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Arctic Drilling Discrete Event Simulation

Fredrik Stang Heffermehl
Henrik Mikael Rode

Marin teknikk
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Hovedveileder: Bjørn Egil Asbjørnslett, IMT

Norges teknisk-naturvitenskapelige universitet
Institutt for marin teknikk

Preface

This report presents theory, results and findings of our Master Thesis at the Norwegian University of Science and Technology, Department of Marine Technology. Our group consisted of two students cooperating on the project, where all tasks have required an equal amount of input and discussion from both. We started this work as a student project for Statoil during the summer of 2013, and continued it as a project thesis during the 9th semester.

We dedicate this report to the memory of our mentor at Statoil, Arent Arntzen, with whom we had the privilege to work with during 6 months, before his unexpected and tragic death in January 2014. We would like to thank everyone at Statoil for continuing to guide us in the time afterwards, and providing the necessary data and knowledge to complete the thesis. Especially Ivan Metrikin, Francesco Scibilia and Arne Torsvoll for their guidance on ice management and drilling operations. We would also like to thank Stein Ove Erikstad and Matthias Nowak for guidance in ExtendSim. Finally, we want to thank Professor Bjørn Egil Asbjørnslett for his advice, guidance and help keeping us focused on the task.

Abstract

Increased need of energy is driving oil companies to search for hydrocarbons in Arctic waters, but they must overcome the challenge of completing a well in within a short drilling season with a potential of frequent disruptions. To evaluate the benefit of different technological solutions that can meet these challenges, a discrete event simulation model has been built in ExtendSim to represent an offshore exploration drilling campaign in the Arctic.

The model handles input data from a range of different operations and technology, and provides time estimates for the campaign in order to facilitate analyses of input parameters. A review of the operations, events and state of the art technology for an Arctic drilling campaign, combined with comparisons of simulation methods laid the foundation for the development of the model.

The model has been developed and verified in cooperation with Statoil, who provided guidance on simulation, knowledge of Arctic drilling and data for input parameters to the model. Validation of the model has been confirmed by comparing subarctic campaigns, and changes in four different parameters are analysed to evaluate the use of different technology. The results proved the models' quality, and ability to give an indication of what technological solutions will be beneficial to the campaign. There are a number of improvement areas, before the model can give accurate estimations of total campaign time.

Keywords: Arctic drilling, discrete event simulation, ice management, modelling

Sammendrag

Økt energibehov har tvunget oljeselskapenes søken etter hydrokarboner til Arktiske farvann. Det vil være utfordringer med å ferdigstille en brønn i løpet av en kort boresesong, med et stort potensiale for hyppige avbrudd. For å vurdere nytten av ulike teknologiske løsninger som kan møte disse utfordringene, har en diskret hendelsessimuleringsmodell blitt bygget i ExtendSim for å representere en offshore borekampanje i Arktis.

Modellen håndterer inndata fra en rekke forskjellige operasjoner og teknologi, og gir tidsestimater for borekampanjen for å analysere inndata parametere. En gjennomgang av operasjoner, hendelser og "state of the art" teknologi for en Arktisk borekampanje, samt en sammenligning av ulike simuleringsmetoder la grunnlaget for utviklingen av modellen.

Modellen er utviklet og verifisert i samarbeid med Statoil, som har gitt veiledning om simulering, kunnskap om systemet og datagrunnlaget for parametere i modellen. Validering av modellen har blitt gjort ved å sammenligne tidligere subarktiske borekampanjer. For å simulere ulike teknologiske løsninger har resultatene ved endring av fire forskjellige inndataparametere blitt analysert. Resultatene viste modellens kvalitet og evne til å gi en indikasjon på hvilke teknologiske løsninger vil være gunstig for en borekampanje, selv om en flere områder i modellen må forbedres dersom den skal gi nøyaktige estimater for total kampanjetid.

Nøkkelord: Arktisk boring, diskret hendelsessimulering, is håndtering, modellering

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Acronyms and Abbreviations

BOP Blow Out Preventor

DBR Daily Drilling Rapport - Daglig Bore Rapport

PUIFS Potentially Unmanageable Ice Features

WOW Waiting on Weather

WSOG Well Specific Operating Guideline

Chapter 1

Introduction

As the world's population is growing and living standards are improving, global energy demand is expected to double by 2050 according to the International Energy Agency (2012). Demand for further supplies of oil and gas are increasing, and the search for fossil fuels is now moving to Arctic waters. The U.S. Geological Survey (2008) projects that the Arctic contains 13% of the undiscovered oil and 30 % of the undiscovered natural gas in the world, with an estimated 84% of these resources expected to be found offshore.

The Arctic waters that are to be explored are only partially ice-free for a short season, ranging from July to October. Avoiding sea ice is therefore inconceivable, leaving regular open water drilling solutions inadequate. It is essential that the floating drilling unit is able to maintain a high degree of availability, ensuring that an exploration well can be completed within one season. Completing a well can necessitate an extension of the season, continuing as long as drilling can be operated safely. To meet the challenges of ice infested waters, an array of new solutions must be considered with respect to the design and operations philosophy of the drilling unit and fleet.

Significant uncertainties in environmental data, combined with a lack of operational experience, require an evaluation of the technology and techniques that can ensure safe and efficient extraction of hydrocarbons. The efficiency of ice management operations has been explored in several campaigns and models, comparing operational techniques (Holub 2011). The impact of ice features on the structural design and equipment of offshore drilling units in the Arctic has also been investigated (Eik 2010). Despite the existing research there are few articles that link design and operability, evaluating the total affect on a campaign.

This thesis investigates relevant problems and challenges associated with conducting an exploration drilling campaign in the Arctic, employing a discrete event simulation model to compare technology and operations. A study of operations, events and state of the art technology for an Arctic drilling campaign is conducted, combined with a review of simulation methods. This background theory lays the foundation for the development and verification of the simulation model.

The model facilitates a comparison of different technological solutions and their effect on the events and time spent during a campaign. The model focuses on the effects of sea ice and weather on the drilling operations for an exploration well in the Barents Sea, but it is open for development and addition of further considerations should the correct data be made available. A thourough discussion of the simulation techniques and input data is done to verify all assumptions that are made.

The structure of this thesis is planned out to be simple to follow, with 10 chapters and their sections focusing on similar topics in a logical order. Everything required to understand the model can be found in the main report, with larger tables and coding in ExtendSim placed in the appendix.

Chapter 2 gives a brief introduction to the Arctic environment. The 3rd chapter reviews the essentials of an Arctic drilling campaign, ranging from state of the art technology to operational challenges. Chapter 4 introduces simulation concepts and simulation techniques that are relevant for the problem. The 5th chapter presents the build up of the model, with all assumptions that have been taken in the development process. In Chapter 6 all data that has been collected and implemented in the model is declared, since some data is subject to confidentiality it is not included in the main report. The results and validation of the model are documented in Chapter 7, with analyses of the findings and a discussion of the validation process. A full discussion regarding methodology, assumptions and results can be found in chapter 8. Concluding remarks and recommendation for further work are displayed in the 9th and 10th chapters.

Chapter 2

The Arctic

The extremity of the Arctic climate combined with remote geographic locations, sea ice and environmental concerns pose a range of new challenges when conducting offshore drilling operations. This chapter presents some of the environmental aspects in the Arctic associated with offshore drilling.

2.1 Location and Infrastructure

The geographic area comprising the Arctic is characterised by being remotely located from existing infrastructure, with long supply routes that are vulnerable to the sea ice and weather conditions. As the interest for the Arctic is increasing the infrastructure in the area is developing. The Barents Sea is a marginal sea of the Arctic Ocean, spanning from Franz Josef Land in the north to northern Norway in the south, and is the base case for the model. In west is bordered by Svalbard, and in east by Novaya Zemlya. In the southern part of the Barents Sea exploration licenses have been given and a number of wells have been drilled. Of the Norwegian coast wells have been drilled as far north as 73,3 degrees, between Norway and Bear Island. During the 23th licensing round licences as far north as 75 degrees north will probably be given (Teknisk Ukeblad 2014b).

Figure 2.1: The Barents Sea (FPT 2014)

2.2 Temperature, Precipitation and Wind

According to Teknisk Ukeblad (2014a) icing due to low temperatures may become a problem in the Arctic, both regarding the drilling unit and supporting vessels. This is an important subject which must be assessed.

Combinations of low temperature, precipitation and wind can cause ice to form on the drilling unit. Icing can either be caused by by rain freezing as it comes into contact with the structure, or by sea spray freezing on the structure. Ice formation will then typically happen on one side of the unit, resulting in stability problems for the drilling unit.

2.3 Sea ice

The ice in the Arctic Ocean reaches its maximum extent in March and its minimum extent in September (NASA 2009).

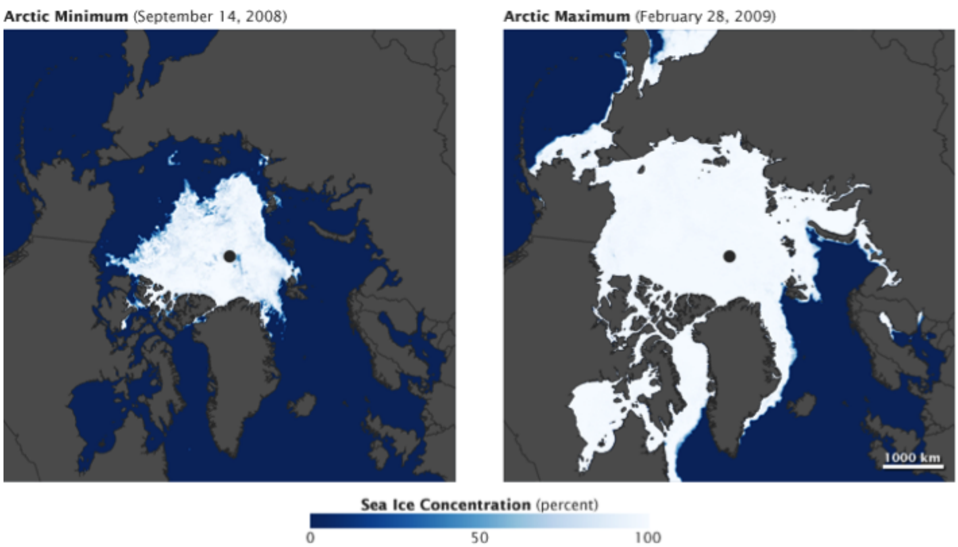

Figure 2.2: Minimum and maximum extend of sea Ice in the Arctic (NASA 2009)

Figure 2.2 shows the extent of ice in the Arctic Ocean in September 2008 and February 2009. In September the entire Barents Sea remains more or less free from permanent ice. The southern part of the Barents Sea remains ice free year around because of the Gulf Stream, while the northern part is covered by ice in the winter season. The period between July and October is the period which is referred to as the open water season or the drilling season.

2.3.1 Pack ice

Also known as drift ice, pack ice differs from landfast ice in the respect that it is free to move with wind and current. Pack ice can occur far offshore and away from any landfast ice, covering large geographic areas and consists of floes; individual pieces 20 metres in diameter or more. The consistency of pack ice can vary considerably, from thin first year ice to multi-year ice and contain embedded ice ridges and icebergs.

2.3.2 Icebergs

Icebergs are large pieces of freshwater ice, broken off from glaciers or ice shelves drifting freely in the ocean or embedded in pack ice. Icebergs usually only reveal 1/10th of their full volume above water; making them at times hard to detect and estimate their size.

Iceberg and multi-year ridged ice can develop keels that reach down to the seabed, scouring the ground and creating gouges as they drift along potentially posing a hazard to equipment at the sea bed. The maximum water depths measured for ice gauges is 40-50 metres. Ice gouges have been measured up to 5 metres although most do not exceed 1 metre, and anything above 2 metres is characterised as an extreme event (Héquettea et al. 1995; Oickle et al. 2006).

2.3.3 Data on Ice

The available data on sea ice in the Arctic varies considerably depending on the specific geographic area, some areas are more extensively explored and charted than others. However data on sea ice for a specific location is harder to find and according to Liferov (2014) there has never been a sufficient amount of ice data for Arctic projects. The most reliable data concerns landfast ice in the high Arctic, from satellite surveillance ongoing since the 1960's up until today. This data contains probabilities concerning thickness and other sea ice properties, such as ridges and their extent during different seasons. Only locations with an open water season are considered for an Arctic drilling campaign, and therefore ice floes, icebergs and thin ice covers at the start and end of the season are of most interest. There is little reliable data concerning thickness and probability of encountering pack ice in the Arctic.

2.4 Arctic Phenomena

2.4.1 Polar Lows

Polar lows are mesoscale vortices at high latitudes, generally characterised by severe weather in form of strong winds, showers and occasionally heavy snow (Rasmussen and Turner 2003). Polar lows could potentially cause a severely hazardous scenario and must be considered a risk factor for a drilling campaign.

2.4.2 Geomagnetic Storms

Geomagnetic storms are temporary disturbances in Earth's magnetosphere, caused by increased solar activity and solar winds. They are especially heavy on the north and south poles, in 1989 a geomagnetic storm caused the collapse of the Hydro-Quebec power grid in Quebec, Canada. Induction of electric currents along long oil pipelines has also been of observed. Heavy geomagnetic storms may cause electronic equipment to fail onboard vessels.

2.4.3 Arctic Haze

During the winter and early spring the Arctic atmosphere becomes contaminated with pollution from the Eurasian continent (Shaw 1982). These pollutants are effective at scattering light and reducing visibility and are commonly referred to as Arctic Haze (Cahill and Wilcox 2003).

2.5 Summary

- Remoteness and lack of infrastructure create new challenges
- Pack ice and icebergs pose threats to drilling campaigns
- Arctic specific environmental phenomena are hard to predict and can cause breakdown of equipment and operations

Chapter 3

Arctic Drilling Campaign

An Arctic drilling campaign is extensive and complex, with unique environmental conditions and technical challenges that must be overcome. The short open water season combined with occasional disconnections due to unmanageable sea ice, requires a high degree of efficiency to complete an exploration well within one season. Hamilton et al. (2011) claim that anything less than several wells per year will not be economically viable.

To make justified assumptions and simplifications in the modelling process, it is necessary to be familiar with all parts of the system. Law and Kelton (2000) assert that intimate knowledge of processes, events and technology are required to create and verify a model. The amount of detail and precision in a model needs to be evaluated, as the complexity of a model must be suited to its purposes. Creating a model that is purposeful, limited and yet realistic is therefore a challenge, and decisions must be made as to what elements of a real life system are relevant to include. This chapter presents the essentials of an Arctic drilling campaign, with special focus on elements of the system important to a simulation model.

3.1 Scope of Operations

An Arctic drilling campaign can be divided into a range of operations from start to finish. This section presents operations that are planned for an Arctic drilling campaign, explaining their importance to the total campaign.

Depending on the well and mission, there are a number of operations that must be completed for the campaign to be deemed successful. Each well is different, the set up of a well and the technology used is highly dependent on the bedrock geology. There are a number of different techniques and operations that can be applied, but the purpose of this thesis is to be able to model all operations. A general overview of the campaign is presented here, with further details on the modelled operations explained in section 6.1. An drilling campaign can be divided into 5 main steps:

1. **Transit and Mobilisation**
   The first step in the campaign, consisting of moving the the drilling unit to the planned location. The drilling unit requires a large number of supporting vessels before drilling can start, and the fleet can arrive from many different places.

2. **Mooring**
   When the drilling unit is in place at the drillsite, it is moored according to it's equipment. Mooring can be extra tricky in early or late season due to an increased prevalence of sea ice.

3. **Drilling Operations**
   Once the unit is in place and moored, the actual drilling can take place. Drilling the well can be divided into:

   - **Top sections**
     The top sections are drilled prior to landing the BOP and marine riser. Drilling of top sections may be distinctive for Arctic drilling due to extra equipment and precautions specified by regulations.
   - **Lower sections**
     The lower sections usually consist of two or more parts. These parts do not vary much from drilling ordinary wells, consisting of drilling and logging/coring (Torsvoll 2013). Any zones that are, or potentially might be hydrocarbon bearing require extreme precaution against spills due to the sensitivity of the Arctic environment.

4. **P&A**
   Plugging and abandonment consist of plugging the well and retrieving all re-useable equipment such as casings and the BOP. These operations do not differ much from regular exploration drilling.

5. **Demobilisation**
   Moving to a new location, or the disbandment of the fleet. Precautions must be taken to avoid a scenario like the Kulluk with Shell (DOI 2012), especially when transport phases are undertaken in seasons notoriously subjected to bad weather.

There is a need for routines to handle events that are not defined in the scope of operations, but can be expected to happen some time during the campaign. Accounting for the time needed for these unplanned events is essential when planning the campaign, to avoid the problems Shell experienced in their 2012 Alaska Offshore Oil and Gas Exploration Program (DOI 2013). These unplanned events are reviewed in section 3.6 and 3.7.

3.1.1 Process Times

To predict the total time needed and cost of a campaign, the process time to complete each operation must be estimated. Statoil and other oil companies have governing documents and software detailing how the time estimation of a well should be conducted. By taking data from existing reference wells and identifying project specific risks an estimate can be made. There are also guidelines recognising learning curves effects on time with respect to new equipment, crew, rig and lack of experience (Statoil 2014). Taking the learning curve into consideration for process times is especially important for Arctic operations, because of the climate, technology and added challenges brought by the unusual location and conditions.

To illustrate the necessity of finding good predictions of process times, the US Department of the Interior's review of Shell's Arctic campaign (DOI 2013) pointed sharp criticism at Shell for "... consistently underestimated the length of time required to complete each step of its drilling operations. The timelines provided by Shell proved to be unrealistic and did not account for complications and delays that should be budgeted for when operating in the Arctic". The lack of backup equipment also contributed to operations being prolonged, as the crew needed to be extremely cautious. This goes to show the importance of accounting for the effect of equipment, learning curve and complications in time estimation of operations.

3.1.2 Regulations

Arctic offshore operations need to meet the same requirements as open water design criteria. A typical requirement for open water operations is that the installation needs to maintain structural integrity after incidents with a probability of happening less than once every 10,000 years. Liferov (2014) mentions discussions in the Arctic engineering community regarding the application of open water design criteria such as 100-year and 10.000-year events, and whether these are precautious enough. Operational and technical requirements for station keeping follow traditional guidelines such as WSOG, although with modifications for the relevant equipment and environment. The significant differences between offshore drilling in the Arctic and other regions arise from environmental regulations and regulations regarding ice.

Environmental
Environmental regulations vary depending on the specific country with legislative power in the relevant location. Regulations for emissions are generally much stricter, both to the air and to the sea. Mud, cuttings and other hazardous waste are required to be transported to an approved treatment/disposal site onshore by boat (Shell 2009).
Wildlife and local inhabitants demand special consideration to avoid any lasting impact on the fragile Arctic ecosystem, or harming the livelihood of indigenous peoples. During Shell's 2012 campaign drilling was stopped both during bowhead whale migration and during the Inuits traditional hunt.

Ice Class
Ice class gives necessary requirements for transit and starting operations in ice. Specific criteria include ability to handle ice vaning, ice features, ice concentration and ice floe size.

ISO 19906
This is the governing document detailing requirements for Arctic offshore structures. ISO 19906 specifies requirements and provides guidelines for considerations associated with the design and operational measures of petroleum and natural gas industries in Arctic and cold regions (Liferov 2014).

- Sea ice conditions
  Site-specific ice criteria shall be determined for the structure under consideration. Data from nearby sites or geographical regions with similar ice environments can be used if local ice data is unavailable. Numerical or statistical modelling can be used to extend these data sets, taking uncertainties into account.
- Ice management
  The expected performance of sea ice surveillance and physical ice management shall be documented, including associated uncertainties. Ice management performance may be measured in terms of its ability to extend operations, reduce downtime levels, allow disconnection, facilitate structure move off, and enable safe and efficient reconnection.
- Disconnection
  The installation may be designed with a system for disconnection and reconnection of mooring lines as well as lines necessary for hydrocarbon drilling, production and export. The required time to move off location shall be considered to ensure that the structure can move off site without incident.

3.2 Technology

Arctic exploration requires innovative solutions that adhere to high standards, ensuring drilling is completed in a safe and effective manner. All equipment to be used in Arctic drilling requires a high level of availability and a low downtime; the choice of equipment affects both process times and scope of operations. Longer lead time to resupply broken equipment, requires extra measures to avoid breakdown and loss of vital equipment that could halt the entire drilling operation. This section focuses on the equipment and technological solutions essential to the drilling operation proper.

3.2.1 The Drilling Unit

The design of the drilling unit requires dedicated solutions to meet the challenges in the Arctic, especially to maintain operational limits for extreme conditions and maximise production time. Wassink and van der List (2013) outline a list of requirements that all Arctic drilling solutions must strive to meet regardless of overall design:

- Health, safety and environment focus in all aspects of the design, to ensure maximum crew safety and limit exposure in case of evacuation.
- Multiple options for escape, evacuation and rescue under both sea ice and open water conditions, integrated into the overall operations philosophy.
- The working environment should be winterised by covering up work areas, resulting in less exposure for personnel and reducing power consumption.
- Other winterisation considerations must be made, such as de-icing equipment, to avoid a buildup of ice on the unit.
- To meet Arctic environmental policies, the design must focus on incorporating clean design methodology, a zero harmful discharge philosophy and reduction of air emissions by reducing power consumption and waste heat recovery, as well as employing state of the art technology for exhaust gas cleaning.
- High degree of autonomy, reducing the need for resupply of equipment and mud/cuttings in remote locations. This can be done by having a high variable deck load.
- Transit speed shall be sufficient to economise mobilisation and allow the unit to mobilise to and from the areas of operation under safe circumstances.

The main technical challenge for Arctic drilling units is their ability to handle ice in locations where sea ice is present during operations. With the ice management system as the main line of defence against incoming ice, drilling units should be able to handle ice that has been broken into sufficiently small pieces.

Ice that has been successfully managed can still cause challenges for the hull of the drilling unit due to increased ice loads, build up of rubble and broken ice pieces causing fatigue and abrasion to subsurface equipment. The design of the unit and shape of the hull can help protect subsurface equipment and reduce loads. By pushing ice away to the sides with aid from the dynamic positioning and thruster systems, illustrated in figure 3.1. The figure shows thrusters working against the ice direction whilst maintaining position. It is important to take into account that subsurface appendages may still come in contact with ice, necessitating extra protection to upper parts of mooring lines and riser systems.

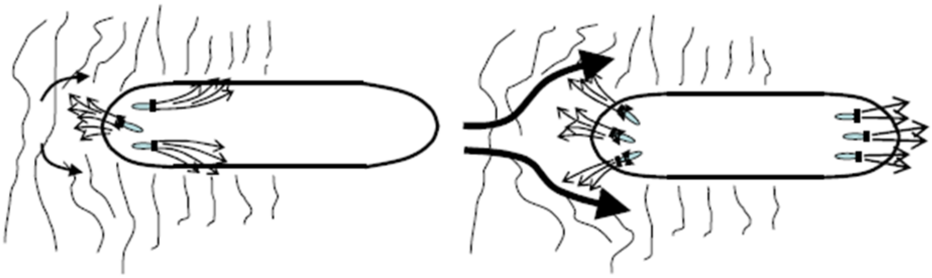

Figure 3.1: Thrusters pushing sea ice out from hull, and counteracting to maintain position (Statoil 2013)

The choice of drilling unit solution depends on the sea state, sea ice conditions and depth of the relevant location, with different solutions having different merits. Stationary units are for obvious reasons unsuitable for exploration drilling. Three different solutions are presented below:

Semi-submersible

Semi-submersibles possess good motion characteristics in harsh sea states. The drawbacks of a semi-submersible include a low variable deck load and transit speed. Some semi-submersibles also require towing to and from site, which poses a challenge under storms when they may tear and run ashore, such as in Shell's drilling campaign with the Kulluk (DOI 2012). There are two different types of semi-submersible platforms that have been used in the Arctic:

Regular: A regular semi-submersible with columns are well suited for open water conditions, and have been used in subarctic locations. In ice covered waters there is a big risk of sea ice "clogging up" in between the columns, and no ice protection for equipment in the splash zone, making them unsuitable in these locations.

Conical: Conical semi-submersibles have been thoroughly tested out, such as in the case of Kulluk that has been in use since the 1980's. A conically designed platform is equally resistant to incoming weather and ice from all angles, implying no need for weather- and ice vaning. There is no risk of clogging and plenty of protection for equipment around the splash zone.

Jack-up

Jack-ups are limited to water depths of 180 metres, where they have many advantages, especially the ability to stay directly above the well when dynamic positioning systems are unsuitable. They suffer from the same problems with ice clogging as regular semi-submersibles.

Drillship
Ships are well suited for operations in sea ice, and there exists ample experience from the maritime industry with operating ships in sea ice conditions. Ships can be considered inherently safe in sea ice if they are sufficiently ice strengthened, and offer good protection to the equipment running through the splash zone. In comparison to semi-submersibles, they offer a high variable deck load and good transit speeds, without the need of being towed. Their motion characteristics are not as good as a semi-submersibles in harsh sea states.

3.2.2 Mooring and Station Keeping Equipment

For any offshore drilling operation the primary challenge is keeping the drilling unit directly above the well to avoid excessive riser bending moments. With stationary solutions this is generally not a problem, but floating units are dependant on their mooring and station keeping equipment to stay within the limitations for maximum allowable offset from the wellhead. The maximum allowable offset is defined by the angle of the Marine Drilling Riser/drill pipe and a hypothetical vertical line above the wellhead, as illustrated in figure 3.2. The unit must also have the capability to move off the site, if conditions become unmanageable, given ample time by forecasts or other threats to station keeping.

