased. The degree of depletion varies across the field.	Consider circulating lighter mud prior to drilling reservoir section	⇧		
1.5		Gelling							
1.6		Loss zones							
1.7		Cooling							
1.8		Formation damage							
1.9		Other							
2. Well bore stability									
2.1		Weak formation / high collapse gradient							
2.2		unconsolidated, brittle or unstable zones							
2.3		Anomalies (boulders, stringers etc.)							
2.4		...							

Figure 7: Risk analysis checklist as used by D&W. Left part (DW916): Field specific concept risk analysis. Right side (DW601): Well specific concept risk analysis. Examples of three risk factors are shown under the Operational pressure window risk condition. Redraw from Statoil (2018a).

4.4.1 The manageability column

The manageability term is a new addition to risk analyses by D&W. According to Statoil (2017a), the manageability level reflects how challenging it will be to ensure an acceptable risk level in a well project. The following manageability levels apply:

Green: Acceptable risk level achievable using standard solutions.
Yellow: Well specific measures necessary to obtain acceptable risk level.
Orange: Challenging to establish well specific solution with acceptable risk level.
Red: Uncertain whether acceptable risk level will be achievable.

Note that the interpretation of these colors is different from those used to rate risk elements in the risk analysis logsheet in the following section.

4.5 The Risk Analysis Logsheet in DW600

The Risk Analysis Logsheet (referred to as the logsheet) is used primarily in the operational detailed planning phase but can also be used in the concept phase. The detailed planning phase includes operational risk analyses with greater levels of detail than the concept phase. The purpose of the operational risk analysis is to:

- Identify risks related to the matured operational plans.
- Identify the need for further analysis of selected risks.
- Serve as a basis for the risk mitigation in the detailed planning and execution phases.
- Contribute to an optimized operational plan and identification of need for contingency plans.
- Provide input to the decision of proceeding to the execution phase (Statoil, 2017b).

Figure 8 shows the risk analysis logsheet. The logsheet also has a spreadsheet base.

Risk Analysis Logsheet												
Hazard	Causes	Consequences	Existing safeguards	Risk before				Proposed risk reducing measures	Risk after			
				Prob	Impact				Prob	Impact		
					HSE	OBJ	TC			HSE	OBJ	TC
1. Drilling Reservoir Section												
1.1 Stuck drill pipe	Poor cleaning in horizontal reservoir section	• Fishing operation • Circulating and cleaning the well • Side track	Performing well path simulations	P3	I1	I1	I3	Perform additional circulations to clean well	P1	I1	I1	I3
1.2 Influx of hydrocarbons	Too low mud weight when drilling high pressure zones	• Hydrocarbons reaching surface	Pressure detectors. Downhole Safety Valve	P2	I4	I4	I4	Reduce ROP when drilling through rock with potential of high pressure zones. Increase well pressure. Control one way valve on last trip.	P1	I3	I3	I3
1.3 ...												
1.4 ...												
...												

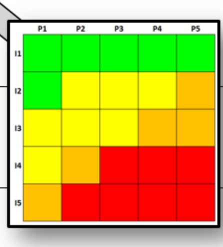

Figure 8: Operational risk analysis with logsheet tool as used by D&W in the detailed planning risk analysis. Redraw from Statoil et al. (2013)

The logsheet tool is actively used during the risk meetings and according to Figure 8, its main activities include:

1. A brainstorming session to identify relevant hazards, their causes and consequences.
2. Identifying existing safeguards for each risk element.
3. Rating each consequence in terms of probability and impact for each category (given existing safeguard).
4. Proposing risk reducing measures.
5. Rerating each risk element based on the effect of risk reducing measures.

It is common to describe one risk element (row) at the time before moving down to the next risk element. Each risk element is continuously evaluated as part of the analysis process when proposing risk reducing measures. All risk elements are transferred into the project risk register after proposing risk reducing measures. Rerating risk elements are therefore important parts of finalizing the project risk register. The overall risk level in the risk register is evaluated by the management. See Appendix B.II for as-is example of the logsheet.

4.5.1 The risk column

Risk elements in the logsheet are rated based on the probability and impact of the consequences. As shown in Figure 9, probabilities range from P1 – P5. Impacts range from I1 – I5 and are divided into three categories (revisit section 3.2 for details). This two-dimensional description of risk is based on the risk matrix as shown in Figure 9.

Increasing probability →

Increasing impact ↓

	Monetary		HSE	P1	P2	P3	P4	P5
	OBJ	TC	HSE	< 1 %	1 - 5 %	5 - 15 %	15 - 30 %	> 30 %
I1	< 10 MNOK	< 10 MNOK	No impact					
I2	10 - 30 MNOK	10 - 30 MNOK	Moderate injury					
I3	30 - 100 MNOK	30 - 100 MNOK	Serious permanent impairment					
I4	100-300 MNOK	100-300 MNOK	Severe (1-3) fatalities					
I5	> 300 MNOK	> 300 MNOK	Major (>3) fatalities					

Figure 9: Risk matrix used to describe risks in terms of consequence and impacts. Impacts are objective (OBJ), time and cost (TC) and HSE. Well integrity impacts are ignored. Redraw from Statoil et al. (2013).

The following risk levels apply in the logsheet:

Green: Risk elements that are considered as low risk due to a low combination of impact and probability. Acceptable risk level. Risk reducing measures to be assessed based on the ALARP principle[1].

Yellow: Risk elements that are considered as low/medium risk due to a low/medium combination of impact and probability. Risk reducing measures should be identified and discussed with management and implemented based on the ALARP principle.

Orange: Risk elements that are considered as medium/high risk due to a high combination of impact and probability. Risk reducing measures should be identified and evaluated.

Red: Risk elements that are considered as high/major risk due to high level of impact and high probability. Risk reducing measures should be identified and evaluated. (Statoil, 2016)

[1] As Low As Reasonably Practicable (ALARP) means that a risk reducing measure should be implemented unless it can be demonstrated that the cost of implementation is grossly disproportionate to the gained benefits.

Green and yellow risk elements in the risk register do not have to be lifted to a higher management level. Orange risks must be lifted one level while red risks must be lifted two levels. Lifting requirements are important to make sure the management are aware of large risks in the corporate portfolio. These lifting requirements are part of the activities described in DW600. The planning team is responsible for identifying the risk elements and communicating them to the management who is responsible for evaluating the risks.

This chapter has described how D&W use the work process DW600 and risk analysis tools to plan construction of development wells and manage risks. In the coming chapters, the risk analysis checklist and risk analysis are evaluated with focus on the uncertainty dimension and reusability.

5 Evaluation of Two Risk Analysis Tools in DW600 and Potential Improvements

This chapter evaluates two tools used for risk analysis in DW600. The basis of the evaluation is introduced before discussing pros and cons of the tools with respect to the uncertainty dimension and reusability in the tools.

5.1 Introduction to the evaluation

The purpose of this section is to describe the information necessary to understand the evaluation.

5.1.1 Two risk analysis tools in DW600

The following risk analysis tools in the work process DW600 are evaluated:

- Concept Risk Analysis Checklist (Figure 10)
- The Risk Analysis Logsheet (Figure 11)

Field specific concept					Well specific				
ID		Risk Factor	Concept specific aspects	M	Well specific aspects	Proposed measures	Change	M	Comment
1. Operational pressure window									
1.1	X	Pressure margin	Small pressure window in Tor formation due to uncertain pressure conditions		Most recent well experienced losses and difficulties predicting the pressure window.	Plan to include pressure points during drilling	⇧		Mud weight should be planned according to logging results
1.2	X	Faults	N/S fault with possible migrating gas is present in TOR formation.		Well path for this well avoids the fault.		⇩		
1.3		High ECD							
1.4	X	Depletion	The reservoir is expected to be depleted.	Manageability	Depletion may have increased. The degree of depletion varies across the field.	Consider circulating lighter mud prior to drilling reservoir section	⇧	Manageability	
1.5		Gelling							
1.6		Loss zones							
1.7		Cooling							
1.8		Formation damage							
1.9		Other							
2. Well bore stability									
2.1		Weak formation / high collapse gradient							
2.2		unconsolidated, brittle or unstable zones							
2.3		Anomalies (boulders, stringers etc.)							
2.4		...							

Figure 10: Concept risk analysis checklist used by D&W in the concept phase. Left part (DW916): Field specific concept risk analysis. Right side (DW601): Well specific concept risk analysis. Redraw from Statoil (2018a).

Risk Analysis Logsheet												
Hazard	Causes	Consequences	Existing safeguards	Risk before				Proposed risk reducing measures	Risk after			
				Prob	Impact				Prob	Impact		
					HSE	OBJ	TC			HSE	OBJ	TC
1. Drilling Reservoir Section												
1.1 Stuck drill pipe	Poor cleaning in horizontal reservoir section	• Fishing operation • Circulating and cleaning the well • Side track	Performing well path simulations	P3	I1	I1	I3	Perform additional circulations to clean well	P1	I1	I1	I3
1.2 Influx of hydrocarbons	Too low mud weight when drilling high pressure zones	• Hydrocarbons reaching surface	Pressure detectors. Downhole Safety Valve	P2	I4	I4	I4	Reduce ROP when drilling through rock with potential of high pressure zones. Increase well pressure. Control one way valve on last trip.	P1	I3	I3	I3
1.3 ...												
1.4 ...												
...												

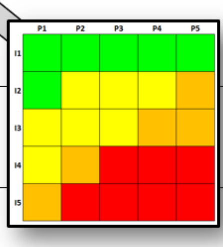

Figure 11: Operational risk analysis logsheet used by D&W in the detailed planning phase. Redraw from Statoil et al. (2013)

The checklist and logsheet are not alternatives to choose between; the checklist is used in the concept phase and the logsheet is used mainly in the detailed planning phase. Other tools exist for other purposes in different phases.

5.1.2 Criteria for risk analyses in D&W Equinor

This section presents the purpose of risk analyses and 10 criteria for risk analyses in D&W Equinor. As described in section 4.3, the main purpose of a well construction risk analysis is to provide decision support with respect to:

I. Deciding if the current risk level is acceptable

II. Selecting the best solution among a set of decision solutions

III. Optimizing the selected solution

Focus in the coming evaluation is on I and III. II is of less relevance as a solution has already been selected when it is relevant to use the selected tools. It is difficult to measure or verify if a risk analysis complies with these purposes. However, it is believed that the criteria in Table 1 can help achieve I and III.

