ARCTIC OIL SPILL RESPONSE
RECOVERY OPERATIONS - MANAGEMENT AND PERFORMANCE

VICTOR WESTERBERG
vwes@kth.se

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Preface

This report contains the work of a Master Thesis project performed in spring 2012 at SSPA Sweden AB in Gothenburg. The work was performed by one student studying Naval Architecture at Centre for Naval Architecture at The Royal Institute of Technology (KTH), in Stockholm. The work was supervised at SSPA by Jim Sandkvist, Björn Forsman, Johannes Hüffmeier, Edvard Molitor and examined at KTH by Karl Garme.

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Abstract

With increasing presence and interest of shipping activities in the Arctic, the risk for an oil spill also increases. The activities are coupled to a growth of Arctic tourism (cruise vessels), exploitation of oil and gas resources as well as possibilities for merchant ships to sail the routes of Northwest and Northeast passages.

The Arctic offers an impressive environment with high potential for tourism and offshore activities, however the Arctic is also highly vulnerable. Thus, higher demand of awareness of the risks as well as the possibilities and opportunities to take care of an oil spill and reduce the consequences are needed. Initially the report gives a background to the subject of Arctic oil spill which is followed by a review of Arctic oil spill response. The processes involved and oil spill countermeasures that are used or have shown potential in Arctic conditions are handled.

To increase awareness a decision support tool which aims to cover preparedness, response and performance of an Arctic oil spill response operations is developed and presented. In the model structure, a wide range of input and sub-models are included to be able to cover the whole operation and different sub-areas that are identified.

Finally a further developed part of the decision support tool is presented concerning the window of opportunity which review the response methods. The model, which is based on a Bayesian Network approach, provides the user with estimations of response method potentials as function of time. The model output are easy and clear to interpret for contingency planning as well as for operational use.
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1 Introduction

The energy demand is continuously increasing over the world. With estimates of signifi-
cant oil and gas reserves in the Arctic, this highly vulnerable environment is now facing
an increased industrial activity. Accessing oil and gas resources in the Arctic sets new
demands on operations, equipment and crew as the conditions are extreme with e.g.
tough ice conditions, low temperatures and low visibility.

Increasing average temperatures yields lower ice concentrations during the Arctic sum-
mer, resulting in an increasing presence of cruise vessels and an expected increase of
merchant vessels using the possibility to sail the routes of Northwest and Northeast pas-
sages. As the industrial activity and merchant ship presence increases, the risk increases
for an oil spill that needs to be taken care of.

Highly vulnerable environmental areas together with new response conditions and con-
straints set a high demand on development of oil spill response contingency plans and
management to be able to minimize the impact on the environment that a possible oil
spill could bring.

1.1 Background

Arctic oil spill response or oil spill in ice is a field of research and development that
has gained focus during the last decade. In the past the Arctic area was remote and
conditions considered too harsh for industrial operations and only minor tourism took
place. With increased world-wide demand for natural resources, increasing average tem-
peratures and technical development new possibilities are available.

The Arctic nations have been developing contingency plans and guidelines for an oil
spill in ice. A joint effort by the Arctic nations (through the Arctic Council) to stan-
dardize the contingency planning, methods and strategies resulted in [5]. Independent
environmental organizations have also put their attention to the subject of the increas-
ing industrial activity by identifying environmental and safety problems thus asking for
sustainable solutions, [17] and [18].

For governmental approval prior to industrial activity in the Arctic well established
contingency plans are required. This has further increased the interest in the subject.
Companies have together invested in ‘Joint Industry Programs, JIP’ which have been
implemented by research institutes, [24].

With increasing interest in the Arctic oil resources, tourism and an overall increased
environmental awareness, Arctic oil spill response is a hot topic. Knowledge of oil spill
response, contingency planning and management has become an essential and important
selling point for industrial companies and sub-contractors. This work intends to, by the
use of current response methods, create guidelines for an Arctic oil spill response tool.
1.2 Objectives and purpose
The objective is to develop guidelines for a decision support tool, *response tool for Arctic oil spill* (RAOS), that determines possible countermeasures and the extent of an Arctic oil spill response force for a given oil spill\(^1\).

