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Geological and environmental uncertainty and risk assessment in the Arctic, how can these be integrated?

by

Camilla Husebø Hinna

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Camilla Husebø Hinna
University of Stavanger
05/07/2018

Abstract

Geological and environmental uncertainty and risk assessment in the Arctic, how can these be integrated?

Camilla Husebø Hinna, MSc
The University of Stavanger, 2018

Supervisor: Roger Flage

The petroleum industry is now entering more and more areas in the high Arctic, and this thesis studies the geological and environmental uncertainties and risks related to this region. Risks and uncertainties special to the cold climate are identified and explained. Uncertainty exists during the conceptual stage of all petroleum projects, with uncertainties related to the subsurface, surface, and commercial aspects. In the case of an offshore oil blow-out event the involved events include geological processes down in the reservoir, then fluid dynamics in the well flow, and finally dispersion at sea level causing environmental damage in the effected ecosystem. These events are studied by different scientific disciplines, using different types of models, where the output of one model serves as input to another model. In this study a common uncertainty analysis framework is identified and explained as an attempt on combining different scientific disciplines into one unifying model. The main focus of an environmental risk analysis is to identify, evaluate, select, and implement actions to reduce the risk that can lead to environmental consequences. Arctic Canada and Norway are used as examples of how the governments are handling these issues related to hydrocarbon exploration in the Arctic. Both countries have common guidelines that all companies have to follow when exploring for hydrocarbons in these areas.

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1 Introduction

1.1 Background

During the last 40 years there has been a significant decrease in sea ice in the Arctic (Comiso et al., 2018) along with increased global demand of energy. This has opened the eyes for the petroleum industry and more and more oil companies find Arctic exploration innovative and interesting. Figure 1 illustrates the historical extent of the sea ice showing that large parts of the Russian and Norwegian Barents Sea is today more available for petroleum exploration than it was only 40 years ago (Comiso et al., 2018). Since the petroleum industry is now entering more and more of these areas in the high Arctic it is of interest to investigate the geological and environmental uncertainties and risks related to this region.

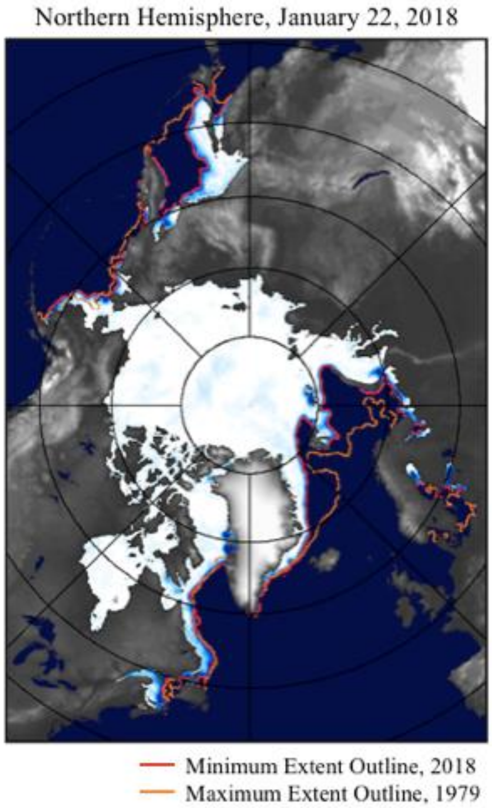


Figure 1: Illustration of the historical extent of sea ice in the Arctic. Red line indicates the extent today (2018) and orange line represents the extent in 1979 (Comiso et al., 2018).

Exploration in the Arctic is by many seen as harmful to the environment and is considered more technically challenging than other environments. However, already in the 1960s the first offshore drilling and production in ice covered waters started, in the Cook Inlet, Alaska, where the sea surface was frozen for a couple of months every winter (Yue, n.d.). Although it may started a long time ago, it is today more relevant than ever due to the increased demand of hydrocarbons. The United States Geographic Survey (USGS, 2008) completed an assessment of undiscovered conventional oil and gas resources north of the Arctic Circle and estimated that 134 billion barrels of undiscovered oil and gas was present. Today, there are discoveries in the Arctic which potentially will be developed in the longer term, such as for example the Wisting discovery in the Norwegian Barents Sea.

Rystad Energy (Duesund, 2015) has suggested how the Arctic oil production will grow rapidly in the future. They suggest that there will be a step-up in production after 2020 when some of the discoveries are mature. Figure 2 shows how they have predicted production from Arctic regions divided by countries. Although the largest increase in production is suggested to be in Russia, the common trend is increasing also in Norway and Canada. In addition to this, the Norwegian Petroleum Directorate (NPD, 2018) suggests that a large part of the reserves left at the Norwegian Continental Shelf are located in the Barents Sea (Figure 3).

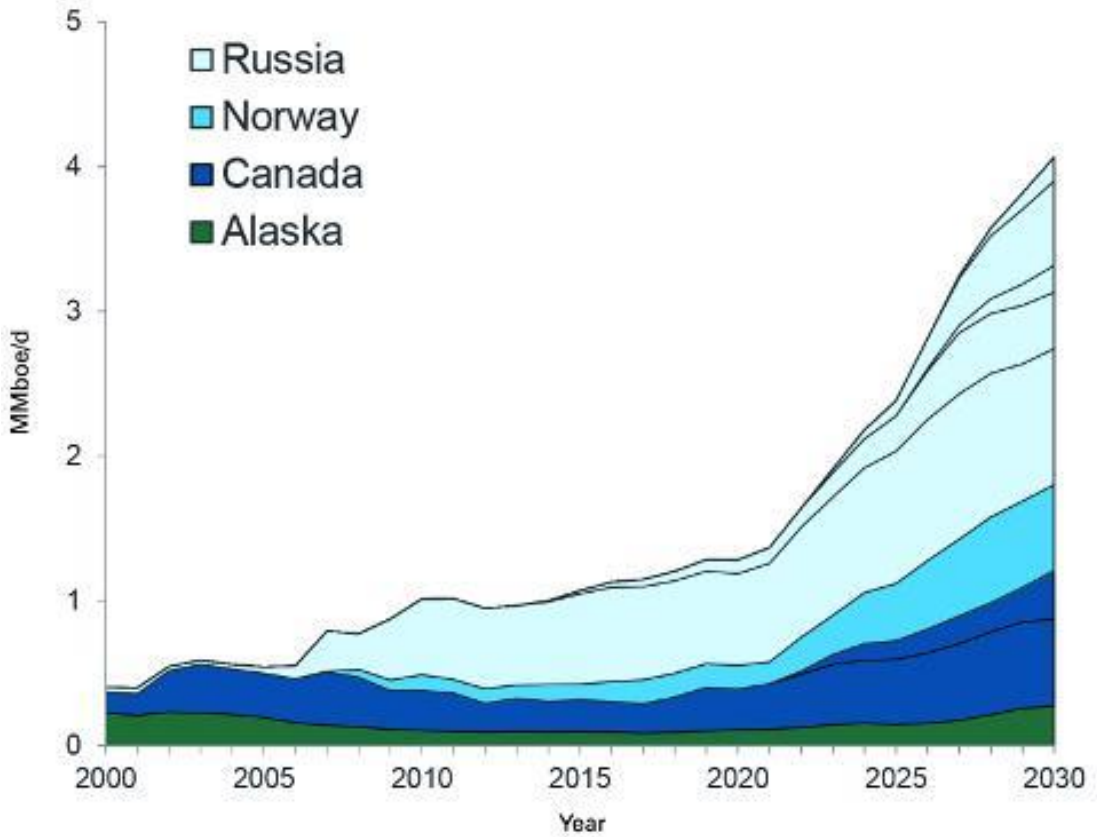


Figure 2: Arctic offshore production from 2000 to 2030 shown by country and province in MMboe/d (Duesund, 2015).

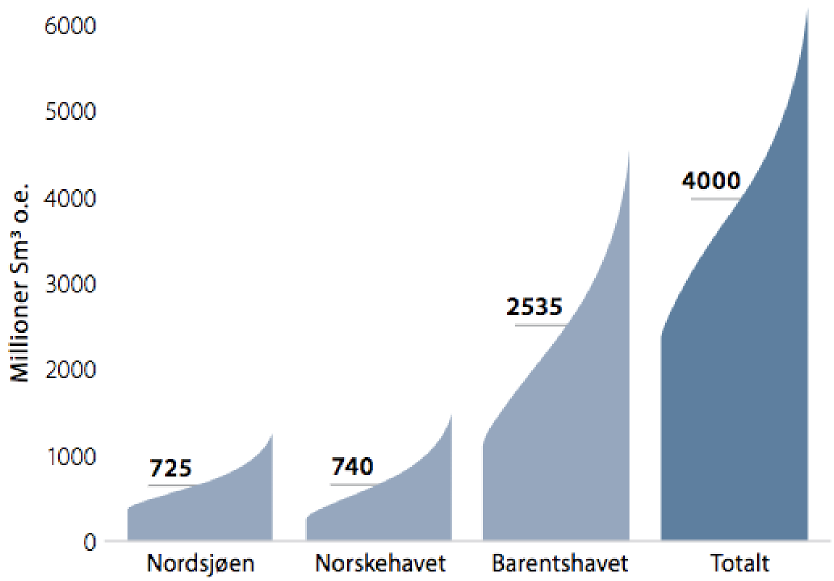


Figure 3: Estimates of undiscovered resources on the Norwegian Continental Shelf divided by sea-areas (NPD, 2018).