Table 1: Criteria 1 - 10 for risk analyses in D&W Equinor. Sources for all criteria are indicated.

A risk analysis should as a minimum:	Source:
1. Identify hazards in well construction.	Modified according to PSA (2017). See section 2.2 for details.
2. Analyse hazards to understand causes and consequences.	Modified according to PSA (2017). See section 2.2 for details.
3. Rate consequences based on impacts and probabilities.	Modified according to PSA (2017). See section 2.2 for details.
4. Determine necessary risk reducing measures.	Modified according to PSA (2017). See section 2.2 for details.
5. Reflect the uncertainty dimension including uncertainties about a. Unknown quantities b. The future (activities) c. Phenomena	Motivated in section 2.4.1 and by the definition of risk by Equinor in section 3.1.
6. Make applicable parts of the analysis reusable in later activities.	Motivated in section 2.4.2.
7. Be intuitive, efficient and have clear goals.	Motivated by a high demand of resources and efficiency as described in section 2.4.2.
8. Consider risks in a level of detail matching the context of the planning phase.	Experience shows that too much time is spent analysing risks relevant in other planning phases.
9. Provide a risk picture that directly compares to relevant risk acceptance criteria.	Motivated by the need for an efficient evaluation of the risk analysis to fulfil purpose I.
10. Be transparent, meaning that the work behind the analysis is available to decision makers.	Motivated by the need to decide between competing risk reducing measures in purpose III.

These 10 criteria are considered when evaluating and comparing the risk analysis tools in section 5.6.

5.1.3 Evaluation structure

The discussion and evaluation in the coming sections are limited to selected elements in the tools. Selected elements are those considered interesting. What qualifies as interesting is determined based on:

- Personal industrial experience from using the tools combined with risk management literature.
- Discussions and meetings with a risk management specialist in D&W Equinor to determine the current state and areas of improvement in the tools.

The following elements were selected as interesting and subject for evaluation:

- The effect of using a pre-defined checklist to analyse conceptual risks and uncertainties about phenomena (section 5.2.1)
- The effect of using manageability to reflect uncertainties about activities (section 5.2.2)
- How to measure uncertainties about unknown quantities in the checklist (section 5.2.3)
- The effect of presenting a detailed risk picture to reflect uncertainties about phenomena (section 5.3.1)
- How to use SoK to measure uncertainties about probabilities in the logsheet (section 5.3.2)
- Using a field specific template to reuse applicable risk analyses in well construction (section 5.4)
- The effect of reusing information and previous risk analyses in the logsheet (section 5.5)

The discussion and evaluation of these elements are structured in the following sections:

- Uncertainty dimension:
    - 5.2 discusses and evaluates the risk analysis **checklist** with respect to uncertainties
    - 5.3 discusses and evaluates the risk analysis **logsheet** with respect to uncertainties
- Reusability:
    - 5.4 discusses and evaluates the risk analysis **checklist** with respect to reusability
    - 5.5 discusses and evaluates the risk analysis **logsheet** with respect to reusability
- Comparison:
    - 5.6 compares and evaluates the two tools in terms of the 10 criteria in section 5.1.2.

5.2 Selected elements in the risk analysis checklist with respect to uncertainties

This section evaluates the selected elements in the checklist related to the uncertainty dimension. Refer to Figure 10 for an example of the checklist.

5.2.1 The effect of using a pre-defined checklist to analyse conceptual risks and uncertainties about phenomena

This section discusses the pros and cons of using a checklist to analyse risks in the concept phase.

Description

As previously mentioned, experience in D&W shows that it is difficult to maintain a narrow scope when analyzing risks in the concept phase of well construction. Engineers tend to have a practical and visualizing approach when identifying hazards. The result is that operational risks are too often discussed during concept phase risk meetings. The pre-defined checklist approach shown in Figure 10 was designed to help maintain a limited scope. Can a checklist justify the need for high quality risk analysis in complex projects like well construction?

Discussion

Risk analyses in well construction are conducted in the feasibility phase, concept phase and detailed planning phase. The checklist approach is used to analyse risks in the feasibility phase and in the concept phase. While the feasibility checklist is ignored, the pros and cons in this discussion concerns two issues in the concept phase:

1. Can a checklist approach be justified as a risk analysis in the concept phase of well construction?
2. Is the checklist approach sufficient to reflect the uncertainties about phenomena, i.e. the uncertainties about the dependency of risk factors, how they are structured and which risk factors contribute to major risks?

Table 2: Pros (green) and cons (red) of using pre-defined checklists in well construction risk analyses with respect to the uncertainty dimension

Using a checklist is more efficient as it is not necessary with a laborious risk factor identification process and it limits the scope to conceptual risk factors. The concept phase is influenced by general risks that will not influence the execution phase without being reanalyzed in the detailed planning phase. A checklist also maintains the practical and methodological approach of engineers.	A checklist can indicate that the tool is perfect. The checklist is not perfect and this is reflected by including the "Other" option where engineers can fill out additional risks. However, experience in D&W shows that this option is rarely used. One reason can be the challenge of rapidly turning the checklist-identification-mode-switch.
A checklist contributes to proper distribution of resources when analyzing risk Excessive resources are not spent on a few risk factors. Key risk are factors are split into several occurrences to make up a larger part of the risk picture.	A checklist lacks the option to sort risk factors. This can make the evaluation process by the management more difficult and time consuming.
The checklist is transparent as it also shows which risk factors were not considered as relevant for the specific field or well. The decision maker can easier identify conflicting and dependent risk factors and this transparency therefore reduce the uncertainty about the risk picture.	Based on experiences in D&W, it can be challenging to maintain a focus on identification with a pre-filled spreadsheet (checklist) on the wall. The identification process tends to be influenced by the risks already on screen.
Resources beyond what is available in single risk analyses was used to design the checklist. Therefore, the checklist will most likely include more risk factors than a regular team of engineers would identify if starting from scratch and "blank sheets".	Checked risk factors can appear certain to a decision maker. The tool does not reflect how applicable a risk factor is. Theoretically, an unchecked 49% applicable risk factor is treated differently than a checked 51% applicable risk factor.
The checklist has sorted the pre-define risk factors under major risk conditions. This sorting makes it easier for the engineers to focus on one area at the time. This removes the common back and forth discussion.	There are clearly uncertainties about the chosen pre-defined risk factors. Do they represent common risks? Are they well distributed? Do they capture the major risks? The checklist lacks a direct measure of such uncertainties.

Improvements

One weakness of the checklist is the challenge to maintain a good identification mind set while checking pre-defined boxes. The “Other” row is intended for additional risks. It is suggested to change the name of this row to something more intuitive and educational. Examples are:

- “Unique risk factors”
- “Remaining risk factors”
- “Remaining and unique risk factors for this field/well”

These entries emphasize that the checklist is not complete and require additional identification. In addition, a brief description of focus areas could be included to guide the identification and make it more efficient. Alternatively, the risk meeting could be held without displaying the checklist and using it for discussion points to maintain an identifying mindset.

5.2.2 The effect of using manageability to reflect uncertainties about activities

Description

As described in section 4.4.1, the manageability level reflects how challenging it will be to ensure an acceptable risk level for the relevant risk condition in the risk analysis checklist. The manageability level is currently visualized for each risk condition by applying colors (green, yellow, orange and red). The manageability level is assigned first in the field specific part and then in the well specific part. The manageability level is just one component of the risk description and is indicated by an M.

Discussion

The manageability term is used only in the checklist, i.e. it is limited to the concept phase of well construction. In this phase, decisions are related to well design and concepts. Due to the low level of details in this phase, it is challenging to assign exact probabilities and monetary impact values as this information is not available. Manageability is a term that makes the risk description fit better the general context of the concept phase. Is there a relation between manageability and uncertainty? The following suggestion was based on the risk level used by D&W in section 3.2.

In D&W the risk level is proportional to the product of uncertainty and complexity. It is reasonable to say that the manageability of an activity decreases with increased uncertainty or complexity. Based on this idea, manageability is roughly described as:

$$Manageability \propto \frac{1}{Uncertainty * Complexity} \tag{5.1}$$

By qualitatively describing the manageability for relevant risk conditions, the engineer reflects the inverse of the uncertainty level. Green manageability may now reflect low uncertainties while red manageability reflects large uncertainties. Unfortunately, the expression cannot be that simple as uncertainty also depends on complexity. The purpose of the expression is to help D&W engineers to better understand how manageability and uncertainty is related to the risk level. So how can an engineer determine the manageability level?

Manageability is an intuitive term that doesn't require precise probability or impact values. It forces the engineers to reflect if all the risk factors in a specific risk condition can be managed or not. To answer this question the engineer must consider several aspects of risks:

- Can the event occur?
- What can be the magnitude?
- What are possible risk reducing measures and effect of these?
- What is the effect of existing safeguards?

Assigning a manageability level indirectly makes the engineers reflect on uncertainties and complexities. Such reflections motivate good discussions in the risk meetings. The manageability level is visualized using the same colors as when rating risk elements in the logsheet. Using the same color scale in both tools can be confusing. As described in sections 4.4 and 4.5, the colors have different interpretations in the two tools. Green color in the logsheet indicate a low probability and low impact while green in the checklist indicates that the risk can be managed. Theoretically, a risk condition can be of high probability and high impact i.e. a red risk, but still be manageable through efficient risk reducing measures i.e. a green manageability. To properly use manageability to describe risk factors and reflect uncertainties it is necessary with a different color scale.

Improvements

Practical improvements are demonstrated for how to better visualize the manageability level in the checklist. The following three criteria for a new manageability scale were set:

1. The design must be different from the one used to rate risks in the logsheet.
2. The design must be intuitive and reflect how uncertainty and complexity contribute to the manageability level.
3. The design must be easy to implement and not require a substantial amount of additional resources.

Based on these criteria, three designs are suggested and shown in figure Figure 12.