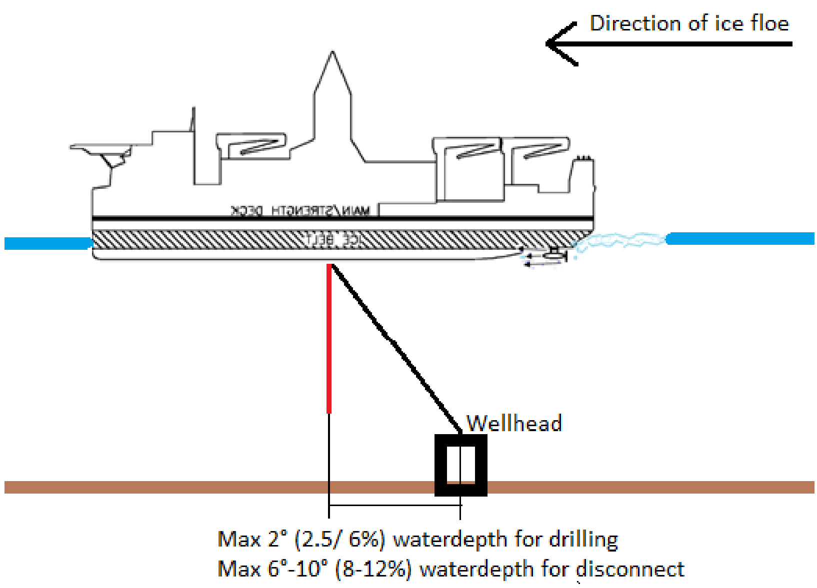

Figure 3.2: Stationkeeping and Anchoring

In the figure an ice floe is exerting a force on the drilling unit, this could however also be caused by wind, current or a combination of external conditions. The angles given in the figure are illustrative and do not necessarily represent real limits, which would be stated in the campaign's WSOG.

Dynamic Positioning
A drilling unit with exclusively dynamic positioning does not need any installation of mooring systems, allowing for the drilling operation to commence as soon as the unit is in place above the well. For the same reason time to move off site is significantly reduced compared to other options. Manoeuvrability is good, although under sea ice conditions the control systems may encounter trouble necessitating manual control according to Keener and Allan (2009).

A dynamically positioned solution faces significant loads with increased horizontal loads in sea ice conditions, and a small maximum allowable offset in shallow water. These loads necessitate higher power specifications, resulting in high fuel consumption and increased emissions to the atmosphere. Generators in the Arctic have already been shown to have problems complying with air permits, owing to not being adequately designed to handle colder temperatures (DOI 2013). As restrictions on air pollution are stricter in the Arctic this poses a problem as to how much dynamic positioning can be used. The extra power requirements for the propulsion system are therefore a major drawback for a pure dynamically positioned solution.

Conventional Mooring
As the title suggests this is the most common solution for offshore drilling units, and many years of experience in open water have shown this to be an effective and uncomplicated system. Fixed mooring can be used in conjunction with dynamic positioning, and compared to dynamic positioning alone, fuel consumption is significantly reduced. A major drawback is that fixed mooring does not allow for weather- or ice vaning. For a circular semi-submersibles vaning is less critical, but for other solutions this can cause a big loss in operability due to extra high loads and motions from sea ice and weather. Exposed mooring lines restrict the maximum ice thickness of ice floes, necessitating frequent disconnections unless they are protected. Getting ready to move off site requires more time than with pure dynamic positioning, as mooring lines should be retrieved in a safe and effective manner.

Turret Mooring
A turret allows for many of the options that conventional mooring does not, such as ice vaning and protection of mooring lines from sea ice, at the same time a turret possesses all the features of a conventional system. The turret is however more complicated to install, and may require subsea access for anchor handling, depending on the solution. Combined with dynamic positioning and thruster assist, maneuverability is much greater than for conventional options, whilst having a relatively conservative fuel consumption, though this is also true for conventional mooring. A convenient connection and disconnection system to the turret must be

applied, as moving off site otherwise could provide a much bigger challenge than with conventional mooring. A solution been proposed; a detachable turret that can be lowered below the ice and recovered when move off is needed. The viability of a detachable turret has been explored in several papers, and tested in an ice laboratory, but the functionality is uncertain as it has not yet been tried out full scale (Bonnemaire et al. 2007). A turret is certainly much more expensive than conventional mooring, and a detachable turret requires an heftier investment.

3.2.3 Drilling Technology

Technology that can increase safety, or decrease the time and frequency of interruption of operations can potentially be decisive for the time to complete a campaign, below three such technologies are listed.

Riserless Drilling
The limitations in allowable angle of the Marine Drilling Riser and drill string can vary depending on solutions. Riserless drilling uses a hose instead of a riser. A riserless solution allows considerably more maneuverability for the drilling unit, and a bigger margin for allowable offset (Torsvoll 2013).

Drilling Fluids
The application of drilling fluids and muds that are not harmful to the environment and can be released quickly, can decrease the time for disconnections significantly (Torsvoll 2013).

Mudline Cellar
This is an insurance measure designed to protect the BOP from being damaged by scouring ice in shallow waters, a mudline cellar is a hole excavated which the permanent guide base and BOP is lowered into. In the case of a move off, retrieving the BOP may require a lot of time. With a mudline cellar it can be left on the seabed until reconnection, which can be a convenient and faster option.
In Shell's drilling campaign, several problems were encountered in construction of the mudline cellar that led to operations taking much more time than originally estimated (DOI 2013). It is not unreasonable to expect that these challenges could be met by other operators as they include; unexpected boulders, crew inexperience with the mudline cellar bit and extreme cautiousness due to lack of back up equipment.

3.2.4 Supporting Vessels

Restrictions on emissions, lack of infrastructure and difficult logistics require the supporting fleet to fulfill several different functions, giving increased redundancy during operations. Many critical operations are reliant on the availability of the supporting fleet. Below is a list of capabilities the fleet needs to meet (ABS 2013):

- Offshore supply: transports and stores materials and equipment to and from the drilling unit and shore.

- Storage: storing of chemicals and equipment necessary to the drilling operations, reducing the variable deck load on the drilling unit.
- Anchor handling and mooring: handle mooring equipment for the drilling unit.
- Transit and escort: provide assistance to lower ice class and disabled vessels.
- Diving and ROV support: provide support for diving systems and underwater remotely-operated vehicles (ROVs).
- Safety and standby rescue: evacuating and receiving personnel from the drilling unit, also used in the rescue and care of people from another vessel at sea.
- Firefighting: carry out firefighting operations.
- Spill response: recover oil or fuel from the water and ice in response to a spill.

Icebreakers
The task of the icebreakers is to break and tow ice features, ensuring the drilling unit is not subjected to unmanageable ice loads. Typical requirements are high bollard pull, ice breaking performance and manoeuvrability in ice. There are three types of icebreakers currently in operation (Statoil 2013):

Fixed Propeller Shaft
Traditional icebreakers have been used for ice management operations and have a proven ability to cover severe ice conditions. During operations in sea ice they require a large fuel consumption.

Azimuth
Azimuth icebreakers such as the Pacific Enterprise, Fennica and Botnica have been used in ice management operations for first-year ice. They have not been used in multi-year ice environments. The azimuth propulsion is a fairly recent innovation in ship building and requires less fuel consumption than traditional icebreakers (Statoil 2013).

Nuclear-Powered
Nuclear-powered icebreakers are the most powerful icebreaker, they are significantly more powerful and larger in size than traditional icebreakers. Currently only Russia has this kind of icebreaker, and they are not in use by regular companies.

3.2.5 Sea ice Surveillance

The drilling fleet needs to be continuously fed with a forecast of sea ice conditions based upon satellite images, meteorological studies and reports from the supporting fleet. Monitoring equipment will never be 100% accurate, and there is always associated a Probability of Detection, which will be a function of equipment used, size of ice feature, sea state and weather conditions.

Satellite
Satellite surveillance is dependent on weather and cloud cover and can only be acquired once or twice a day, so it cannot be relied upon on its own. The data

received from satellites is used for strategic decision making, such as indicating ice features that need further investigation by aerial reconnaissance. Synthetic Aperture Radar is the most common satellite surveillance system used in measuring ice thickness, though Sandven et al. (2006) mention that other microwave systems such as scatterometer and radar altimeter data have shown promising results for observation of ice parameters. Synthetic aperture radar covers a large area and gives the opportunity to spot incoming ice floes several days ahead, giving an indication of ice conditions.

Aerial
The most effective and reliable way to measure sea ice thickness is with aerial surveillance, either fixed wing aircraft or helicopter. The drawback of aerial surveillance is its vulnerability to weather conditions, and the need for infrastructure. Currently there are two ways to detect ice thickness that are tried and tested, Electromagnetic Induction and Ground Penetrating Radar methods are reliable and tested technologies that can be deployed by helicopter or fixed wing aircraft (Garas et al 2014). However they require flight at extremely low altitudes with a swath width of measurements between 10-20 metres. Fenz et al. (2013) calculated the largest sector an electromagnetic induction survey can cover upstream is only 17°, if it is to give a 24-hour warning period for an incoming ice floe. Blunt et al. (2012) contend that it is unlikely that ice drift forecasting can be forecasted correctly for such a small angle for 24-hourr periods.

New ways to detect ice features are therefore constantly being developed, the most anticipated aerial technique is Multi-band Synthetic Aperture Radar, which is being investigated as a tool to conduct remote, broad-swath ice thickness surveys as stated by Scheuchl et al. (2002) and Holt et al. (2009). If this method proves successful, it would enable a much wider swath of 8 km and could cover a sector of 244° in one day. This solution is deployed by fixed wing aircraft, which can be a problem in the high Arctic due to a lack of infrastructure.

Marine Radar
Marine radar can be fixed on supporting vessels and the drilling unit, giving a high frequency of acquisition. However their detection capabilities can be limited by a number of factors such as; sea states, distance to target, weather and size and shape of target. Most marine radar do not give an indication of ice thickness or other features, but O'Connell (2008) report that enhanced radars can improve both detection in higher sea states and differ between ice features.

Subsurface Sensors
Underwater sensors can be used completely independent of weather conditions, and can in theory be deployed to control ice thickness in a wide ranging geographical area. Unfortunately there are other drawbacks, and they are currently being tested out. Haugen et al. (2011) list some current disadvantages including costs, limited coverage, communication challenges, navigation and difficulty of logistics .

3.3 Logistics and Communication

The remote location and lack of infrastructure brings added challenges to Arctic drilling, according to North Atlantic Drilling logistics is one of the biggest challenges (Teknisk Ukeblad 2014a). Supplying the drilling fleet with necessary equipment, personnel and fuel is key to minimise downtime during operations. The drilling fleet must balance supply, stand-by abilities and ice management during operations to find an optimal combination for the campaign. Transit, mobilisation and demobilisation of the fleet before and after a well is complete also requires careful planning and vigilance, avoiding the same mistakes as Shell did in their 2012 campaign (DOI 2013).

The design of the drilling unit affects the required rate of resupply, for example:

- A solution with a high variable deck load can carry more equipment and supplies and will have a higher degree of autonomy.
- The station keeping equipment affects the fuel need; for example the high fuel consumption of a pure dynamically positioned solution necessitates a higher rate of fuel transfer to the drilling unit.
- Used lube oil, chemical products considered hazardous waste, water-based drilling fluids not meeting discharge limits, trash and debris and oily water are to be transported to an approved treatment/disposal site onshore by boat. The rate at which these wastes are produced depends on well conditions, and how the well is drilled.

Communication between vessels of the fleet and other supporting functions is a requirement for many operations especially during ice management, a loss of communication could require a curtailment of drilling operations (Shell 2009). In contrast to operations in the North Sea with a high degree of infrastructure both on land and at sea, the drilling fleet operating in the Arctic needs to be more self sufficient than normal offshore units, and must be able to handle fallouts in communication. Supporting vessels need to be in touch at all times to coordinate ice handling procedures and stand by for potentially hazardous situations such as on or offloading off fuel and personnel. Therefore terrestrial, satellite, ship-to-ship and ad-hoc systems must be employed and are required to have a high level of redundancy. The consequences of a faulty communication system can lead to a stop of all drilling operations, or to a disconnection if the ice conditions in the proximity are unknown.

3.4 Weather

Handling weather in the Arctic is in many ways similar to normal offshore operations, though the Arctic brings some extra considerations to take into account such as icing on the drilling unit.

Weather can affect operations in many ways, it is important to have knowledge of the drilling units response to evaluate which parameters are most likely to cause disruptions. The station keeping ability of the vessel, loads on riser equipment and offset from the well are the most critical aspects, whilst some crane and lifting operations require calm wind. According to (Statoil 2013a) the most important weather states that should be monitored are:

- Sea state (significant wave height and mean wave period)
- Wind speed and direction
- Ocean current speed and direction

A disconnection on the drilling unit is usually not undertaken until conditions are threatening the integrity of the system according to experts at Statoil (2014). The drilling unit can be made ready for a disconnection if weather forecasts predict unmanageable weather, but the choice to disconnect is not made until the motions of the unit are critical. To decide what actions must be undertaken at each stage, the WSOG has limits that specify when operations must be curtailed. Time costly disconnections can be avoided as the disconnection operation is easily reversed, whilst any hasty or emergency disconnection unlikely as the unit is prepared for a worst case situation.

Experience from handling weather in offshore drilling is vast, data and statistics can be found from campaigns all around the world. No forecast is always 100% correct, there will always be a deviance between a forecast and observed weather, with the deviation increasing with the length of the forecast. The lack of infrastructure and observational data in the Arctic, means that the forecasting models used are slightly less accurate compared to the North Sea and other similar regions. Roth (2014) maintained that the forecasts for a 24-48 hour period are accurate regarding wind, temperature, pressure and waves, but the deviation increases significantly for longer periods. Some deviations occur in short periods too, but are becoming less frequent as weather models get better and the number of observational stations increase.

3.5 Ice Management

Eik (2008) defines ice management as: "The sum of all activities where the objective is to reduce or avoid actions from any kind of ice features. This will include, but is not limited to:

- Detection, tracking and forecasting of sea ice, ice ridges and icebergs
- Threat evaluation
- Physical ice management such as ice breaking and iceberg towing
- Procedures for disconnection of offshore structures applied in search for or production of hydrocarbons."

In Arctic drilling operations, unmanaged drifting sea ice can produce significantly larger loads than conventional station keeping systems are able to manage. With purpose built station keeping equipment and well executed ice management the drilling unit can be protected from incoming ice floes and icebergs in open water conditions, extending the drilling season beyond the open water season. Therefore it is necessary to have a system of protecting the drilling unit from potentially unmanageable ice features (PUIF) that can be deemed a danger to the operation. Ice management has already proven to play a big role for what kind of ice a drilling campaign can manage, the difference is considerable according to Liferov (2014).

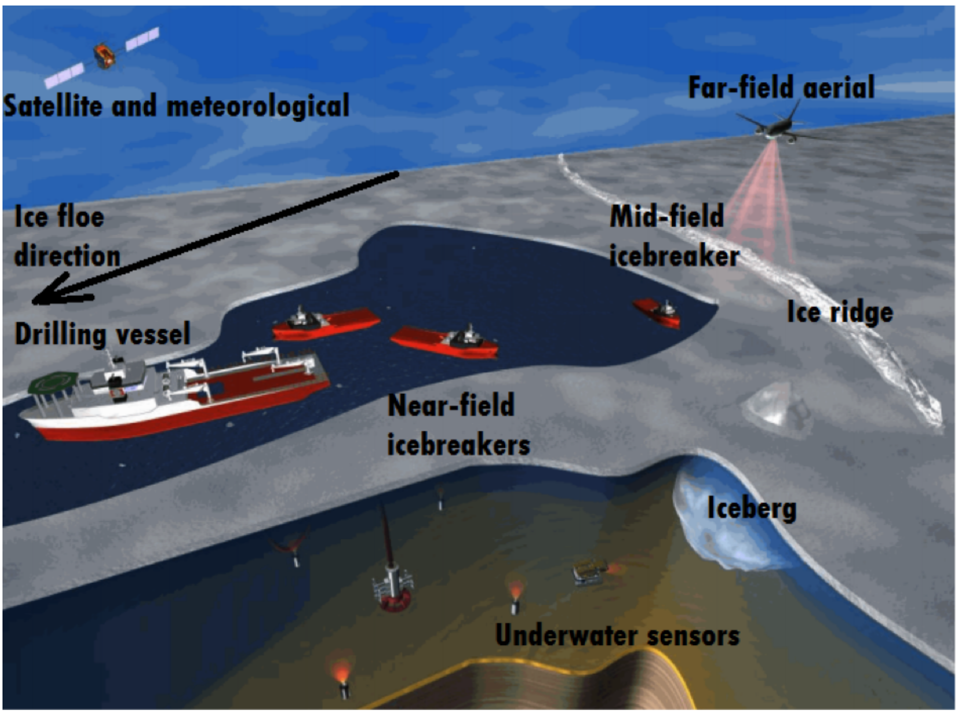

Figure 3.3: Icemanagement (Eik 2008)

Unmanageable Ice Conditions
Potentially unmanageable ice features (PUIF) consist of icebergs that cannot be successfully deflected, heavily ridged ice, ridged second year ice, multi-year ice floes, and fragments of multi-year ice or ice islands embedded within first year ice floes. Detecting PUIFs can be challenging as they are often embedded in manageable ice, and Hamilton et. al (2011) report that relatively small fragments of a few hundred metres in size can be quite capable of stopping the progress of the icebreakers.
Although the ice is deemed manageable there are a number of situations where it can pose a threat to operations, such as; unnoticed features, changing ice drift direction, ice pressure and ice drift reversal. These unexpected ice situations can cause an unacceptable position and accident scenarios (Statoil 2013).

3.5.1 Fleet Distribution and Operations

There have already been several missions in the Arctic to measure the efficiency of ice management and test out different ice management strategies (Holub et al. 2011). Depending on conditions at the site of the drilling campaign, the fleet of supporting vessels can be arranged accordingly. In this section the typical arrangement and operations for an ice management fleet are presented. Figure 3.4 illustrates a typical distribution of the fleet and surveillance units. The ice management system is divided into into 3 different fields, based on surveillance and ice handling capabilities: far-field, mid-field, near-field. Associated actions are represented by letters A, B, C and D. ISO 19906 and presents this as the most common ice management strategy (ISO 2010).

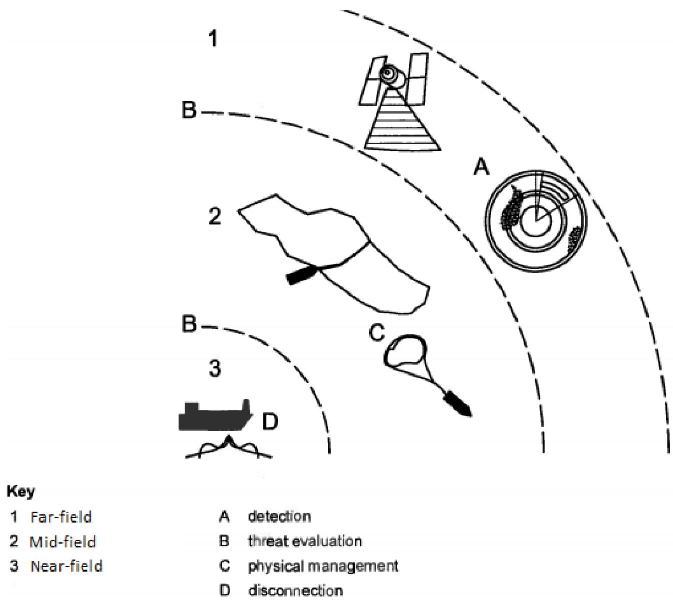

Figure 3.4: Typical arrangement of an IM system. (ISO 2010) Figure A.17-1.

Far-field

Since satellite surveillance cannot measure the thickness of incoming ice or detect PUIFs with 100% percent reliability, it is necessary to utilise equipment that can improve the probability of detection. To ensure that icebreakers are deployed in time to handle incoming PUIFs, far-field surveillance must be able to produce reliable alerts of incoming ice at least 24 hours ahead of the drilling vessel.
Forecasting the path of sea ice is necessary once the ice enters the far-field, to make tactical decisions regarding the deployment of the icebreakers. The actual and forecasted ice drift path are demonstrated in figure 3.5. There have been many attempts at modelling the path of ice, and new models are being developed (Hamilton 2011). These models can assist in guiding the early work of the icebreakers, evaluating the threat from PUIFs to the drilling unit.

Mid-field

The only certain method to guarantee that incoming PUIFs can be broken into manageable ice or towed away, is to use a scouting icebreaker. As shown in figure 3.5 a single icebreaker is stationed around 6-10 hours upstream of the ice floe, functioning as a scout verifying thickness, breakability and ability to handle any suspected PUIFs. The scout icebreaker receives far-field observations of incoming ice, using this information it can locate PUIFs and asses the ability to tow or break the ice. The information regarding location and characteristics of incoming ice is then passed on to the floe reduction icebreakers in the near-field.

Near-field

Two icebreakers work closely upstream of the drilling vessel, continuously towing or breaking and reducing the incoming ice to create a channel of managed ice for the drilling unit illustrated in figure 3.5. The icebreakers balance staying close to the drilling unit, ensuring the drilling vessel stays well within the managed ice channel, and keeping far enough upstream to allow a margin in case an emergency disconnection is necessary due to the discovery of unmanageable ice.

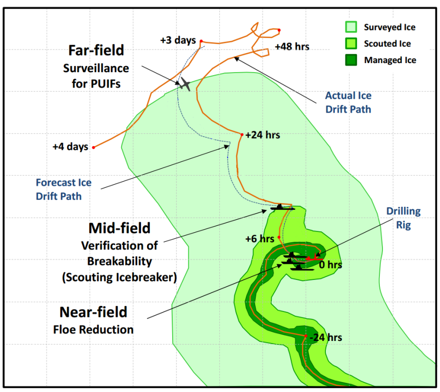

Figure 3.5: Ice management fields and ice drift (Fenz et. al 2013)

3.6 Interruption of Operations

In the Arctic there many new operational aspects, and it is not likely that all operations will follow the scope of operations. There are a range of unplanned events that are likely to happen sometime during the campaign, and can potentially lead to accident scenarios if not handled correctly. The drilling unit is required to have procedures and technology to handle these events routinely. Though operations may also stop due to banal incidents such as the breakdown of equipment, this section focuses on events that threaten the station keeping abilities of the drilling unit. Often these shutdown routines are caused by weather and ice conditions being above operational limits, but they could also be triggered if the safety of the operation, drilling fleet or environment is compromised due to a lack of equipment or personnel.

These interruptions can constitute a stop in the operation whilst waiting for better conditions, to a full disconnection and the drilling unit moving off the site. It must be noted that real time threat evaluations are taken on board, and preparations that are made to shut down or disconnect operations can be reversed when a hazard has passed. Generally, the better time to prepare for a shutdown of operations leads to less negative consequences and a quicker resumption of operations later. The time required to shut down and restart operations depends on the technology and operations used on board as mentioned in Section 3.2.2.

3.6.1 Operational Limits

Due to the limited time an Arctic campaign has within an open water season to drill a well, spending time on unnecessary disruptions is highly undesirable. The tolerance of an operation to external conditions and the ability to quickly shut down and resume operations in the face of a potential threat, can be crucial when minimising downtime in a harsh environment. Compared to operations in the North Sea, there are less exact descriptions to predict conditions that are unmanageable according to Liferov (2014).

Discussions with drilling experts at Statoil and a review of (Statoil 2013a) revealed how complex drilling operations are, and how much they vary for drilling unit, location and environmental conditions. There are also internal guidelines developed by Statoil and other oil companies concerning time limits for shutdown of operations due to incoming ice. Each drilling unit has its own tolerance to sea and ice conditions. A drilling unit's operational limits can be divided into 4 or 5 different zones, that are dependent on the equipment's station keeping abilities in weather and ice conditions.

Operations can have specific time limits dependent on their criticality called a weather window. Some operations requiring pristine conditions from start to completion. Whilst other operations can be scheduled to go ahead even if there they can only work for a short period before being aborted. From conversations with experts at Statoil it is known that due to the costliness of time in a drilling campaign, it is desired to commence operation whenever possible; some operations will commence even if processing is possible only for a few hours.

Strict regulations and procedures in the Arctic may require operations to be ceased on a more often to ensure rules and safety regulations are met. Prominently, clean up equipment and other health, safety, security, communication and environment critical systems that do not meet minimum requirements, may cause operations to be suspended if it is deemed unsafe to continue.

Critical Operations
Certain operations are more likely than others to generate conditions that could lead to an accident scenario, therefore requiring lower operational limits. To avoid accidents and minimise downtime, it is important to identify critical operations and assess their operational limits. Cleaning up after accidents can both be very time consuming and damaging to the environment, which is highly undesirable in the Arctic. These critical operations are often be dependent on other factors such as sea states, sea ice, availability of support vessels and communication.

Many of the operations are in a section of the well where hydrocarbons is expected to be present (Shell 2012 J):

- Coring
- Pulling out of the hole with the drill string
- Wireline logging in the open hole
- Running casing, circulating and cementing
- Refuelling
- BOP handling
- Heavy lifts during resupply
- Anchor line tensioning, if anchored

3.6.2 Waiting on Weather (WOW)

An operation can be set to wait on weather if an operation is outside it's limits, but there is no immediate need to disconnect from the well. The operation is therefore set to stand by whilst updates on weather and forces on equipment are being assessed. Waiting on weather can also be necessary before starting operations that require a long weather window to be completed, such as lowering the BOP.

If there is enough uncertainty regarding an incoming hazard, suspension of drilling operations and preparation for disconnection whilst waiting on weather may be started. The required action depends on the probability of severe weather combined with criticality and necessary time for the given operation to be suspended. Though regulations are absolute limits, necessary actions are often defined by guidelines and the good judgement of the personnel on board.

3.6.3 Planned Disconnection

Planned disconnection is the desired method for disconnecting, it requires the most time and is usually done at the end of the season or upon completion of the drilling campaign. A planned disconnection requires notice several days ahead to be thoroughly executed. This disconnection method may also be adequate for incoming storms or unmanageable ice that is detected days in advance, or maintenance of critical equipment. The well is left in optimal condition with less than a day necessary to reconnect and resume operations if this type of disconnection is successfully achieved.