The work is intended to expand the current SSPA developed decision support tool IceMaster further and be a useful tool when managing oil spill response operations in the Arctic.

1.3 Methods
The first part of the work focus on current Arctic oil spill response techniques and the possibilities that are available. This is summarized through a review of important oil response concepts and available response methods.

To get a broader view, real cases with documented spill response in ice operations are sought for and the lessons learned from these situations highlighted.

When conditions and constraints are well established a decision model structure concerning response operations and management is presented and explained. The work then proceeds with modeling of a certain sub-model of RAOS in more detail.

**Modeling**

The modeling method used to describe the sub-model of RAOS is based on the same methodology as the important reference IceMaster. The main modeling method uses the Bayesian Network approach with probability calculations where the connection between submodules and variables within the model is implemented and based on either quantitative or qualitative information.

This modeling method is beneficial in its graphical presentation where the different variables and submodules are linked together which makes the dependencies and relations easy to grasp.

See example in Figure 1, where sun hours may be derived based on the causal relation between latitude and date.

\[\text{Latitude} \rightarrow \text{Sun hours} \rightarrow \text{Date}\]

Figure 1: Simple Bayesian Network.

---

\(^1\)Focusing on Tier 2 and Tier 3 spills according to definitions by IPIECA in [3]
2 Arctic oil spill

The Arctic is defined in different ways, the area north of the Arctic Circle (66°33′N) or the area in the most northern part of the earth where the monthly warmest average temperature is below 10 °C, see Figure 2.

Thus an Arctic Oil Spill is here defined as an oil spill that occurs within the Arctic area or in areas with the same or similar climate, sea and ice conditions.

An oil spill can be defined by a wide range of parameters although the most important handles the spill character (surface or sub-sea), spill volume (batch or chronic leak), oil type (properties) and current ice condition.

Figure 2: Definitions of the Arctic (WWF, [25]).
The overall goal after an accident or failure that causes an undesirable oil spill is to respond to the oil spill and try to minimize the adverse consequences. Therefore a tiered approach that defines marine oil spills have been established by IPIECA\(^2\). The tiered approach classifies the size of an oil spill according to the expected size of the following response operation that is needed. The scale is divided into Tier levels 1-3.

**The Tiered response, [9]:**

- **Tier 1:** Operational-type spills that may occur at or near a company’s own facilities, as a consequence of its own activities. An individual company would typically provide resources to respond to this type of spill.

- **Tier 2:** A larger spill in the vicinity of a company’s facilities where resources from other companies, industries and possibly government response agencies in the area can be called in on a mutual aid basis. The company may participate in a local cooperative where each member pools their Tier 1 resources and has access to any equipment that may have been jointly purchased by a cooperative.

- **Tier 3:** The large spill where substantial further resources will be required and support from a national (Tier 3) or international cooperative stockpile may be necessary. It is likely that such operations would be subject to government controls or even direction.

This report will focus on Tier 2 and Tier 3 spills.

Possible sources that could cause an oil spill of Tier 2 or Tier 3 level in the Arctic due to accidents or failures are associated with offshore operations and merchant ships. The spill scenario may therefore differ ranging from light refined grades and bunker oils to untreated crude oils.

The possible spectra of oil types have a wide dispersion in physical properties which needs to be accounted for in the following response operation. The most important physical oil properties according to spill response depends on the chemical composition of the oil which affects the specific gravity, distillation characteristics, viscosity and pour point [3].

Directly after oil is spilled natural processes starts which changes the properties of the oil, a common used term for this process is ‘weathering’.

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\(^2\)IPIECA - International Petroleum Industry Environmental Conservation Association
3 Arctic oil spill response

In this section available offshore oil spill in ice concepts, mechanisms and response methods will be presented and the process from spill to response operation described. In the last part of the section a review of a real spill case is made. Fortunately there have not been that many major oil spills in ice so far. However available information about oil spill from the grounded vessel Godafoss in the south of Norway in February 2011 is presented, see Figure 3.