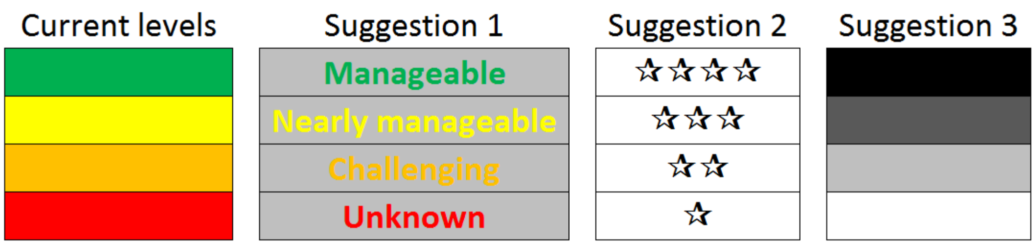

Figure 12: Current manageability levels (first from left) and the three improvement suggestions.

In suggestion 1 the following interpretations of the words are suggested:

Manageable: The risk condition is manageable, no attention needed.

Nearly manageable: The risk condition is nearly manageable, consider measures based on ALARP.

Challenging: It is challenging to obtain a manageable risk condition. Actions are required.

Unknown: It is unknown if a manageable risk condition can even be achieved. This level emphasizes that there is too much uncertainty to even determine the manageability.

The current and three suggestions are compared to the criteria in Table 3.

Table 3: Pros and cons of the three suggestions based on the three criteria.

Criterion	Current levels	Suggestion 1	Suggestion 2	Suggestion 3
1	Same levels as in the logsheet.	Levels are understandable, logical and different from risk rating in the logsheet. It is challenging to precisely define the words.	Levels are understandable, logical and different from risk rating in the logsheet.	Levels are different from the logsheet.
2	Intuitive but does not reflect the uncertainty and complexity contribution.	The scale remains intuitive by maintaining the traffic light color in the font. It is possible for decision makers to get an overview of the risk level. Using "Unknown" emphasizes that there are large uncertainties. Complexity is not reflected.	Partly intuitive as more stars are preferred to less. Difficult to describe the difference between the levels. The overall risk picture can be confusing with too many stars and no reference value.	Similar to the current approach but different enough. Not intuitive that black is preferred to white. Difficult to describe the difference between the levels. Does not reflect uncertainty or complexity.
3	Requires no time.	Requires a one-time implementation.	Requires a one-time implementation.	Requires a one-time implementation.

Based on the pros and cons above, suggestion 1 is preferred as it is both intuitive and reflects the uncertainties. One suggestion that is applicable to all the designs is to implement a slider to show the uncertainty and complexity contribution as described in criterion 2. Implementation of suggestion 1 and the slider option is shown in Figure 13.

Field specific concept					Well specific				
ID		Risk Factor	Concept specific aspects	M	Well specific aspects	Proposed measures	Change	M	Comment
1. Operational pressure window					Uncertainty ← → Complexity				
1.1	X	Pressure margin	Small pressure window in Tor formation due to uncertain pressure conditions	Nearly manageable	Most recent well experienced losses and difficulties predicting the pressure window.	Plan to include pressure points during drilling	⇧	Challenging	Mud weight should be planned according to logging results
1.2	X	Faults	N/S fault with possible migrating gas is present in TOR formation.		Well path for this well avoids the fault.		⇩		
1.3		High ECD							
1.4	X	Depletion	The reservoir is expected to be depleted.		Depletion may have increased. The degree of depletion varies across the field.	Consider circulating lighter mud prior to drilling reservoir section	⇧		
2. Well bore stability					Uncertainty ← → Complexity				
2.1		Weak formation / high collapse gradient		Manageable				Manageable	
2.2		Unconsolidated, brittle or unstable zones							
2.3		Anomalies (boulders, stringers etc.)							
...		...							

Figure 13: Risk analysis checklist showing the implementation of suggestion 1 and the slider option for uncertainty and complexity distribution in each risk condition.

The purpose of this slider is to describe the distribution in equation 5.1. The slider option is only included in the well specific part as it is difficult to say something about general uncertainties and complexities for the entire field. The slider is used by engineers to describe the source of increased risk (reduced manageability). Increased manageability (a better situation) leaves the slider in the middle position. While this improvement fails to describe "uncertainty about what?" it still serves an educational effect that can motivate good discussion in the risk meetings. The slider in the well specific analysis in Figure 13 shows that the pressure window has reduced manageability caused by increased uncertainties compared to the field specific risk concept.

Field specific concept					Well specific				
ID	Risk Factor	Concept specific aspects	M	Well specific aspects	Proposed measures	Change	M	Comment	
1. Operational pressure window					Uncertainty ← → Complexity				
2. Well bore stability					Uncertainty ← → Complexity				
3. Hole cleaning					Uncertainty ← → Complexity				
4. Well geometry tolerances					Uncertainty ← → Complexity				
5. Torque and draw window					Uncertainty ← → Complexity				
6. Cementing					Uncertainty ← → Complexity				

Figure 14: Collapsed risk conditions showing all sliders in the well specific risk analysis checklist.

While looking at one slider at the time provides little information it is when all sliders are considered at once that the value is evident. Looking at the sliders for all risk conditions in Figure 14 gives a good indication that uncertainty is the main contributor to reduced manageability. This overview provides good decision support to decision makers and engineers.

5.2.3 How to measure uncertainties about unknown quantities in the checklist

This section demonstrates and discusses an improvement that can be used to reflect uncertainties about the change in risk level (arrows in the checklist). Figure 15 is part of the checklist and is used to show this improvement. First, the current approach must be described before demonstrating the suggested improvement.

Description

Field specific concept					Well specific				
ID		Risk Factor	Concept specific aspects	M	Well specific aspects	Proposed measures	Change	M	Comment
1. Operational pressure window									
1.1	X	Pressure margin	Small pressure window in Tor formation due to uncertain pressure conditions	Manageability	Most recent well experienced losses and difficulties predicting the pressure window.	Plan to include pressure points during drilling	⇧	Manageability	Mud weight should be planned according to logging results
1.2	X	Faults	N/S fault with possible migrating gas is present in TOR formation.		Well path for this well avoids the fault.		⇩		
1.3		High ECD							
1.4	X	Depletion	The reservoir is expected to be depleted.		Depletion may have increased. The degree of depletion varies across the field.	Consider circulating lighter mud prior to drilling reservoir section	⇧		

Figure 15: Left: Field specific risk analysis checklist. Right: Well specific risk analysis. Four risk factors 1.1-1.4 are included.

The *Pressure margin* risk factor in Figure 15 is used as an example. The upward arrow indicates that this risk factor is more difficult to manage in this well compared to the field specific concept. In the current state, a box with the same color as the manageability is used to indicate which risk factor contributes the most to reduced manageability. The current approach is described in step 1 and 2 while the suggested improvement is described in step 3 below:

1. Well specific aspects are qualitatively described. For *1.1 Pressure margin* the most recent well in the field experienced losses of mud as a result of too high well pressure. This risk factor resulted in reduced manageability (going from yellow to orange).
2. Measures are proposed to increase the manageability. For *1.1 Pressure margin* it was proposed to take pressure points during drilling to maintain the correct well pressure.
3. (New) As *1.1 Pressure margin* is the main contributor to reduced manageability, the engineer is asked to reflect on the uncertainties related to this risk factor. The uncertainties about the risk level are then qualitative described in the comment section:
   I. The engineer is asked if there are significant uncertainties about the risk factors influence on the risk level.
   II. No further action is required if a "No" is selected.
   III. If a "Yes" is selected the engineer must describe why there is significant uncertainties. A score list is made to help the engineer identify significant uncertainties and describe them.

The score list is based on the scoring system by Flage and Aven (2009) in section 2.4.1. There is significant uncertainty about the risk level if one or more of the aspects in Table 4 are true.

Table 4: Modification (right) of the significant uncertainty aspects (left) originally by Flage and Aven (2009)

Aspects to consider by Flage and Aven (2009):	Modified aspects to consider in well construction:
The phenomena involved are not well understood.	This risk factor includes new elements or there is little experience in the field of with this type of wells.
Models are non-existent or known/believed to give poor predictions	Calculations or simulations on casing program, casing wear, well trajectory, pressure plot, etc. are imprecise, conflicting or non-existent.
The assumptions made represent strong simplifications	At least one of the assumptions on the front page represent strong simplifications and is relevant for this risk factor.
Data are not available, or are unreliable	There are too few or no reference wells available. Necessary downhole data is missing or unreliable.
There is lack of agreement/consensus among experts.	There is lack of agreement between disciplines or experts in the risk analysis meetings.

Figure 16 demonstrates how step III could be implemented.

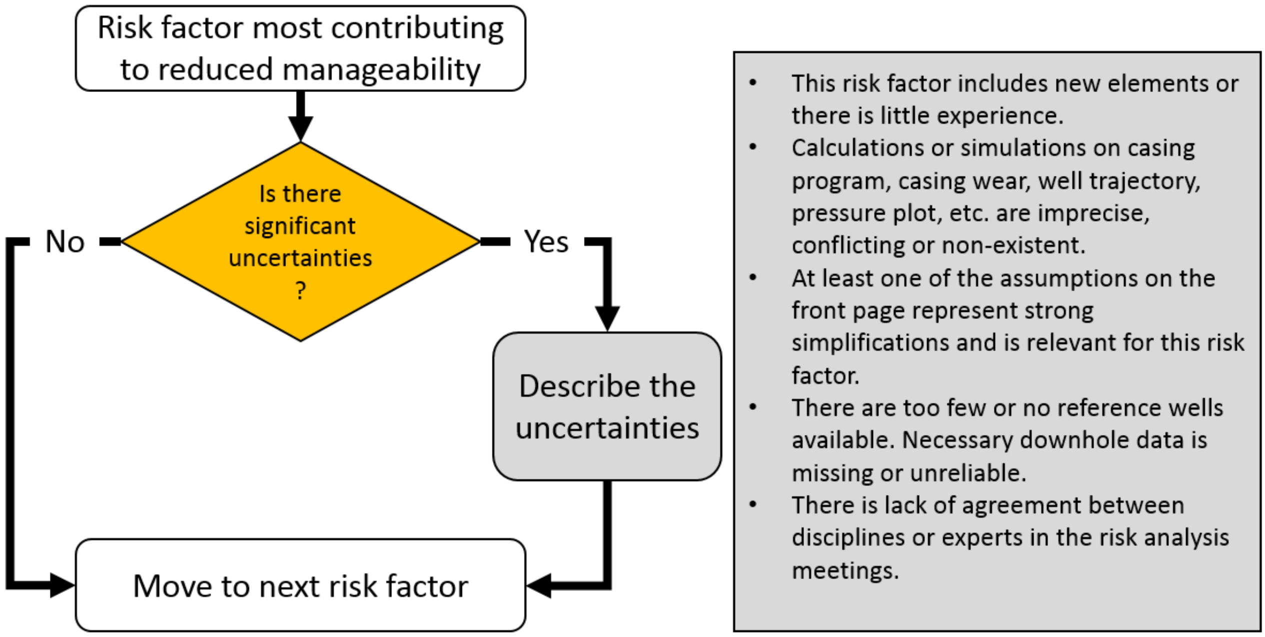

Figure 16: Implementation of a qualitative description of the uncertainties about the risk level. The grey pop-up box is used to support the engineer when deciding between Yes and No and when describing the uncertainties.