1.2 Motivation

It is made clear that large parts of the world's hydrocarbon reserves are located in the Arctic. Due to the difficulties caused by the cold climate it is interesting to investigate the risks and uncertainties associated with drilling in such conditions. Uncertainty exists during the conceptual stage of all petroleum projects, with uncertainties related to the subsurface (geological structure, reservoir quality, well placement etc.), surface (transportation of hydrocarbons, types of facilities etc.), and commercial parts (current oil price, costs, net present values etc.). The upside of drilling here is the extremely high break-even cost, however, it is also important to look at the down-side, where for example a major oil spill will harm the ecosystem and cause significant costs for a drilling company.

In the case of an offshore oil blow-out event the involved events include geological processes down in the reservoir, then fluid dynamics in the well flow, and finally dispersion at sea level causing environmental damage in the effected ecosystem. These events are studied by different scientific disciplines, using different types of models, where the output of one model serves as input to another model (Flage, unpublished, b). The motivation for this thesis is therefore to try to combine these scientific disciplines and find one common model as this has not yet been done.

1.3 Objectives

The purpose of this thesis is to review the already established approaches for handling geological uncertainty and environmental risk assessment in Arctic petroleum exploration. Moreover, the aim of the thesis is to suggest a unifying methodology combining the geological and environmental aspects. As part of this thesis several sub-objectives will be answered:

(1) Study the vulnerability and remoteness of this region through literature review. How are the environmental conditions affecting petroleum exploration in the Arctic?
(2) Discuss and delimit the terms "geological uncertainty" and "environmental risk assessment".
(3) Identify and describe the current approach for environmental risk assessment and geological uncertainty.
(4) Discuss how to integrate environmental risk assessment and geological uncertainty.

1.4 Delimitations

This thesis investigates the environmental and geological uncertainties and risks influencing Arctic petroleum exploration. Due to the time limit of the thesis, the study area has been delimited to the Norwegian and Canadian part of the Arctic (Figure 4). These regions are selected based on availability of information and increased interest for petroleum exploration.

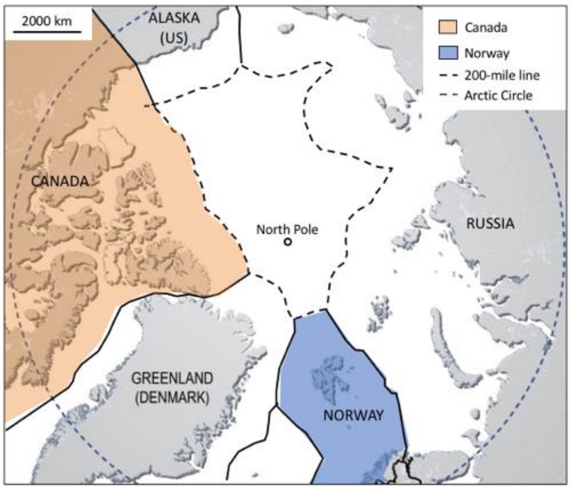


Figure 4: The Arctic divided into regions highlighting the focus areas of Canada and Norway (Modified from WWF, 2016).

1.5 Methodology

This thesis is based on theoretical study methods, where the results are based on literature review from articles, relevant books, and reports covering the investigated subjects. Already established methodologies for handling uncertainty and risk regarding each topic is analyzed, discussed, and compared. Furthermore, implementation of geological and environmental uncertainty and risk analysis related to petroleum exploration in the Arctic will be discussed. The regulations of Arctic Canada and Norway were reviewed using guidelines, regulations, and reports.

1.6 Structure of Thesis

Chapter 1 provides the introduction which consist of some background information, objectives and motivation for the thesis, limitations and finally a short description of the methodology.

Chapter 2 provides the reader a theoretical foundation, where terms and necessary theory is defined, including an overview of geostatistics and environmental risk assessment.

Chapter 3 defines the uncertainty analysis framework, which is the main focus of this thesis. The frameworks are described and this information will be used in the discussion part of the thesis (Chapter 5).

Chapter 4 defines risks and uncertainties related to the Arctic region with the purpose of explaining why it is important to take special precautions when exploring for oil and gas in this area.

Chapter 5 gives the discussion and conclusion of the thesis, where the most appropriate uncertainty analysis framework is defined. References are in the end of the thesis, in Chapter 6.

2 Theoretical Foundation

2.1 Risk and Uncertainty

The terms risk and uncertainty are closely related and often used interchangeably in both daily communication and in the industry. However, in academia there are several attempts on differentiating these terms (e.g. Virine and Rapley, 2003; Ross, 2004; Aven, 2007; Perminova et al, 2008; Suslick et al., 2008; Bratvold and Begg, 2010; Knight, 2012). In this chapter different definitions of the terms risk and uncertainty will be addressed.

2.1.1 Uncertainty

Knight (2012, p. 19) were probably one of the first to separate the terms risk and uncertainty. He defined uncertainty to be a situation where an analyst cannot assign a given probability. Bratvold and Begg (2010, p. 11) states that uncertainty is defined to occur when a person does not know if a statement is true or false. Another definition is suggested by Aven (2008, p. 186) where uncertainty is defined as lack of knowledge. These definitions are similar and shows that the problem of defining risk does not lie in the understanding of the term uncertainty, but in the manner the term uncertainty is used when associated with the term risk.

2.1.2 Risk

Knight (2012, p. 19) defined risk to be a situation where a probability distribution can be assigned. Another suggestion was proposed by Bratvold and Begg (2010, p. 11) where risk is defined to be an undesirable consequence of the uncertain event. Aven (2007, p. 41; 2010) defines risk as a combination of possible consequences (outcomes) with associated uncertainties, "*the two-dimensional combination of the consequences and the associated uncertainties*" (Aven, 2010). More resent definitions of risk are proposed by the Society of Risk Analysis (SRA, 2015) and the Petroleum Safety Authority Norway (PSAN, 2015). SRA (2015) defines risk in relation to consequences of specific activities that humans value. Furthermore, it is stated that: "*There is always at least one outcome that is considered as negative or undesirable*". Similarly, the Petroleum Safety Authority Norway (PSAN, 2015) defines risk as "*the consequences of the activity, with associated uncertainty*". A significant difference between these new definitions and the former used in probabilistic risk assessment are that the part involving probability is no longer included. In probabilistic risk assessment, the measure of uncertainty is probability, P, making the risk description defined by consequences, C, probability, P, and background knowledge, K. Although the term probability is removed from the new definition it is stated that in certain cases probability still will be partly used (PSAN, 2015). In this thesis risk is understood as the combination of the consequences, C, of an activity, a measure of uncertainties, U, and the background knowledge, K, which is in line with the recently published definitions of risk mentioned above.

The uncertainties associated with well-known solutions are significantly smaller than what is associated with new and unknown solutions (PSAN, 2015). Looking at this in light of petroleum exploration, it is known that the possible outcomes/consequences often are severe and usually relatively unlikely. However, as the petroleum industry moves further north, and into the relatively unknown Arctic, the related uncertainties are larger and risk assessment is highly valued and needs to be given much attention.

Vinnem (2007, p. 15) expressed a practical calculation of risk multiplying the likelihood of a hazardous event and a number representing the severity of the consequence:

$$R = \sum (p_i \cdot C_i)$$

Where R represents risk, p is probability, C is consequence and i is the specific accident sequence. This formula is a statistical approach calculating an expected value, meaning that the actual value most likely is not represented (Vinnem, 2007, p. 16). Since severe environmental threatening accidents are rare, an average value based on a long period of time will in this case be established for the calculation. An example is stated by Vinnem (2007, p. 16), where it for 40 years has been confirmed five major accidents with a total of ten fatalities, leading to an annual average of 0,25 fatalities per year, which is an unobservable, but representative value.

In association with a petroleum exploration project Ross (2004) defines three parts of risk: (1) Geological Probability (GP); (2) Development Probability (DP); and (3) Commercial Probability (CP):

(1) Geological Probability refers to the probability that an exploration well will discover petroleum. It does not consider the volume of the accumulation as long as the volume is large enough to be defined as a discovery.