3.6.4 Managed Disconnection

Minimum alert time for managed disconnections is above 24 hours, allowing operations to be suspended and disconnection can be completed in a timely manner. This disconnection require less time than a planned disconnection, but the well is left in bad condition, requiring more time when reconnecting. A managed disconnection is the most common reaction when a threat for station keeping appears, such as incoming ice or weather.

3.6.5 Emergency Disconnection

A highly undesirable operation that is necessary if station keeping is no longer possible and there is insufficient time to perform a more timely disconnection. Examples could be surveillance and ice management systems failing to detect unmanageable ice up until the near-field, and inability to break the ice necessitating an emergency disconnection to avoid damage to the drilling unit. An emergency disconnection leaves the well in a safe, but highly undesirable condition, so there is a big probability of the well being abandoned.

The frequency of this operation occurring should be very rare, comparable with unplanned emergency disconnects in open water drilling operations, i.e. almost never and all other disconnections should be favoured as it could mean the failure of a campaign.

3.6.6 Mooring System Release and Move off

A disconnection can include mooring system release time and move off, so that the drilling vessel can safely move to a secure position off site if it is threatened by ice or extreme weather conditions. Move off time is dependent on the distance the drilling unit needs to travel to the secure location and weather conditions.

The time to release the mooring system and ready the drilling unit for move off depends on the mooring system the drilling unit employs, three solutions were presented in section 3.2.2. Except for a pure dynamically positioned solution, the other alternatives usually have several options when releasing mooring lines. Similar to disconnections, the mooring system can be released at short notice; with the risk of damaging or losing equipment (Shell 2009). A quick and hasty release of mooring systems can possibly compromise the integrity of the system, possibly requiring repairs or replacement before redeployment of mooring.

3.7 Accidents and Contingency Plans

When planning an offshore drilling program, risk identification is a requirement, and especially crucial for Arctic drilling due to the vulnerable environment. There are a number of accident scenarios that must be avoided, but should they occur the drilling fleet is required to have procedures to minimise the outcomes.

Many unexpected events are similar for Arctic operations and common open water campaigns. Some of the risks for drilling in the Arctic are presented below, together with unexpected events that can lead to serious consequences for the environment, personnel, critical equipment and the success of the campaign.

3.7.1 Loss of Communication

A loss of communication could be triggered by a geomagnetic storm, potentially knocking out all electronic equipment for extended periods of time, or a simple failure of equipment. Depending on the proximity of any potential hazards, suspension of all drilling operations could be required until equipment is up and running.

3.7.2 Emergency Disconnection

Although already mentioned in section 3.6.5 on the interruption of operations, due to its similarity with other disconnections, an emergency disconnect will cause a lot more damage to equipment. The consequences entail adverse effect on the whole campaign, possibly rendering irreparable damage to mooring equipment and the well. Therefore it is more suitable to label emergency disconnections as an accident scenario.

3.7.3 Impact

Following a complete failure of the ice management system, where an unmanageable ice feature has not been detected or handled, and disconnection procedures have not been successful. An impact is defined as exerting a force that damages the structural integrity of the drilling unit, perhaps leading to worse consequences such as an oil spill or environmental and loss of human life. Continuing the campaign without extensive repairs will not be possible.

3.7.4 Hydrocarbon Spill

For the purposes of exploration drilling, there are two potential categories of oil spills in connection with exploratory work; a fuel spill from operations and a well blowout (Shell 2009).

Fuel Spill
Historical data demonstrates that the probability of a large oil spill occurring during exploration is insignificant. Based on data from the Gulf of Mexico, the most likely area of a large spill would be from a pipeline or oil tanker, neither of which is present during exploratory operations. Historical operational spill data suggests that the most likely cause of a spill of liquid hydrocarbons during exploration would be operational, such as a hose or tank rupture, constituting a minor fuel spill. Since no oil is produced in an exploratory well, the only conceivable source of a large oil spill is from a catastrophic well-control failure, also known as a blowout.

Blowout
A blowout during exploration drilling is extremely unlikely, no exploration drilling blowouts have occurred as a result of Arctic exploration drilling from the approximately 98 wells drilled within the Alaskan OCS (MMS 2007). For exploration wells drilled in analogous water depths to planned Beaufort Sea wells (30 to 60 m), Bercha (2008) predicts adjusted frequency is 0.000612 per well for a blowout sized between 10 000 bbl to 149 000 bbl and 0.000354 per well for a blowout greater than 150,000 bbl. A blowout would necessitate the drilling of a relief well, ending the entire drilling campaign as all resources are pulled to limit environmental damage.

3.7.5 Accidental or Unintentional Riser Disconnect

Subsurface ice that is not carried to the side of the vessel, nor managed by the dynamic positioning and thrusters, may pose a threat to the riser system; if ice impacts the risers they could be damaged or tear off. Unless the ice is noticed and operations are suspended an impact may result in a spill of drilling fluids. Operations are shut down, especially if drilling is being undertaken in hydrocarbon bearing zones, and spilled fluids are recovered. A disconnected riser, whether damaged or not, may require some form of subsea intervention causing all drilling operations to be halted for the time required to remediate the damage.

3.7.6 Shipboard Fire

A fire will require all other operations to cease and may necessitate an emergency well suspension procedure, including assistance from other available vessels. Depending on the severity of the fire and which areas and equipment are affected on board, three scenarios can play out; operations cease but no well suspension is necessary and work is delayed for a day, emergency well suspension is required and time to restart operations is 2-4 days, or an entire abortion of the drilling campaign is necessary (Shell 2012 J).

3.8 Summary

This chapter has presented the essentials of an Arctic drilling campaign, with focus on aspects from the system that are relevant for the model.

- To build a good simulation model it is essential that the modeller has intimate knowledge of all operations and events, planned and unplanned, and their effect on an Arctic drilling campaign.
- State of the art technology for use in the Arctic, and how the choice of technology affects operations and process times.
- How weather affects an offshore drilling campaign, the accuracy of forecasting.
- How sea ice is handled for an Arctic campaign, components of an ice management system.
- How unexpected events, interruption of operations and accident scenarios are handled by the drilling fleet.

On the next page a list of the different drilling technologies from section 3.2 are summarised:

Technology	Alternatives	Comments
The drilling unit	Semi-submersible	Good motion characteristics in harsh weather, but low variable deck load. Two options; conical or regular. Regular is not suited for ice covered waters.
	Jack-up	Good for shallow depths, not well suited for ice covered waters.
	Drillship	High variable deck load, suitable in all ice conditions with turret mooring. Motion characteristics not as good as semi-submersible.
Mooring and station keeping	Dynamic positioning	Fast mooring. Requires a lot of fuel. May experience trouble in ice covered waters. Allows weather- and ice vaning.
	Conventional mooring	Tried and tested in open water, can be used in conjunction with dynamic positioning. Does not allow for weather- or ice vaning. Requires the most time for mooring.
	Turret mooring	Conservative fuel consumption. Allows for weather- and ice vaning. More expensive option. Requires a convenient connection solution, this can be solved with a detachable turret, though this is a new and expensive option.
Drilling technology	Riserless drilling	Can give an increase in offset from well and better maneuvrability
	Drilling	Disconnection times can be reduced by using environmentally
	fluids	friendly fluids that can be released to the sea
	Mudline cellar	Allows faster disconnection in locations prone to ice scouring
Icebreakers	Fixed propeller shaft	Traditional, tried and tested for all ice conditions with proven abilities. High fuel consumption.
	Azimuth	Tested for first year ice. Lower fuel consumption.
Sea ice surveillance	Satellite	Covers a large geographic area, and can spot incoming ice several days ahead, but does not give reliable thickness measurements. Dependent on weather and cloud cover, and cannot be relied upon alone.
	Aerial	Most effective and reliable approach to measure ice thickness. There are several methods, that can be either mounted on fixed-wing or helicopter aircraft. Dependent on infrastructure, weather and design of the drilling unit.
	Marine radar	Can be fixed on all vessels, with a high frequency of acquisition but do not give indications of ice thickness or features.
	Subsurface sensors	Still in the development phase, but can in theory be very useful.

Table 3.1: Technology comparison

Chapter 4

Simulation

The word simulation is derived from the latin ”simulare” - to imitate. A simulation is a technique computers utilise to imitate a real-world system, by making a set of simplified assumption to define a model.

A system consists of different elements that have given relationships and interact, which the model attempts to replicate. A system can be interpreted as a limited part of the real world, that only concerns the problem to be simulated. Elements that have no relation are therefore not part of the system.

4.1 A Simulation Study

When modelling real-world systems, intimate knowledge and understanding of the system is crucial. The modeller must be familiar with all possible outcomes in each stage of an operation, including the difficulties the system encounters, when deciding how to limit the model and realistically replicate the system.

A simulation study is not a simple sequential process, but rather an iteration where increasing complexity can be added to a model as understanding of the system is obtained. Increased understanding helps set limitations, and often the problem is reformulated as knowledge of the system increases. Law and Kelton (2000) outline 10 steps that are present in a typical simulation study, illustrated in figure 4.1. However, the order of steps in the figure do not necessarily need to be present, a good and sound simulation study could be based on an iteration of these:

- Define the system
- Start with a moderately detailed model
- Verify and validate the model
- Add complexity
- Verify and validate again until a satisfactory level is reached

Verification should come from people who are intimately familiar with the system, and validation by comparing output from runs to see if the model matches with a similar existing system.

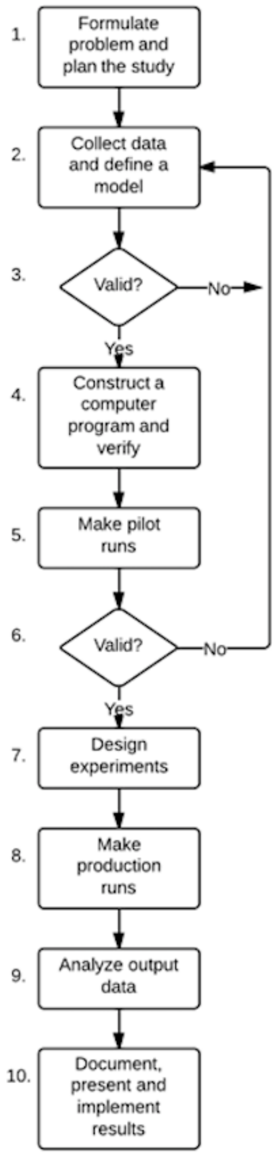

Figure 4.1: Simulation Study Steps (Law and Kelton 2000)

4.2 Advantages, Disadvantages and Pitfalls of Simulation

Complex systems are often impractical to describe analytically, and simulation is therefore used due to the many advantages when replicating the design aspect of systems. Common for these advantages are that testing systems in real life can be very expensive. By applying simulation techniques, existing systems can be tested under new operating conditions. Changes in system design can also be tested, without actually building full scale experiments. In many cases the experiment conditions can be controlled better than when experimenting with an actual system. When studying systems over long periods of time simulation is often a useful tool, as a systems response can evaluated over its life period in a short period of time.

Since simulation is often employed when valid analytical models are not valid, this implies that simulation does not provide optimal solutions. While analytical models can be applied to find optimal solutions and provide exact answers, a simulation model only provides estimates. Another disadvantage with simulation is the cost of development, since developing good simulation models is time consuming. According to Law and Kelton (2000) there is also a tendency of being too confident with the results of an simulation study.

There are also several pitfalls that the modeller should be aware of when utilising simulation methods. A typical pitfall mentioned by Law and Kelton (2000) is the lack of well-defined objectives when starting the simulation study. The level of detail in a model representation is important, and the modeller should be aware of which level of detail is appropriate for his or her purposes. Failure of collecting good system data is mentioned as another pitfall, applying arbitrary distributions as input to the model should be avoided. Attributing true credibility to the output from a simulation model is a pitfall when using simulation as a tool.

4.3 Continuous and Discrete Event Simulation

In simulation a system is represented by entities and state variables. Continuous and discrete event simulation are defined by how these state variables change. Continuous simulation concerns modelling where state variables change continuously as time transpires in the model, for example; the position of the truck in transit from point A to B illustrated in figure 4.2. The truck's position can be measured at any time in the process of driving between the points, represented by the dotted line. In discrete event simulation the state variables change instantaneously at discrete points in time. Taking the example of the truck in transit in figure 4.2; the truck is either at point A or point B, and the amount of time the journey has taken is updated at point B.

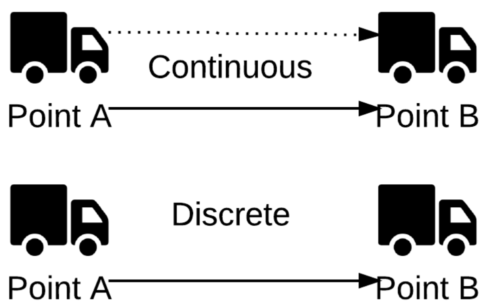

Figure 4.2: Discrete and continuous simulation

Because of the dynamic nature of discrete event simulation models, it is important to keep track of the current value of simulated time as the simulation proceeds. The mechanism that advances simulated time from one value to another in a model and gives the value of time for a current event is called the simulation clock. There are two approaches to handle time in a discrete event simulation model, next-event time advance and fixed-increment time advance. In the fixed-increment time advance approach the simulation clock is updated with a fixed increment Δ t. After the update of the simulation clock, a check is done to determine whether an event has occurred or not.

The next-event time advance approach is the most popular approach implemented in software. When the simulation starts, an event-queue is created that consists of future events scheduled at specific points in time of the simulation clock. The simulation clock is updated to the time when the first event in the queue is scheduled. Events can be interdependent, adding and removing other events in the queue, as well as rescheduling the whole event queue. The simulation clock is updated to the next scheduled event, and this process proceeds until some pre-specified stopping condition is satisfied. Since all state changes only occur at event times, periods of inactivity are skipped over by jumping the clock from event time to event time.

The entities are conceptual objects that travel through a task network and indicate by their location when each task or queue is processing or waiting to process. The entity may represent physical objects performing tasks, such as the truck driving from A to B. The entities may have attributes attached that can be considered a special variable, to accurately define the entity, for example the capacity of the truck in figure 4.2. Or the attribute can define a special condition that needs to be satisfied if the entity represents a task.

Since this thesis is interested in the campaign as a whole, and not the specifics in each part of an operation, discrete event simulation is the most suitable approach to model the campaign. The system state at a particular moment is of little interest.

4.4 Simulation Software

There are several discrete event simulation software packages on the market, ranging from specific simulation language software to multi-purpose software capable of handling a wide range of models, including continuous, discrete event, agent-based and non-linear. Law and Kelton (2000) state that simulation packages were historically classified to be of two major types: simulation languages and application-oriented simulators. Simulation languages were general in nature and provided the modeller with great flexibility, but required extensive programming skills to model correctly. The application-oriented simulators were often oriented toward a particular application, but easier to use. With time, the development of simulation languages have grown towards a more graphic modelling approach in order to make the software easier to use, and the borders between the types are less clear.

Common for all types of simulation software is the need for features to:

- Generate random numbers
- Generate random variates from a specified probability distribution
- Advance simulated time
- Determining the next event in the event list, and change the event list while simulation is running
- Provide results and output

Several software packages also include tools for animation and visualisation, both 2D and 3D. Ability to communicate with Excel is another advantage, to handle the output data in an effective manner after running the simulation.

When selecting simulation software it is important that the modeller is aware of the needs of the model, Albrecht (2010) defines a number of characteristics to compare the functionality of different software on the market. However, choosing software should also be affected by how well the modeller can handle the program, where user friendliness and availability of aides must be considered; Dias et. al (2011) compare simulation software with a popularity ranking, based on the software's mention in scientific journals and on the internet.

4.5 Parametrisation

Parameters are numerical characteristics that are used to describe the system or elements of the system, and can change during the model's process (ExtendSim 2013). The input parameters are values that are known or can be estimated, such the mean process time of an operation. Output parameters are collected after the simulation has been run, and are the result of the model transforming the input; an example is the total time spent processing an operation.

Parameters are fixed or variable. Fixed parameters represent the unchanging properties of an operation, for example its operational limits. Variable parameters are updated and changed as events in the model transpire, an example can be a status describing if the drilling unit is connected or not.

It is important that the parameters of a model are correctly scaled to be compatible with input data, when representing the interactions of a system. For example, weather data and operational limits do not necessarily have a linear relationship, the drilling units response to wave height could be exponential (Statoil 2013a). Therefore it is essential to apply knowledge of the system, and verify that parameters have a faithful correlation with input data and other elements of the model.

4.6 Data Input

Finding reliable data for an Arctic drilling campaign is challenging, mainly due to limited knowledge and statistics of Arctic operations. There are some similar campaigns that can be used as reference, but updates in technology and the effects of learning curve mean that data is uncertain. Meteorological and environmental data on the Arctic climate is another difficult aspect, not only due to a limited time frame and scope of observations, but also because of changing conditions such as receding ice and the effects of global warming.

In accordance with Law and Kelton (2000) data should be collected to specify operating procedures and probability distributions for random variables used in the model. To realistically replicate the system being modelled, it is important to clearly define what data is essential. Focus should be kept on what information is necessary, avoiding overcomplication of the model. Ideally the model should be created in the proper manner without being limited by unavailability of correct data, this is however seldom the case and the development of a model often depends on the data. However, Law and Kelton (2000) assert that parameters in a model rarely correspond on a one-to-one ratio to real life systems, as this requires an excessive level of detail, often causing the model to be hard to execute.

To acquire representative parameters of how a system performs, it is essential that process times and other stochastic elements are generated randomly from distributions rather than using averages. However, acquiring accurate distributions is only possible if there is an ample amount of statistics or intimate knowledge of the input data related to the system. Hillier and Lieberman (2010) argue that it is usually only possible to estimate these distributions and data, but it is important to do so. To validate the model and calibrate input data, a similar system with comparable data can be used. Although relevant input data may be lacking or inaccurate, Nelson and Henderson (2006) maintain that knowledge of the process is enough to create input, and perform a sensitivity analysis to investigate the significance of the data.

4.7 Modelling an Arctic Drilling Campaign

There are a number of ways to create a model, and there is no definitive correct way to replicate a system. However it is possible to say that some techniques are more suited than others, depending on the purpose of the model. Choosing between different modelling techniques can be a trade-off situation, therefore it is important to decide what the purpose of the model is, and what output is desired. This section describes different modelling alternatives that have been considered during the course of this project, presenting advantages and disadvantages of each option.

The following criteria have served as guidelines, when assessing relevant modelling techniques to replicate the system:

- Modelling logic

How can detail be incorporated in a general manner, since the model must be valid for a variety of different drilling campaigns.

- Availability of data

What data is available, and how does this affects assumptions in the modelling process

- Output

What kind of output is desired, and how can it be attained in a presentable manner.

4.7.1 The Sequence of Events

As mentioned earlier, entities are processed through a task network in the model. This network is usually represented by a series of interconnected blocks, where each block represents a task. The structure of this task network, the block's relationships defines the model and how it handles the sequence of events.

Depending on the well, the scope of operations of a campaign can contain a range of different events. Both the scope of operations and unplanned events define the sequence of events, which requires the model to handle this variation in operations. Therefore the model needs nonspecific parameters that can represent all characteristics of events and operations associated with an Arctic drilling campaign. There is a need for data to be tied to each event, giving the possibility to analyse the output data and comparing campaigns and input parameters.

Two ways to build the model have been taken into consideration:

Traditional
A drilling unit is represented by an entity with attributes describing it's characteristics, such as operational limits. The entity is processed by activity blocks, see figure 4.3, through a task network that represents the scope of operations and other events. The status of the drilling unit directs it to the next activity. External conditions such as weather and ice, are simultaneously updated and can schedule events that affect the status of the entity, altering which activity blocks it can pass through. This is the most common way of modelling a system, where the entity represents a real object that must pass through set of blocks to completion. The advantage with this modelling technique is it's intuitiveness. Most discrete event simulation software is arranged to facilitate the traditional modelling approach, with features from data collection to predefined boxes created specifically for this purpose.

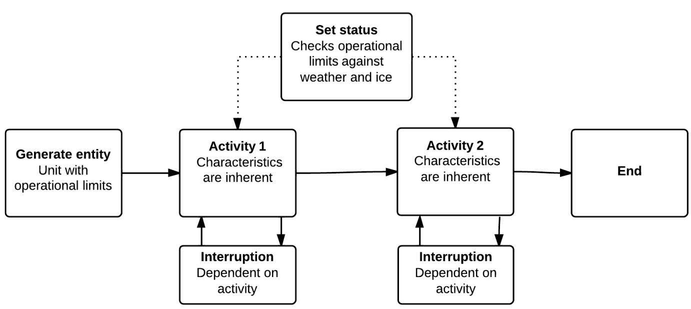

Figure 4.3: Traditional approach

The main disadvantage of the traditional modelling technique is that a new block must be made for each specific activity, necessitating a complex and large model to handle a variety of different campaigns. All operation specific parameters would have to be added in each activity block, requiring a lot of preparation for each run unless the software has an embedded shortcut function for these kinds of alterations.

Abstract
In this set-up, the task network of blocks represent the statuses of a drilling unit, where each status is processed by a distinct block. The scope of operations is represented by a list of activities, that can be uploaded before the simulation, and carries the characteristics of each operation. The activities are sent out one by one as entities and processed stepwise by the blocks according to their status and characteristics. For each step of the activity that is processed, external conditions are updated affecting it's status.

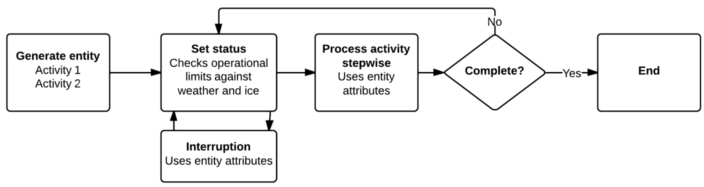

Figure 4.4: Abstract approach

With the abstract method the number of activities and their parameters can be predefined in a single activity list, with no need to alter the model new campaigns. The size of the model requires fewer blocks than the traditional model, as the number of activities are represented by entities. An abstract model facilitates altering, but is harder to construct, requiring more programming and customisation compared with the traditional model. There may also be issues gathering output data, as most software packages are constructed to gather data from specific blocks not entities.

4.7.2 Technology and Process Times

The choice of technology and equipment for a campaign will be a deciding factor for the time spent on the whole campaign, as it affects everything from the scope of operations to operational limits and process times. The input parameters should be able to describe a range of different technologies. By changing these parameters the model can be used to compare the effect on the drilling campaign.

Since real-world processes contain an element of randomness, operations need to be modelled with a stochastic distribution. Deterministic process times are used for the validation of the model, by applying data from an existing system, the output data can be compared with the results from. When running the model, randomness is necessary to replicate the distribution and deviations of real processes. The next step is determining what distributions are right for the process times. Log-normal distributions are a general assumption that has given the best correlation to drilling and well operations (Statoil 2014). When little or no data is available, a triangular distribution can be assumed. Nelson and Henderson (2006) confirm that a triangular distribution may be useful when there is no strong basis for selecting a particular distribution.

Operational limits are not be set by a distribution, but are fixed values that specify what variables require the operation to be stopped. These fixed values represent conditions in the real world that limit or stop operations due to hazards, such as adverse ice and weather conditions or a lack of supporting vessels.

Data on drilling operations' process times often contain non-productive time, except for time spent waiting on weather. Without non-productive time inherent in the process time, this can be modelled with data on the redundancy and availability of equipment.

4.7.3 Logistics and Communication

The supply of logistics is vital to an Arctic exploration drilling program, the long distances and lack of infrastructure is likely to cause new challenges compared to drilling in developed locations. The redundancy of the supporting fleet and communication affects the availability of drilling operations. The model should correlate logistical and communication aspects with the activities in the task network.

Modelling offshore supply, fleet size and operational planning is a widely covered subject, it is likely that many models are applicable to use in the Arctic with slight modifications. Presented below is one way to model logistics and communication for an Arctic drilling campaign:

A supporting roundtrip model could be created for the supporting fleet, describing the logistical operations that must be undertaken during drilling operations, where the same weather and ice conditions affects both models. The operations of the drilling unit use a set of resources for each process, that are refilled by the roundtrip model running to and from bases on the mainland. Redundancy of communication and equipment can be modelled by using similar data from other offshore operations. Data on availability would be specific to Arctic conditions, for example, longer and more unpredictable lead time.

4.7.4 Weather

There are several ways to model weather, it often depends on available data and the purpose of the model. Since weather forecasts delivered in the Arctic may be less accurate, the effect of uncertain conditions on the operations of a campaign could be interesting. Identifying weather that may require a disruption of a planned operation is essential, to give ample time to shut down operations and possibly disconnect from the well. Using weather data from past years in the Arctic can be unreliable, due to global warming and rapidly changing conditions.

There are many weather related factors that can affect the drilling program, and they will all influence operations to some degree. Parametrising them in the model can be hard as they may be correlated and together magnify negative effects on operations, for example, low temperatures, precipitation and wind causing icing on the platform. A simple correlation must be found between weather data and operational limits, as it is beyond the scope of this project to find a realistic response of all parts of the campaign for all weather conditions. Two techniques have been evaluated:

Zones
Charts and diagrams are often used to estimate vessel response and motions (Statoil 2013a), by translating wave height and period into zones by degree of operability. By combining weather data and the drilling units' specifications and capabilities, one could pre-generate a datastring with the zones the drilling unit will be in at a particular time. This could be done by a script or in a separate model.

Pure weather
Setting operational limits purely based on one parameter, such as wave height, temperature, wind or current. This approach is less realistic, but a reasonably good degree of correlation could be found, and it requires a lot less resources and data.

Forecast
The best approach should combine the forecast uncertainty and parametrise weather in a realistic manner, below the different approaches considering uncertainties that have been evaluated for the model are presented:

Two Series
Ideally, the model would use two sets of data from the same location. One set consisting of the actual observed weather at a certain position, the second with the forecasts predicted for a period ahead. This approach would give realistic simulation of how many times a season the weather forecast predicted wrongly, and would be able to deal with actions taken due to uncertainty regarding weather. Acquiring the right data may be hard, as records of forecasted weather may not be available.