Discussion

While literature such as Flage and Aven (2009) present methods to distinguish between varying degree of uncertainty, the idea of this suggestion is to focus only on the risk factors with significant uncertainty. Focusing on the extreme case of uncertainties is beneficial as:

- It is efficient and easy to treat uncertainty as binary.
- It can be challenging to decide between minor, moderate and significant uncertainty.
- It is closely related to the major accident potential in well construction. Major accidents can be greatly reduced by avoiding significant uncertainties.

Considering the aspects in Table 4 when analyzing risks can also educate the engineers and decision makers to give weight to uncertainties rather than expected values and probabilities. In the current version of the checklist there is no place for the user to say, “I don’t know”. The tool requires inputs. The suggestion demonstrated in Figure 16 is one way for engineers to express this uncertainty.

Answering "No" to the question of significant uncertainty in a risk factor is not saying that there are no uncertainties. This is an important difference. "Yes" means there is significant uncertainty, a "No" means that there can be moderate, minor or no uncertainties. A "No" must be broadly defined like this to avoid the challenge of saying that there are no uncertainties. Another argument is that no uncertainties must mean that there is perfect knowledge, i.e. it is known exactly what will occur, when and how. Looking into the future, there will always be uncertainties.

The demonstrated suggestion also has some weaknesses:

- Engineers must spend additional time to determine if there are significant uncertainties. This is time that also could be used elsewhere.
- It is challenging to choose which D&W specific aspects to include in Table 4 for justifying significant uncertainty. These aspects depend on the context of the operation and will likely change over time.
- Compared to the daily work of a D&W engineer, uncertainty is an abstract term. To avoid dissatisfaction and confusion it is necessary to have intuitive and straight forward aspects to consider when justifying significant uncertainty.

Based on the above pros and cons, it is recommended to implement the uncertainty description as demonstrated in Figure 16. Mainly because identifying significant uncertainties provides a better risk picture while also educating the engineers and decision makers to consider uncertainty as a main component of risk. This measure can also contribute to a mind-set influenced by uncertainties rather than probabilities.

5.3 Selected elements in the risk analysis logsheet with respect to uncertainties

This section evaluates the selected elements in the logsheet related to the uncertainty dimension. Refer to Figure 11 for an example of the logsheet.

5.3.1 The effect of presenting a detailed risk picture to reflect uncertainties about phenomena

This section discusses if detailed risk descriptions can reflect uncertainties about phenomena such as the focus area in a risk picture and conflicting risks elements.

Description

As described in section 3.2, risk in D&W is considered as the sum of probabilities and impacts for all consequences in an event. The logsheet tool is designed based on this concept of risk. A row in the logsheet is called a risk element and includes:

Hazards: Initiating events are identified.
Causes and consequences: Causes and consequences to a hazard is identified.
Existing safeguards: Relevant existing safeguards are listed.
Probability and impacts: Probability and impact of each consequence is rated.
Risk reducing measures: Based on the risk rating, necessary risk reducing measures are proposed.

The logsheet is made up of potentially hundreds of risk elements, depending on the complexity and context. These risk elements make up the risk picture presented to the decision makers. The risk picture has two dimensions:

- Horizontal dimension: The left to right description of a risk element
- Vertical dimension: The number and distribution of risk elements

Discussion

The horizontal dimension of the logsheet includes a detailed description of a risk element. It requires a substantial amount of resources in the risk meetings to identify and analyze hazards, causes, consequences, safeguards, probabilities, impacts and risk reducing measures. This description provides transparency in the risk analysis which improves the knowledge of the decision maker. Increasing knowledge reduces uncertainties.

Another part of this detailed risk description are the impact values which are divided into categories. As described in section 4.5 the categories are HSE, OBJ and TC. Using multiple categories removes the uncertainty about transforming different impact values into one common unit. This transparency makes it possible to choose and justify risk reducing measures. This benefit is shown when comparing the two risk elements in two cases in Figure 17.

One cumulative monetary impact value

Logsheet			
Hazard	Risk before		Proposed risk reducing measures
	Prob	Impact	
1.1 Drilling reservoir			
1.1.1 Stuck drill pipe	P2	I3	Pay cost to perform additional circulations to clean the well
1.1.3 Drilling into fault in reservoir	P2	I3	Pay cost for a geologist to conduct additional pressure test

Non-monetary and monetary impact values

Logsheet					
Hazard	Risk before measures				Proposed risk reducing measures
	Prob	Impact			
		HSE	OBJ	TC	
1.1 Drilling reservoir					
1.1.1 Stuck drill pipe	P2	I1	I1	I3	Pay cost to perform additional circulations to clean the well
1.1.3 Drilling into fault in reservoir	P2	I3	I3	I3	Pay cost for a geologist to conduct additional pressure test

Figure 17: Left: Probability and impacts for risk elements with one common unit for impact. Right: Probability and impact with impact categories. Note that cause, consequence and existing safeguards columns have been removed.

The left part of Figure 17 shows that having one impact category makes it difficult to choose between risk element 1.1.1 and 1.1.3. Both risk elements are rated with P2 and I3 for probabilities and impacts. However, in the right case it is clear that a risk reducing measure is needed in risk element 1.1.3 due to larger HSE impact. This level of detail and transparency in the horizontal dimension provides information to the decision maker beyond the common risk matrix approach.

The vertical dimension also contributes to a transparent risk picture by including all consequences of an activity and not combining them into one cumulative consequence. This benefit is presented in Figure 18.

Logsheet						
Hazard	Causes	Consequences	Risk before measures			
			Prob	Impact		
				HSE	OBJ	TC
1.1 Drilling reservoir						
1.1.1 Stuck drill pipe	Poor cleaning in horizontal reservoir	• Fishing operation	P3	I1	I1	I3
1.1.2 Stuck drill pipe	Poor cleaning in horizontal reservoir	• Circulating and cleaning the well	P3	I1	I1	I3
1.1.3 Stuck drill pipe	Poor cleaning in horizontal reservoir	• Side track	P3	I1	I1	I3
1.1.5 Higher well pressure than the reservoir pressure	Reservoir is more depleted than prognosed resulting in a lower pressure	• Losing mud to the reservoir reducing the productivity	P3	I3	I3	I3

Figure 18: Risk analysis logsheet showing how the hazard "Stuck drill pipe" is divided into three risk elements (1.1.1, 1.1.2 and 1.1.3) due to several identified consequences.

In this case it is clear that risk reducing measures should be prioritized in risk element 1.1.5. Using a technology called managed pressure drilling (MPD) to avoid losing mud to the reservoir could be suggested as a risk reducing measure. There are several weaknesses of presenting such a detailed risk picture consisting of hundreds of rows with information:

- It can be challenging to identify conflicting risk elements.
- There can be loops in the risk elements such that risk A influences risk B which influences risk C which again influences risk A.
- Does the risk picture present the actual risk level? What describes the risk level? Is it the number of risk elements? What are the major risk drivers?
- It is difficult to compare risks. What is preferred between two orange risks and one red risk? What about 5 yellow risks and one red risk?
- The logsheet does not show risk elements that was not considered (like the checklist does). It is unknown if these risk elements were never identified or if they were neglected.

The problems described above is described as risk pulverization and exists because risk elements are broken into too many details which makes them difficult or impossible to evaluate. It is always possible to divide an activity (risk) into smaller activities (risks). There is obviously a lot of uncertainties in risk pulverization. How do we know that the described activities represent the actual activities and are not just pulverized? This large vertical dimension of the risk picture with hundreds of risk elements needs to be improved.

Improvement

As described in section 2.4.1, uncertainty about phenomena is related to the presentation of the risk picture including the number of risk elements, the distribution of risks and now risk pulverization. The uncertainties in such cause-effect relationships can be reduced by isolating, sorting, arranging and describing important risk elements. HSE is clearly the most important impact category in the logsheet. It is suggested to generate a report that visualizes and describes all orange and red HSE risks. An example of this report is shown in Figure 19.

HSE Summary Report				
Hazard	**Causes**	**Consequences**	**Risk after measures** Prob	Impact HSE
1. Drilling overburden				
2. Drilling reservoir				
Challenges in the risk picture: The risk picture is influenced by high risks resulting from challenging pressure management (2.4 and 2.15).				
2.1 Casing wear when re-using old casing	Re-use casing	Re-drill section	P4	I3
2.4 Mud losses when drilling into permeable zone	High mud weight due to unstable shale	Heavy losses and re-drill section	P4	I3
2.8 High gas levels when drilling 8 1/2" section combined with high losses	Geological uncertainties. Premature exposure of gas	Gas on rig. Abandon branch or well.	P2	I5
2.15 Kick when drilling into local high pressure zone at 2700m MD. 300m TD above reservoir.	High pressure in shale located at 2700m MD causes underpressure in the well and influx of potential hydrocarbons.	Hydrocarbons on surface. Shut down of well. Abandon well.	P2	I4
3. Completion				

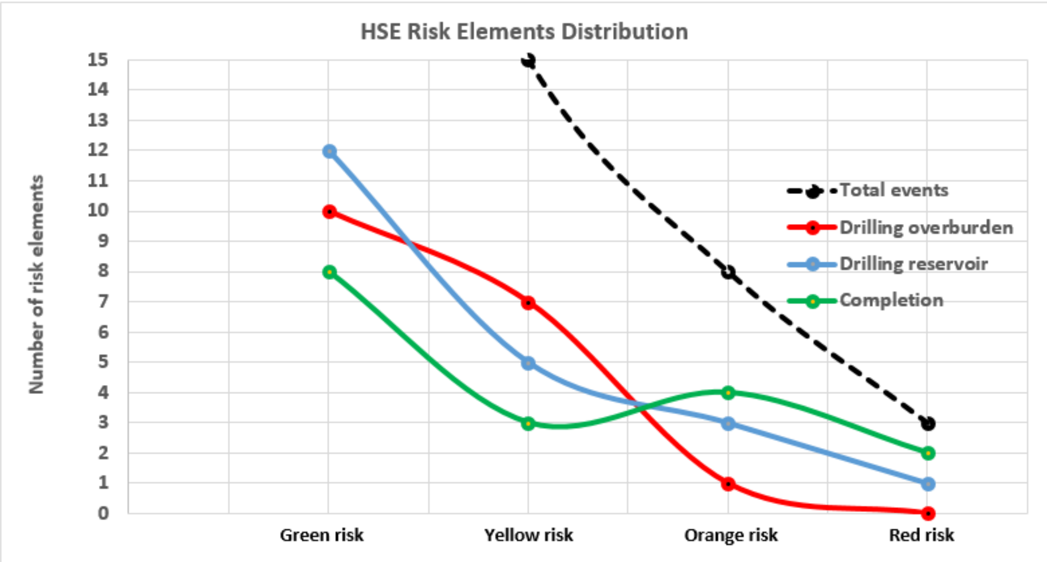

Figure 19: Example of layout for HSE Summary Report. Top shows summary of orange and red HSE risks. The bottom shows the distribution of these risk elements.