(2) Development Probability implies that a hydrocarbon discovery, if found, is large enough to be developed and result in production and revenue. The decision to abandon or develop is based on economic evaluations at that given time and sunk costs will not be considered.

(3) Commercial Probability is a multiplication of the geological and development probabilities, meaning the probability of making a discovery that is large enough to be considered commercial and generate revenue.

If a discovery is made the geological probability must be set to one, even though a significant risk might be present regarding the hydrocarbon volumes present in the discovery. This uncertainty regarding the size of the discovery must be covered in the development probability, which therefore needs to be less than one. If the project is committed for development the risk of not achieving production or generate revenue should be very little. However, there might still be a small risk present as for example political issues or other above ground risks, which also is to be incorporated in the development probability (Ross, 2004).

2.2 Risk Management

Risk management is by Aven (2007, p. 13) defined as all measures and activities that are taken to manage risk. It involves understanding of risk factors, impact of measures, degree of risk controllability, as well as methods, processes, and strategies in order to identify and manage the risks (Aven, 2007, p. 13). Terms like risk analysis, risk evaluation and risk assessment are included in risk management. Risk analysis involves identification of initiating events such as threats, root cause analysis, cause and consequence analysis and risk description. The results from the risk analysis is then evaluated, and necessary actions are taken. The complete analysis and evaluation are referred to as risk assessment (Aven, 2007, p. 15). After the risk assessment is completed it is time for risk treatment, which is a process of actions leading to risk avoidance, risk reduction, risk optimization, risk transfer or risk retention.

2.3 Geostatistics

Geostatistics is a branch of statistics concerned with the research issues specific to geosciences (Bohling, 2005; Nemec, 2011). The main objective is to characterize spatial systems that are only partly known, which is common in geology (Olea, 2009). It models possible values of variables at unobserved and un-sampled locations (Caers, 2005, p. 7). The basic format for univariate geostatistical data is:

$$(x_i, y_i) : i = 1, \dots, n,$$

where x_i represents a spatial location and y_i a scalar value associated with the location x_i. Special for geostatistics is that the variable is defined in a continuous study region (Diggle and Ribeiro Jr., 2007, p. 9).

When it comes to geology a sort of nonrandomness occurs since the values measured close to each other are more similar than values measured farther apart. This is what is called spatial relationship and defines different forms of relations among the available data and the unknowns (Isaaks and Srivastava, 1989, p. 51; Caers, 2005, p. 7; McKillup and Dyar, 2010, p. 334). The spatial relationship can occur randomly, more regularly than expected and clustered as illustrated in Figure 5. A random distribution of the points will have the characteristics of a random variable, while a regular distribution is more predictable since the points are evenly distributed. A clustered distribution of points will give a large variation with areas of many points and areas almost without points. This distribution model can be used to compare the given randomness to what is expected from a random variable, where the frequencies of the points are compared to a probability distribution (McKillup and Dyar, 2010, p. 336). If a few wells in an area are distributed randomly and shows river deposits at a certain depth it is common to suggest possible river streams within this area. Through several simulations with given data points from the wells it is illustrated how different the geology could be based on different models. This will reflect the uncertainty present in a new area and the importance of other data, like for example seismic sections. In Figure 5 is a suggestion of what a possible floodplain would have looked like based on the given data points indicating river deposits.

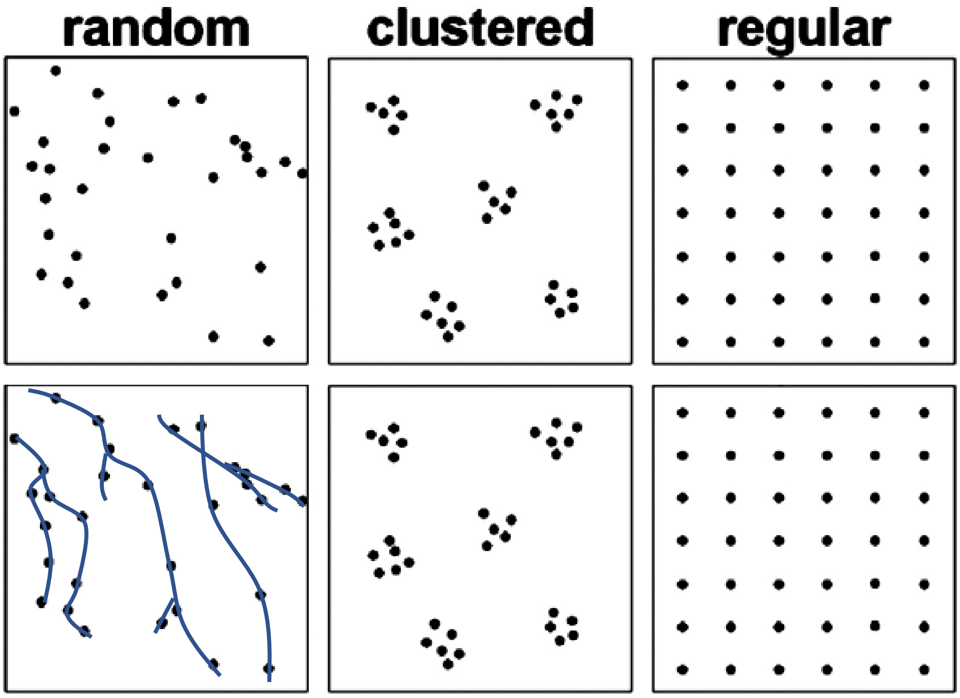


Figure 5: Examples of the distribution of points, whit a suggestion of river deposits drawn into the bottom random distribution (Carranza, 2009).

The theory of the random variable is very important when it comes to geostatistics and is used to model the uncertainty about an imperfectly known attribute or variable. A random variable is defined as a variable that represents several possible outcomes with different probability and/or frequency of occurrence. The random variable is usually represented by a capital letter, e.g. Z, while the related outcomes are represented by the small case letter, e.g. $\{z_i, i = 1, \ldots, n\}$ for a discrete variable with *n* outcomes, or $\{z \in [z_{min}, z_{max}]\}$ for a continuous variable valued within an interval between a maximum and minimum value (Remy et al., 2009, p. 30).

The use of geostatistics when it comes to petroleum exploration involves a lot of mapping, which includes a set of variables at several locations in space and/or time. Some of these variables are known through for example well information as used for the example above, but most of them are unknown with varying degree of uncertainty and are therefore modeled as random variables. Since the points have to fit a geological history they are dependent on each other, meaning that we need a random function that considers all unknown variables together, which is fixed by the random function. A random function is represented by Z(**u**) and is a set of dependent random variables $\{Z(\boldsymbol{u}), \boldsymbol{u} \in S\}$, marked with a coordinate vector **u** covering a study area S (Remy et al., 2009, p. 33).

2.3.1 Probability Distributions

Probability is a measure of the likelihood that an event, A, occur and is often denoted by P(A). There are several distinctive probability distributions in statistics to visualize this P(A), and in Figure 6 the most common distributions and parameters to quantify uncertainty are illustrated (Ross, 2004; Bratvold and Begg, 2010, p. 91). When a distribution like this is used in geological settings outliers/extreme values representing "unreal" data is often erased, and the details are lost in favor of a simple representation.

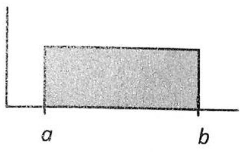
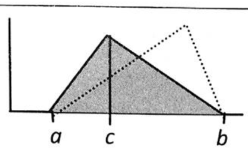
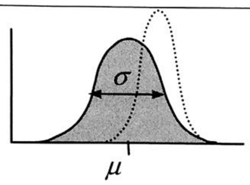
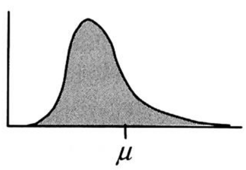
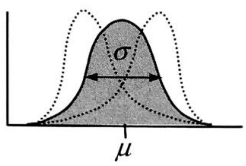
Name	Shape(s)	Mean and Variance
Uniform (*a*,*b*) Minimum, *a* Maximum, *b*	 	$\mu = (a+b)/2$ $\sigma^2 = (a-b)^2/12$
Triangular (*a*,*c*,*b*) Minimum, *a* Most Likely, *c* Maximum, *b*	 	$\mu = (a+b+c)/3$ $\sigma^2 = a(a-c)+c(c-a)+b(b-a)/18$ $\equiv \mu^2/2 - (ab+bc+ac)/6$
Normal (μ,σ^2) Mean, μ Variance, σ^2	 	μ = as specified σ^2 = as specified
Log Normal Mean, μ Variance, σ^2	 	μ = as specified σ^2 = as specified
Beta (*a*,*b*) Shape parameter, *a* Shape parameter, *b* (The Beta can take on a wide variety of shapes, depending on the relationship between *a* and *b*.)	 	$\mu = a/(a+b)$ $\sigma^2 = ab/[(a+b)^2(a+b+1)]$

Figure 6: Examples of different probability distributions used in geostatistics (Bratvold and Begg, 2010, p. 91).