The intention with the section is to provide the reader with an introduction and overview for the following chapters, readers familiar to the subject may move on to section 4.1.
When oil is spilled, processes immediately starts where oil, water and air are involved. These processes are called weathering. The weathering process and rate is for instance affected by temperature, waves and ice. The processes affects the spilled oil and changes its properties which in turn affects the window of opportunity for different response methods, their availability and estimated potential.

The research and development on oil spill in ice is a continues work. Well known methods are improved, new systems and techniques are developed and processes are investigated to increase understanding. However, so far, the previously known processes and response methods may be divided into five different groups.

- Weathering - The processes changing the properties of the spilled oil.
- Remote sensing - How to identify, track and follow an oil spill.
- Mechanical recovery - Techniques used to recover oil from spill site.
- In-situ burning - Burning of oil at spill site to remove the spilled oil.
- Dispersants - Chemical compounds added to dilute and increase rate of natural processes.

The presence of ice and cold water during a response operation change the circumstances which sometimes hinders the response units in its work but sometimes the ice and cold water may be favorable as well.

Important properties and added constraints during operations involves icebreaking capabilities, low temperatures, low visibility, lack of basic infrastructure etc.

3.1 Spill response concepts

In contingency plans and spill response there are two commonly used concepts; ‘window of opportunity’ and ‘response gap analysis’.

3.1.1 Window of opportunity

The ‘window of opportunity’ (WoO) is a strongly time dependent concept as it describes the possibilities to respond to an oil spill. As the duration of the spill increases the oil slick is weathered and oil is eventually spreading which may ‘close opportunities’ such as ignitability of the slick or the use of dispersants. For a successful and effective response operation a rapid and distinct response is important before the window of opportunity changes, decreases or closes.
3.1.2 Response gap analysis

‘Response gap’ is a concept used to identify situations when there are risks for oil spill but effective response resources are missing. The response gap is used to identify and highlight operational conditions or locations where environmental protection preparedness and safety cannot be established. Several surrounding factors may be calculated for in a response gap analysis.

Operational limits need to be set for variables such as weather (wind, current, visibility, temperature etc.), location (ice conditions, ocean currents etc.) and then considered in calculations for the specific location and operation. The availability of response units, remoteness of location and lack of basic infrastructure should be accounted for in a thorough response gap analysis.

If a response gap is found for certain circumstances, two options are available. One is to improve the operation and response resources to overbuild the gap. The other is to restrict the operation under the specific conditions where the response gap occurs to ensure environmental protection and personnel safety.

3.2 Remote sensing - Spill detecting and surveillance

Depending on spill source, oil type and spill type it may be difficult to know where the oil is situated and how it is spreading. Therefore different methods, so called, remote sensing methods have been developed. Remote sensing is a generic name for all detection and surveillance methods available and involves for instance airborne units, response vessels, satellite pictures and on ice personnel.

After an accident or detection of an oil spill airborne units often arrive to the area in an early stage and remote sensing starts. The airborne units is favorable in its ability to cover large areas in a short time which hopefully gives an overview of the spill and its magnitude. During the response operation continued remote sensing and documentation (e.g. GIS-mapping) from all included units is essential for operation management.

Different systems have been developed to aid the work of detecting and monitor an oil spill. Techniques with various properties and potential in different situations have been tested and used: Side-Looking Airborne Radar (SLAR); Satellite-based Synthetic Aperture Radar (SAR); aircraft and vessel-based Forward Looking Infrared (FLIR); Ground Penetrating Radar (GPR) and Laser Fluorosensors. The sensors are operated using airborne units, see example Figure 4, vessels, satellites and on ice stationed personnel.

The aim with the different systems is to have a complete toolbox of sensors that covers all probable spill situations. The remote sensing and spill surveillance area is a field with high potential for research and development.
3.3 Weathering - Oil and ice interactions

Directly as oil is spilled it is also exposed to air, water and possibly sunlight which starts processes summarized as weathering processes. The weathering processes in open temperated waters are more or less the same as in ice infested waters with low temperature. However the rates of the processes changes and additional variables are inferred through the oil-ice interactions.

3.3.1 Ice conditions

The oil and ice interaction and the weathering processes is highly affected by the ice condition. Depending on location and environmental state variables the ice condition may vary significant and also change relatively fast.