Always Correct
This approach would only use observed weather from a location, and assume that the forecast is always correct. Using this approach the uncertainty considerations regarding forecast is lost. Unnecessary actions due to wrong forecasts are not modelled with this approach.

Distribution
This approach uses the Forecast is always correct approach as a basis, but a distribution of the forecast error could be linked to create periods where the forecast is wrong. This may not be a statistically valid technique, as the forecast error distribution varies locally and from season to season.

4.7.5 Ice

The model should be able to use available data to evaluate how ice affects the campaign and the effect of equipment and operations to handle the ice. Modelling ice coupled with operational limits of the drilling unit is dependent on the available data. There is some data to compare techniques and equipment used for ice management, giving different probabilities of handling different kinds of ice. Choosing a correct way of parametrising ice in the model, can be extremely hard as speed, density, floe size and many other factors must be taken into consideration. According to ISO 19906 (a.8.2.2.4) Monte Carlo methods are generally used in practice when simulating ice, due to the complexity of calculation forces exerted by ice.

Forecast
Ideally, incoming ice could be parametrised in the same way as forecasted weather, either by dividing it into zones based on expected effect on the drilling unit or using pure data such as thickness, where unmanageable features could be given infinite thickness. Due to a lack of statistics, knowledge of ice and unreliable forecasting techniques, ice actions cannot be parametrised into zones in the same way as weather. The review of different modelling techniques is based on what kind of data that is likely to be available, in combination with the most convenient way of parametrising ice actions.

Data Series

It is possible to make a data series on ice thickness, Sælen (2010) created a series for evaluating the transit of ships through landfast ice. If the same technique could be used for open water and pack ice, this could be used in the model. Generating a synthetic long-term ice data series as described by Bonnemaire et al. (2011), could also be used to evaluate the ice management abilities at the start and end of a season. However, there were not found any papers describing the creation of data series for pack ice in open water seasons.
With the correct strings describing ice floes and a good parametrisation of pack ice, ice management could be divided into zones much like the weather zones. Due to a limited amount of available data, this approach is most likely not possible.

Pure Distribution

A pure distribution giving the probabilities of disconnection could be applied. There may be limited data on ice statistics and offshore drilling operations, but assuming that regulations, norms and rules are followed the probability of disconnecting could be estimated. Fenz et al. (2013) found a set of notional values describing anticipated frequency of disconnections in a season:

- Planned: As needed
- Managed: <3-6 times
- Rapid: <1 time
- Emergency: As infrequent as emergency disconnections in open water drilling.

The problem with defining these frequencies is that they do not allow distinctions to be made for seasons, giving a year over average, when ice is more frequent at the start and end of a season. These numbers do not allow for any analysis of the detection or ice management equipment, only how these disconnections affect the campaign. These figures are purely speculative, based on the authors estimation of the cost of disconnection which the necessary equipment should be designed according to. The model has to find and analyse the number of disconnects, based on the equipment, Fenz et al. (2013) has started with these values and tried to find equipment that will realise them. That being said, the values can be used for reference and as a starting point.

Binary

The limited data on ice and uncertainty of ice handling equipment could cause some campaigns to avoid ice altogether, as did Shell (DOI 2012). Binary ice data is available, however this would mean a disconnection every time ice is present in the vicinity of the drilling unit. There is also no distribution or forecast associated, so it would be assumed that the forecast is a 100% every time. The disadvantage of this approach is the limited information on ice handling this would give, unless the operation or unit does not tolerate any ice.

Event Tree

Event tree analysis is a logical modelling technique used to analyse accident scenarios, by exploring the probabilities and outcomes started by an initiating event and the success or failure of the inherent safety functions of the system. Each event in the tree is conditional on the previous event in the chain, and the probability of a final outcome is dependent on all events that lead up to it.

Eik and Gudmestad (2010) define an initiating event as a PUIF that is within a certain distance of the drilling unit. The next event is determined by the probability that the PUIF is detected by the monitoring equipment. The branches do not necessarily need to be as in the figure 4.5, there are many different ways of orienting the event tree, depending on what is seen as necessary or deemed to be a first event. The tree continues to branch down for each scenario, as shown in figure 4.5. Ending up with probabilities of a range of outcomes, that can be interpreted as different types of disconnection operations.

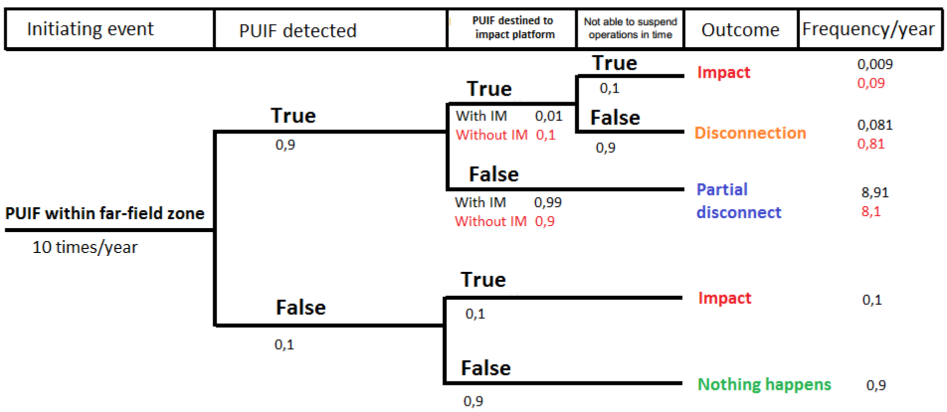

Figure 4.5: Event Tree Ice Ridge

Different probabilities can be altered according to the data from the equipment's ability to handle ice, thus allowing the comparison of different solutions. This is illustrated in figure 4.5 by the red writing showing the same tree, but without ice management and how the probabilities change. Coupling weather conditions and ice management capabilities can also be modelled by adding other probabilities, as it is known that the probability of iceberg towing success decreases with higher waves stated by Eik and Gudmestad (2010). The event tree method could also be used for modelling ice floes with the correct data.
The disadvantages of an event tree is that it requires a good availability of data and statistics on each event, something that could be hard to acquire. However, assuming that regulations and ISO 19906 are followed, then the relevant data on ice management and ice statistics in the relevant location should be available to create an event tree, covering all features of sea ice and ice management.

4.7.6 Interruption of Activities

The frequency and time spent on interruption of operations will affect the total time spent on a campaign, therefore it is essential to identify conditions and events that necessitate a stop in operations. The model needs to realistically replicate these conditions and events that will cause interruptions of activities in the model. Typical interruptions like shutdown of operations and disconnection are dependent on technology and operations. There are a number of details that can be added for these parameters, but it is important to start basic, then verify and validate the model before adding complexity. For example, the time interruptions take could be modelled stochastically, however this could make the sensitivity analysis harder.

How interruptions of operations are modelled depends entirely on the modelling of the sequence of events. Most simulation software packages facilitate the traditional method, with inherent special features in processing blocks that facilitate the modelling of unexpected events. For the abstract approach, interruptions of activities would require that the activities are routed to separate interruption blocks, depending on their status. The characteristics of the interruption activity will be represented by attributes, that the interruption blocks could use to process the activity, as illustrated in figure 4.4.

4.7.7 Accidents and Contingency Plans

The Arctic environment is fragile, accidents may have unknown environmental consequences. Many of the possible scenarios are so severe that they require an abortion of the entire campaign, not necessarily due to actual damage to the well or environment, but also because of the negative attention it could cause. For example, a small spill resulting in images of wildlife covered by oil, could call for an immediate ban on Arctic drilling, even though the damage is localised and relatively small. Therefore it can be assumed that any accident scenario would lead to a suspension of the campaign without completion, as the rest of the season would be spent repairing the damage. The purpose of this model is not to simulate the response of the drilling fleet after an accident scenario, if the accident requires the campaign to be ended, this may indicate that the accident scenario aborts the simulation run.

4.8 Summary

Simulation is a technique used to replicate a real-life system, this chapter has reviewed different techniques relevant for the modelling of an Arctic drilling campaign.

- A simulation study consists of several steps, constituting an iteration process.
- Simulation methods and software should be chosen to suit the model's intentions
- The system is represented by numerical characteristics called parameters in the model.
- The data input of a model is essential to its credibility, data should be faithfully converted into parameters to correctly describe elements of the system.
- Modelling logic, availability of data and output have served as the three most important criteria when assessing modelling techniques

On the next page a list of the different modelling techniques from section 4.7 are summarised:

Section	Approach	Comments
Model	Traditional	Common way of modelling, intuitive to understand, but requires a complex model.
	Abstract	Model can be kept simpler, as all operations are defined in a table called the activity list.
Technology and process times	Traditional	Characteristics are defined by activity blocks in the model, and can be altered to specific cases.
	Abstract	Characteristics are defined in the activity list, and can easily be altered but require a common set of parameters for all.
Logistics	Roundtrip model	Transit and supply can be linked to operational requirements of the drilling unit.
Weather limits	Zones	Operational limits of the drilling unit are pre generated from weather data into zones describing degree of operability.
	Pure weather	Linking operational limits directly to certain parameters, such as wave height, wind etc.
Weather	Two series	Two sets of data, one describing the forecasted weather at a location for a given time ahead, the other with the actual reported weather.
	Always correct	Weather data from one location, and the weather forecast is always assumed to be correct.
	Distribution	Uses Forecast is always correct as basis, but also contains a probability that the forecast is wrong and appropriate action must be taken
Ice	Data series	Generate a synthetic long term string, containing zones of operability.
	Pure distribution	Use the probabilities of certain kinds of disconnections, reliable data may be hard to acquire.
	Binary	Ice or no ice, reliable data does exist, but does not allow for analysis of ice management.
	Event tree	Using the frequency of an initiating event, and probabilities of equipment handling the event, different scenarios can be evaluated.
Interruption of operations	Traditional	Each activity block requires a dedicated route to handle an interruption.
	Abstract	The status of the drilling unit sends the activity to an appropriate process.
Accidents & cont. plans	Simulation abort	Accident scenarios lead to abortion of the simulation, as the aftermaths are out of the scope of this thesis.

Table 4.1: Simulation methods comparison

Chapter 5

The Simulation Model

Law and Kelton (2000) assert that the main challenges of simulation modelling are limiting the model and finding the essence of the system for the purposes for which the model is intended. To support the development of the modelling process, the background theory presented a study of an Arctic drilling campaign and modelling techniques. This chapter presents the correspondence between elements of the system and elements of the model, defining the model and the assumptions on which it is built.

5.1 Purpose of the Model

The purpose of the model is to realistically simulate a drilling campaign in the Arctic, to facilitate a comparison of different technological solutions. The model needs to be general, and able to handle statistical input data from different kinds of equipment, operations and specifications of the drilling unit, therefore event descriptors and process times must be parametrised. It is important that the model does not need modification for specific process descriptions or data, only parameter data will be changed to model the effect of using different kinds of equipment or changing operations. The model must provide adequate output data in order to enable analyses of parameters, this will lay the basis for a discussion of the merit of changing parameters.

The system that the model intends to replicate consists of the drilling operations of an exploration well, from mooring over the drill site to plug and abandonment. Ice and weather are the only conditions that affect the sequence of events.

5.2 Conceptual Model

An abstract modelling technique was chosen due to its benefits when modelling different campaigns and the ease of adding features to the model. The model is constructed so that additional data input and features can be complemented to add complexity to the model after it has been verified and validated. The conceptual model is illustrated in the figure 5.1 below, with a general description of the main mechanisms. A detailed step-by-step review of the model in ExtendSim is presented in section 5.5.

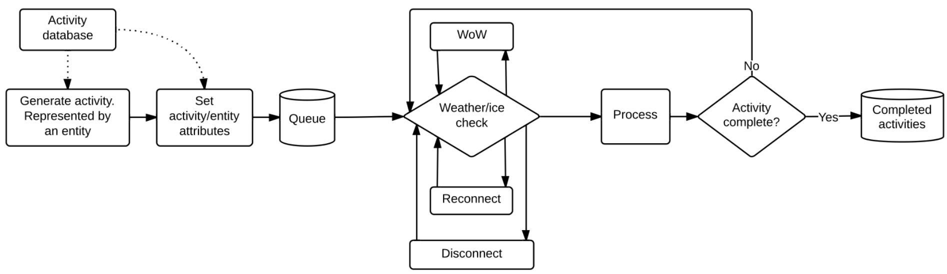

Figure 5.1: Conceptual Model

The drilling campaign is represented by an activity list, which can range from mobilisation to demobilisation. The activity list consists of activities, that correspond to operations for the drilling campaign. The activities are characterised by their attributes. An activity can for example be to drill 24" to target depth.

The activity list is uploaded as a database from Excel to ExtendSim where the activities, represented by entities, are generated one by one and sent to be processed. The time to complete an activity is stochastically drawn from the distribution given by it's attributes, and is continuously updated as the activity is being processed to track how long the activity has until completion.

Only one activity is processed at a time whilst the others are held in a queue. Before the activities are processed, their statuses are set according to their operational limits and a comparison of the weather and ice forecast. The status decides the routing of the activity, sending it to boxes representing the status of the drilling unit. If the activity is sent to wait on weather or disconnect, it spends time completing these activities before it can be sent back to check the weather and ice forecast again. When the forecast is suitable, the activity is sent to process one hour of its duration, before checking the forecast again until the set processing time is complete and the activity can leave the processing area.

Each time an activity leaves the processing area, its details regarding time spent and number of disruptions is stored in a database for later analyses. This is repeated until all activities are completed, and the drilling campaign is finished.

5.3 Modelling Assumptions and Decisions

This section presents what elements of the system that are included in the model as parameters, with justifications for assumptions and simplifications that are made.

5.3.1 Activity List and Process Times

All the activities in the list share a common set of parameters to define the specific characteristics of the activity, and some to record processing data to enable an analysis of the output after simulation. General descriptions of the attributes that each activity possesses are presented here. Section 5.5 describes implementation and the application of the activity list in the model, Chapter 6 shows how the data was collected and organised.

Based on interviews with drilling experts at Statoil and comparing well plans with available data on ice and weather, three important assumptions have been made for all activities:

- For process times the log-normal distribution is a general assumption in the time estimation model that has proven to give the best correlation to drilling and well activities (Statoil 2014). But he model is open to use with 3-parameter distributions, such as triangular or a normal distribution depending on the data.

- The time needed to process an activity is stochastically drawn from a distribution and set after the activity is created. Weather and ice can add extra time to the total time spent processing the activity, but they do not affect the drawn process time.

- The availability and redundancy of equipment is included in the distributions describing process times.

The model implements 15 parameters to describe distributions, name, status, operational requirements and time limits for an activity. The parameters are presented in table 5.1 with descriptions. Availability of data in connection with weather, ice, operational limits and interruption of activities has been decisive in the development of the model, many of the parameters and their assumptions have to be seen in connection with the other sections in this chapter. Table 5.1 names all parameters with a description of their purposes:

Name	Description	Type
CreateTime	Schedules when entities are to be created, ensuring that they are made according to the activity list.	Fixed
Number	Keeps track of which activity the entity represents.	Fixed
Location	Describes the distribution of the process time. The location is the mean of the data set after transformation by taking the logarithm.	Fixed
Scale	Describes the distribution of the process time. The scale is the standard deviation of the data set after transformation.	Fixed
Shape	Describes the distribution of the process time. The shape parameter is equal to the standard deviation of the logarithm of the distribution.	Fixed
Worktime	The Worktime is drawn stochastically from the distribution parameters that are specified by location, scale and shape.	Fixed
Worktime remaining	Specifies the worktime remaining worktime needed to complete the activity.	Variable
Zone requirement	Specifies the maximum of the unit's operational zones the activity can be processed in. Each of these four zones are given corresponding numbers from 1-4.	Fixed
Status	Specifies the current status of the drilling unit, each status is given a corresponding numbers ranging from 1-12 in the ExtendSim model.	Variable
Window	Specifies the weather window that needs to be clear before an activity can be started.	Fixed
Weather disconnect	Specifies the time needed to disconnect due to weather.	Fixed
Weather reconnect	Specifies the time needed to reconnect after a disconnection due to weather.	Fixed
Ice disconnect	Specifies the time needed for disconnecting and moving off due to ice.	Fixed
Ice reconnect	Specifies the time needed to reconnect and moving back on site after ice disconnection.	Fixed
Disconnecting started	Specifies the time spent when starting a disconnection process that is reversed shortly after start.	Fixed
Disconnecting halfway	Specifies the time spent in a disconnection process that is reversed before completion .	Fixed

Table 5.1: Deciding attributes

There is also need for 12 attributes to record data for the output, they do not affect the model, and are all variable parameters:

Name	Description	Type
Total worktime	Records the total time spent to complete an activity, included interruptions.	Variable
OPWOWdisc	Records the total time spent on WOW for an activity while it is disconnected.	Variable
OPWOWcon	Records the total time spent on WOW for an activity while it is connected.	Variable
OPIcediscstart	Records number of Disconnecting started statuses for an activity.	Variable
OPIcedischalf	Records number of Disconnecting halfway statuses for an activity.	Variable
OPEmergency	Records number of Emergency Disconnect statuses for an activity.	Variable
OPImpact	Records number of Impact statuses for an activity.	Variable
OPWeatherdisc	Records number of Weather disconnect statuses for an activity while it is connected.	Variable
OPWeatherrec	Records number of Weather reconnect statuses for an activity while it is disconnected.	Variable
OPIcediscfull	Records number of Ice disconnect statuses for an activity.	Variable
OPIcerec	Records number of Ice reconnect statuses for an activity.	Variable

Table 5.2: Recording attributes

5.3.2 Status

The drilling unit's condition is represented as a status attribute in each activity, which is variable. The status defines what process the activity is allowed and scheduled to perform next, and keeps track of what process the activity has previously been through. The status is decided when the weather or ice forecast is compared with the drilling unit's and activity's operational limits.

Below the 12 statuses are listed, their counterpart attributes can be found in table 5.1 where they have a similar name, defining their process times. Process and Starting are the only statuses that are not associated with the interruption of an activity, the rest of the statuses can be seen in connection with Section 5.3.7.

Name	**Description**
Starting	The starting status for all entities, before they are processed.
WOW	The activity is waiting on weather because the forecast and operational limits are not good enough for processing, but not bad enough to disconnect.
Process	The activity is clear to process it's Worktime.
Weather disconnect	A disconnection due to the weather forecast predicting a storm or conditions too bad to operate in, therefore necessitating the well to be shut down. Does not need the drilling unit to move off or release anchors.
Weather reconnect	Reconnection after a disconnect due to weather, does not require redeployment of mooring systems.
Ice disconnect	A disconnection due to incoming PUIFs, necessitating a disconnection and a move off.
Ice reconnect	Reconnection after a disconnect due to PUIFs, requires the unit to move back over the site and a redeployment of mooring systems.
Finished	The activity is fully processed and will be sent out of the model.
Emergency disconnect	An emergency disconnect has been performed and the integrity of the well is too damaged to continue the same drilling campaign.
Impact	An iceberg has impacted with the unit, damaging the integrity of the structure enough to abort the drilling campaign.
Disconnecting started	A disconnection process that has started due to the observation of a PUIF, but not completed after the iceberg has been determined not to drift into the unit.
Disconnecting halfway	A disconnection process that has been halfway completed due to the observation of a PUIF, which is determined to impact into the unit but is successfully managed and deflected.

Table 5.3: Status Descriptions

5.3.3 Rigdata

To show the models capabilities, zones are used to describe the degree of operability for the drilling unit. By examination of available data that are presented in section 7.1.1, it was concluded that for the purposes of this model only wave height is considered. The model uses pure weather data and divides the drilling unit's level of operability into 4 colour coded zones, based on wave height:

Zone	Description
Delicate - (Green)	Calm sea and vessels motions. Unrestricted well operations, suitable for deploying BOP and other delicate activities.
Advisory/Max drilling - (Blue)	Moderate sea and vessel motions exerting the drilling unit's station keeping system, but within capacity. Landing the BOP and other sensitive activities are not possible. Normal operations are not a problem.
Stand by connected - (Yellow)	Severe sea and vessel motions above the drilling unit's station keeping abilities for operation. Equivalent to waiting on weather.
Survival mode - (Red)	Abnormal sea and vessel motions. Survival/accident condition.

Table 5.4: Rigdata Zones

Figure 5.2 below illustrates an example of a drilling unit's zones in relation to wave height:

	A	B	C
1	Rigname		
2	Polar Pioneer		
3			Waveheigth
4	Delicate	Green	1
5	Advisory	Blue	3
6	Stand-by connected	Yellow	5
7	Survival	Red	>5

Figure 5.2: Rigdata Example

5.3.4 Logistics and Communication

The only data available on process times for drilling operations included downtime, information on supply and logistics was not researched thoroughly enough to be included. Without good enough data on redundancy and availability of equipment and supplies, it was decided that logistics and communication could not be included in this model, and the focus is kept on the effects of weather and ice on the campaign.

5.3.5 Weather

A hindcast archive containing weather sets ranging back to 1957 was made available, with intervals of 3 hours. After discussing the lack of any other suitable data with Statoil, it was decided that the model only use this hindcast archive data, not considering the effects of forecast uncertainty. The Always Correct approach described in section 4.7.4 was chosen.

Limitations regarding temperature are not taken into account due to lack of data, and all equipment is assumed to be suited for Arctic temperatures.

5.3.6 Iceberg Event Tree

The only truly reliable data found on ice is binary, from the same hindcast archive as the weather archive. There is however a substantial amount of statistics regarding icebergs from the Grand Banks on the East Coast of Canada (Eik and Gudmestad 2010). This data is reliable and is easily parametrised into the probability of encountering ice in a certain area at a certain time. After consulting with Ivan Metrikin, it was decided to go for an event tree approach, based on the work of Eik and Gudmestad (2010). The event tree can also be useful if data is made available on pack ice and drift ice, as many of the same principles can be applied.

As a starting point the same assumptions from Eik and Gudmestad (2010) were chosen. Although there a number of assumptions from Eik and Gudmestad's paper that differ slightly in the model, it was decided to start with these numbers and use them for a sensitivity analysis. Taking these numbers simplifies the modelling process, and stops resources being spent on data collection.

The iceberg event tree couples wave height and iceberg towing efficiency, the red figures in figure 5.3 give the probability of successful iceberg towing in wave heights above 6 m.

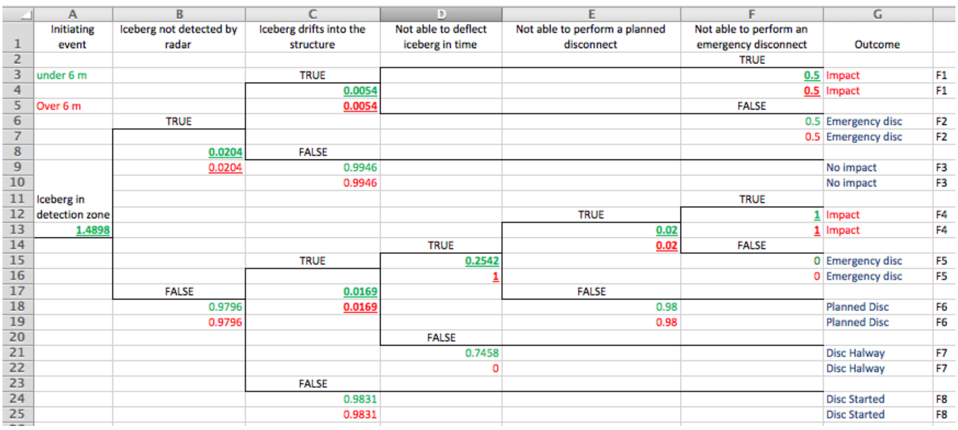

Figure 5.3: Event Tree

From the iceberg event tree there are 5 different scenarios that can play out, these lay the basis for the statuses associated with ice and interruption of activities. The first three scenarios correspond with scenarios from Eik and Gudmestad (2010), the last 3 are assumptions have been made to show the capabilities of the model, and how an event tree could be extended:

Outcome	Description
Impact F1 + F4	By summing the probabilities of the two impact scenarios in the event tree, an hourly probability of impact is found.
Emergency disconnection F2 + F5	By summing the probabilities of the two emergency disconnection scenarios in the event tree, an hourly probability of emergency disconnection is found.
No impact F3 F3	If the iceberg is not detected by the radar and does not drift into the drilling unit, it passes by undetected and no action is taken on the drilling unit.
Disconnection ice F6	Planned disconnection takes place after the iceberg is unsuccessfully deflected.
Disconnection halfway F7	The drilling unit starts a disconnection procedure as soon as an iceberg is detected. The modelling and forecast techniques quickly give accurate prediction that the iceberg will impact the drilling unit and support vessels are deployed to tow the vessel. Once the iceberg is deflected the disconnection operation is reversed. The disconnection operation has advanced halfway, and therefore requires more time to reverse.
Disconnection started F8	The drilling unit starts a disconnection procedure as soon as an iceberg is detected. The modelling and forecast techniques quickly give an accurate prediction that the iceberg will not impact the drilling unit, therefore reversing the disconnection.

Table 5.5: Event tree outcomes and probabilities

5.3.7 Interruption of Activities

Assumptions taken on how weather and ice are modelled have affected which events and actions that are defined as interruption of activities. Since external conditions such as ice and weather are the focus of the model, interruptions due to logistics and missing safety equipment and personnel are not included. These are the following activities that are triggered by unmanageable weather and ice:

Waiting on Weather WOW

WOW entails that the activity is suspended until the weather is good enough for processing its Worktime. The activity is sent to wait on weather if future weather is worse than operational limits, but there is no need for disconnection.

Weather Disconnection
Disconnects due to weather are always assumed to be managed and entail that all equipment is on board ready to move off the site. The drilling unit starts to disconnect when the time needed for disconnection is equal to time remaining before disconnection weather emerges.

Ice Disconnection
The iceberg event tree gives the probabilities of ice related events. The iceberg event tree has 5 different outcomes besides from no impact, these are reviewed in Section 5.3.6. Ice disconnections differ from weather disconnections as they require the drilling unit to move off the drilling location to avoid ice, whereas weather disconnection does not require a change of location for the unit. Emergency disconnection and impacts due to ice are considered as accidents.