A uniform distribution is used in settings with very high uncertainty (lack of knowledge) where the only numbers known by the assessor is a minimum and maximum value, as for example 0 % to 100 % (Bratvold and Begg, 2010, p. 88). Triangular distributions are used in settings where the lower and upper limits are known as well as the most likely value. In many cases it is easier to estimate the maximum, minimum and most likely values than the mean and standard deviations which is necessary when using other distributions. Normal distribution is the most versatile of all probability distributions and is often used since a lot of variables, including geological variables, are distributed this way. The normal distribution fit a lot of geological occurrences like the grain size distribution in rocks or the distribution of minerals on a beach (McKillup and Dyar, 2010, p. 66). If two uncertain geostatistical variables are multiplied together the result tends to bend towards a log normal distribution. An example of this is the calculation of oil in place in a reservoir, where the average porosity is multiplied by average area, meaning that uncertainty regarding oil in place is often log normally distributed (Bratvold and Begg, 2010, p. 89). A beta distribution does not have any particular shape and will be shaped based on the relationship between two shape parameters (Bratvold and Begg, 2010, p. 91).

2.3.2 Geological Uncertainty Assessment

Geological uncertainty assessment is an important part of reducing the risk before drilling an undrilled prospect. Geologists characterize prospects in terms of their level of project maturity and volumetric uncertainty (Ross, 2004). In geostatistics, the term risk can be used as a synonym to chance, where it represents a single probability estimate, e.g. there is a 20 % chance that a specific well will result in a hydrocarbon discovery. Usually the term is associated with a negative undertone as it often represents the downside possibilities (Bratvold and Begg, 2010, p. 11; Ross, 2004). Uncertainty, on the other hand, represents the inability to estimate an exact value, such as for example the future oil price or the volumes of a hydrocarbons in a reservoir (Ross, 2004). It is important to distinguish between risk and uncertainty as it is possible to have uncertainty and zero risk. For example, there is uncertainty when a coin is tossed, but there is no risk if there is no betting on the outcome (Bratvold and Begg, 2010, p. 11).

Terminology like play, lead and prospect are widely used by geologists to illustrate the maturity of a basin, which often will reflect lower risk (Ross, 2004). A play is in the oilfield glossary by Schlumberger (2018) defined as "*an area in which hydrocarbon accumulation or prospects of a given type occur*". In the case of an exploration project where an exploration well is to be drilled, there are made estimates of the risk (chance) that the well will be a dry hole or a discovery not large enough to be commercial. On the upside, there are also made estimates of the recoverable volume present in the reservoir, often represented by P10, P50 and P90 values. These values are representing the uncertainty and are closely linked to monetary values (Ross, 2004).

2.4 Environmental Risk Assessment

Environmental risk assessment is an important part of the petroleum industry´s planning phase for understanding the risk picture and achieving acceptable risk levels. The main focus of an environmental risk analysis is to identify, evaluate, select, and implement actions to reduce the risk that can lead to environmental consequences (Jones, 2001). It is always important for a business to get familiar with the risk aspects and to suggest actions to reduce the risk before they act. Environmental risk includes both human health and ecosystems (Jones, 2001).

It is necessary to get a better understanding of the environmental risk assessment in the offshore industry. Even more important in new and less explored areas, such as in the Arctic (Fidler and Noble, 2012). Environmental risk factors especially related to exploration in the Arctic are mainly caused by the cold climate. Consequences of the icy weather includes floating icebergs, icing of equipment, and polar lows among other issues. This differs from exploration in more temperate areas and previous experience could possibly be less relevant. This leads to increased need of new models and understanding of the strength of today´s knowledge as well as understanding the current lack of knowledge (i.e. uncertainty) associated with this region. The consequence analysis related to environmental risk assessment includes modelling of environmental impacts of discharge of hazardous substances (Flage, unpublished, a).

The methodology for handling this risk is in Norway based on a report defining guidelines for how to handle environmental risk (metode for miljørettet risikoanalyse/method for environmental risk assessment) (DNV, 2007). In Canada a similar guide is present focusing on what to do if the Canadian Arctic is threatened by a spill (Indigenous and Northern Affairs Canada (INAC), 2017).

2.4.1 Norwegian Petroleum Exploration in the Arctic

In Norway the government regulates in what areas an exploration company can acquire data with basis on environmental aspects. Because of these regulations the northernmost part of the Barents Sea is still not open for exploration. However, the Norwegian Petroleum Directorate (NPD) has already investigated the resource potential in the northern part of the Barents Sea and the predictions are that large structures potentially carrying oil are present (NPD, 2017). This is naturally increasing the interest among the operating companies, and also their willingness to take the risks associated with drilling operations in this remote area as soon as the Norwegian government opens it for exploration. Although at present only the southern Barents Sea is available for drilling operations it is necessary to have more specified guidelines that includes the problems occurring in the marginal ice zone. This will also be useful in the future when areas even further north releases for exploration. These guidelines are presented in a report explaining a methodology for how to calculate environmental risk for the marginal ice zone (DNV-GL & Akvaplan-niva, 2014).

The petroleum industry in Norway are following the "Method for environmental risk assessment" guidelines defined by DNV (2007). These guidelines describe a method for environmental risk assessment (ERA) and was developed as a collaborative effort between various operating companies and the Norwegian Oil and Gas Association. Several versions of these guidelines have been made since the first edition, and the most resent one from 2007 is used in this study. In the guidelines three types of assessments are distinguished:

(1) reference-based assessment;
(2) exposure-based assessment; and
(3) damage-based assessment.

These types of assessment have increased level of details and therefore comes with different levels of effort. In a reference-based analysis the starting point is a 'reference assessment', assuming that the oil drift simulations in the reference assessment are applicable also to the influence area under consideration in the new assessment. An exposure-based analysis includes new oil dispersion calculations and contains damage assessment of vulnerable resources in affected areas. Lastly, a damage-based analysis is similar to an exposure-based analysis although it in addition assesses recovery time for selected species, populations, and habitats (referred to as Valued Ecosystem Components (VECs)). These VECs are considered suitable indicators during assessment of environmental risk related to acute oil spills. The main steps of the ERA methodology are as follows (DNV, 2007, p. 11):

(1) Define risk acceptance criteria;
(2) Establish an activity description;
(3) Establish probability estimate of unwanted event;
(4) Establish a sufficient number of probable combinations of release durations and rates in the environmental risk assessment;
(5) Oil drift simulations;
(6) Perform damage calculations; and
(7) Calculate environmental risk.

Since the focus of this thesis is in the Arctic it is also important to include the additional guidelines focusing on the problems of operating in the marginal ice zone. This methodology for calculations of environmental risk was developed by the Norwegian Oil and Gas Association on behalf of the operators on the Norwegian Continental Shelf (DNV-GL & Akvaplan-niva, 2014). The scope of these guidelines is to give an additional input regarding the marginal ice zone to the current MIRA approach (DNV, 2007) described above. The focus of these guidelines is the ice edge of the Barents Sea that could be affected by oil spills from current oil and gas activities on the Norwegian Continental Shelf. This means that the oil from an accidental release will have drifted on the sea surface for several days after the release before the oil reaches the marginal ice zone, which is very different from a situation where oil is released in ice infested waters, i.e. in terms of toxicity over time. The proposed methodology does not cover spills of oil directly in or underneath ice or exposure scenarios resulting from oil that has been frozen into the ice. The model structure of the marginal ice zone guidelines is more or less the same, meaning that existing data can be applied with no or minor modifications. The main difference is the handling of seabirds, marine mammals and sympagic fauna.

2.4.2 Canadian Petroleum Exploration in the Arctic

In Canada, the Arctic region is divided into different basins: Beaufort Sea, Sverdrup Basin, Eastern Arctic and Offshore Labrador. About 100 wells are drilled in the Beaufort Sea, however, only one well has been drilled within the past 20 years. The Sverdrup Basin is located north-east of Beaufort Sea, and have 20 significant oil and gas discoveries, and one commercial oil discovery. The Canadian Association of Petroleum Producers (Barnes, 2015) see the Eastern Arctic as an area with high potential for hydrocarbon resources. Hydrocarbon development in Arctic regions presents significant challenges, and Canadian Arctic Offshore still remains a focus area for industry but not on near term.

In Canada most of the drilled wells are located south of 60°N, although the hydrocarbon potential further north is significant (Morrell et al., 1995). Since large parts of the Canadian Arctic is not yet explored it is by Fidler and Noble (2012) seen as necessary to establish the scope and intent of environmental assessment prior to drilling new wells. North of 60° the oil and gas resources are administered by the Department of Aboriginal Affairs and Northern Development Canada (AANDC).