The table in Figure 19 summarize orange and red HSE risk elements when drilling the reservoir. Decision makers can use this information to gain knowledge about the important focus areas. The plot in in Figure 19 shows that the completion operation includes 4 orange risks and 2 red risks. In terms of risk level, the completion operation will require the most attention. Plots and graphs are generated automatically based on the risk analysis logsheet. The only input required by the user is to describe the risk picture challenges under each section in the top table.

The purpose of the report is to increase the decision support and increase the knowledge by reducing the risk picture to a comprehendible size. Increasing the knowledge about the risk picture naturally reduce the uncertainties about the risk picture.

5.3.2 How to use SoK to measure uncertainties about probabilities in the logsheet

This section demonstrates and discusses how SoK can be used to measure the uncertainties about the assigned probabilities in the logsheet tool.

Description

As discussed in section 5.3.1, uncertainties about the risk picture are indirectly reflected in the logsheet. However, there is no measure of the uncertainty about the assigned probabilities. As described in section 2.4.1, the SoK behind a probability estimate can describe the uncertainties. This section demonstrates a practical implementation of SoK in the risk analysis logsheet. Pros and cons of this implementation are discussed. The suggestion is demonstrated in Figure 20.

Risk analysis logsheet

Hazard	Causes	Consequences	Existing safeguards	Risk before measures					Proposed risk reducing measures and certainty improvements	Risk after measures					Comments
				Prob	Impact			U		Prob	Impact			U	
					HSE	OBJ	TC				HSE	OBJ	TC		
1.1 Drilling reservoir															
1.1.1 Stuck drill pipe	Poor cleaning in horizontal reservoir section	• Fishing operation • Circulating and cleaning the well • Side track	Well path simulations	P3	I1	I1	I3	No	Perform additional circulations of the well to clean	P2	I1	I1	I3	No	
1.1.2 Drilling into underlying water zone	Well path set too close to water zone	Reduced productivity	Geological steering	P3	I1	I1	I3	Yes	Include a safety factor for distance to water zone. Consult with PETECH discipline to verify probability.	P4	I1	I1	I3	No	Expanding the knowledge, the probability was increased to P4 and impacts was verified.

Figure 20: Risk analysis logsheet showing the implementation of SoK as a measure of the uncertainties in risk elements. Red writing indicates new elements. Refer to Figure 11 for the original version.

1. The rating of a risk element is expanded by adding an uncertainty column (U).
2. The uncertainty column is used to identify risk elements with weak SoK.
3. Weak SoK is analogous to the significant uncertainty scoring described by Flage and Aven (2009) in section 2.4.1.
    - "Yes" is used when the SoK is weak.
    - "No" is used when the SoK is not weak (i.e. medium or strong)

2. Table 4 in section 5.2.3 is used to determine if the SoK is weak (significant uncertainty).
4. A "Yes" will turn the risk rating grey to represent weak SoK.
5. Addressing the uncertainty column (U) is required for risk elements that originally were rated as orange or red.

6. The “Proposed risk reducing measures” column is expanded to “Proposed risk reducing measures and certainty improvements”
7. If the SoK increases after the risk reducing measures and improvements, the risk rating colors reappear.

Discussion

This discussion includes pros and cons of this implementation is presented in Table 5.

Table 5: Pros (green) and cons (red) of implementing the SoK measure in the risk analysis logsheet.

Risk ratings become more informative as the SoK behind the probability estimates are reflected. Greying out risk elements with significant uncertainties clearly demonstrate that probability estimates are less precise if there are large uncertainties.	Measuring the SoK requires extra work in a work process that is already influenced by a limited schedule. Focusing only on weak SoK is one way to reduce this work. Precise SoK aspects (such as those in Table 4) will be crucial to reduce this time further.
Including grey coloring for risk elements with weak SoK makes the analysis transparent for decision makers as risk elements that used to be uncertain is still visible. Knowing that a risk element used to be uncertain is valuable information for a decision maker.	The decision is qualitative and subjective and will therefore vary among engineers.
Elements with weak SoK can be summarized on the front page of the analysis to prepare the decision maker on which parts of the analysis require most focus.	
Introducing SoK and uncertainty can have an educating effect on the engineers using the tool. Addressing the scoring list for SoK provides valuable information alone.	
Sorting important risk elements based on uncertainty can reduce the issue of an overwhelming risk picture as described section 5.3.1.	

As shown in Table 5, even though implementing a SoK measure includes extra work, the pros are many.

5.4 Using a field specific template to reuse applicable risk analyses in well construction

This section evaluates the selected element in the checklist related to reusability. Refer to Figure 10 for example of the checklist.

Description

As described in section 4.4, the well specific risk analysis checklist is an extension of the field specific risk analysis checklist. Risk factors are described for the specific well relative to the risk level for the field specific concept. The checklist is based on the idea that creating a field specific concept will save time when planning new wells by not having to start from scratch. Using such a template is an approach that ensures applicable reuse of information.

Discussion

Pros and cons of using templates for well construction risk analyses are discussed in Table 6:

Table 6: Pros (green) and cons (red) of using a field specific concept as a starting point for new well construction risk analyses.

Conducting well specific risk analyses based on a field specific template is efficient as: ○ Less time is spent identifying risks as most common and major risks are already included in the checklist. ○ Less time is spent incorrectly discussing operational risks as the checklist is specific and focused on concept and design risks.	The quality in the reuse of the field specific risk analysis for specific wells depends on the competence, experience and resources of the developers. The time and resources invested in the field specific risk analysis and the certainty in each checked risk is not communicated.
A field specific risk analysis template is easy to continuously update when drilling additional wells in a field. Knowledge and experiences are transferred across wells, projects, disciplines and departments. Continuously improving the checklist by adding applicable risks is an important part of the organizational learning.	Field specific concepts are developed using ranges for well specific values and parameters. Two wells can be within these ranges but in opposite ends and therefore be very different.

	Say the well length interval for a field specific concept is 1500 m – 2000 m. Then two wells of 1501 m and 1999 m will appear equal in the logsheet but in reality, they are different. If this is the case for several field specific parameters, then the wells will be very different.
The template avoids reusing nonapplicable risks as new experiences are carefully justified before added as a new risk in the checklist. The checklist is designed by teams with time and resources to do the process properly.	Time is spent developing and assessing the field specific concept. This is time that can be used efficiently elsewhere. However, this time can be justified if several wells are planned.
As an alternative for unique wells or fields with few planned wells, the checklist can be used as a quality check. The checklist is then used to ensure that obvious or major risks are not missed.	Reusing a field specific risk analysis can give a false sense of security in that the risk analysis is complete and perfectly reusable. However, risk analyses are always unique and never complete.
Using a checklist ensures that non-relevant (unchecked) risks are also communicated to the decision maker. Presenting both relevant and non-relevant risk factors provides a broader risk picture. The risk picture is then more transparent as the decision maker is able to separate unidentified risks from non-relevant risks.	Reusing a checklist limits the imagination of the engineers conducting the analysis. This can reduce the quality of the identification process when addressing the “Other” row for additional risks.
The checklist includes about 50 risks factors compared to the risk logsheet which can include a hundred risk elements. This makes the tool easier to use, straight forward and comprehendible. Without these properties, reusing risks would be challenging and time consuming.	
A checklist allows reused risks to be evenly distributed and properly focused. This focus makes sure no important areas are missed or overrepresented.	

Shown by the numerous pros in Table 6, the increased efficiency of using a checklist outweighs the cons. The following improvement can demonstrate to further improve the reusability.

Improvement

One of the main weaknesses in reusing a checklist is that there is no indication on how applicable the field specific concept is for the specific well (see second con in Table 6). One suggestion is to produce a score based on field specific parameters and well specific parameters. The scores range from 1 - 6 where 6 indicates an identical value and 1 indicates just within the range. Values outside of the range are indicated by a zero and the final score is based on the average of parameter scores. An example of such parameters and the calculated score is shown in Table 7.

Table 7: Example of parameters to determine the specific well (A-01) score. Parameters and numbers are made up.

Field specific parameter	**Field specific range**	**Well A-01**	**Score**
Casing length m	3000 – 4000	3500	6
Highest dog-leg deg	4 – 6	6	1
TD Top of reservoir m	2400 – 2600	2450	3
Reservoir inclination deg	88 – 92	91.5	2
Dominant fluid type	Oil	Oil	6
Secondary fluid type	N/A	N/A	-
Mud type (WBM or OBM)	WBM	OBM	0
…	…	…	…
Total			**3.00**

This table can be presented on the front page of the analysis to inform the decision maker about the degree of similarities between field specific concept and the specific well (A-01 in this case). This table is also useful when comparing previously conducted risk analyses.

5.5 The effect of reusing information and previous risk analyses in the logsheet

This section evaluates the selected element in the logsheet related to reusability. Refer to Figure 11 for example of the logsheet.