Started Disconnection and Halfway Disconnection
These interruptions are assumptions taken from the iceberg event tree and are explained in Section 5.3.6.

5.3.8 Accidents and Contingency Plans

Due to the severity of accidents in the Arctic and uncertainty regarding their outcomes and consequences on a drilling campaign they are not included in this model, except for emergency disconnection and impact due to ice. A lack of data concerning frequency of polar lows and geomagnetic storms has led to these events also being excluded from consideration in the model.

5.4 The ExtendSim Software

Through discussions with Stein Ove Erikstad, ExtendSim was chosen as this model's simulation software. Reviewing several comparisons of software, ExtendSim also showed to be a popular tool. According to Albrecht's (2010) ExtendSim offers the most ready to use and comprehensive tools, it also ranks well for several of his other criteria. Dias et. al (2011) find that ExtendSim ranks sixth in popularity on their total score distribution, out of 19 different software.

ExtendSim is a multi-purpose simulation tool, with large possibilities for customisation and can handle a wide range of models, including continuous, discrete event, agent-based and non-linear. The possibilities for customisation, a comprehensive user guide and developer reference were points that led to ExtendSim being chosen. ExtendSim also has the capability of communicating with external databases, such as Excel. The Department of Marine Technology and Marintek have good previous experience with the ExtendSim, and have been very helpful in providing assistance in the modelling process.

ExtendSim is intended to handle traditional models as described in section 4.7.1, unlike this model which is abstract. There was therefore some barriers to overcome, and the implementation requires more customisation and programming. However, the internal databases in ExtendSim have proven to be useful when modelling complex systems, and collecting necessary output by saving state variables. For modelling with an abstract approach using internal databases has eased the collection of output data, providing the model with greater flexibility when running the model.

In the simplest terms ExtendSim models are made up by blocks and connections. Processes are represented by blocks, with entities flowing through the system of blocks. The blocks are divided into 5 categories, depending on their properties; Item-, Plotter-, Rate-, Utilities- and Value-Blocks. In the model Item-blocks and Value-blocks are used. The Item-blocks represent time consuming processes and are also used for routing, see section 5.5. The Value-blocks are used to generate a random number to provide a stochastic element to the model.

5.5 Implementation

This section demonstrates how the model is implemented in ExtendSim. The model is divided into 5 sections, with the purpose of making the model coherent and understandable.

Before running the model the Excel sheets with Rigdata, Activitylist, Weather and ice data for the specific drilling campaign must be uploaded in the Background processing section. The Activity generation section creates entities, sets their specific characteristics and holds them in a queue in figure 5.4, as only one entity can be present at a time in the processes section to the right. In the Disconnected processes section entities are routed based on their previous status and a comparison of the forecasted weather and their operational limits.

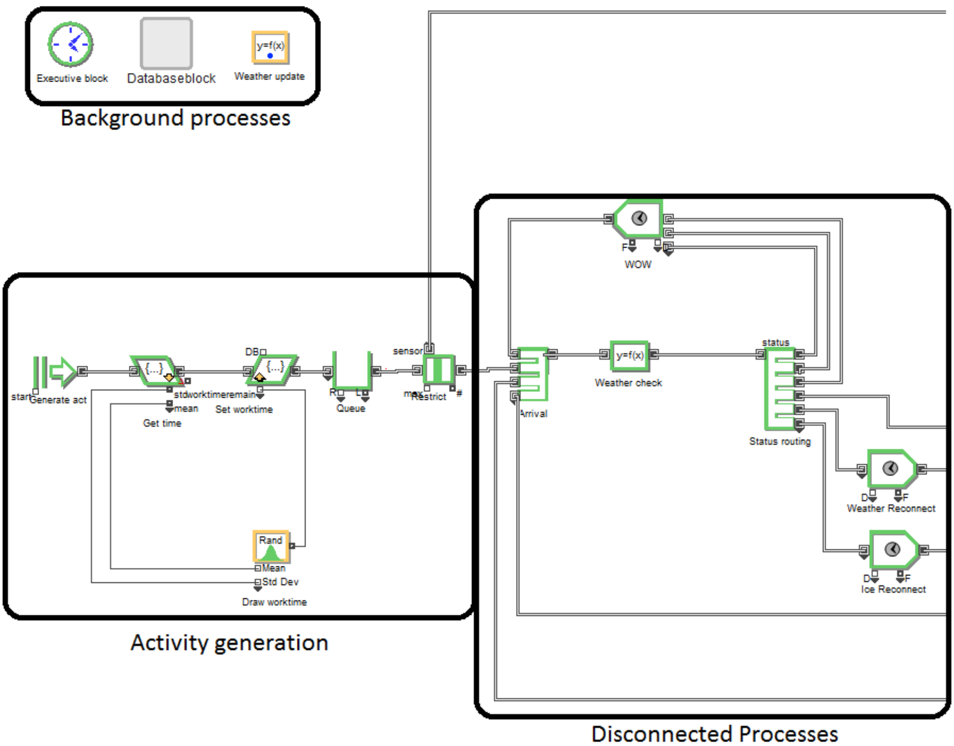

Figure 5.4: ExtendSim Implementation 1/2

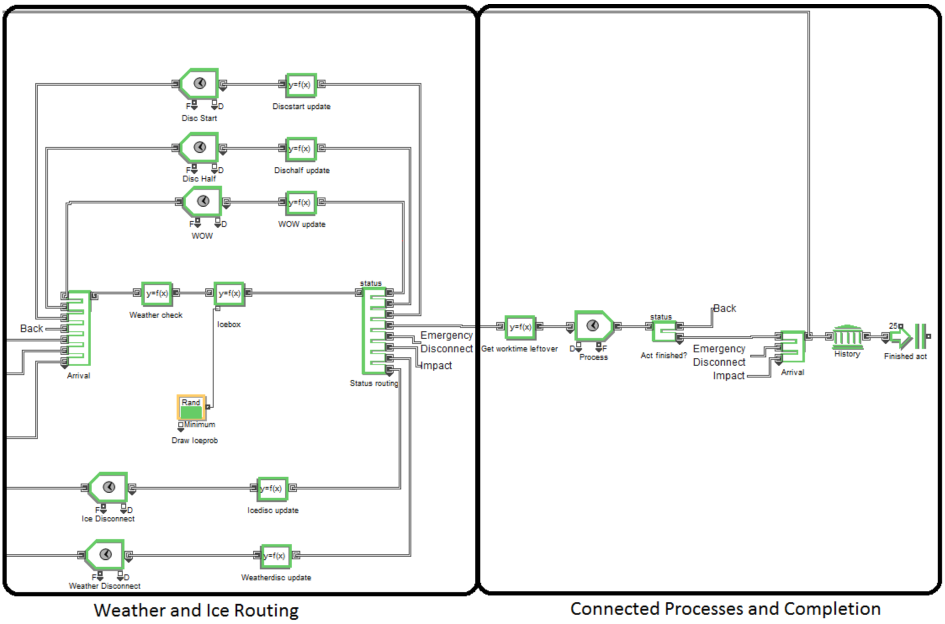

Figure 5.5: ExtendSim Implementation 2/2

The Weather and Ice routing section checks operational limits against the forecast and the iceberg event tree to route the entity either to an interruption of the activity, or to the Connected Processes and Completion section. The last section processes one hour of the entity's Worktime, and checks its Worktime remaining to either send it back to Weather and Ice routing, or to exit the model if it is complete 5.5. After an entity has passed out of the model, the next entity in the queue can enter the processing sections.

5.5.1 Background Processes

The background Processes is a small, but very important part of the model. The Executive block in figure 5.6 initialises Discrete Event Simulation mode, and keeps track of the simulation clock.

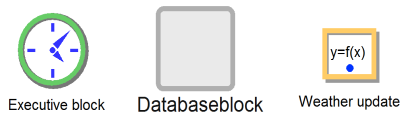

Figure 5.6: Background Processes

The Database block consists of the blocks in figure 5.7. These blocks import the Activitylist, Rigdata, iceberg event tree probabilities and weather hindcast archive from Excel at the beginning of the simulation, and uploads the information to an equivalent ExtendSim database. The data files from Excel are explained in Chapter 6 and listed in the appendix, they vary depending on the specific well and equipment.

The Weather update block, in figure 5.6 above, keeps track of the weather as the simulation runs. Every hour this block checks the weather for the next 48 hours and returns the amount of time before weather of a particular category defined by the rigdata will arrive at the drilling unit. This information is then uploaded to an ExtendSim database that is used by the forecast checking blocks later in the model.

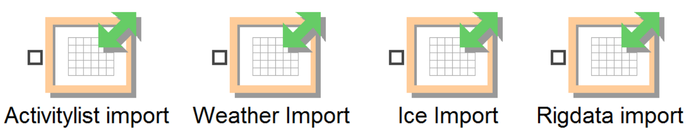

Figure 5.7: Database import/export

5.5.2 Activity Generation

In this section the entities and their attributes that represent activities are generated and put in a queue, where they wait until the previous entity has been completed and exited the model.

The Generate act block to the left in figure 5.8 reads data from the database containing the Activitylist and creates an entity for each activity with attributes.

The Get time block reads an entity's attributes and signalises to the Draw worktime block to draw a worktime based on its Location, Scale and Shape attributes. The Worktime is then set as a fixed attribute in the Set worktime block. After the Queue block, only one entity is allowed to be processed at a time until it exits the model, and all other entities are held in a first in first out queue in this block.

The Restrict block ensure that only one entity can be processed at a time, all other entities are held up in the Queue block until the entity being processed pass the Arrival block in the Connected Processes and Completion part of the model.

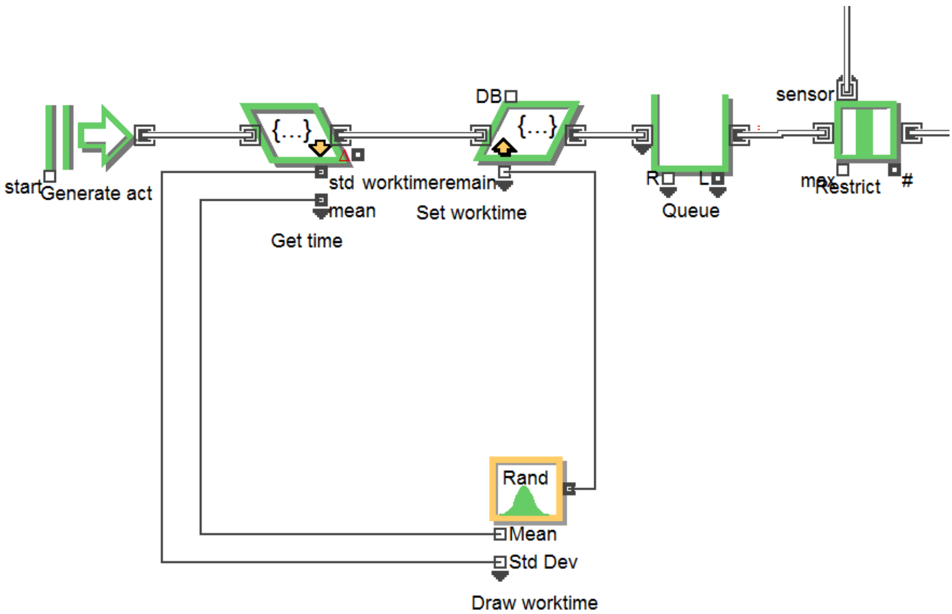

Figure 5.8: Activity generation

5.5.3 Disconnected Processes

The Disconnected Processes section represents the activities that can be performed by the drilling unit when it is disconnected from the well. The purpose of the section in the model is to route entities based on their status, operational limits and the upcoming weather forecast.

Arrival

Entities can arrive at this section from 4 different areas of the model, with corresponding statuses; Starting, WOW, Weather disconnect or Ice disconnect. The entities are brought together to have their weather forecast checked, before allowing them to be sent to the next section.

Weather Check

The Weather check block in figure 5.9 sets the status of the incoming entities, based on its previous status, operational limits and the database containing the weather forecast. For the statuses Ice or Weather Disconnect, the Weather and Ice reconnect times are compared against the forecast and the rigdata. For a Starting or WOW status that has not previously been a disconnected status, the entity's weather window is checked against the weather.

This block also updates the OPWOWdisc, OPWeatherrec and OPIcerec attributes to record the number of these statuses. The Total worktime attribute is updated by one hour for WOW statuses, which is equivalent to the time the entity spends in the WOW block. For Weather and Ice reconnect statuses, the Total worktime is updated according to the Weather and Ice reconnect attributes, respectively. For code see appendix E.

Status Routing

Based on the status set by the Weather check block, entities are routed to the next relevant block. The entities are sent to the Weather and Ice routing section if the status is Process. Entities with WOW status are sent to the WoW offline block. Ice and Weather Reconnect statuses are sent to the Ice and Weather Reconnect blocks, respectively.

WOW

In the WOW block the simulation clock is updated one hour, before the entity is sent back to the Weather check block.

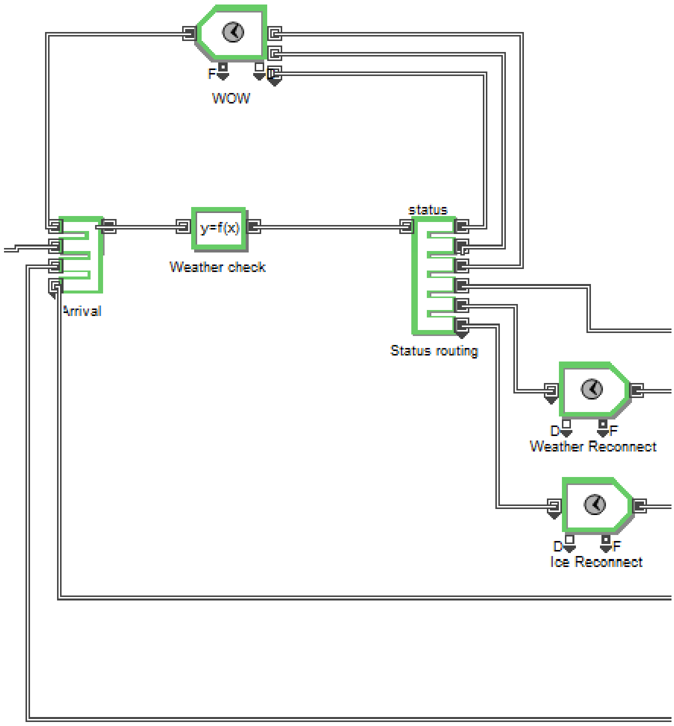

Figure 5.9: Disconnected Processes

5.5.4 Weather and Ice Routing

The Weather and Ice routing section represents decisions that are made regarding weather and ice when the drilling unit is connected. The purpose of this section in the model is to route entities based on their status, operational limits, the upcoming weather forecast and probabilities of ice scenarios determined by the iceberg event tree.

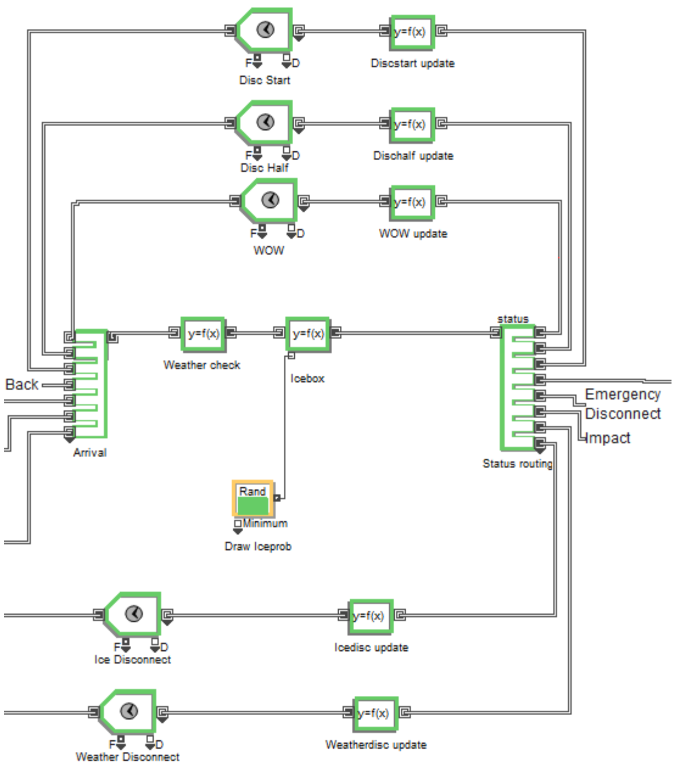

Figure 5.10: Weather and Ice Routing

Arrival

Entities can arrive at this section from 7 different areas of the model, with corresponding statuses; Starting, WOW, Weather reconnect, Ice reconnect, Process, Disconnecting started and Disconnecting halfway. The entities are routed to have their weather forecast checked and probability of ice scenario drawn, before allowing them to be sent to the next block.

Weather Check
The Weather check block reads the Zone requirement, Rigdata, Window and Weather disconnect attributes for an incoming entity, comparing them with the weather forecast database. For code see appendix E.

- If the forecasted weather is above the rigdata limit for Stand by, the status is updated to Weather disconnect.
- If the forecasted weather is not above the rigdata limit for Stand by, but above the entity's Zone requirement, the status is updated to WOW.
- If the forecasted weather is none of the above, the status is updated to Process.

Icebox
If an entity enters the Icebox block with a Weather disconnect status, it passes through the block immediately without changing the status. For all other statuses, the Icebox block signals to the Draw Iceprob block to draw a random number to compare it with the probabilities from the iceberg event tree. Depending on the number drawn, the block updates the entity's status according to the relevant ice scenario, the ice statuses that require some kind of disconnection overrule all other statuses set by the Weather check box. This box also updates OPEmergency and OPImpact to record these statuses, should they be drawn. For code see appendix E.

Status Routing
Based on the status set by the Weather check and Icebox blocks, the entities are routed to the next relevant block:

- The entities are sent to the Icedisc or Weatherdisc update blocks if the status is Ice or Weather disconnect, respectively.
- Entities with WOW status are sent to the WOW update block.
- Disconnecting Started and Halfway statuses are sent to the Discstart and Dischalf update blocks, respectively.
- If the status is Emergency disconnect or Impact, the entity is sent to Emergency disconnect or Impact, respectively.
- For the Process, Emergency Disconnect and Impact statuses, the entity is sent to the Connected Processes and Completion section.

WOW, Discstart and Dischalf Update
These blocks update the Total worktime attribute according to the respective attributes Disconnecting Started and Halfway, whilst WOW update adds one hour. The OPWOWcon, Opicediscstart and Opicedischalf attributes are also updated to record the number of these statuses.

Icedisc and Weatherdisc Update
These blocks update the Total worktime attribute according to the respective attributes Weather and Ice disconnect. The Opweathercon and OpIcediscfull attributes are also updated to record the number of these statuses.

WOW, Disc Start and Disc Half
In the WOW block the simulation clock is updated one hour. The entity is then sent back to the Weather check block. The Disc Start and Disc Half blocks update the

simulation clock according to the entity's Disconnecting started and Disconnecting halfway attribute specified times. The entity is then sent back to the Weather check block.

Ice disconnect and Weather Disconnect

The Ice and Weather disconnect blocks update the simulation clock according to the entity's Ice and Weather disconnect attribute specified times. The entity is then sent to the Disconnected Processes section, see section 5.5.3.

5.5.5 Connected Processes and Completion

The Connected Processes and Completion section represents the processing of an activity when it is connected, for example drilling one hour of the top section of a well. Entities that are cleared to process are sent to this section. The activities subject to an impact or emergency disconnection are also routed out of the model in this section.

Get Worktime Leftover and Process

This block reads the Worktime remaining attribute. If the Worktime remaining is above one hour, then the entity's status remains the same, and the Total worktime attribute is updated by one hour.
If not the status is updated to Finished, and the remaining time less than one hour is added to the Total worktime attribute. In Process the simulation clock is updated one hour if the remaining is more than one hour, if not it is updated with the remaining worktime.

Act Finished

This block routes entities based on their status:
Entities with the status Process are sent back to the Weather check block.
Entities with status Finished are sent to the Arrival block.

Arrival

The Arrival block routes entities that are completed out of the model, once an entity has passed, the next entity in the Queue block is allowed to enter the processing sections.

History

The history block records all the output attributes, uploading them to a database each time an entity passes.

Finished act

The entity exits the model.

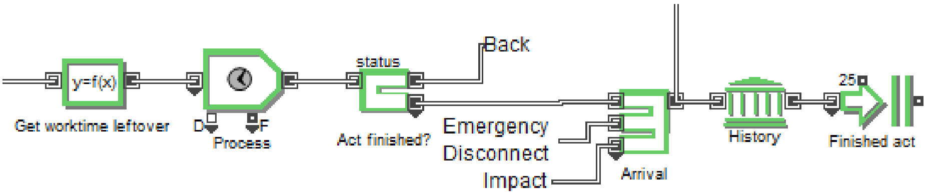

Figure 5.11: Connected Processes and Completion

5.6 Output - KPI's

To enable an analysis of the output, it is essential that the data produced by the model is presented in an understandable and informative matter to identify how changes in parameters affect the campaign. Because of the stochastic nature of the model, it is necessary to run the model multiple times for each different technological solution to get reliable output. The uncertainty of the time spent to complete the campaign, needs to be made evidently clear in the measure of merit. This uncertainty is illustrated with two charts for each technological solution.

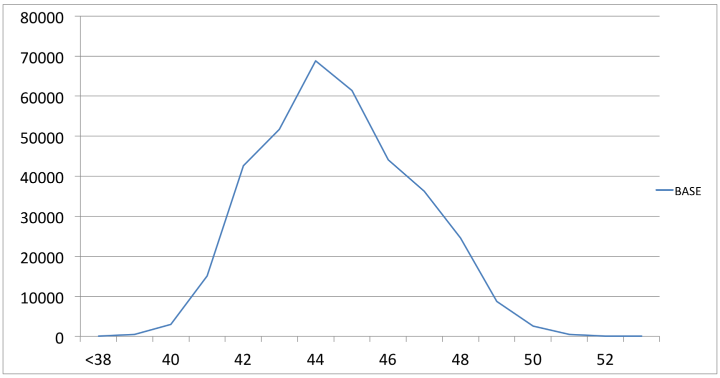

Figure 5.12: Completion days - Example KPI

In figure 5.12 the x-axis shows the days needed to complete the campaign, while the y-axis shows how many of the simulation runs where the campaign was completed in x days.

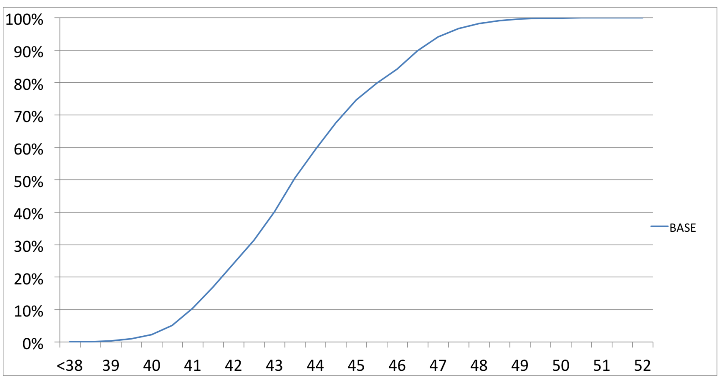

Figure 5.13: Cummulative completion days - Example KPI

The chart in figure 5.13 show the cumulative probability of completion within x days. With this representation the different solutions can be compared.

In addition to the charts, some other important KPI's are shown in table 5.6

KPI	**Description**
P50	Time required to finish the campaign for 50% of the model runs
P70	Time required to finish the campaign for 70% of the model runs
Total WOW	Average total time spent WOWing, disconnected and connected included. Time spent on disconnection and reconnection not included.
Weather Disc	Number of weather disconnections due to weather per 1000 run.
Disc Started	Number of diconnections started due to ice per 1000 run.
Disc Halfway	Number of diconnections halfway due to ice per 1000 run.
Ice Disc	Number of completed diconnections due to ice per 1000 run.
Impacts	Total number of impacts due to ice per in all runs.
Emergency disc	Total number of emergency disconnects due to ice in all runs.

Table 5.6: KPIs

The expected process time for an operation will typically be in the range of P50 and P70 according to Statoil's time estimation model principles (Statoil 2014), and are consequently used as references for output data in the expected time to complete a campaign. All other KPI's are recorded to see how much time of the campaign they constitute, to enable analyses and investigate how much they are reduced when changing input parameters.

Chapter 6

Data Collection

The data collection for this thesis has been an ongoing process since the first phases of the project, and often the availability of suitable data has defined the development of the simulation model. This chapter presents the main sources of data found suitable for the model's purposes, and how they are implemented.

To validate the model, input data from a similar existing system is necessary to compare the output data from the model and an existing system's real response. The input data for this model is taken from a platform called the Polar Pioneer that has drilled 4 wells in the subarctic. Other data and assumptions that are used in the expansion of the model, are taken from correspondence with drilling experts at Statoil and based on the literature study of this thesis.

6.1 Activity List and Process Times

To replicate the scope of operations from a real campaign, Daily Drilling Reports (Daglig Bore Rapport, DBR) have been studied for 4 reference wells south in the Barents Sea. The DBRs contain information on the scope of operations, constituting how the well was drilled, and the time spent on each operation, see table 6.1.

Start time	**End time**	..	**Hours spent**	..	**Description**
01.01.01 12:00	01.01.01 14:00	..	2.0	..	Drill 26”
01.01.01 14:00	01.01.01 18:00	..	4.0	..	WOW
01.01.01 18:00	02.01.01 16:00	..	22.0	..	Continue Drill 26”
01.01.01 12:00	28.01.01 17:00	..	437	..	WOW for entire well 7%

Table 6.1: DBR Example

Depending on the level of detail in a DBR and length of the relevant campaign, the DBRs consist of 70 to 300 rows with information. The DBRs state what type of operation that was executed in a specific period of time, and can be seen as a detailed scope of operations with all associated events included. Periods spent WOW are in some DBRs specified in a separate row, as row 3 in table 6.1. Common for all DBRs is that WOW is always summed up in the bottom of the report, as a percentage of the entire time spent on the well, illustrated in the last row in table 6.1.
An activity list template was created by studying the DBRs, as shown in table 6.2.