Because of the heavy debate regarding the climate changes, the Arctic offshore of Canada was declared indefinitely off limits to new exploration licenses by the Canadian government in 2016. This decision will be reviewed every five years based on current climate change and science findings (INAC, 2017). Due to this decision, it is very difficult to find valid guidelines for hydrocarbon exploration in this area. However, the Indigenous and Northern Affairs Canada (INAC) have established an Act called Canada Oil and Gas Operations Act (COGOA) which have responsibility for safety and protection of the environment. In areas where COGOA applies there are strict rules avoiding people from carrying on any work or activity unless the person holds an operating license and authorization for each activity, which is quite similar to the Norwegian rules.

The National Energy Board, Canada-Nova Scotia Offshore Petroleum Board and Canada-Newfoundland and Labrador Offshore Petroleum Board have issued guidelines to assist operators in developing Environmental Protection Plans (EPP) (National Energy Board, 2011). The EPP is a component of an operator’s management system and is an operator’s plan to effectively implement its environmental protection measures. An effective EPP should include the following elements:

(1) Means to comply with requirements of relevant legislation;
(2) Environmental protection measures identified as part of an environmental assessment; and
(3) Environmental commitments made as part of an application for exploratory drilling or a development application.

In this thesis the focus is on the environmental protection measures and commitments made as a part of an application for exploratory drilling or a development application. The environmental assessment should describe the predicted environmental hazards and risks, including the mitigation measures that have been identified to reduce those risks, should be implemented in the EPP. The EPP shall contain a summary of the studies undertaken to identify environmental hazards and to evaluate environmental risks; the results of those studies; and a summary of the means to avoid, prevent, reduce, or manage risks to the natural environment. In the EA, identification of potential hazards to the environment, assessment of risks associated with these hazards, and identification of mitigation measures to reduce these risks are fundamental tasks that are undertaken. The EPP should refer to the proponent´s environmental impact studies as appropriate, and reflect the commitments to environmental protection contained in the EA. Operators are expected to identify hazards and to assess associated risk and mitigation requirements on an ongoing basis throughout the full lifecycle of a project.

3 Uncertainty Analysis Framework

de Rocquigny et al. (2008, p. 7) expresses four categories of quantitative uncertainty assessment goals:

(1) *Understand*: the ability to understand the uncertainties;

(2) *Accredit*: meaning that an acceptable quality level needs to be reached;

(3) *Select*: compare relative performance, and optimize the choices; or

(4) *Comply*: demonstrate compliance of the system.

A given study may have several of these goals, where *Select* and *Compl*y refer to more advanced steps in operational decision-making. *Understand* and *Accredit* refers to more upstream modelling or measurement phases. The identification of these goals is important to be able to choose the most relevant methodologies for uncertainty analysis (de Rocquigny et al., 2008 p. 7). Two distinctive generic uncertainty analysis frameworks have been suggested in the literature, by de Rocquigny et al. (2008) and Aven (2010). In addition to these two frameworks, Flage (unpublished, b) is currently proposing a new framework based on these suggestions, as those models do not have the required sharpness with respect to treatment of model uncertainty.

3.1 Model- and Parameter Uncertainty

Model uncertainty is defined as uncertainty about which model best represents the system in question (NRC, 2013). In a case of two alternative models, G(X) and F(X), the model uncertainty is the uncertainty about which of those models most adequately represents the system (Flage, unpublished b). Model uncertainty is used in cases where it is crucial to know a quantity Z, whose value is realized in the future. The quantity Z could for example represent the amount of oil reaching vulnerable areas in case of an oil spill. In such cases a model G(X) is developed, where the output is dependent on the input parameters X and the function G (Aven and Zio, 2013).

In the context of the uncertainty analysis framework it is necessary to explain the term ‘parameter uncertainty’, which refers to uncertainty about the values of the model input quantities, i.e. X (Flage, unpublished, b; NRC, 2013).

3.2 Uncertainty Analysis Framework as defined by de Rocquigny et al., 2008

The input in the framework (Figure 7) is the uncertainty model, which refers to the quantification and characterization of the sources of uncertainty. Normally, one distinguishes between probabilistic and deterministic frameworks. A probabilistic framework will theoretically have an uncertainty model as a joint pdf of the vector of uncertainty inputs ($\underline{x}$). However, it can also be identified as e.g. a Gaussian distribution, with some independence hypotheses and simple parametric laws for the components. A deterministic framework includes the maximal range of each component of $\underline{x}$ (de Rocquigny et al., 2008, p. 10).

The next step in the framework is the uncertainty analysis step, with computation of the quantity (or quantities) of interest. This step transforms the measure of uncertainty in the inputs into a measure of uncertainty in the outputs of the pre-existing model. In the case of a probabilistic setting, this involves estimation of the pdf of $\underline{z} = G(\underline{x}, \underline{d})$, when $\underline{x}$ is known and values of $\underline{d}$ are given (de Rocquigny et al., 2008 p. 10).

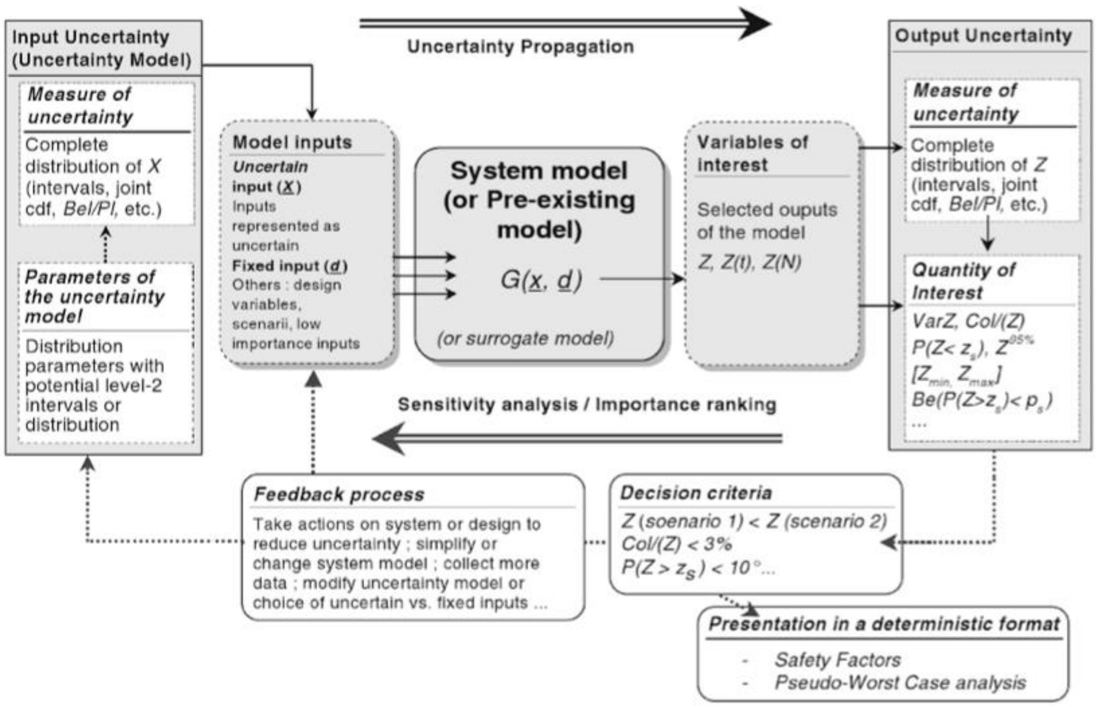


Figure 7: Illustration explaining the quantitative uncertainty assessment in industrial practice as presented by de Rocquigny et al. (2008).

The situations of the pre-existing system vary, and examples includes a metrological chain, a mechanical structure, a maintenance process, an industrial or domestic site threatened by a natural risk, etc. This system will generally be modelled through a single numerical model or chain of models, as long as the uncertainty studies are quantitative. Some models are straightforward analytical formulae which is quite simple, while others are more complex, like physical models based on unsteady partial differential equations, coupled 3-D finite element models or intrinsically probabilistic models (de Rocquigny et al., 2008, p. 4).

3.3 Uncertainty Analysis Framework as defined by Aven, 2010

Aven (2010) builds on the framework suggested by de Rocquigny et al. (2008), and he believes that the understanding of basic concepts along with the framework structure has some improvement potential. Further, it is stated that the uncertainties about the input and quantities of interest are epistemic and knowledge-based (subjective) probabilities that are used to express these uncertainties. This modified framework suggested by Aven (2010) is presented in Figure 8. In this model all the probabilities, P, are knowledge-based with reference to a standard expressing the analysts' uncertainty about the unknown quantities. This means that the probabilities are conditional on a background knowledge, K, which is an integral part of the results of the analysis. Uncertainties may be hidden in the background knowledge and it is therefore essential that the knowledge is presented as an integrated part of the results.