Description

Different from the risk analysis checklist approach, risk analyses using the logsheet should start from scratch, i.e. with “blank sheets”. The engineers are however free to find reference wells to base their analysis on. Reference wells must be similar and are identified based on personal experience, consulting with colleagues or searching old wells for similar risk analyses.

This is a direct type of reusability. Already existing risk analyses can be used:

- To quality check or describe specific risk elements in the current risk analysis
- To check for risks that have been left out in the current risk analysis
- As a starting point for the current risk analysis

Discussion

Pros and cons of directly reusing information from previous risk analyses in the logsheet is discussed in Table 8.

Table 8: Pros (green) and cons (red) of reusing information in the risk analysis logsheet.

Previous risk analyses can be addressed to better describe or fill in the missing gaps of current risk elements.	Locating previous risk analyses is based on experience and the engineers must manually search for similar wells or risk analyses. Engineers are responsible to select what information is reusable. This decision can be difficult. The consequence can be a corrupted or conflicting risk picture.
Using old risk analyses as a starting point in the current risk analysis is time efficient as less time is needed to identify hazards.	Using a previous risk analysis as a starting point for the current risk analysis reduce the imagination in the identification process. It is challenging to identify irrelevant risks in the previous risk analysis while identifying new additional hazards.

Using previous risk analyses to quality check the new risk analysis can ensure a more complete risk picture and reduce the likelihood of missing important risks.	Uncritically reusing risks from old risk analyses can result in dependent risk elements. Dependency means that the occurrence of one risk element is affected by the occurrence of another risk element. This results in a corrupted risk picture with over or under-rated risks.
Recommended practice in D&W is to copy-paste the left part of the logsheet (hazard, cause, consequence and existing safeguards) and then rerate the risk element and suggest risk reducing measures accordingly.	A proper identification process results in valuable discussions on causes, consequences and risk reducing measures. Reusing and copy-pasting risk elements reduce the underlying understanding of a risk element.
	Technology and best available risk reducing measures are continuously improving. Reusing old risk elements means to reuse old risk reducing measures which may not be the optimal solution.
	Reusing information and risk analyses results in a "negative identification process" or a falsifying process. This means that the focus is on rejecting risks rather than identifying new ones. To become robust against surprises it is necessary to emphasize on the identification process.

Shown by the numerous cons in Table 8, using previous risk analyses as a starting point in new risk analyses should be avoided.

Improvement

This idea is based on features in the checklist. It is suggested to create a *Generic Well Template* for use in operational detailed planning risk analyses. Generic risks can provide a basis to help identify specific risks and motivate structured and good discussions. The logsheet is still sorted by the operational steps but each step will now include a few generic risks. Unlike identified operational risks, generic risks are briefly described qualitatively, similar to the risk factors in the risk analysis checklist (see section 4.4). Figure 21 shows the logsheet including two generic risks "1.1 Stuck equipment" and "1.2 Losses". These are both part of the operational step "1. Drilling reservoir section".

Risk Analysis Logsheet							
Hazard	Causes	Consequences	Existing safeguards	Risk before			
				Prob	Impact		
					HSE	OBJ	TC
1. Drilling Reservoir Section	**Qualitative risk description**						
1.1 Stuck equipment	Long horizontal section with high inclination and soft formation makes it likely to experience stuck equipment during drilling						
1.1.1 Stuck pipe	Keyseating	Working operation. Side track.	Torque and drag simulations and monitoring.	**P2**	**I1**	**I3**	**I3**
1.1.2 Stuck bit / No ROP	Poor drilling parameters	Additional bit trips to surface to change bit	Real time drilling data and monitoring drilling parameters	**P3**	**I1**	**I3**	**I3**
1.1.3 ...							
1.2 Losses	Long trips, difficult to maintain stable well pressure. High swab and surge potential. Losses is likely.						
1.2.1 Losses in rat hole	Poor tail cement in previous casing shoe	Influx of hydrocarbons. Emergency shutdown.	Logging of cement prior to drill into shoetrack.	**P2**	**I4**	**I3**	**I3**
1.2.2 Losses tripping out	Too fast tripping (high ECD)	Losses resulting in influx of hydrocarbons and potential kick	ECD calculations and RTDD monitoring	**P1**	**I4**	**I3**	**I3**
1.2.3 ...							

Figure 21: Risk analysis logsheet including the generic well template. 1.1 Stuck equipment and 1.2 Losses are examples of generic risks.

The different levels are now:

- 1. Operational step
- 1.1 Generic risk (qualitatively described)
- 1.1.1 Identified operational risk (qualitatively or semi-quantitatively rated based on probability and impact)

The color of a generic risk becomes the same as the most severe identified operational risk.

This improvement makes the identification process more targeted without losing imagination. This makes the identification part of the logsheet more efficient.

5.6 Comparing the two well construction risk analysis tools

This section summarizes the evaluation by comparing the two risk analysis tools based on the criteria described in section 5.1.2. Fulfilment of a criterion is based on a qualitative judgement. The following colors are used to describe a tool's fulfilment of a criterion:

- Green: Fulfilment of the criterion
- Yellow: Unknown or incomplete fulfilment of the criterion
- Red: Failure to fulfil the criterion

Table 9: Comparison of the risk analysis checklist and the risk analysis logsheet with respect to criteria 1-10.

Criterion:	**Risk analysis checklist:**	**Risk analysis logsheet:**
1 Identify hazards in well construction	Ref. 5.2.1. The pre-defined checklist includes common and important hazards which reduce the time spent identifying hazards. "Other" hazards must still be identified and this can be challenging.	Ref. 4.5. The first column in the tool is used to identify hazards. Identification of hazards is considered the first and an important part of the logsheet. It is suggested to start from scratch in the identification process.
2 Analyse hazards to understand causes and consequences	Ref. 4.4 and 5.2.1. Causes and consequences of a risk factor are qualitatively described based on likelihood and outcomes. This qualitative description of a hazard is justified due to the general nature of the concept phase; low level of details and far from operational phase (see pros in Table 6)	Ref. 4.5. Columns 2 and 3 is for causes and consequences. Each identified hazard is analyzed to determine possible causes and consequences.
3 Rate consequences based on impacts and probabilities	Consequences are rated as part of the qualitative description explained above.	Ref. 4.5. Column 5 is for rating the consequences in each risk element. Ref 5.3.1. Consequences are rated by specifying monetary and non-monetary impact values and probabilities.
4 Determine necessary risk reducing measures	The checklist includes a column to specify risk reducing measures for each risk factor.	Ref. 4.5. Column 6. The logsheet includes a column to specify risk reducing measures for each risk element.
5a Reflect uncertainties about unknown quantities	Ref.5.2.3. The checklist fails to reflect uncertainties about unknown quantities. This is mainly because the checklist is used in the early concept phase where precise estimates of unknown parameters such as probability is unavailable and often avoided. 5.2.3 discuss a possible improvement.	Ref. 5.3.2. The current state of the logsheet fails to reflect uncertainties about unknown quantities. Most relevant is the uncertainty related to the assigned probability. It is suggested to include a SoK measure to reflect this uncertainty.
5b Reflect uncertainties about the future	Ref. 5.2.2. The checklist use manageability as one way to reflect the uncertainties about future activities. The manageability of an activity depends on the uncertainties and complexity in the activity. However, this dependency needs to be clearer and a solution is suggested in 5.2.2.	Future activities are described as the sum of hazards, causes and consequences. The logsheet does not measure or reflect the uncertainties about these identified causes and consequences.
5c Reflect uncertainties about phenomena	Ref. 2.4.1 and 5.2.1. Phenomena is related to the structure, logic, size and focus of risk elements	Ref. 5.3.1. As for the checklist, the logsheet has no direct measure of the uncertainties about phenomena. However, the logsheet

	in the risk picture. The checklist has no direct measure of such uncertainties.	indirectly reflects the uncertainties about phenomena by specifying causes, consequences, existing safeguards and risk reducing measures for each risk element.
6 Make applicable parts of the analysis reusable in later activities	Ref. 5.4. The checklist is a standardized template for well specific risk analyses that can be used by all future wells in a field. Ref 2.4.2. This is an efficient approach to reuse risk analyses. The checklist can be continuously improved by adding new risk factors. These risk factors can be added to the template under supervision to ensure they are applicable.	Ref. 5.5. Previous risk analyses can easily be reused by copy pasting risk elements into the current risk analysis. However, there is no efficient way of supervising this reuse. Uncritically copy-pasting risk elements can cause conflicts and a corrupted risk picture. Reusing previous risk analyses as a starting point or template limits the imagination in the identification process. Such reuse results in a falsification process rather than an identification process. Based on these downsides, information should not be reused in the logsheet.
7 Be intuitive, efficient and have clear goals	Ref. Figure 10. The columns in the checklist provides a streamlined and chronological way of adding inputs. Conducting a well specific risk analysis based on a field specific analysis is a logical and efficient approach that explains the goal: to elaborate on the field specific risk analysis for this specific well. It is clear for the users that the checklist tool is designed for the concept planning phase and not for the operational detailed planning phase.	Ref. Figure 11 in section 4.5. The columns in the logsheet provides a streamlined and chronological way of adding inputs. The logsheet approach is not as efficient as the checklist as there is no template or starting point available. Experience shows that the logsheet tool is often used in the concept phase rather than the detailed planning phase its designed for. The goals and purpose of the tools is not clear.
8 Consider risk in a level of detail matching the context of the planning phase	Ref. Figure 10 and 5.2.1. The checklist tool is designed for the concept phase and using a pre-defined checklist ensures a narrow scope focused on concept risks only. The pre-defined checklist is designed by teams with the necessary time and resources to properly separate concept risks from operational risks. A qualitative description of a risk factor is an efficient and proper way of rating risk factors in the concept phase where probabilities and impacts are not available.	Ref. Figure 11 there are no generic risk template or checklist to guide the risk analysis in the right direction. Therefore, experience shows that operational risks are too often included when using the tool in the concept phase. The logsheet require input on probability and impact which is often not available in the concept phase.
9 Provide a risk picture that directly compares to relevant risk acceptance criteria	Ref. 4.4.1 and 5.2.2. The manageability description is an efficient way of describing the severity of risk conditions. The scale could be more precise to make it easier to evaluate risk conditions. However, decision makers have clear and defined risk acceptance criteria (RAC) that correlates with the existing manageability levels.	Ref. Figure 9 and 3.2. Risk elements in the logsheet are rated based on probability and impact. The categories are based on non-monetary and monetary values that can easily be compared to RAC by the decision maker. This evaluation works when using the tool in the operational detailed planning phase but is difficult in the concept phase.
10 Be transparent, meaning that the work behind the analysis is available to decision makers	Ref. Table 6. In the checklist it is clear which risks were relevant and which risks were not considered relevant for the specific well. It is clear how risks are related to main risks in the field. The checklist describes risk factors in detail by including risk reducing measures and manageability. These measures make the tool transparent.	Ref. 5.3.1 and Figure 11. The logsheet presents a detailed risk description including hazard, causes, consequences, existing safeguards, probability, impacts and risk reducing measures. Presenting this to the decision maker provides a transparent risk picture.