Section	**Part**	**Act. nr.**	**Time required**	**Zone required**
MOB		1	24	2
9 7/8"		2	12	1
Pre-Spud		3	6	2
36"	Drill	4	18	2
	Conductor & Cement	5	19	1
	Drillout	6	8	2
12 1/4"	Drill	7	35	2
	Casing & Cement	8	14	2
	BOP	9	20	1
	Drillout	10	5	2
.....	.....	.....	.....	...
P&A	Cement & plugging	19	18	2
	Retrieve WB & BOP	20	35	1
	Retrieve Casings	21	12	1
DEMOB		22	24	1

Table 6.2: Activity list template

By dividing the DBRs into activities that matched the operations, four activity lists were created for the reference wells in the Barents Sea. The length of the operations in the DBRs were used to calculate the process times in the activity lists. In sections with specified WOW, the DBR does not include WOW time in the process time for an operation. For the reference wells the process time are deterministic, meaning they are not drawn from an distribution, since they are used to replicate the reference wells.

A fictive campaign was created to mask the data received from Statoil, based on the reference wells. The fictive activity list is used for simulation runs in Arctic conditions, and is attached in appendix B. Time distributions for the fictive well activities were not made available, therefore the process times have been placed within the range between the maximum and minimum times for an activity from the reference wells. In lack of known distribution of the process times, a normal distribution with a standard deviation of 15% is given to the activities. For discussion about this choice refer to section 8.1.4.

6.2 Rigdata

The data used for the drilling unit's parameters was obtained by iteration in the model, described in section 7.1.1.

6.3 Weather Data

Weather data for the wells was obtained from the NORA10 hindcast archive from Statoil. The archive provides a continuous time series of weather data from 1957 to 2013 in ASCII format, in 3 hour intervals. An example is given below in table 6.3.

yyyy	mm	dd	hh	ws	wd	hs	tp	Mdir
1957	9	1	6	5.20	286.00	1.00	5.03	288.00
1957	9	1	9	5.50	289.00	0.90	4.99	294.00
1957	9	1	12	4.50	302.00	0.90	5.37	299.00
1957	9	1	15	5.10	283.00	0.90	4.98	304.00

Table 6.3: NORA10 Weather Data Example

The first four columns in table 6.3 represent the date and time. The following columns describe wind speed, wind direction, wave height, spectral peakperiod and mean wave direction in that order.

The weather forecasts and data regarding ocean current used by the Polar Pioneer during drilling of the reference wells was not available.

6.4 Ice

The iceberg event tree approach described by Eik and Gudmestad (2010) is the method chosen, as presented in section 5.3.6. The model uses the same probabilities provided by Eik and Gudmestad (2010) with some alterations.

Interruption	Probability Green Zone	Probability Red Zone
Emergency disc.	0.009E-06	0.009E-06
Impact	0.023E-06	0.065E-06
Planned disc.	0.701E-06	2.759E-06
Halfway	2.099E-06	0
Started	163.786E-06	163.786E-06
Nothing	999833.382E-06	999833.382E-06

Figure 6.1: Ice Probabilities

As described by Eik and Gudmestad (2010) there is a correspondence between wave height and probability of successful iceberg towing. To demonstrate the capabilities of the model, a correspondence between wave height and probability was added. The green zone probabilities are for wave heights below 6 metres, and the red above 6 metres.

6.5 Operational Limits

The weather windows, zone requirements, disconnection and reconnection times are parameters that are difficult to obtain exact data for without having intimate knowledge of each planned operation, relevant equipment, bedrock geology and other factors. By studying the DBRs, the list of critical operations and talking to drilling experts at Statoil these parameters were set according to good judgement.

For the sections and activities before landing the BOP the windows, disconnection and reconnection times are short compared with the sections after landing the BOP due to the absence of the marine riser. As an example, the window for starting drilling a 36" sections is equal to the amount of time needed to pull out of hole, which is stated in some of the DBRs. The time to pull out of hole is dependent of depth drilled, so the value is nominal.

Act nr.	**Zone required**	**Weather window**	**Weather disconnect**	**Weather reconnect**	**Ice disc.**	**... ...**
1	2	5	3	3	7	...
2	2	5	3	3	7	...
3	2	5	3	3	7	...
4	2	5	3	3	7	...
5	1	10	3	3	7	...
6	2	2	3	3	7	...
7	2	5	10	10	14	...
8	1	10	10	10	14	...
9	1	20	24	24	28	...
10	2	3	24	24	28	...
...	...	...	...	...	...	...
22	2	17	24	24	28	...
23	1	10	24	24	28	...
24	1	10	24	24	28	...
25	1	10	24	24	28	...

Table 6.4: Operational limits Example

Table 6.4 shows operational limits for some activities, the activity number can be seen in connection with the activities in table 6.2. Differences in operational limits can be seen by cementing and BOP activities, requiring calmer weather. Cementing and landing the BOP are represented by activity numbers five and nine. Some activities have longer weather windows, as they may be required to be completed without interruption such as landing the BOP. The choices of operational limits are reviewed in the Chapter 8.

Chapter 7

Results

7.1 Reference Wells

Prior to including ice considerations and starting analyses, it was necessary to validate the model. For validation of the model four exploration wells were chosen in the southern part of the Barents Sea as described in section 6.1. All reference wells were drilled by the same rig, the Polar Pioneer, in the period between 2008 and 2011, in conditions without the presence of sea ice.

7.1.1 Estimation of Rigdata and Replication of Drilling activities

To be able to replicate the reference wells, the operational limits of the Polar Pioneer had to be found. A search for the correlation between operational limits and weather was done by comparing the periods of WOW from the DBRs with the weather from the NORA10 archive.

The only common denominator found for periods of WOW was wave height. Periods with strong wind were usually followed by periods of high waves, but the comparison did not find any WOW as a direct result of strong wind. Nor was there any correlation found between the wave period and WOW. The periods of WOW were often found to occur with a certain wave period interval, but always in combination with high waves. WOW was not observed with similar wave period intervals and smaller waves. The angular differences between waves and wind were also anaysed, with the conclusion that there was no correlation with WOW.

According to the DBRs three of the wells had a WOW percentage above 10% whilst the last well had not spent any time WOW. Finding correct numbers for WOW was hindered by the difference in the level of detail in the DBRs, illustrated in table 7.1.

Well	% of tot in DBR	Waiting on Weather Implied by % [hrs]	Specified in DBR [hrs]	Deviation [hrs]	Disc. [nr]
A	13.7	246	130	116	0
B	15.0	235	>48	>100	1
C	10.7	111	128	-17	0
D	0	0	0	0	0

Table 7.1: WOW in reference wells

Column two represents the percentage sum of WOW for a well specified in the DBRs, and column three reflects the hours spent on WOW that this percentage indicates. The fourth column shows how many hours of WOW that are specified by the DBR. In the DBRs for well A and B more than 100 hours of WOW were not specified, when compared with the WOW percentage, illustrated in the fifth column. The DBR for well C specified 17 hours more WOW than indicated by the sum of WOW. Column six gives the number of disconnections.

After analysing the DBRs and weather, wave height was decided to be the only parameter to affect operations, and the search for exact limits began. When aligning the DBRs and the weather data it became clear that most operations were suspended in waves with heights exceeding 7 - 7.5 metres. Some operations, for example landing the BOP and testing, were not started in wave heights above 4.5 - 5.5 metres. As shown in table 7.1 well B was the only well that experienced disconnection. The disconnection in well B happened prior to a period with waves above 9 - 9,5 metres. Well A also experienced similar wave heights to Well B, but it was during the 36" section prior to landing the BOP and Riser. These numbers were then used as a starting point for the iteration process of finding the right wave height limits for the rig.

The model was run for the four reference wells with corresponding weather data from the NORA10 hindcast archive, using the same rig data. Replicating the operations on the rig for each well, using the same rig data, confirms that the model was valid regarding weather conditions. In the iteration process to find the right rig parameters, the parameters were adjusted and the model was run again for all wells. Aligning the WOW periods in the model with the DBRs, was the target for the iterations. The main problem was the lack of detail in the DBRs.

In table 7.2 the amount of time spent WOW for an activity in the model is compared with the DBRs. Well D is not included in the table as neither the model nor the DBR experienced WOW.

Well		3	4	5	6	7	11	12	13	16	17	18	19	21	22	23	25
		Activity number															
A	DBR	16	0	14	7	17	57	0	19					0	0	0	
	Model	6	9	0	18	49	33	0	57					0	13	0	
B	DBR									0	0	0	>48				0-30
	Model									6	0	0	84				0
C	DBR									0	32	0	0	16	20	60	
	Model									0	42	6	0	9	25	70	

Table 7.2: WOW Comparison DBR and Model

The activities are placed in bulks because of the misalignment on the timeline between the DBRs and the model. When the time the model spends WOW deviates from the DBR, the timeline for startup/finish for the next activity shifts on the timeline compared with the DBR. The reason for this misalignment is further outlined in Section 7.1.2.

Well	WOW Implied by % in DBR [hrs]	WOW Specified in DBR [hrs]	WOW Model [hrs]	Disconnections DBR [nr]	Disconnections Model [nr]
A	246	130	185	0	1*
B	235	>48	90	1	1
C	111	130	152	0	0
D	0	0	0	0	0

*Recorded as disconnection in the 36” section, before landing the BOP and riser.

Table 7.3: Model results: Reference wells

Table 7.3 presents number of disconnections and the hours of WOW indicated by the total WOW percentage, specified in the DBRs and in the model. The model has recorded total hours spent WOW to be in between the specified and indicated amount for well A. The amount spent WOW is above both the specified and indicated amount for well C. It is difficult to describe well B as the level of detail in the DBR is low.

Well B was the only well that disconnected through the campaign, the disconnection was recorded in the model at the same place on the timeline as in the DBR. The model also recorded a disconnection for well A, in the 36” section, before landing the BOP and Riser.

The rig data used for the results in table 7.2 and 7.3 is given in table 7.4 below.

Zone	**Wave Height**
Delicate	5.0
Advisory	7.0
Stand-by Connected	9.4
Survival	>9.4

Table 7.4: Best Rigdata Results

7.1.2 Analysis of the Validation Results

As table 7.2 demonstrates a match between periods of WOW in the DBR and model. However, there is a mismatch between total percentage WOW in the DBR's and the model, as indicated in table 7.5.

Well	**Model WOW %**	**DBR WOW %**
Well A	10.7%	13.7%
Well B	6.3%	15.0%
Well C	14.1%	10.7%
Well D	0.0%	0.0%
NCS Barent Sea Avg.		7.1%

Table 7.5: Model WOW percentage

Matching periods of WOW from the DBRs with the model was prioritised ahead of matching total WOW time. For well A and B the model gave a total WOW percentage below the percentage from the DBRs. According to Statoil the average WOW is 7.1% for semi-submersibles on the Norwegian Continental Shelf in the Barents Sea. Well A is between the average and the percentage given in the DBR, whilst well B is below the average and the percentage given in the DBR. For well C the WOW percentage is above both the average and the percentage given in the DBR.

The disconnection recorded in Well B is in line with the DBR. Well A did not disconnect, but a disconnection was recorded in the model. This is due to the setup of the rig data, since all activities are sent to disconnection if the weather is above the Advisory zone. When disconnection in zones after landing BOP and Riser will mean disconnection of the riser, a disconnection before landing BOP and Riser would in most cases indicate a wait or pull out of hole, depending on the weather. As the time specified as Weather disconnect and Weather reconnect for the activities before landing BOP and Riser are short, this is not a crucial flaw in the model.

7.1.3 Quality of Validation and Model

Before any analysis of input parameters or addition of ice considerations in the model is presented, this section will review how the model was validated and the resulting quality of the model. Replicating the campaigns without possessing detailed data on operations, weather and including more aspects on drilling are discussed below.

As mentioned in the previous section, the level of detail in the DBRs vary, this restricts the development of the activity lists and consequently replication of rig operations. Well A and B had either underreported more than 100 hours of WOW, or the total percentage of time spent WOW was higher than specified.

The activity list is to some degree sensitive to changes in process time, since the campaign is divided into large activities spanning over large periods of time. The lack of detail in the activity list causes a loss of nuances in the model, for example, some parts of an operation could be done during WOW instead of all operations being stopped on the rig. However, the lack of detail is also an advantage of the model, as complexity is reduced and it is more open to a variety of different activities.

When replicating rig operations there was a choice between matching the periods of WOW or matching the total percentage. Matching periods was prioritised since WOW was certain in those periods. By trying to match the total WOW percentage, the model would record periods of WOW in activities, thus causing further misalignment in start up times between the model and the DBRs. The reason for this misalignment is that the actual time spent from the DBRs is used to create the process times for the activities in the activity list. When an activity is WOW in the model, which might be included in the actual process time, the amount of time spent finishing the activity after WOW is too long, and this causes a misalignment in the weather timelines.

Another important aspect of the model is the weather forecast data used. Two aspects of the weather should be discussed, the quality of the data and the certainty of the weather in the model.

The NORA10 hindcast archive uses discrete observations to create a "continuous" time series with a 3 hour interval. The archive uses an observation to simulate weather for a period of time in the proximate future, before it corrects this simulation with the next observation. The purpose of the archive is to provide a statistically viable weather time series. Ideally the observed weather at the rig would be used for validation. Nevertheless, we believe applying hindcast data is good enough for further analysis of wells. For validation purposes, there might be local variations that are not present in the hindcast archive and better data should be acquired.

In the model the incoming weather is known with 100% certainty. A 100% certain forecast is not representative of real life conditions, where the rig receives forecasts regularly and actions are taken accordingly. According to Statoil, weather forecasts are accurate in a 24-48 hour range regarding wind, temperature, pressure and waves. Some deviations happen, but are becoming less frequent as weather models get better and the number of observational stations increase. Due to uncertainty the rig has to take preventive actions in advance, assuming worst case conditions, which may result in some unnecessary actions. The uncertainty will affect decisions taken by personnel, although there are a guidelines and regulations setting final limits.

7.2 Fictive Well Results

In this section the results from a fictive drilling campaign in the Barents Sea are presented. The rig data from the validation has been used, with a fictive activity list. The activity list and all parameters are fictive, but based on the reference wells, see appendix B. When running the reference wells ice considerations were not included. In these runs ice considerations are taken into account. Firstly the results from model runs in different areas of the Arctic are demonstrated, later the results and effects from alteration of input parameters are presented.

7.2.1 Arctic Weather

The base case for these runs are taken from a location in the Perseyevsky licence, 76 degrees North and 38 degrees East. The model was run 40 000 times each for ten seasons, totalling 400 000 models runs. The results are presented in figure 7.1 and 7.2, and table 7.6 and 7.7 below. Figure 7.1 shows the distribution of days to completion. The y-axis shows describes how many runs that have been completed within X days.

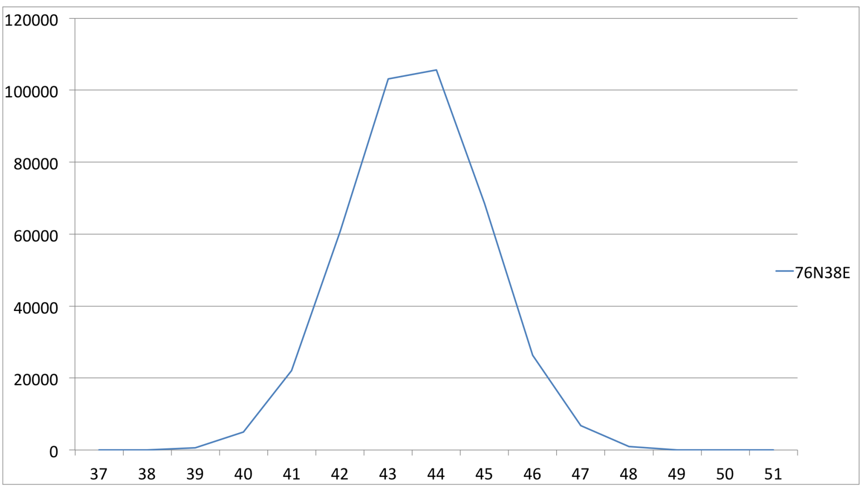

Figure 7.1: Completion days 76N38E

Figure 7.2 shows the cumulative distribution function for days to completion. The x-axis denotes the number of days, while the y-axis represents the percentage of the runs that are completed within X days.

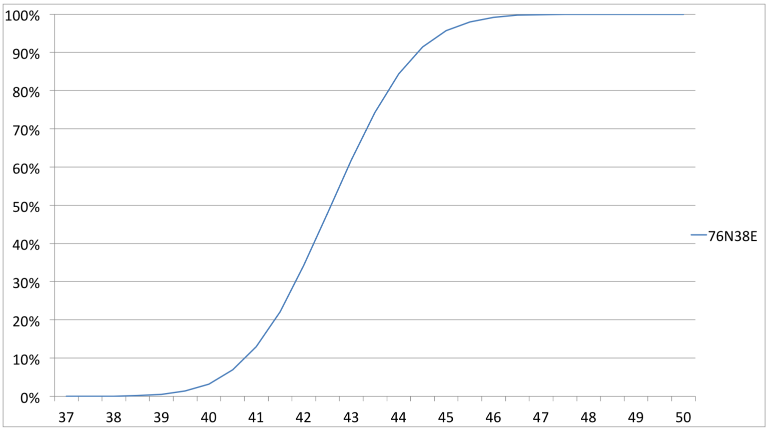

Figure 7.2: Cumulative Completion days 76N38E

Run	**P50** [hrs]	**P70** [hrs]	**Avg WOW per run** [hrs]
76N38E	1031.6	1049.9	0.0

Table 7.6: KPI 76N 38E part 1

Run	**Weather Disc** [nr/1000run]	**Disc. Started** [nr/1000run]	**Disc. Halfway** [nr/1000run]	**Ice Disc.** [nr/1000run]	**Impacts** [Tot all runs]	**Emgcy. Discs** [Tot all runs]
76N38E	0.0	168.9	2.23	0.85	11	0

Table 7.7: KPI 76N 38E part 2

Table 7.6 and 7.7 illustrates that the rig did not WOW or disconnect as a result of wave height for this weather series. The probabilities for ice related events are distributed evenly across all activities and runs, consequently the time until completion is also normally distributed, which is clearly seen in figure 7.1. A closer look at the weather data for these runs reveals that maximum wave height is 4,2 metres. In the period June-October from 1957 to 2013 the maximum wave height measured was 8.3 metres. Average wave height is recorded to be less than 1.6 metres. The lack of severe weather does not allow for a good analysis of input parameters representing operational limits, therefore another location was chosen as a base case.

7.2.2 Subarctic Weather

In order to show the capabilities of the model and allow for an analysis of input parameters, the fictive well was run with weather data from the location of reference well A. In the next sections this results will be referred to as the base case. The weather in this location is harsher than in the Perseyevsky license, affecting the distribution of completion days. The results below are taken from 40 000 runs for nine different seasons, totalling 360 000 model runs.

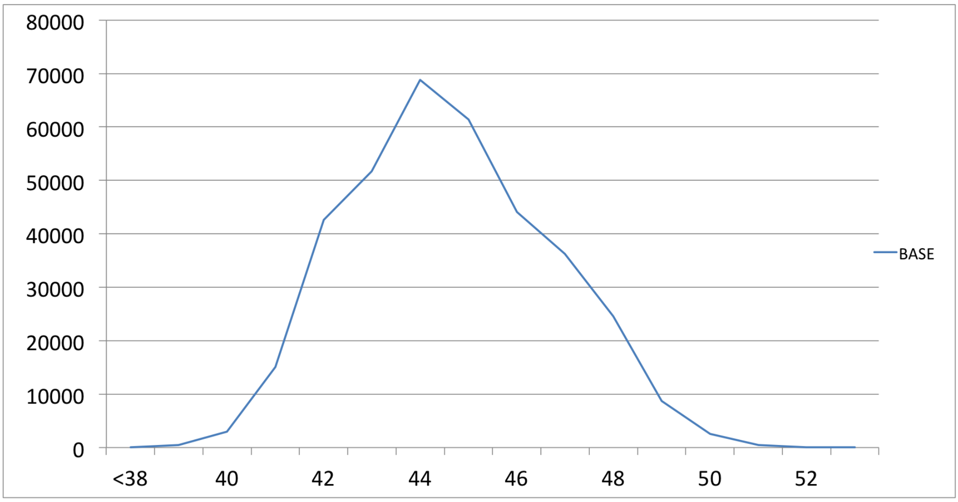

Figure 7.3: Completion days Subarctic Weather

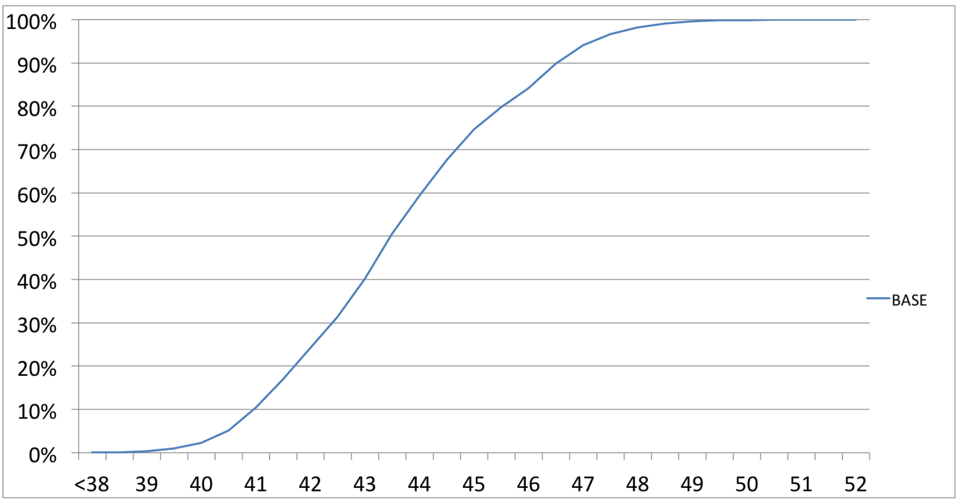

Figure 7.4: Cumulative Completion days Subarctic Weather

RUN	P50 [hrs]	P70 [hrs]	Avg WOW per run [hrs]
BCase	1057.2	1082.2	35.8

Table 7.8: KPI Subarctic Weather part 1

Run	Weather Disc [nr/1000run]	Disc. Started [nr/1000run]	Disc. Halfway [nr/1000run]	Ice Disc. [nr/1000run]	Impacts [Tot all runs]	Emgcy. Discs [Tot all runs]
BCase	110.7	173.6	2.10	0.97	7	0

Table 7.9: KPI Subarctic Weather part 2

Table 7.8 and 7.9 show the KPI's described in section 5.6 for the Subarctic well runs. As seen in table 7.8 the harsh weather in this location resulted in an average WOW time of 35.8 hours for each run. On average one out of ten runs disconnected due to weather, presented table 7.9. The result is a more jagged distribution of the time required for completion, seen in figure 7.3.

7.2.3 Higher Wave Tolerance

An important purpose of the model is to evaluate the effect of changing equipment parameters on the total time spent to complete a campaign. In this and the next two sections, the results from model runs with altered parameters are presented.

To simulate improved station keeping equipment the model was run with heightened rig parameters, whilst all other parameters and weather data were kept the same as in the base case. The initial requirement for wave height was 5 metres for the Delicate zone, 7 metres for the Advisory zone, and disconnection in the Survival zone with waves above 9.4 metres. The rig parameters were increased by 10% to 5.4, 7.7 and 10.34 metres, see appendix C. As shown in figure 7.5 and 7.6, more runs completed earlier compared with the base case, illustrated by the red curve being shifted to the left.