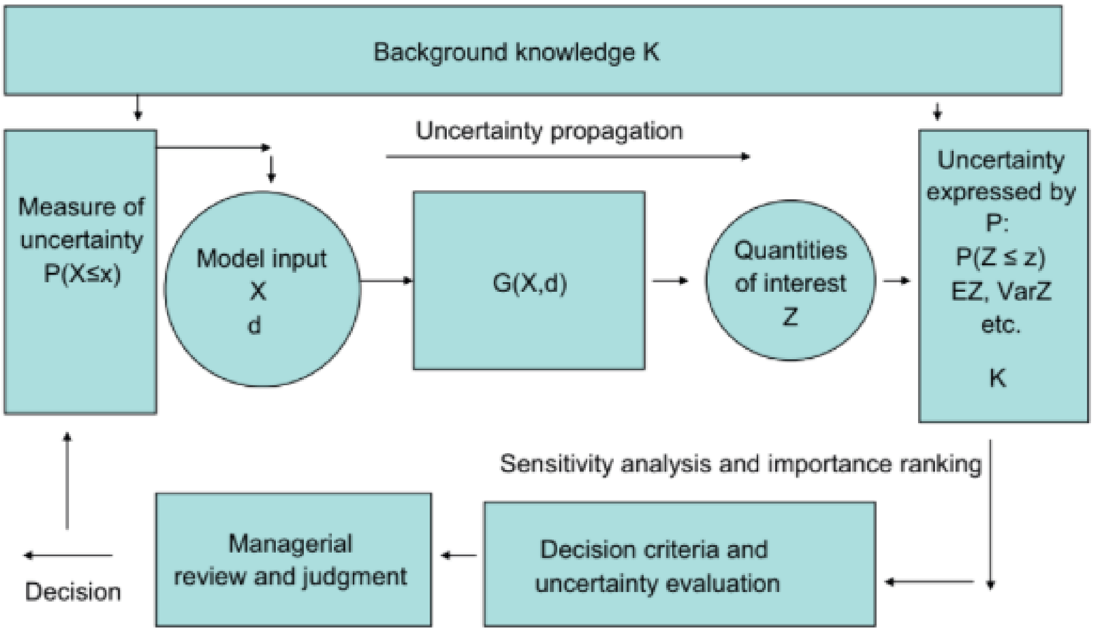


Figure 8: Suggested structure of an uncertainty analysis as proposed by Aven (2010).

The uncertainty evaluation covers probabilities and related background knowledge, as well as the results of the sensitivity analyses. This gives an extensive uncertainty description providing input to a broader managerial review and judgement, corresponding to the feedback process in the framework suggested by de Rocquigny et al. (2008). This step concludes on the implications of the analysis and balance different concerns, resulting in for example an acceptance of the uncertainties related to an activity, the need for design changes, or the choice of an alternative, etc.

de Rocquigny et al. (2008) and Aven (2010) have presented these two frameworks for quantitative uncertainty analysis and management in industry. The most common tool used for expressing uncertainties is probability, although the frameworks seem to be neutral with respect to different approaches for expressing uncertainties. Aven (2010) states that it is important that chances are considered as unknown properties and treated as X and Z in this framework. All X and Z needs to be properly defined for the framework to be sensible.

3.4 Uncertainty Analysis Framework as defined by Flage, unpublished, b

The uncertainty analysis framework as defined by Flage (unpublished, b) is created based on the frameworks described above by de Rocquigny et al. (2008) and Aven (2010). The goal of this framework is to include more information regarding the treatment of model uncertainty in the context of coupled models, and to tie in with recently developed uncertainty-based conceptualizations of risk highlighting the knowledge dimension (Figure 9).

A global model G(X) is located at the center of the framework, and can be seen as a set of coupled models. As inputs to G(X) is the model parameters, X, which results in a prediction of the quantity of interest, Z, as output. The uncertain quantities used in this framework is X, Δ_G and Z, and from these, Flage (unpublished, b) has identified three main levels of quantitative treatment of uncertainty:

(1) *Parameter and model*: Quantitatively establishing an uncertainty distribution $Q_{X,\Delta G}$ on both the parameter X as well as on the model error Δ_G(X). The output of the uncertainty assessment will then be a distribution Q_z on the quantity of interest, Z;

(2) *Parameter*: Establishing a distribution Q_X on the parameter X, with no quantitative assessment of model (output) uncertainty. This results in a distribution $Q_{G(X)}$ on the model prediction G(X), and not on the quantity of interest Z; and

(3) *Neither parameter nor model ('plug-in' approach)*: A point prediction/estimate X* of the parameter X is inserted into the model G to give a point prediction/estimate Z* = G(X*) of the quantity of interest, Z.

A new part in the framework of Flage (unpublished, b) that has not been included in the frameworks proposed by de Rocquigny et al. (2008) and Aven (2010) is the strength-of-knowledge (SoK) step. He argues that this step is necessary since the basis of the uncertainty measure may be weak, and the assumption of no model error in the second level of the quantitative treatment of uncertainty needs to be considered. In some cases, the model is considered sufficiently accurate, in which case it is reasonable to ignore the model uncertainty. It is important to make an explicit assessment of this assumption and to communicate it as part of the uncertainty assessment (Flage, unpublished, b).

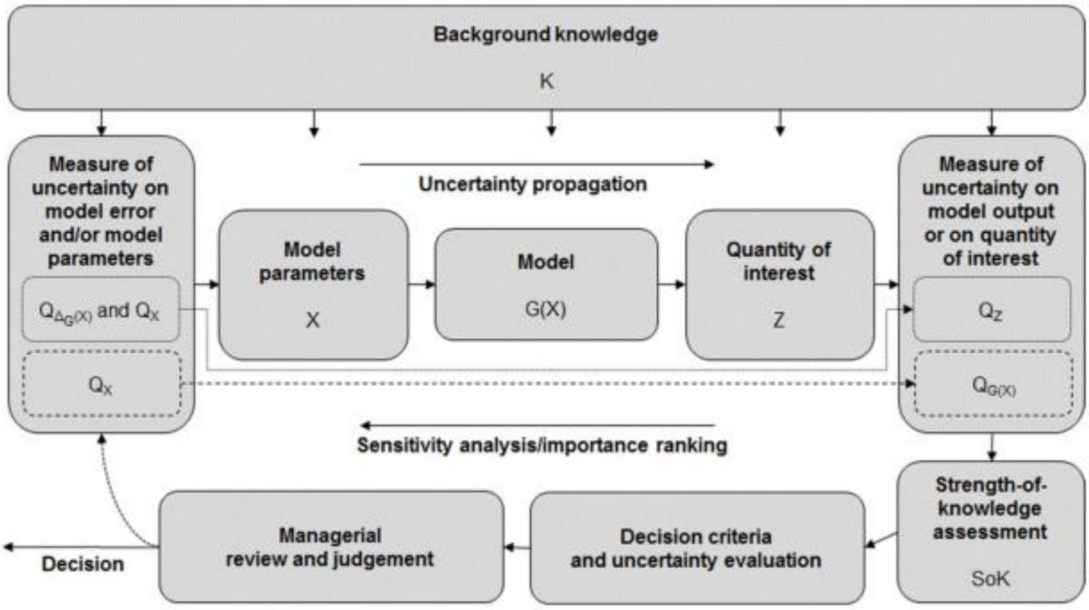


Figure 9: Proposed uncertainty model from Flage (unpublished, b).

4 Risks and Uncertainties Associated with Arctic Petroleum Exploration

Risks and uncertainties related to petroleum exploration in general are as previously mentioned large due to several uncertain parameters and variables, as well as limited access to exact information. While the same risks and uncertainties occurs in the Arctic, it is important to mention the additional challenges including both physical and holistic factors. Physical factors like low temperatures, sea ice (including ice features up to 30 meters thick), ice bergs, permafrost and/or icing, winter darkness and long distance to facilities/markets are special for this region. Holistic factors include economical, technical, human factors, environmental and geopolitical issues (Barnes, 2015).

Various aspects of risks and uncertainties are associated with different phases of the petroleum exploration process. Seismic operations occur at an early stage and is a necessity for further progress. It can often only be executed at certain time windows during a year in the Arctic region, when the ocean is either free from ice, or have thin ice. Another uncertainty regarding seismic acquisition is the noise pollution which in varying and uncertain degree is affecting the animal life. Additionally, in the planning, developing, and constructing phase, production facilities are also affected by extra challenges. During these phases it is among other issues important to consider the wear and tear on the installations from the harsh weather conditions. For example, satellites and pipeline may need to be placed in trenches to avoid destruction from possible icebergs scraping the seafloor. Other associated risks include explosions and fires, where health and safety of all involved are very important. In this case it is important to have a predefined plan for fire extinction and safe evacuation of people. All the extra issues related to drilling in the Arctic makes it more challenging and expensive than in non-Arctic environments.