The ice condition is characterized by a wide range of parameters such as multi-year ice (MYI) or first-year ice (FYI), ice type, ice concentration, ice thickness, ice floe size, ice ridges, ice drift and season (freeze-up/thaw). The combination of parameters often leads to the use of ice descriptions such as fast ice, pack ice, drift ice, broken ice, brash ice, grease ice, frazil ice.

Spreading of oil is highly affected by the ice condition. With ice concentration about 40% and a slow drift ice situation the ice may work as a natural barrier. The ice may capture the oil slick between the ice floes and thereby prevent it from spreading.

If the spill occurs on top of an ice field the presence of a snow layer also affect the behavior of the spill as oil may be absorbed and contained by the snow. Different oil-ice interactions are described in Figure 5.
Figure 5: Oil-ice interactions (p. 4 [15]).
3.3.2 Oil types

Weathering processes and response performances are also affected by, and changes, the properties of the oil. Therefore understanding of the properties and behavior of the oil in cold and icy waters are important for the management of the response operation. The oil types may vary from very light refined grades (e.g. gasoline), different fuel and lubricant oils to crudes.

![Oil in ice during tests](Photo: Jim Sandkvist)

The properties that defines the oil are [3]:

- Specific gravity/relative density
- Distillation characteristics
- Viscosity
- Pour point

The specific gravity or relative density to sea water determine whether the oil will be gathered at the surface or submerge. An oil with low specific gravity tend to have low viscosity and high proportion volatile compounds [3].

The distillation characteristics are coupled to the chemical composition of the oil and the volatility of the different compounds.

The viscosity of the spilled oil affects the spreading and the equilibrium slick thickness which affects the efficiency and possibilities to pump oil during mechanical recovery and ignition during in-situ burning. The viscosity is affected by temperature and oils often get higher viscosity in lower temperatures.

The pour point is the lowest temperature where the oil becomes semi-solid and don’t flow. If the temperature decreases below the pour point it may hinder the response operation.
3.3.3 Weathering processes

The weathering processes that change the properties and affect the response opportunities begin when the oil is spilled into the water and is characterized by evaporation, emulsification, dissolution, biodegradation, oxidation and sedimentation, see Figure 7.

Figure 7: Oil weathering processes (p.18 [9]).

All weathering processes act together and change the properties of the oil. Biodegradation, oxidation and sedimentation are long-term processes. Since the weathering processes are affected by temperature, wind and waves, the presence of ice often implies low air and water temperatures and reduced waves which leads to a significant reduced rate of the weathering processes.
3.3.4 Oil weathering models

It is important to understand the weathering processes in response planning and during the response operation. A great tool is therefore a so called ‘oil weathering model’ (OWM) [24].

The OWM may be interpreted as a database with understanding of the weathering of different oil types under various circumstances and will work as information source to the response operation planning. The OWM may for instance contain information on if, and for how long, a spilled oil is ignitable for the possibility to use in-situ burning as a response method. In-situ burning method is further described in section 3.4.2.

3.4 Response methods

In this report ‘response methods’ are interpreted as available countermeasures to be used as a response to a specific spill, i.e. methods that removes or minimizes the consequences. By that, weathering processes and remote sensing are not here classified as ‘response methods’ however these topics are not less important in the oil spill response operation as whole. To get a general overview, description of the available response methods; mechanical recovery, in-situ burning and dispersants are found below.

A fourth response alternative to consider is the ‘zero option’. The alternative could hardly be called a method, however in some situations and conditions it may be the best choice or the only choice available. The alternative means to leave the oil spill and let it degenerate through natural biodegradation processes and then eventually start an operation later when conditions have changed and operation potential increased. Example could be in situation as when the extent of the operation and efforts needed are significantly high in relation to recovered/treated oil and the spill effect on the environment is considered relatively low.
3.4.1 Mechanical recovery (MR)

Mechanical recovery is the method approved without special permission in all Arctic areas as it is the only method which intends to recover the oil from the spill site before disposal. The idea behind mechanical recovery is to contain the spilled oil from the ice or water surface. This is done through the use of different skimmer systems.