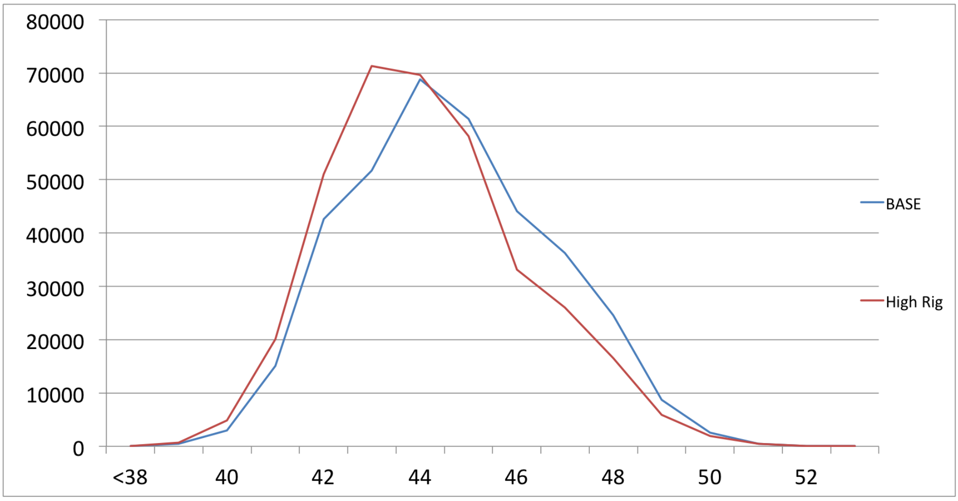

Figure 7.5: Base vs Higher wave tolerance

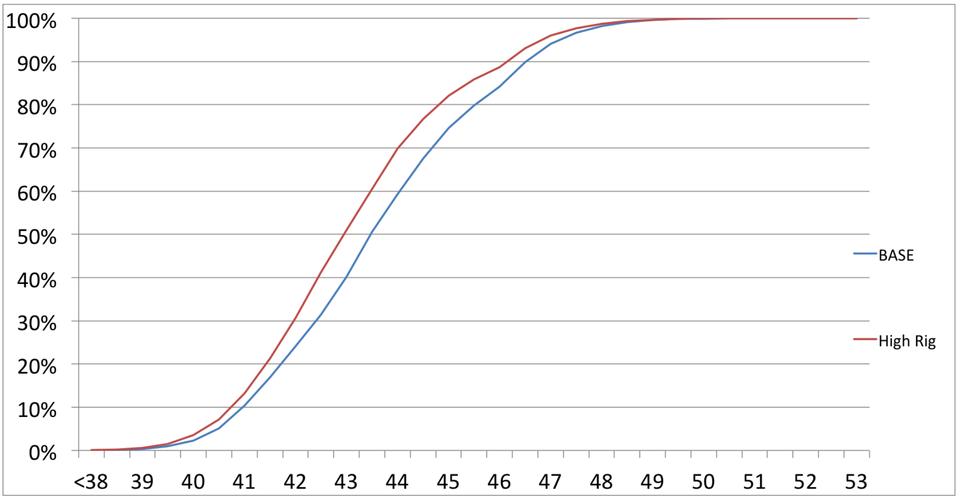

Figure 7.6: Cumulative Base vs Higher wave tolerance

RUN	**P50** [hrs]	**P70** [hrs]	**Avg WOW per run** [hrs]
Base Case	1057.2	1082.2	35.8
Higher Rigdata	1045.8	1066.3	26.9
Improvement	1.07%	1.47%	24.8%

Table 7.10: KPI Higher wave tolerance part 1

Run	**Weather Disc** [nr/1000run]	**Disc. Started** [nr/1000run]	**Disc. Halfway** [nr/1000run]	**Ice Disc.** [nr/1000run]	**Impacts** [Tot all runs]	**Emgcy. Discs** [Tot all runs]
BCase	110.7	173.6	2.10	0.97	7	0
Hi Rig	0.00	172.6	2.21	0.96	8	0
Imp.	100%	0.86%	-5.15%	1.15%		

Table 7.11: KPI Higher wave tolerance part 2

As a result of the improved station keeping abilities the KPI's P50 and P70 improved by 1.07% and 1.47%, shown in table 7.10. Disconnection due to weather was eliminated and the average total time spent on WOW was reduced by 24.8%. While the average number of disconnections started and completed were reduced by 0.86% and 1.15%, the number of halfway disconnections per run increased by 5.15%. The total number of impacts increased by one for all the 360 000 runs.

7.2.4 Shorter Disconnection and Windows

In order to simulate improved drilling technology associated with disconnections, the windows and disconnection times in the activity list were reduced by 50%. The activities and their process times remained the same as in the base case, see appendix B. Figures 7.7 and 7.8 show the improvement resulted in more runs completing earlier than for the base case.

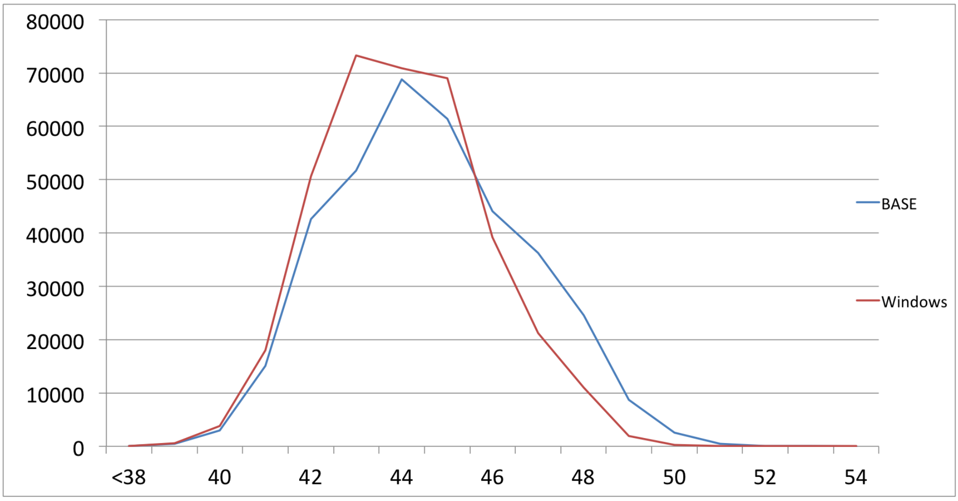

Figure 7.7: Base vs Shorter disconnection and windows

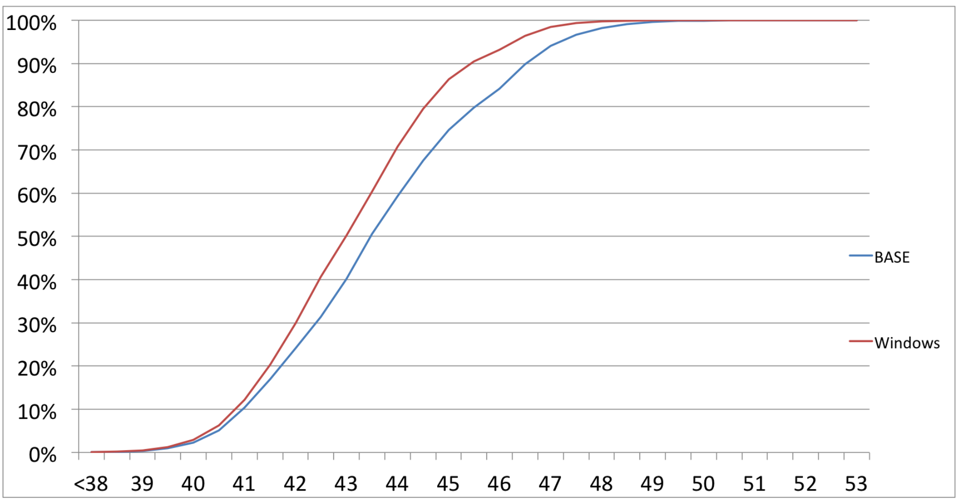

Figure 7.8: Cumulative Base vs Shorter disconnection and windows

Run	**P50** [hrs]	**P70** [hrs]	**Avg WOW per run** [hrs]
Base Case	1057.2	1082.2	35.8
Faster disc & Short wind	1043.3	1065.0	24.5
Improvement	1.31%	1.59%	31.5%

Table 7.12: KPI Shorter disconnection and windows part 1

Run	**Weather Disc** [nr/1000run]	**Disc. Started** [nr/1000run]	**Disc. Halfway** [nr/1000run]	**Ice Disc.** [nr/1000run]	**Impacts** [Tot all runs]	**Emgcy. Discs** [Tot all runs]
BCase	110.7	173.6	2.10	0.97	7	0
FD&SW	111.1	172.3	2.13	0.89	10	0
Imp.	-0.40%	0.71%	-1.06%	7.76%		

Table 7.13: KPI Shorter disconnection and windows part 2

The P50 and P70 values improved by 1.31% and 1.59%. While the average total WOW time was reduced by 31.5%, the number of disconnections due to weather stayed similar, experiencing an increase by 0.40%. The decreased windows, disconnection and reconnection times, did not result in a reduction in the number of disconnections and reconnections, but the periods of non-productive time associated with them were reduced.

While the average number of disconnections started decreased by 0.71%, the number of disconnection halfway increased by 1.06%. A large deviation of completed ice disconnections and number of impacts was also noticed; increasing by 7.76% and 3, respectively.

7.2.5 Improved Ice Management Capabilities

In an effort to simulate a higher probability of detecting and stronger success rate for deflecting icebergs in time, two branches of the iceberg event tree were altered. The probability of detecting an iceberg was increased by 50%, and the probability of successfully deflecting an iceberg in time was also increased by 50%, see appendix D. All other parameters were kept the same. Figures 7.9 and 7.10 present the improvement.

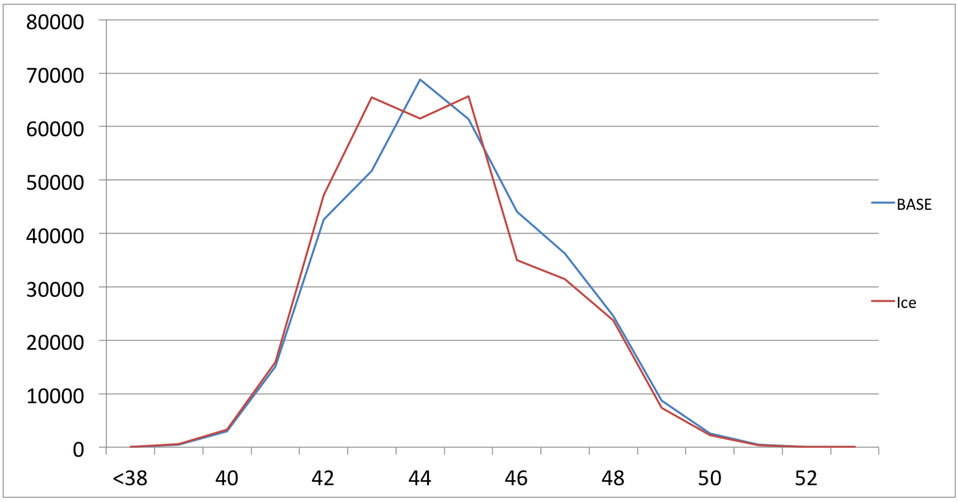

Figure 7.9: Base vs Improved Ice Management Capabilities

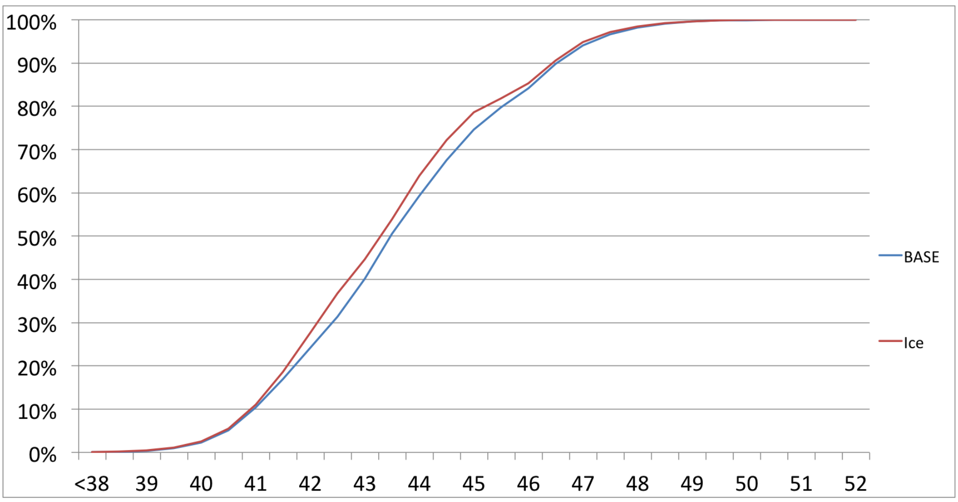

Figure 7.10: Cumulative Base vs Improved Ice Management Capabilities

Run	**P50** [hrs]	**P70** [hrs]	**Avg WOW per run** [hrs]
Base Case	1057.2	1082.2	35.8
Improved Ice Management	1052.3	1074.8	31.2
Improvement	0.46%	0.68%	13.0%

Table 7.14: KPI Improved Ice Management Capabilities part 1

Run	**Weather Disc** [nr/1000run]	**Disc. Started** [nr/1000run]	**Disc. Halfway** [nr/1000run]	**Ice Disc.** [nr/1000run]	**Impacts** [Tot all runs]	**Emgcy. Discs** [Tot all runs]
BCase	110.7	173.6	2.10	0.97	7	0
Ice-M	110.7	176.2	2.89	0.26	0	0
Imp.	-0.1%	-1.5%	-37.6%	73.6%		

Table 7.15: KPI Improved Ice Management Capabilities part 2

The P50 and P70 values improved by 0.46% and 0.68%. While the total WOW time was reduced by 13.4%, the number of disconnections stayed the same. While the average number of disconnections started and halfway per run increased by 1.5% and 37.6%, the number of full ice disconnections declined with 59.6% and the number of impacts was reduced to 0.

Chapter 8

Discussion

This chapter is divided into three sections: first the modelling process and model structure are discussed, secondly the results from the fictive well are reviewed and thirdly the implications of these results on the choice of technology in a campaign are considered.

8.1 Quality of the Model

When running the simulations for the reference wells the model proved it's ability to replicate rig operations to a satisfying degree. This section discusses the choices made in the modelling process, and how these have influenced the structure of the model.

8.1.1 Choice of software

When the work on this project started as a summer project for Statoil in 2013, as study of the different discrete event simulation software was made as mentioned in section 5.4, and Micro Saint Sharp was chosen as the preferred simulation tool. Micro Saint Sharp benefits from it's flexibility, but requires extensive programming knowledge in .NET or C#. Due to unexpected circumstances described in the End note, Micro Saint Sharp was abandoned in favour of ExtendSim. There is no doubt that the the model would have been different if Micro Saint Sharp was employed, due to the differences in the two software packages. ExtendSim is a less flexible tool, and the modelling interface is more dependent on pre-defined blocks and setup. However, ExtendSim was quickly adapted and mastered, and has proven to be a user friendly and effective software.

8.1.2 Modelling the Scope of Operations

The original focus of this project was to build a model encompassing an entire Arctic drilling campaign, with the drilling operations at the core of the problem, several modifications have been made to the scope along the project. In accordance with simulation methodology the approach has been to build the model iteratively, validating and verifying a simple model then adding further levels of complexity. Due to the work done investigating the effects of ice and weather on station keeping and operational limits of the campaign, other work was removed from the scope of the thesis. A decision was made to focus on drilling operations, and how they are affected by weather and ice conditions in the Arctic.

Originally, the model was intended to include aspects such as logistics, communication and availability of equipment and personnel. Without data on availability, redundancy and logistics available, these aspects of drilling operations and the campaign were left out due to limited time and resources. Some of the research in this thesis regarding logistics, and the results from handling weather in the Arctic, may point to the fact that modelling the logistics of an Arctic drilling campaign could be more relevant than weather and ice conditions.

To create a general model that can handle a range of different operations, it was quickly realised that an abstract approach was the most suited method. Since drilling programs vary substantially, creating a fixed list of activities would create an unnecessarily complex and rigid model. An abstract approach is not the intended way of using ExtendSim, as activities are usually fixed blocks and entities represent real world objects, in this case the drilling unit or the progression of the campaign. This presented some challenges in the implementation of the model, these are discussed in section 8.1.7.

A disadvantage with an abstract approach is that each entity requires a long list of attributes describing its parameters, including descriptions for interruptions of activities specific to each activity. This requires extensive knowledge of operations when creating the activity list, and increased levels of detail require longer lists of parameters in the activity list describing and recording attributes. In this regard an abstract approach of modelling an Arctic drilling campaign is perhaps better suited to a simulation software that is open to customisation. Adding complexity to the model also increases the amount of data output which needs to be treated, and can cause problems for the memory of ordinary computer.

The main benefit of an abstract modelling approach is the relative ease of adding new levels of complexity since it builds around statuses not activities as shown in section 4.7.1. The abstract method also lets an activity list be predefined into desirably proportioned parts. The traditional approach would have required a labyrinth of activity blocks, sending the entities back and forth depending on status, requiring an extensive reworking of the model to add extra features. With the abstract approach, the main features of the model are kept simple, and continuing to add levels of complexity after validation has been facilitated.

Adding further alternatives for interruptions of activities was done simply by adding a new status, activity block and altering the router box slightly; no major changes are made in the layout of the model. Although adding further levels of complexity in the model may be relatively easy, without the right knowledge and data, the model cannot be verified in the modelling process.

8.1.3 Interruptions of Operations

The model replicates interruptions and disconnections caused by weather and ice, and a number of simplifications and assumptions have been made with regard to these undesired events that call for discussion.

Each activity has attributes that specify the time it requires to disconnect and reconnect due to a bad weather or ice. Nevertheless, the time to complete an interruption procedure can vary across the operations time, and depends therefore on how finely the activity list is divided. For example, the interruption and disconnection times of an operation varies on what part of the operation is being undertaken. If the operation is nearing completion, instead of stopping, disconnecting and then completing after reconnection again, the operation would probably be completed and then a disconnection would take place. The model has the possibility to define activities in shorter intervals if necessary, which could solve this problem. But the decision to disconnect is always dependent on the judgement of the personnel on the drilling unit, and this is hard to model without extensive knowledge of drilling operations.

Another issue is that interruptions are not processed stepwise like other activities, but their process times are deterministic and are not affected by ice or weather. It was not deemed necessary to model the length of interruptions stochastically, it is fully possible, but adding this complexity was not purposeful for the model. In the real world, a disconnection could go from planned to emergency if something unexpected were to happen during the operation. However, with the rarity of emergency disconnection, and precautionary measures on the drilling unit, disconnections are usually planned for. Modelling interruptions stepwise would require a greater level of detail and larger amount of statuses to track the progression of a an activity, such as disconnection. Too much detail could be excessive, this thesis does not comment on what level of detail is optimal, there can be many nuances.

Operational limits are usually defined by physical motions of the drilling unit and loads and strains on equipment, these are established and defined in the WSOG where a set number of zones are given for degrees of operability (Statoil 2013a). The model does not take these real-time measurements into account, only coupling limits with significant wave height, this is discussed further in section 8.1.5. Ice is modelled with scenarios drawn stochastically by the event tree, and therefore the physical effect on the drilling unit is completely avoided, unless this aspect is considered in the event tree.

Redundancy, availability and logistics of equipment and supplies do not affect the interruptions of activities in the model, though downtime due to equipment breakdown is included in the process times. It is known from one DBR that operations have waited for supply of personnel, and logistics is a problem. The interaction between supplies, break down of equipment and weather conditions are not investigated in this model, it could be speculated that they have a connection, and the loss of one aspect might lead to negative consequences for another. For example, bad weather and breaking equipment could perhaps magnify each others effect on downtime, especially due to longer lead times in the Arctic.

8.1.4 Process Times and Distributions

To estimate process times and distributions, reference data from similar wells are commonly used both in time estimation programs and internal guidelines (Statoil 2014). Due to a lack of sufficient reference data, it is not possible to say that estimates for process times and distributions are accurate in the activity list for the model. The process times are calculated guesses, based on process times from the 4 reference wells. Without any reliable familiarity with the process times or knowledge of minimum or maximum values that could be used in a triangular distribution, it was decided that a normal distribution with 15% standard deviation was suitable for the purpose of the analysis.

In section 4.2 using arbitrary distributions in lack of good input data is mentioned as a pitfall. However, as the purpose of the model is to look at the effect of changing parameters and verifying the capabilities of the model, using accurate distributions was not considered to be essential. Arbitrary distributions were assigned to all the activities since correct data was too time consuming to find. With a limited amount of suitable weather data it was necessary to acquire a variance from stochastic process times in order to demonstrate the capabilities of the model. The exact results acquired from the model runs are therefore not representative of real campaign times, but valid for use in an sensitivity analysis and comparison of input parameters.

8.1.5 Weather

As mentioned in section 7.1.3 the model does not take into account two important aspects regarding weather, and a full discussion can be found in that section.

Possibilities on how to implement weather in the model, including uncertainty, was described in section 4.7.4. Including uncertainty in the model would require extensive research regarding the quality of the forecast given to the drilling unit. Though the uncertainty would benefit the model if a more detailed activity list is developed, as small, but weather sensitive operations affect the time use significantly and should be modelled correctly.

The model is built to facilitate the use of zones, as described in section 4.7.4, although it presently only handles wave height divided into zones for illustration of its capabilities. Using zones gives a better description of the systems response to weather, but requires weather data to be translated according to the equipments response. Zones can be used for ice, equipment and supplies also, although finding zones for these other aspects may not be possible due to the difficulty in parametrisation and other techniques or modelling approaches are probably more suited.

8.1.6 Iceberg Event Tree

The event tree approach is useful for investigating the efficiency of an ice management system, and can be altered without making radical changes in the structure of the simulation model. We believe that with the limited availability of data and knowledge of sea ice, stochastic methods are superior for simulation. The choice to use Eik and Gudmestad's (2010) event tree came from it's suitability as a flexible tool that could be improved with more data, and the simple way of visualising the probabilistic framework. A benefit of Eik and Gudmestad's iceberg event tree is the relative simplicity of adding scenario branches, to make the simulation more realistic.

The model uses the same exact probabilities found in Eik and Gudmestad (2010), however, there a number of extra assumptions that bring along a number of issues:

Frequency of Initiating Events
Only iceberg's that can cause an impact of 85MJ are classified as an initiating event, this depends entirely on the drilling unit's ability to withstand iceberg impacts and must be altered for the specific unit. The data is taken from different locations, although both Eik and Gudmestad and the model's sites are located in the Barents Sea, the iceberg occurrence should be used for the site. The data is collected for a whole year, whilst the model only focuses on a short season.

Detection
In real life iceberg detection probability is a function of time and how long the iceberg is within the detection zone, this could be solved by a step wise approach with more zones.
The other probabilities in the model vary depending on what equipment is employed. The addition of a correspondence between iceberg towing success in wave height above 6m, is also incorrect, as it is already accounted for in the statistics used to find the probability of success in Eik and Gudmestad (2010). The correspondence was implemented to illustrate how weather and ice management can be linked together, and how the model can be adjusted to add complexity.

Extra Scenarios
Eik and Gudmestad's (2010) event tree model only distinguishes between impact, emergency disconnection and planned disconnection in the outcome scenarios. A number of extra assumptions for the remaining scenarios, that are not part of Eik and Gudmestad's (2010) original paper, have been made to illustrate the capabilities of the model:

- It is assumed that after the detection of an iceberg, the drilling unit immediately starts a disconnection. The next step of the tree reveals whether the iceberg is headed for the drilling unit or not, and if the disconnection should continue. This scenario was called Started Disconnecting
- If the iceberg continues to head for the unit, but is successfully deflected, the disconnection can be reversed which is set to a Halfway Disconnecting.

The two extra scenarios were added, to show how the event tree can support a wider range of scenarios. Ideally, a comprehensive event tree could be created, including all the different aspects of an ice management fleet, together with data on ice features from the drill site. Constructing an event tree for ice management in ice floes is especially interesting, as many Arctic campaigns are situated in locations where pack ice is prevalent at the start and end of the season. This could demonstrate the differences between a regular semi-submersible and a drillship, or compare conventional mooring with turret mooring.

Time spent on disconnections can take a lot of time from the campaign, it is desirable to avoid as much time spent on false alarms as possible. Bonnemaire et al. (2011) developed simulation methodology for assessing sea ice downtime for a floating platform, and found that most of the downtime was spent disconnected and WOW before reconnection. Whilst preparing to disconnect and false alarms were numerous compared to real alarms, but constituted a smaller portion of downtime. We believe this supports our interpretation of the ice tree, with the added scenarios, where false alarms are numerous but less time consuming than real events.

Following ISO 19906 the Arctic campaign should have data on ice management and ice conditions from the geographical site to be drilled. This has been a major assumption during development of the model, to find an approach that can be applied if the relevant data is provided. As such, the event tree used in this paper is a good tool that can be built upon and modified. Albeit, the results that are acquired cannot be used except in a relative comparison with other results i.e. the sensitivity analysis, similarly as with process times and distributions. According to Eik (2010), environmental data in most Arctic regions are both expensive and complicated to collect, and therefore significant uncertainties must be expected. Therefore it may be hard to estimate how accurate the data required by ISO 19906 are, but it is reasonable to assume that these figures are available in the design phase to enable fleet and drilling unit specifications.

8.1.7 Implementation and Statistical Viability

This section discusses verification of the model in ExtendSim, and issues regarding statistical viablity of the results.

A problem associated with the abstract approach, include not being able to set different distributions for each specific activity in ExtendSim without a significant amount of customisation programming. This may not be of much importance as most operations are assumed to have a log normal distribution (Statoil 2014). The model has been created to handle all 3-parameter distributions in ExtendSim, so a range of different distributions can be used as long as they are more or less valid for all activities.

ExtendSim has inherent data collection capabilities that could have been exploited if the traditional modelling approach had been chosen. The blocks in ExtendSim are created to facilitate a large number of output data, and gathering information on specific activities would be easier. The abstract way of modelling requires more manual data processing in Excel after running simulations, and a long list of attributes to record data. Since the model intends to analyse the total completion time, identifying output from specific activities was not prioritised.

In the Disconnected processes section of the model, see subsection 5.5.3, there is no ice check, even though reconnecting may require a lot of time and ice could force the activity to disconnect. This was not included due to the base case where ice is so rare, it should be included for a model that simulates campaigns who are required to start or reconnect in ice floes.

When running this simulation a problem was identified with the set-up of the iceberg event tree, see appendix D. If the tree is altered in order to reduce the probability for impacts, as in section 7.2.5, the probability for full disconnection increases. While this shift in probability might be logical, we believe that the model could benefit from more branches in the tree to add to the realism of the model. The problem with more branches is to find good estimates regarding probabilities.

The number of runs are not sufficient enough to record any emergency disconnections. When creating the output, ExtendSim writes one row for each activity to an internal database. The limit to rows in ExtendSim is above one billion, meaning each season could have been run at least 400 000 times with 25 activities. Because of Excel's limit to about one million rows, the model was only run 40 000 times for each season, in order to handle the output in Excel efficiently and save time. These data handling restrictions could perhaps have been solved better with a traditional modelling approach.

The model does not have a good solution for starting multiple runs and changing the weather data after a given number of runs. Weather data has to be pre-loaded in ExtendSim from Excel before starting simulations, requiring an effort every time the model is run. In order to save time we chose to run simulations using weather data from 9 seasons.

A wider distribution of completion time was expected for an Arctic drilling campaign, including a longer tail for the graphs showing days until completion, resulting from a higher share of the model runs requiring more time to completion. The reason for the almost normal distributed results in the model is probably due to following reasons:

The process times used include non-productive time except WOW. This is important as a real life Arctic drilling campaign would probably experience a higher frequency of serious problems. For example, one of the reference wells experienced spending more than 10 days fishing for lost equipment in the well. This causes the completion time to be log normal distributed. Due to a lack of data a normal distribution was chosen, which is unsatisfactory to model real process times.