4.1 The Arctic Region and its Challenges

4.1.1 Drilling in the Arctic

Compared to drilling operations in non-Arctic environments, drilling safely in the Arctic requires a different strategy where environmental factors specific to this region is included. It is especially important to protect and enclose equipment from this harsh and cold environment. During drilling, the lack of secure infrastructure and availability of resources is a significant challenge. To be able to have people working here it is important to be able to transfer them into safety within a short amount of time in case of an accident. Accidents will include fires and blow-outs, possibly leading to oil spills, which makes the access of water for fire extinction very important (which can be a severe problem if the water is buried under several meters of sea ice).

Platforms produced for Arctic environments needs to be constructed differently from platforms produced for more temperate and ice-free areas. In this region sea ice will scrape on the platform-legs and generate resonance, which causes the platform-legs to vibrate. The lifetime of the concrete is therefore dramatically reduced, and the entire platform may rest on dampeners to prevent the vibration from going from the platform-legs and into the platform itself. Today, steel plates are attached to the platform-legs to increase the strength and reduce the friction (Løset et al., 2006).

4.2 Physical Environment

Although there is a large amount of variation throughout the Arctic, the climate is in general characterized by long and cold winters. Some parts of the Arctic are covered by ice, in form of sea ice, glaciers or snow all year round. In January the average temperatures range from approximately -40 to 0 ºC, with temperatures dropping below –50 ºC over large parts of the Arctic. During the summer the temperatures are still below 0 ºC in some regions, although the average temperatures in July are between -10 to +10 ºC, with some exception with temperatures exceeding +30 ºC (Narvik University College et al., 2010). These cold temperatures can cause problems with icing of equipment and structures, but also for people working in these conditions. These temperatures, with associated sea ice etc., makes petroleum exploration in this region especially challenging compared to non-Arctic regions.

When drilling an offshore well, environmental factors like wind, waves and currents are important to consider anywhere in the world. In the Arctic different ice conditions that presents risks to offshore structures including ice sheets, ice ridges and icebergs also needs to be considered.

Floating production facilities and stationary platforms are in danger of iceberg collisions and must be designed to be able to withstand this. To reduce the risk of an iceberg collision, the movement of the icebergs are tracked by satellites, and icebreakers are ready to tow away the iceberg. A large challenge regarding icebergs is that the movement is difficult to predict due to wind and sea currents combined with the Coriolis effect. One way this is sorted out is by installing trackers on certain icebergs to track their movement (Løset et al., 2006).

Icing is also a big concern for floating facilities in this cold climate. The sea spray transports water onto the ships and weights them down. The ice growth rate is higher than the possible melt rate, which may result in ships having to retreat from the location. Navigation can also be affected as ice covers the deck and windows. (Løset et al., 2006).

The visibility in this region can be reduced by winter darkness, cloud coverage, rain, snowfall and fog. This can then lead to increased risk related to collision between structures, like icebergs, and vessels. Another issue is the ability to bring people into safety by helicopter, which are dependent on visualization to be able to help.

4.3 Vulnerability and Remoteness

Important aspects of petroleum exploration in the Arctic is the remoteness and vulnerability of the ecosystem. Due to little experience in this area the consequences of a major accident are significant and difficult to predict. The Norwegian government are taking the ecosystem of the Barents Sea seriously, and if a company are to apply for operatorship in this region a part of that application has to consider how the environment is affected.

Limited infrastructure and long distances are in general a problem in the Arctic region. This, together with the climatic conditions leads to a significant challenge if an accident should occur. The relatively long response time in the case of an accident may lead to severe consequences (Jacobsen, 2012).

4.3.1 Oil Spill

The largest potential environmental threat related to petroleum exploration is oil spill, which is difficult to control and harmful for the ecosystem. Oil spill is a disaster for the environment, and in the case of sea ice the oil dissolves into the ice, making it even more difficult to remove. Currently, no good solution to this issue exists. To reduce this risk, and decrease the consequences, a solution is to limit the period of drilling to when the sea is ice-free in areas where this is possible. Although there may not be ice at the location of drilling the oil will likely spread towards ice covered waters, still making it an issue. One of the main sources of oil pollution to the marine environment are open flows and blow-outs from the wells, which can cause great amounts of spilled oil.

4.3.2 Animal Life

The Arctic region has a special animal life, with species only living in these conditions. Before entering this region, it is therefore important to study and understand the threats petroleum exploration is causing. Animals like polar bears, Arctic hare, Arctic fox, caribou, and muskox lives in these conditions, as well as many birds and marine species endemic to this cold region. The effect of petroleum exploration, including acquiring seismic data and drilling wells, have to be well documented in this region and special cautions needs to be taken.

5 Discussion and Conclusion

In this chapter, the objectives of the thesis will be discussed towards the conclusion of the thesis. The already established approaches for geological and environmental uncertainty and risk analysis will be discussed in two sections, one focusing on the geological aspect, and one on the environmental aspect. Then, the discussion will move into the main task of this thesis, on proposing a common geological and environmental risk assessment methodology.

5.1 Geological Uncertainty and Risk Assessment

In association with petroleum exploration, the main goal of a drilling decision is associated with the possible presence of hydrocarbons in potential reservoirs. A large concern associated with geological models are the large uncertainty coming from imprecise and scarce input data, as well as approximations of true geological processes originated from modeling algorithms.

The term geological uncertainty often refers to a probabilistic approach, meaning that probability distributions are generated for each of the uncertain parameters going in to the fixed uncertainty analysis framework. This inability to estimate exact values makes the possibility of creating different probability distribution as defined in Chapter 2.3.1 very important. This method of setting a few values for different input parameters makes it possible to have some control and hopefully cover the one actual or true value, instead of setting one specific random value that is certainly not true. Furthermore, this makes the uncertainty of the model clear to everyone involved, and misunderstandings regarding the state of the background knowledge diminishes. Another way geologists handle uncertainty is in relation to the size of the potential discovery. Here they set up a P10, P50 and P90 value representing the possible volumes, which also creates a sort of distribution.

There may be several models available based on different calculation methods in the case of geological features. Meaning that it is important to always know the background information for the modeling workflow and also the inputs to the models. This is clearly identified in the uncertainty model proposed by Flage (unpublished, b) where arrows are indicating that background knowledge is important in every step until the output model is defined. Inputs to a model may include some actual well data points that will be combined with a random function to predict the geology in between. If these wells are distributed randomly and shows river deposits at a certain depth as described in Chapter 2.3, several variations of river streams within this area will be suggested based on the type of model used. These points have to fit a geological history suggested by the geologist based on real well data from the area. These points of information are dependent on each other and the random function are filling in the gaps between the wells.

5.2 Environmental Uncertainty and Risk Assessment

Environmental risk assessment is an important part of the petroleum industry´s planning phase for understanding the risk picture and achieving acceptable risk levels. In the Arctic it is even more important to consider the risks involved than in non-Arctic environments, as described in Chapter 2 and 4. The important steps of risk assessment includes identification of hazards, evaluation of the possible consequences, and planning of actions to reduce the risks. In the case of human health risks, it is important to include the uncertainty regarding sudden illnesses, and to have clear guidelines of how to bring them back into safe conditions.

A major environmental threat is as mentioned an oil spill caused by for example a collision. It is important to have considered a common plan for accidents like this, with a mutual definition of risk and uncertainty. It is also important to have requirements regarding the probability of this happening, where the vulnerability of the environment is included. Is the probability too large compared to the requirements defined by the guidelines and regulations described in Chapter 2.4, the well can simply not be drilled due to large probability of accident or the severe consequences related to the activity.

It is important that a plan based on knowledge is created prior to an accident. This can be done by looking at previous accidents and learn from them, and experiments where new tools for collecting the spilled oil are tried out. The importance of some background knowledge is important also in the case of the environment as it can help determine a more precise probability to an event and the expectations of the consequences are maybe more realistic.

Other issues are as defined in Chapter 4 also present in the Arctic, causing uncertainties and other types of accidents and consequences. Among other issues is the icing of equipment, which can cause severe consequences for installations and ships. With more knowledge it may in the future come better equipment made of other materials, less receptive for icing, or some products to shield the installations making it more resistant.

5.3 Proposed Combination of Geological and Environmental Risk Assessment

It is important to consider the cold climate and harsh winter conditions in this region when defining which of the uncertainty analysis frameworks is the best fit. The consequences related to accidents including ice are highly uncertain and unpredictable. One year the summer period can be ice free, and the next suddenly full of ice due to a cold summer. Based on this it is difficult to plan the work period to be during ice free periods based on a calendar, as these periods varies a lot from year to year.