6 Conclusions

This work has primarily described and evaluated the risk analysis process for single well construction in D&W Equinor. Two risk analysis tools have been evaluated to understand if and how D&W Equinor has adapted to the recent change in risk definition by the PSA. Discussion of the selected elements in the tools showed that they reflect parts of the uncertainty dimension but are unable to reflect the entire dimension. In terms of reusability, the checklist tool outperforms logsheet tool. The following conclusions address the five goals presented in section 1.2 and list some main points:

Describe requirements and expectations for risk analyses in well construction

1. The PSA is the regulating body in well construction activities in Norway. D&W Equinor has developed internal requirements and work processes for risk management based on certified standards such as the Norwegian NORSOK Z-013 and the international ISO 31000. These standards ensure compliance to regulations (sections 2.1 and 4.1).
2. Based on expectations by the PSA, risk analyses in D&W Equinor should as a minimum:
    - identify hazards that can occur in the executing phase of a well construction
    - discuss these events to determine causes and consequences
    - analyse the risk elements by rating the consequences in terms of impacts and probabilities
    - risk reducing measure should be identified and analysed for significant risk elements (section 2.2)
3. The PSA recently redefined risk to focus more on the uncertainties about future activities. The corporate definition of risk in Equinor have adapted to this change. Equinor’s definition focuses on uncertainties about a deviation from a reference value rather than activities (Section 2.3 and 3.1 for definitions).

Describe the risk management process in Equinor and D&W

4. The management system in Equinor is based on a set of fundamentals. Requirements exist to ensure that all activities are in line with these fundamentals. Guidelines and recommendations explain how to meet these requirements (Figure 3).
5. Based on these requirements, D&W Equinor has developed a work process called DW600 for development of construction wells. DW600 is a chronological flowchart including all activities necessary to plan and execute a development well. Risk analyses is an important part of DW600 and is based on NORSOK Z-013 and ISO31000. DW600 ensures efficient and safe well construction in line with national laws and regulations (section 4.2)
6. The interpretation of risk within D&W has not adapted to the corporate focus on uncertainties. Instead, risk in a D&W activity is interpreted as the range of consequences and probabilities for each of the identified undesirable events in that activity (Figure 2). However, it is important to emphasize that the recent introduction of the manageability term is a good addition to a concept phase risk analysis process.
7. D&W Equinor has developed a set of risk analysis tools in DW600. The risk analysis checklist and the risk analysis logsheet are efficient tools that allow for engineers without a background in risk management to conduct proper well construction risk analyses. However, high quality risk analyses depend on a proper use and procedure. Poor understanding or wrong use can result in a corrupted and conflicting risk picture.
8. It is justified to use a checklist approach in the concept phase, mainly due to the general nature of this phase.
9. Both tools are easy to use, efficient and tailored for use by engineers. They provide a detailed risk picture that, if presented correctly, manage to describe the major accident potential in well construction activities.

Evaluate the uncertainty dimension in two risk analysis tools used in well construction

10. For risk analyses in D&W, there is uncertainty about assigned probabilities of the consequences. Both the checklist and logsheet fails to reflect or measure this type of uncertainty (5a in Table 9).
11. Considering uncertainties about future activities, the manageability concept used in the checklist tool is an interesting approach. Manageability depends on uncertainty and complexity of activities and is used to evaluate if the risks are manageable. Even though manageability can be considered an indirect reflection of uncertainty it needs a more precise scale to be properly measurable. The logsheet tool fails to reflect or measure uncertainties about the assigned causes and consequences of a hazard (5b in Table 9).
12. Considering uncertainties about the phenomena (in well construction; the number, magnitude, importance and dependencies of all risk factors), the checklist fails to reflect or measure such uncertainties. The logsheet describes causes and consequences, existing safeguards and risk reducing measures for all risk elements. This is an indirect reflection of the uncertainties (5c in Table 9).
13. To summarize, both tools contain elements that indirectly reflects uncertainty but there are no direct measures. Including direct measures of uncertainty could educate the user and introduce a mindset based on uncertainties rather than probabilities. Direct measures of uncertainty are considered necessary to adjust to the new risk definition by the PSA.

Evaluate the reusability in two risk analysis tools used in well construction

14. The checklist tool is based on reusing a field specific template when planning single wells. This is an efficient approach that allows risk analyses to continuously improve by changing the template when new knowledge is obtained. The main challenge in a checklist approach is the reduced imagination of participants when identifying additional (“Other”) risk factors.
15. The logsheet tool is based on starting from scratch with “blank sheets”. Experience shows that previous risk analysis logsheets are too often used as a starting point. Such reuse makes the identification process focused about disqualifying risk elements rather than identifying new ones. This limits the imagination of the participants and can cause a conflicting or corrupted risk picture.

Suggest and demonstrate practical improvements to the uncertainty dimension and reusability

16. An uncertainty-description in the checklist and a measure of SoK in the logsheet is suggested as measures of uncertainty about unknown quantities in the tools (sections 5.2.3 and 5.3.2).
17. A slider option is suggested to include in the checklist to better describe the contributions of uncertainty and complexity in manageability (section 5.2.2).
18. For the logsheet, it is suggested to develop impact reports to better reflect the uncertainties about phenomena. Impact reports could highlight important risks for that category and allow the decision maker to easily identify dependencies, conflicts and focus areas in the risk picture. An example of a HSE impact report is shown in section 5.3.1.
19. In terms of reusability, it is suggested to develop a generic well template for use with the logsheet. This generic well template allows risks analyses to be reused and improved without reducing the imagination in the identification process. This is similar to what is done in the checklist.

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Appendix A – Detailed description of DW600

A.I Description and key terms

DW600 covers the construction of development wells. Development wells include production and injection wells. The two wells are similar in terms of design but their purposes are different. A production well is designed to produce oil or gas from the reservoir. An injection well is designed to inject fluids into the reservoir to build or maintain pressure. In terms of risks the well designs are similar.

Key terms in DW600 include:

- **Maturation** – One-year process of identifying potential well candidates and prioritizing them for further assessment.
- **Feasibility** – Assessing the feasibility of the selected well.
- **Concept selection** – Develop and assess a well concept and design.
- **Detailed planning** – The well concept is planned in detailed operational procedures.
- **Execution** – The planned well is drilled.

A.II The frameworks

Figure 22 shows a detailed description of DW600 with processes and decision gates (DG).

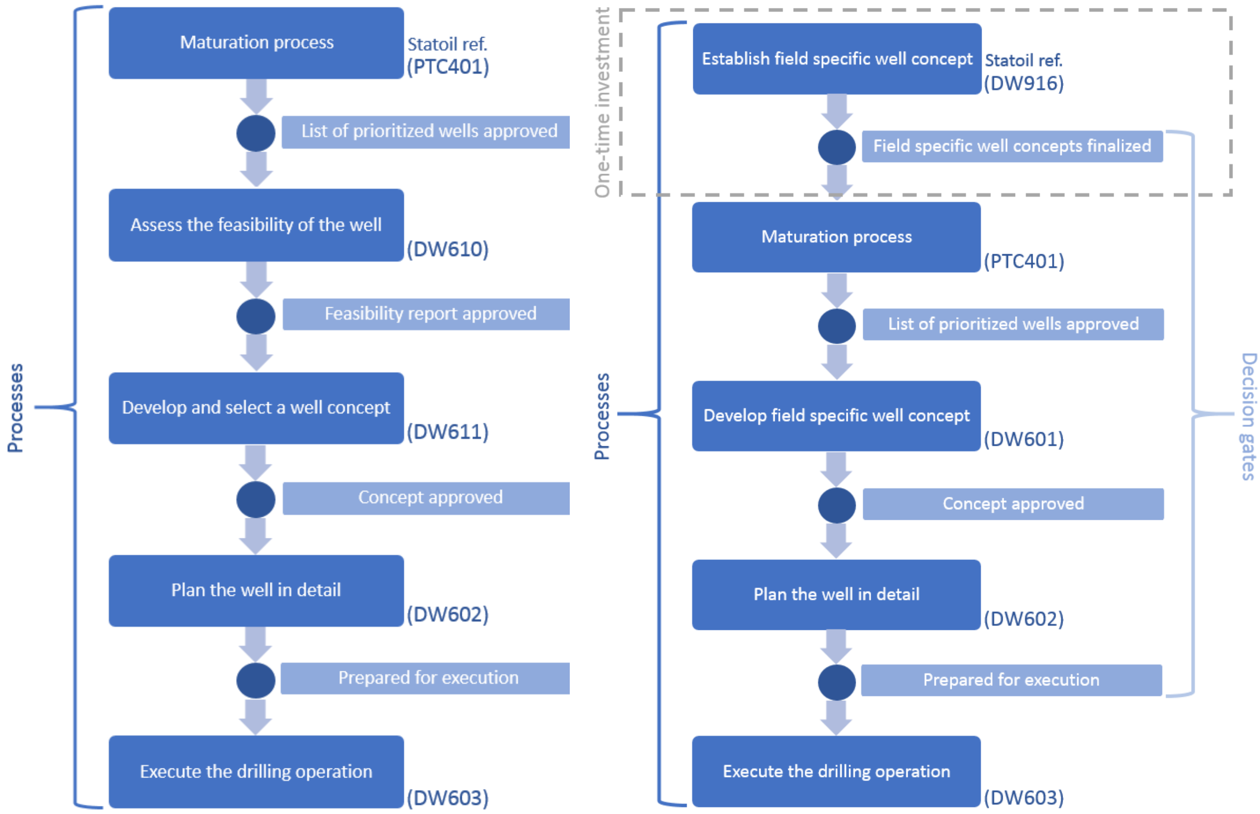

Figure 22: Left: DW600 flow chart describing the work processes and the DGs for construction of a development well when no field specific well concept is available. Right: Same when a field specific well concept is developed. Redraw from ARIS (2017a).