Lack of deviation in weather. The 9 seasons the model was run with, did not contain enough variation in weather conditions. The lack of deviation can be seen in the results from the small difference between P50 and P70; a consequence of little deviation in the completion times.

8.2 Fictive Well Results

This section discusses the results collected from altering input parameters.

As seen in the results from section 7.2 when improving the parameters for the rig, the required times associated with disconnection and probabilities in the ice event tree the KPI's P50 and P70 were reduced. When improving the parameters a reduction of the time needed for completion of a well was expected, but since the input data is uncertain, a discussion about the extent of the improvement is difficult, and there is no reference literature found on the subject.

For the run with improved rig parameters the number of times spent WOW was reduced, and number of disconnections due to weather were eliminated, as expected. As the rig parameters only regard the weather and actions due to ice is independent of the rig data, a reduction within the range of the P50 improvement value could be expected for ice related events. We believe that the increase in the average number of disconnections halfway by 5.5%, and the increase of one impact is a result of too few model runs, not giving a good spread of the results. There were no emergency disconnections, also due to few runs compared to the probability of ice related interruptions, see appendix D. These unsatisfactory conditions have resulted in relatively large deviations, but could be amended by employing a larger variation in data and running more simulations.

The results from the runs with improved disconnection times show much of the same as for improved ice management. While the average number of disconnections due to weather is stable compared to the base case, the hours spent are reduced, which is expected. As the required window and disconnection times are shorter, the drilling unit can reconnect faster. The deviation in terms of ice related disruptions is not in line with the improvement of the P50. The number of impacts increase from 7 to 10, signalising too few model runs.

When changing the probabilities in order to simulate improved ice management, the reduction in the number of full disconnections and impacts were large. The average number of full disconnections was reduced by almost 74% and the number of impacts reduced to zero for all 360 000 runs. The reduction agrees well with the altered probabilities in the iceberg event tree. The results show that the average number of disconnections halfway and started increased.

Improved ice management increases the total probability for an ice related incident with 1.0%, but the probability is shifted towards ice scenarios that require less time, halfway and started disconnections. This problem could be solved by making the event tree more accurate by adding more branches and features.

8.3 Potential Improvements in Technology

This section discusses what the results, from altering input parameters, could potentially indicate for the choice of technology in an Arctic drilling campaign.

8.3.1 Rigdata

What kind of drilling unit would be most suited to the Arctic, could the model reveal if a semi-submersible or a drillship would be best? Probably yes, as seen in Section 7.2, the weather for the location in the Perseyevsky lisence was too calm regarding wave height to cause any WOW. The subarctic does not have the same occurence of ice as further north, but more violent seas. From this one might conclude that the motion characteristics of a semi-submersible are not required for drilling in the high Arctic, especially since pillared semi-submersibles do not possess good ice characteristics and a low variable deck load to carry equipment and supplies in such a remote location. Compared to a drillship, semi-submersibles are probably best suited for subarctic conditions, where they have a superior tolerance to rough weather.

On the other hand we saw that by improving the drilling unit's operational limits by 10% when running the model with harsher weather disconnection due to weather was eliminated. We maintain that this shows the models ability to evaluate the design of a drilling unit, for a specific geographic location and the model can give important inputs to what kind of capabilities that are needed.

8.3.2 Operational Limits

Shorter disconnection time is associated with the kind of technology and mooring equipment the drilling unit possesses. Runs that show a benefit from shorter windows, disconnection and reconnection times, can indicate that dynamical positioning or turret mooring is beneficial or the use of drilling muds and fluids that are water based and can be released quickly.

A shorter weather window could also indicate technology that allows for operations to be temporarily abandoned whilst the drilling unit has to disconnect or move off. This could be for example a mudline cellar in shallows waters where there is potential for ice scouring, the drilling unit could save time by leaving the BOP on the sea floor.

Since real weather forecasts have a sufficient level of certainty, we believe an improvement in technology that improves the operational limits changed in this model, are only necessary in waters with a regular occurrence of sea ice.

8.3.3 Ice Management

The results are taken from regions with limited threat by ice features and employed a somewhat stunted event tree, therefore they do not give much indication as to what benefits a drilling campaign can have from improved ice management.

Liferov (2014) suggests that the majority of ice actions are unnecessary due to conservatism, therefore perhaps pointing to the fact that better detection and ice evaluation is required, although there are uncertainties regarding extremes. The results and research from this thesis also point to the fact that detection of ice features may be more important in locations with less ice. Considering the shift of ice related incidents from emergency disconnections to less time consuming scenarios, such as halfway disconnecting. This may indicate the relative benefit of improved detection and tracking systems, compared to improving the success rate of towing icebergs, as this still leads to time being spent preparing to disconnect. The model must be developed further to be able to assess campaigns in areas that require the fleet to handle ice floes.

Chapter 9

Conclusion

9.1 The Model

By using discrete event simulation, a model was developed to simulate an Arctic offshore exploration drilling campaign. The campaign is divided into a series of activities, that are processed in the model. Weather and ice data affect the activities as they are processed in the model, to estimate the time needed to complete a campaign and the effect of different technological solutions.

The model is general in design in order to allow the simulation of a variety campaign- and well set ups, and open to alterations in the level of detail in the division of the campaign. Aspects included in the model range from a drilling unit's station keeping ability to technology affecting the process time for drilling operations. The design of the model also facilitates implementation of further levels of complexity and additional scenarios.

The model was validated using 4 existing wells from the southern part of Barents Sea, giving satisfying results. After validation, iceberg considerations were implemented in the model, using an event tree approach. Research was done to enable the consideration of ice floes in the model, but no satisfactory data was found for implementation.

9.2 The Results

With background in the assumptions taken in the development of the model, and analyses of the results, we can conclude that wave height does not constitute the greatest challenge north in the Barents Sea, this is also confirmed by North Atlantic Drilling and Statoil. The sea state seems to be more severe in the southern part of the Barents Sea, implying that the design of the drilling unit should consider the location of the drill site.

As drilling moves further north, ice management gains importance as the frequency of sea ice increases. As seen in subsection 7.2.5 the capabilities regarding detection and towing of icebergs affect the total time spent on completing the campaign. The data used in our event tree is based on the Shtokman field. Since the assumptions on ice implemented in the model have not been verified and validated to a satisfactory degree, we are not able to conclude anything certain regarding the importance of ice management. What we can conclude is that the model is suitable for an evaluation of ice management capabilities, provided that the right frequency for an initiating event is given.

The results show that the model is sensitive to changes in the parameters, proving that the use of correct input parameters are important for the results. Several scenarios of different input parameters were run in the model, and the results showed improvement in the total time spent by the campaign. An indication as to what technology is suitable for a specific campaign can be interpreted from the results, but the input parameters are too uncertain to conclude anything. With reliable input parameters, the model is able to predict what technology and operations are best suited for a location.

Chapter 10

Further Work

In this thesis a model has been developed to simulate an Arctic drilling campaign. The model requires additions for more scenarios and validation with reliable data, to be able to give correct estimations of time use for an Arctic campaign. There are several parts of the model that could be improved, altered and parts that are suitable for more in-depth investigation mentioned in Chapter 8. Weather should be modelled to include uncertainties in the forecasts, and ice will require specific data for the relevant location and ice management equipment to be employed. Logistics and the unavailability of crew and equipment is a wide spanning field, modelling the logistical challenges for an Arctic drilling campaign, could form the basis for a simulation problem of its own.

End Note

When the work on this project started as a summer project for Statoil in 2013, an ambitious scope for the model was made. As our mentor Arent Arntzen in Statoil had considerable experience and skills with simulation as a tool, a wide range of aspects associated with a drilling campaign were intended to be included in the model. A study was done of the different discrete event simulation software on the market, and Micro Saint Sharp was chosen mainly because of Arents' experience and programming skills.

The sudden and unexpected death of Arent in January 2014 has affected our model in several ways. Most importantly we lost an extremely competent mentor and a good sparring partner. Arent had huge ambitions for the model and was the driving force behind this project, providing us with plenty of input regarding modelling techniques and data. After his death we found it necessary to start modelling in ExtendSim instead of Micro Saint Sharp, due to our lack of experience in programming in C#. The availability of data was also affected, as Arent was our dedicated contact in Statoil with the connections to get the right data. Even though Statoil have been very helpful providing us with data for the model, we experienced spending a lot of time finding the right people and obtaining data. There is no doubt that both the scope of this project and the model would have been different if it were not for this tragic event. Despite of the sad circumstances, we believe have made the best out of situation, and the development of the model continued in ExtendSim.

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Appendix

A Master Thesis Problem Formulation

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

MASTER THESIS IN MARINE TECHNOLOGY
SPRING 2014
For stud.techn
Henrik Mikael Rode & Fredrik Stang Heffermehl

Arctic Drilling Discrete Event Simulation

Background
This master thesis in Marine Systems Design is a continuation of our project thesis, which started as a summer project for Statoil in 2013.

Arctic offshore exploration drilling must contend with the potential presence of ice, in addition to other environmental challenges. As a first step in a cautious approach to the Arctic, extending the open water season by managing ice and enhancing the drilling unit is considered. However, drilling and abandoning an exploration well within one season will still be a major challenge. The timeliness of the drilling campaign will be of the essence. Towards that goal new technologies can be implemented to decrease the time consumed to drill and work the well. To make rational and cost effective design choices one must have an engineering model that can support the evaluation of the different technologies and techniques selected.
The drilling campaign consists of a series of operations ranging from transit and mobilization, to the return of the drilling task fleet for other missions. All of the operation's process times involved are impacted by the choice of technology, with a naturally occurring stochastic element. Drilling operations will suffer from inclement weather, equipment breakdown, human errors, and plain bad luck. In the design of an optimal floating drilling vessel, the relative merit of technical investments must be compared with the ability to complete the drilling campaign whilst maintaining a high level of safety.To add to the complexity, the design of the drilling vessel may be subject to the designed capacity of the supporting vessels and monitoring equipment (e.g. ice breakers, supply ships and satellites), therefore the true design problem is of a floating drilling unit with an accompanying support fleet and equipment.

NTNU Trondheim
Norwegian University of Science and Technology
Department of Marine Technology

Objective
To develop a discrete event simulation model that can realistically simulate a drilling campaign in the Arctic, and facilitate a comparison of different technological solutions.

The model will need to be general and able to handle statistical input data from different kinds of equipment, operations and specifications of the drilling task fleet, therefore event descriptors and process times must be parameterised. It is important that the model does not need modification for specific process descriptions or data, only parameter data will be changed to model the effect of using different kinds of equipment or changing operations. The model must provide output data in order to facilitate analyses of input parameters, this will lay the basis for a discussion of the merit of different technologies represented by the parameters.

Task
The candidates are recommended to cover the following parts in the master thesis:

a. Conduct a literature review of state of the art theory, regarding drilling and stationkeeping equipment for use in Arctic operations, to be able to evaluate and understand the application of these. This shall be presented as a written report.
b. Acquire an understanding of the problems and challenges that can arise when conducting a drilling campaign in Arctic conditions such as, but not limited to: ice, weather and visibility, location and environmental concerns. We will implement this knowledge in the simulation model, so that it canto handle a suitable range of events.
c. Find specifications and process times for drilling operations with the assistance of Statoil and experienced professionals, to acquire substantiated data for what conditions that may require disruption of activities and parameterising these data in a realistic manner in our model.
d. Research available data sets regarding weather in relevant areas, comparing weather and drilling data to find a suitable technique to parameterise and model the influence of weather and forecasts on the drilling campaign.

e. Research available data on ice, especially unmanageable ice conditions, and find a suitable approach to parameterise and model the influence of incoming ice.
f. Sequencing the chain of events for the drilling campaign and the drilling operation proper, to include all relevant aspects of the operational concept and verify the accuracy of our model by using existing well programs with available weather and ice data.
g. Perform a sensitivity analysis on the process parameters of a typical drilling campaign and acquire results that illustrate the merit of changing parameters.(KPI)
h. Discuss the results, and identifying any key parameters that make a decisive difference for an operation or the entire campaign.
i. Discuss the uncertainty of our methods, results and analyses. Recommendations for improvements and further work
j. Acquire programming and simulation skills, employing ExtendSim, to be able to fully model the problem.

General

In the thesis the candidates shall present their personal contributions to the resolution of a problem within the scope of the thesis work.

Theories and conclusions should be based on a relevant methodological foundation that through mathematical derivations and/or logical reasoning identify the various steps in the deduction.

The candidates should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear statement of assumptions, data, results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, discussion of results and conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidates, in an early stage of the work, present a written plan for the completion of the work.

The original contribution of the candidates and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

Deliverable

- The thesis shall be submitted in two (2) copies:
- Signed by the candidates
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervision:
Main supervisor: Bjørn Egil Asbjørnslett

Sub-supervisor: Stein Ove Erikstad

Company contacts: Arne Torsvoll, Statoil

Deadline: 10.06.2014

B Activity Lists - Not Confidential

B.1 Activity List Fictive Arctic Well

Activity list

										Weather		Ice			
Section	Activity	CreateTime	Number	Mean	std	Location	Zone req	Status		Required Time Disc	Required Time Recon.	Start	Halway	Disctime	Rectime
MOB		0.1	1	40	6	0	2	1	5	3	3	0.75	1.5	7	7
Pre-Spud		1	2	5	0.75	0	2	1	5	3	3	0.75	1.5	7	7
8 1/2"		2	3	50	7.5	0	1	1	20	3	3	0.75	1.5	7	7
		3	4	50	7.5	0	1	1	20	3	3	0.75	1.5	7	7
Pre-Spud		4	5	5	0.75	0	2	1	5	3	3	0.75	1.5	7	7
	Drill	5	6	35	5.25	0	2	1	5	3	3	0.75	1.5	7	7
36"	Conductor & cement	6	7	45	6.75	0	1	1	10	3	3	0.75	1.5	7	7
	Drillout	7	8	10	1.5	0	2	1	2	3	3	0.75	1.5	7	7
12 1/4"	Drill	8	9	50	7.5	0	2	1	5	10	10	2.5	5	14	14
	Casing and cement	9	10	45	6.75	0	2	1	10	10	10	2.5	5	14	14
	BOP	10	11	25	3.75	0	1	1	20	24	24	6	12	28	28
	Drillout	11	12	20	3	0	2	1	3	24	24	6	12	28	28
8 1/2"	Drill	12	13	70	10.5	0	2	1	6	24	24	6	12	28	28
	Logging	13	14	40	6	0	2	1	6	24	24	6	12	28	28
	Liner	14	15	60	9	0	2	1	17	24	24	6	12	28	28
	BOP testing	15	16	18	2.7	0	2	1	17	24	24	6	12	28	28
	Drillout	16	17	30	4.5	0	2	1	17	24	24	6	12	28	28
6"	Drill	17	18	70	10.5	0	2	1	6	36	36	9	18	40	40
	Coring	18	19	60	9	0	2	1	17	36	36	9	18	40	40
	Drill	19	20	60	9	0	2	1	17	36	36	9	18	40	40
	Logging	22	21	50	7.5	0	2	1	17	36	36	9	18	40	40
P & A	Cement & plugging	23	22	60	9	0	2	1	17	24	24	6	12	28	28
	Retrieve warebushing & BOP	24	23	40	6	0	1	1	10	24	24	6	12	28	28
	Retrieve casings	25	24	40	6	0	1	1	10	24	24	6	12	28	28
DeMOB		26	25	40	6	0	1	1	10	24	24	6	12	28	28

B.2 Activity List Fictive Arctic Well - Short Windows

Activity list

Section	Activity	CreateTime	Number	Mean	std	Location	Zone req	Status		Weather: Required Time Disc	Weather: Required Time Recon.	Ice: Start	Ice: Halway	Ice: Disctime	Ice: Rectime
MOB		0.1	1	40	6	0	2	1	2.5	1.5	1.5	0.375	0.75	5.5	5.5
Pre- Spud		1	2	5	0.75	0	2	1	2.5	1.5	1.5	0.375	0.75	5.5	5.5
8 1/2"		2	3	50	7.5	0	1	1	10	1.5	1.5	0.375	0.75	5.5	5.5
		3	4	50	7.5	0	1	1	10	1.5	1.5	0.375	0.75	5.5	5.5
Pre- Spud		4	5	5	0.75	0	2	1	2.5	1.5	1.5	0.375	0.75	5.5	5.5
36"	Drill	5	6	35	5.25	0	2	1	2.5	1.5	1.5	0.375	0.75	5.5	5.5
	Conductor & cement	6	7	45	6.75	0	1	1	5	1.5	1.5	0.375	0.75	5.5	5.5
	Drillout	7	8	10	1.5	0	2	1	1	1.5	1.5	0.375	0.75	5.5	5.5
12 1/4"	Drill	8	9	50	7.5	0	2	1	2.5	5	5	1.25	2.5	9	9
	Casing and cement	9	10	45	6.75	0	2	1	5	5	5	1.25	2.5	9	9
	BOP	10	11	25	3.75	0	1	1	10	12	12	3	6	16	16
	Drillout	11	12	20	3	0	2	1	1.5	12	12	3	6	16	16
8 1/2"	Drill	12	13	70	10.5	0	2	1	3	12	12	3	6	16	16
	Logging	13	14	40	6	0	2	1	3	12	12	3	6	16	16
	Liner	14	15	60	9	0	2	1	8.5	12	12	3	6	16	16
	BOP testing	15	16	18	2.7	0	2	1	8.5	12	12	3	6	16	16
	Drillout	16	17	30	4.5	0	2	1	8.5	12	12	3	6	16	16
6"	Drill	17	18	70	10.5	0	2	1	3	18	18	4.5	9	22	22
	Coring	18	19	60	9	0	2	1	8.5	18	18	4.5	9	22	22
	Drill	19	20	60	9	0	2	1	8.5	18	18	4.5	9	22	22
	Logging	22	21	50	7.5	0	2	1	8.5	18	18	4.5	9	22	22
P & A	Cement & plugging	23	22	60	9	0	2	1	8.5	12	12	3	6	16	16
	Retrieve warebushing & BOP	24	23	40	6	0	1	1	5	12	12	3	6	16	16
	Retrieve casings	25	24	40	6	0	1	1	5	12	12	3	6	16	16
DeMOB		26	25	40	6	0	1	1	5	12	12	3	6	16	16

C Rigdata

C.1 Result from verification

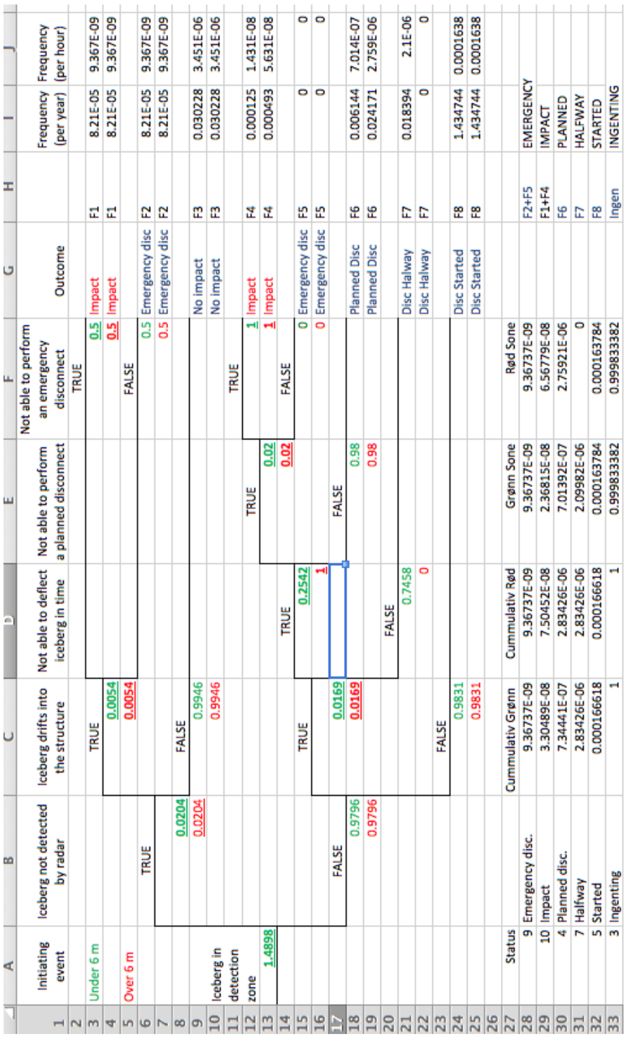
	A	B	C
1	Rigname		
2	Polar Pioneer		
3			Waveheigth
4	Delicate	Green	5
5	Advisory	Blue	7
6	Stand-by connected	Yellow	9.4
7	Survival	Red	>9.4

C.2 Improved technology

	A	B	C
1	Rigname		
2	Polar Pioneer		
3			Waveheigth
4	Delicate	Green	5.5
5	Advisory	Blue	7.7
6	Stand-by connected	Yellow	10.34
7	Survival	Red	>10.34

D Iceberg Event Tree

D.1 Iceberg Event Tree



	A	B	C	D	E	F	G	H	I	J
1	Initiating event	Iceberg not detected by radar	Iceberg drifts into the structure	Not able to deflect iceberg in time	Not able to perform a planned disconnect	Not able to perform an emergency disconnect	Outcome		Frequency (per year)	Frequency (per hour)
2						TRUE				
3	Under 6 m		TRUE			0.5	Impact	F1	8.21E-05	9.367E-09
4			0.0054			0.5	Impact	F1	8.21E-05	9.367E-09
5	Over 6 m		0.0054			FALSE				
6		TRUE				0.5	Emergency disc	F2	8.21E-05	9.367E-09
7						0.5	Emergency disc	F2	8.21E-05	9.367E-09
8		0.0204	FALSE							
9		0.0204	0.9946				No impact	F3	0.030228	3.451E-06
10	Iceberg in		0.9946				No impact	F3	0.030228	3.451E-06
11	detection					TRUE				
12	zone				TRUE	1	Impact	F4	0.000125	1.431E-08
13	1.4898				0.02	1	Impact	F4	0.000493	5.631E-08
14				TRUE	0.02	FALSE				
15			TRUE	0.2542		0	Emergency disc	F5	0	0
16				1		0	Emergency disc	F5	0	0
17		FALSE	0.0169		FALSE					
18		0.9796	0.0169		0.98		Planned Disc	F6	0.006144	7.014E-07
19		0.9796			0.98		Planned Disc	F6	0.024171	2.759E-06
20				FALSE						
21				0.7458			Disc Halway	F7	0.018394	2.1E-06
22				0			Disc Halway	F7	0	0
23			FALSE							
24			0.9831				Disc Started	F8	1.434744	0.0001638
25			0.9831				Disc Started	F8	1.434744	0.0001638
26										
27	Status		Cummulativ Grønn	Cummulativ Rød	Grønn Sone	Rød Sone				
28	9	Emergency disc.	9.36737E-09	9.36737E-09	9.36737E-09	9.36737E-09		F2+F5	EMERGENCY	
29	10	Impact	3.30489E-08	7.50452E-08	2.36815E-08	6.56779E-08		F1+F4	IMPACT	
30	4	Planned disc.	7.34441E-07	2.83426E-06	7.01392E-07	2.75921E-06		F6	PLANNED	
31	7	Halfway	2.83426E-06	2.83426E-06	2.09982E-06	0		F7	HALFWAY	
32	5	Started	0.000166618	0.000166618	0.000163784	0.000163784		F8	STARTED	
33	3	Ingenting	1	1	0.999833382	0.999833382		Ingen	INGENTING	

D.2 Ice-tree - Better Ice Management and Monitoring

	A	B	C	D	E	F	G	H	I	J
1	Initiating event	Iceberg not detected by radar	Iceberg drifts into the structure	Not able to deflect iceberg in time	Not able to perform a planned disconnect	Not able to perform an emergency disconnect	Outcome		Frequency (per year)	Frequency (per hour)
2						TRUE				
3	Under 6 m		TRUE			0.5	Impact	F1	4.1E-05	4.684E-09
4			0.0054			0.5	Impact	F1	4.1E-05	4.684E-09
5	Over 6 m		0.0054			FALSE				
6		TRUE				0.5	Emergency disc	F2	4.1E-05	4.684E-09
7						0.5	Emergency disc	F2	4.1E-05	4.684E-09
8		0.0102	FALSE							
9		0.0102	0.9946				No impact	F3	0.015114	1.725E-06
10	Iceberg in		0.9946				No impact	F3	0.015114	1.725E-06
11	detection					TRUE				
12	zone				TRUE	1	Impact	F4	6.33E-05	7.232E-09
13	1.4898				0.02	1	Impact	F4	0.000249	2.845E-08
14				TRUE	0.02	FALSE				
15			TRUE	0.1271		0	Emergency disc	F5	0	0
16				0.5		0	Emergency disc	F5	0	0
17		FALSE	0.0169		FALSE					
18		0.9898	0.0169		0.98		Planned Disc	F6	0.003104	3.543E-07
19		0.9898			0.98		Planned Disc	F6	0.012211	1.394E-06
20				FALSE						
21				0.8729			Disc Halway	F7	0.021753	2.483E-06
22				0.5			Disc Halway	F7	0.01246	1.422E-06
23			FALSE							
24			0.9831				Disc Started	F8	1.449683	0.0001655
25			0.9831				Disc Started	F8	1.449683	0.0001655
26										
27	Status		Cummulativ Grønn	Cummulativ Rød	Grønn Sone	Rød Sone				
28	9	Emergency disc.	4.68369E-09	4.68369E-09	4.68369E-09	4.68369E-09		F2+F5	EMERGENCY	
29	10	Impact	1.6599E-08	3.78158E-08	1.19153E-08	3.31321E-08		F1+F4	IMPACT	
30	4	Planned disc.	3.70947E-07	1.43179E-06	3.54348E-07	1.39397E-06		F6	PLANNED	
31	7	Halfway	2.85421E-06	2.85421E-06	2.48326E-06	1.42242E-06		F7	HALFWAY	
32	5	Started	0.000168343	0.000168343	0.000165489	0.000165489		F8	STARTED	
33	3	Ingenting	1	1	0.999831657	0.999831657		Ingen	INGENTING	

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