The three uncertainty analysis frameworks presented in Chapter 3 are quite similar, however, the frameworks by Aven (2010) and Flage (unpublished, b) includes background knowledge which in the case of both geological uncertainty and environmental risk assessment is really important. In addition to this the strength of knowledge (SoK) step, added in the framework proposed by Flage (unpublished, b), is important. This will give the people collaborating with each other information on whether the previous step in the model is trustful, or how trustful the information actually is. The strength of knowledge together with the risk picture helps define whether a probability based approach should be used or not. In cases where the risk is defined as high, measures should be implemented before executing the plan.

In geological settings it seems like a probabilistic approach still is the common method, and it appears like it is working well in this context. In environmental related issues it is more varying between probabilistic and deterministic approaches. Even though this is the case, the conclusion is that the background knowledge and strength of knowledge steps in an uncertainty analysis framework is very important, and therefore the newest framework suggested by Flage (unpublished, b) is the best fit when finding one common framework.

6 References

Aven, T. (2007). *Risk Management* [Risikostyring; in Norwegian only]. Oslo: Universitetsforlaget. Pp. 180.

Aven, T. (2008). *Risk Analysis: Assessing Uncertainties Beyond Expected Values and Probabilities*. Chinchester, England: Wiley. Pp. 194.

Aven, T. (2010). Some reflections on uncertainty analysis and management. *Reliability Engineering & System Safety*, 95: 195-201.

Aven, T., Boyesen, M.,, Njå, O., Olsen, K. H. and Sandve, K. (2004). *Samfunnssikkerhet*. Oslo: Universitetsforlaget.

Aven, T. and Zio, E. (2013). *Model output uncertainty in risk assessment*. International Journal of Performability Engineering, NN: 101-116.

Barnes, P. (2015). Industry Perspectives on Offshore Oil and Gas Development and R&D in Canada´s Arctic. Presented October 15, 2015, St. John´s, NL.

Bohling, G. (2005). Introduction to geostatistics and variogram analysis. Kansas Geological Survey, pp. 20.

Bratvold, R.B. and Begg, S.H. (2010). *Making Good Decisions*. Richardson, TX: Society of Petroleum Engineers.

Caers, J. (2005). Petroleum geostatistics. Rischadson, Tex: Society of Petroleum Engineers. Pp. 88.

Carranza, E. J. M. (2009). Controls on mineral deposit occurrence inferred from analysis of their spatial pattern and spatial association with geological features. Ore Geology Reviews. 383-400.

Comiso, J.C., Parkinson, C.L., Markus, T., Cavalieri, D.J. and Gersten, R. (2018). *Current State of the Sea Ice Cover* [Online]. Nasa. Available at: <https://neptune.gsfc.nasa.gov/csb/index.php?section=234> [Accessed 27.01.2018].

de Rocquigny, E., Devictor, N. and Trantola, S. (2008*). Uncertainty in industrial practice – a guide to quantitative uncertainty management*. Chichester, England: Wiley.

Diggle, P. J. and Ribeiro Jr., P. J. (2007). Model-based Geostatistics. New York: Springer. Pp. 228.

DNV (2007). *Method for environmental risk assessment* [Metode for miljørettet risikoanalyse; in Norwegian only]. DNV report no. 2007-0063.

DNV-GL & Akvaplan-niva (2014). *Development of methodology for calculations of environmental risk for the marginal ice zone.* DNV-GL report no. 2014-0545.

Duesund, J. M. (2015). *Arctic Offshore Oil and Gas Outlook* [Online]. Rystad Energy. Available at: <https://www.rystadenergy.com/newsevents/news/press-releases/arctic-offshore-oil-and-gas-outlook/> [Accessed 26.05.2018].

Fidler, C. and Noble, B. (2012). Advancing strategic environmental assessment in the offshore oil and gas sector: Lessons from Norway, Canada and the United Kingdom. *Environmental Impact Assessment Review*, *34*, pp. 12-21.

Flage, R. (unpublished, a). *A risk-uncertainty framework for environmental risk assessment highlighting the knowledge dimensions*.

Flage, R. (unpublished, b). *A risk-uncertainty framework connecting geological uncertainty and environmental risk.*

INAC (2017). *Consultations on Offshore Arctic Oil and Gas Exploration* [Online]. Available at: <https://www.aadnc-aandc.gc.ca/eng/1494424040522/1494424674275> [Accessed 14.06.2018].

Isaaks, E. H. and Srivastava, R. M. (1989). *Applied Geostatistics*. New York: Oxford University Press.

Jacobsen, S. R. (2012). *Evacuation and Rescue in the Barents Sea, Critical issues for safe petroleum activity* [MSc]. Stavanger: University of Stavanger.

Jones, R. N. (2001). An Environmental Risk Assessment/Management Framework for Climate Change Impact Assessments. *Natural hazards, 23 (2-3)*. Pp. 197-230.

Knight, F. H. (2012). *Risk, uncertainty and profit*. New York: Courier Dover Corporation. Pp. 381.

Løset, S., Shkhinek, K. N., Gudmestad, O. T. and Høyland, K. V. (2006). *Actions from ice on arctic offshore and coastal structures*. Pp. 271.

McKillup, S. and Dyar, M. D. (2010). *Geostatistics Explained – An Introductory Guide for Earth Scientists*. Cambridge: Cambridge University Press. Pp. 396.

Morrell, G. R. (1995). *Petroleum Exploration in Northern Canada – A Guide to Oil and Gas Exploration and Potential*. Northern Oil and Gas Directorate: Indian and Northern Affairs Canada.

Narvik University College, Harstad University College, Insamet Tecnalia, Iceland Fire Authority/University of Iceland and Swedish Civil Contingencies Agency. (2010). Arctic region and its concerns, threats and potential challenges. Pp. 60.

National Energy Board (2011). *Environmental Protection Plan Guidelines* [Online]. Available at: <https://www.neb-one.gc.ca/bts/ctrg/gnthr/drllngprdctnrg/nvrprtctngd-eng.html> [Accessed 10.06.2018].

Nemec, W. (2011). Geostatistics – Lecture Notes (Revised 3rd ed.). Department of Earth Science, University of Bergen. Pp. 180.

NPD (2017). *Geological evaluation of petroleum resources in eastern parts of the Barents Sea north* [Geologisk vurdering av petroleumsressursene i østlige deler av Barentshavet nord; in Norwegian only]. NPD report.

NPD (2018). *Resource Report Exploration 2018* [Ressursrapport Leting 2018; in Norwegian only]. NPD report.

NRC (2013). Nuclear Regulatory Commission, US. *Guidance on the treatment of uncertainties associated with PRAs in risk-informed decision making* (NUREG-1855, rev. 1). Washington DC.

Olea, R. A. (2009). *A Practical Primer on Geostatistics*. U.S. Geological Survey, Open-File Report 2009-1103. Pp. 346.

Perminova, O., Gustafsson, M. and Wikström, K. (2008). Defining uncertainty in projects – a new perspective. *International Journal of Project Management*, 26 (1). Pp. 73-79.

PSAN (2015). *Guidelines regarding the Framework Regulations*. Available at: <http://www.ptil.no/framework/category408.html> [Accessed 15.02.2018].

Remy, N., Boucher, A. and Wu, J. (2009). *Applied Geostatistics with SGeMS*. New York: Cambridge University Press. Pp. 264.

Ross, J. (2004). Risk and uncertainty in portfolio characterization. *Journal of Petroleum Science and Engineering*, 44, pp. 41-53.

Schlumberger (2018). *Oilfield Glossary* [Online]. Available at: <http://www.glossary.oilfield.slb.com/> [Accessed 02.05.2018].

SRA (2015). *Society for Risk Analysis glossary* [Online]. Available at: <http://www.sra.org/sites/default/files/pdf/SRA-glossary-approved22june2015-x.pdf> [Accessed 15.02.2018].

Suslick, S. B., Schiozer, D. and Rodriguez, M. R. (2008). *Uncertainty and Risk Analysis in Petroleum Exploration and Production*. Terrae, 6 (1). Pp. 30-41.

USGS (2008). *Fact Sheet 2008-3049* [Online]. Available at: <http://energy.usgs.gov/Arctic/> [Accessed 15.03.2018].

Vinnem, J.E. (2007). *Offshore risk assessment : Principles, modelling, and applications of QRA studies* (2nd ed.) London: Springer.

Virine, L. and Rapley, L. (2003). Decision and Risk Analysis Tools for the Oil and Gas Industry. In *SPE Eastern Regional Meeting*. Society of Petroleum Engineers.

WWF (2016). *The evolution of the Arctic Council and the Arctic Council System* [Online]. WWF Arctic. Available at: <http://arctic.blogs.panda.org/default/evolution-of-the-arctic-council/> [Accessed 15.02.2018].

Yue, Q. (n.d.). Offshore structures in ice-infested waters. *Cold Regions Science and Marine Technology*. Pp. 9.