In terms of risk analyses the interesting phases are feasibility (DW610), concept selection (DW611/DW601) and detailed planning (DW602).

Appendix B – Example of the risk analysis tools

This chapter shows examples of actual use of the risk analysis checklist and logsheet tools.

B.I DW916 Field specific well concept risk analysis checklist

Figure 23 shows the 8 ½" reservoir section part of the DW916 field specific well concept risk analysis on the Heidrun field operated by Statoil.

DW916 DRILLING - Heidrun Field specific well concept risk analysis Rev 2017-10

Front page | NA - Conductor | 24" section | 17.5" section | 12.25" section | **8.5" Reservoir section**

Filter

Condition			Risk factor	Concept specific aspects
Operational pressure window 10 factor(s) selected				
(yellow)	1.01	☑	Pressure margin	* Minimum drilling window size: 0.25sg, or more. (including rock weakening due to depletion and cooling) * Standard FG calculation for the reservoir rock strength is FIP. * Evaluate to shut-in nearby injectors (TR3525, chapt. 2.1.3)
	1.02	☑	Cooling effects	Check injectors nearby (TR3521, chapt 2.2) if they can have provided reduced rock strength due to injection; 400m from gas injectors,
	1.03	☑	Depletion	Pressure prognosis should contain both degree of depletion and potential over pressured zones
	1.04	☑	High ECD	* Typical range: 0.25-0.27 sg EMW * Higher ECD are observed when drilling through shales compared to sandstones. * Be aware that higher ECD is expected when drilling through production riser.
	1.05	☑	Surge / Swab pressures	Evaluate to use the Springar Fm. SFG as input for surge/swab
	1.06	☐	Gelling	
	1.07	☑	Loss zones	In general no problems with losses while drilling. * Coal-sand transitions and paleosols layers are regarded as the weakest point and potential loss zones. * Åre/Tilje-study showed highest potential in Åre Fms. 3-1.
	1.08	☑	Faults	* Faults present below seismic resolution can be present. * Generally no problem to drill through faults, as long as perpendicular to fault plane. * Can affect well economics, depending on formations affected.
	1.09	☑	Formation damage	As low MW as possible, without risking wellbore stability issues, to reduce risk of formation damage.
	1.10	☑	Collapse	Planning for MW above Springar Fm. SFG.
	1.11	☑	Other // abnormally pressured formations	Check for high pressured areas
Wellbore stability 6 factor(s) selected				
(green)	2.01	☑	Weak formation	* Washouts over time often observed in the Ror 1, Not 1 and Springar Fms. * Coal and paleosols - most condense in the lower Åre Fms. 3-1.
	2.02	☑	Unstable zones	Spiky and erratic ECD when drilling through rat hole and Springar Fm.
	2.03	☐	Salt	
	2.04	☑	Fault zones	* Faults below seismic resolution, generally not a problem. * Avoid drilling parallell to fault plane
	2.05	☑	Unfavourable inclination	Inclinations above 60° is not recommended in lower Åre Fm. 3-1 (due to coal)
	2.06	☑	Pressure fluctuations over time	ECD increase and spikes often when drilling through shale.
	2.07	☑	Mud-formation reactions	See risk factor 2.01 and completion risk factor 4.01
	2.08	☐	Other	
Hole cleaning 10 factor(s) selected				
(green)	3.01	☑	Flow rate	Standard: 1800-2100lpm.
	3.02	☑	ROP	* Max ROP with NRZ decoding: 51m/hr in oil bearing intervals * Evaluate to exceed in non-oil bearing intervals
	3.03	☑	Rotation	Standard: 140-160rpm
	3.04	☑	Hole diameter	8 1/2", observed washouts in Springar, Not 1 and Ror 1 Fms.
	3.05	☑	Length of section	* Max 8 1/2": 1100mMD. * Total well length 5000mMD.
	3.06	☑	Unfavourable inclination	Max inclination, relative to structural dip: * 90° in Fangst Fm * 80° in Tilje and upper Åre Fms * 60° in lower Åre Fm. (Åre Fm. 3-1)
	3.07	☑	Mud properties	Standard: KCl/Glycol/Polymeer mud system (Standard inhibitive mud)
	3.08	☑	Formation properties	Find optimal way to clean hole at TD if presence of weak formations or coals. Use HD safe zone for circulation guide.
	3.09	☑	BHA and string geometry	Static pressure measurements while POOH/LOOH
	3.10	☑	Other	Find optimal way to clean hole at TD if presence of weak formations or coals

Figure 23: 8 1/2" section in DW916 field specific well concept risk analysis on the Heidrun field. From DBR (2018b).

B.II DW602 Detailed planning risk analysis logsheet

Figure 24 shows the risk analysis logsheet for the 8 ½" section of well A-19 B on the Heidrun field.

Risk mitigation Measures	Status	Responsible / Deadline	Risk after measures Prob / Impact HSE OBJ TC	Existing safeguards	Risk before measures Prob	Impact HSE	OBJ	TC	Risk mitigation Measures	Status	Responsible	Deadline	Risk after measures Prob	Impact HSE	OBJ	TC
6.1 Drilling 8 1/2" section																
6.1-01	Unable to achieve required FIT	Formation weaker than expected, and/or poor cement quality around 9 5/8" shoe	Cement squeeze. Increased risk for losses during gravel pack operation.	Minimum FIT needed for kick tolerance is for drilling section is lower than 1.20 sg EMW.	P3	I1	I1	I2	Squeeze LCM pill in case of leak-off below minimum test for drilling. Completion engineer to update pump rate and potentially also wash-pipe size if FIT failed	In progress In progress	Drilling Supervisor Completion Engineer	DW603 DW603	P3	I1	I1	I2
6.1-02 WI-PB	Wellbore stability model not valid for dome nearby area in the reservoir section below the dome shadow.	Wellpath planned shallower in stratigraphy than A-17 C below dome shadow (ref 1.1-07). Different stresses or lithologies can be present, e.g salt as it is one of the development theories for the dome structure.	Other stresses or lithologies than predicted. Not able to drill to TD. Stuck BHA. Losses. Wellbore collapse. Well controll situation.	No other lithologies or stresses observed in A-17 C (drilled deeper in stratigraphy than A-19 B).	P2	I3	I4	I3	Follow road maps when drilling Pay attention to well signals and logs/cuttings for different lithology interpretation Monitor salt content in mud out well while drilling Have a strategy ready in case of drilling salt	In progress In progress In progress In progress	Drilling supervisor Wellsite geologist Mud Engineer Program Engineer	DW603 DW603 DW603 DW603	P2	I3	I4	I3
6.1-03	Drill into salt, mud or other unexpected lithology in the reservoir	The creation and properties of the dome are not fully understood, the development theories include a mud diapir and a salt diapir, giving poor seismic below/in the dome area.	Stuck BHA. Sidetrack. Lost production interval Unvalid wellbore stability model.	No other lithologies or stresses observed in A-17 C (drilled deeper in stratigraphy than A-19 B).	P2	I1	I4	I3	Monitor salt content in mud out well while drilling Have a strategy ready in case of drilling salt Check odd lithology with barium carbonate to see if it could be salt	In progress In progress In progress	Mud Engineer Program Engineer Geologist	DW603 DW603 DW603	P2	I1	I4	I3
6.1-04	Wrong well placement	Lack of communication between onshore geosteering team and offshore personell Difficult to place well due to seismic shaddow (ref 1.1-07)	Lost production interval		P2	I1	I3	I4	Have good communication between onshore geosteerings team and offshore WSG Have wellsite geologist present on the TLP for geosteering	In progress In progress	Geologist Operation geologist	DW 603 DW 603	P2	I1	I3	I4
6.1-05	Poor hole cleaning throughout the section	- Long hole section, and circulation rate will be kept as low as possible to avoid washing out weak zones in the section. - Pump failure - High solid contents - Cuttings beds/fill	- Pack-offs. - Reduced ROP - Not able to run screens to TD	Recommended flow rate, RPM, and ROP stated in DOP	P3	I1	I3	I3	If indication of poor hole cleaning, evaluate mud parameters and to reduce ROP. Ensure up/down weights are taken consistently. Ensure all mud pump are available prior to drilling the section (Mixing-, transfer- and mud pumps) Monitoring and follow up T&D trends	In progress In progress In progress In progress	Drilling Supervisor Odfjell Toolpsuher. Derrick man Drilling Supervisor	DW603 DW603 DW603 DW603	P3	I1	I3	I3
6.1-06	RSS/MWD/LWD failure	Failure on tools	Extra trip, extra OH exposure time		P3	I1	I1	I3	Follow tool failure decision tree	In progress	Drilling Supervisor	DW603	P3	I1	I1	I3
6.1-07 WI-PB	Losses / fracturing formation while drilling reservoir section	High ECD while drilling, poor hole cleaning leading to pack-off while drilling/or if backreaming out of hole.	Drill with reduced ROP to avoid too high ECD. Worst case fracturing formation/ losses --> well control situation	ECD simulations indicates ECD of 1.55 sg with 1.30sg mud at TD. Min FG in section is 1.60sg (Åre 5.1 fm)	P3	I3	I3	I3	Note pump pressure for different flow rates before POOH in case of backreaming and pack-offs Ensure if backreaming is initiated that it is done all the way back to shoe Max allowed ECD will be stated in the detailed operational procedure.	In progress In progress In progress	Drilling Supervisor Drilling Supervisor Program Engineer	DW603 DW603 DW603	P2	I3	I3	I3
6.1-08 WI-PB	Unable to read gas	- Wrong placement of gas measurement in spider box - Gas instrument does not work	Well control		P2	I4	I2	I2	Check placement of gas measurement prior to drilling the section Check that gas instrument is operative	In progress In progress	Baker ARTE Baker ARTE	DW603 DW603	P2	I4	I2	I2

Figure 24: Risk analysis logsheet for 8 1/2" drilling on A-19 B on the Heidrun field. From DBR (2018a).