To contain the spilled oil in open water boom systems are used which captures floating oil and prevent it from spreading (e.g. by surrounding the spill source with booms). Booms have been tested in ice covered waters and shows sufficient results for low ice concentrations. Reinforced ice-booms have been developed. The booms are either anchored, moored or operated by work boats. There are several techniques used depending on conditions such as oil drift or to protect areas of special sensitivity. In high ice concentrations and in ice conditions with large ice floes the ice may form natural barriers and thus contain the oil and prevent it from spreading.

To recover the contained oil skimmer systems are often used and there are different ice skimmer systems developed. Brushes or discs where oil is adhered and recovered. Weir systems which creates a sump into which oil and water pour and then is pumped. Suction skimmers where vacuum is used to lift oil from the surface. The skimmer units may be fitted in a vessel or operated by a crane, have their own buoyancy and even own propulsion.

All skimmer systems encounter problems in different ice conditions which is a field with potential of development. One problem is to separate ice, water and oil to avoid recovery of large unwanted volumes of ice and water which decreases efficiency. In ice covered waters brush skimmers is considered to have the best potential, see examples in Figure 8.

Other systems used to mechanically recover the contained oil are rope-mop skimmers and for very high viscosity oils using crane mounted grabs. The rop-mop skimmers uses an oleophilic rope mop that collects oil from the water surface which then is squeezed out in the skimmer unit.

![Figure 8: Example of brush skimmer systems (p.12 & 15 [15]).](image-url)
3.4.2 In-situ burning (ISB)

In-situ burning is considered to be a response method with high potential of oil removal in Arctic conditions. The idea is to ignite an oil slick which is followed by a controlled burn and mechanical removal of the remaining residue. Efficient burn and successful operation is affected by containment of oil, slick thickness, oil type, weathering stage (ignitability), waves and wind.

The low temperatures in the Arctic areas tend to slow down the weathering processes and hence extend the window of opportunity for ISB as the oil is ignitable for a longer time.

Fire resistant booms may be used in lower ice concentrations to obtain the slick thickness needed for ISB, see Figure 9a. In ice conditions with larger ice floes and higher ice concentrations the ice tend to work as natural barriers and contain the oil in pools between the ice floes. In open water or in very low ice concentrations the use of chemical herding agents have been tested with good results. The idea is that the herders contain the oil resulting in sufficient oil slick thickness for ISB, see Figure 9b.

There are different ways to ignite an oil slick. On ice or from work boats personnel may move close to the slick and ignite it, however this can be dangerous and risk the personnel safety. Ignition by the use of equipped helicopters have been used and proved to be an effective method as the targeting of the ignition improves, the personnel risks decrease and safety is raised.

Before performing an ISB operation close contact to agencies for approval is necessary. Wind (speed and direction) must be favorable and distances to human population far enough for ISB approval. After a controlled burn there is always a burning residue left that needs to be mechanically removed. Fortunately the residue tends to be very easy to remove from the surface using equipment such as nets, although the residue may sink when cooled. However the residue compounds toxicity to marine life is considered to be low or nonexistent as the burn removes the low weight aromatic hydrocarbons which tends to be more toxic.

![Figure 9: Example of ISB with booms and herders (p.13 & 20 [24]).](image-url)
3.4.3 Dispersants (DS)

The use of dispersant chemicals is a method used that intends to dilute and accelerate the natural biodegradation of the spilled oil. The added compounds together with sufficient mixing energy, by waves or thrusters, disperse the oil into small oil droplets and spreads it in the water column.

The method has successfully been used in open water and is considered to be a good alternative response method when mechanical recovery and in-situ burning are unusable due to harsh weather. The method has not been an option in ice infested waters until recently [24].

Applying dispersants are usually performed by airborne units, see Figure 10, which has the advantage to efficiently cover large areas, however in high ice concentrations developed spray cranes with movable nozzles have been tested to increase targeting between ice floes.

The use of dispersants are affected by oil type, temperatures and water salinity as the efficiency of the compounds are dependent on the weathering of the oil. The often lower temperatures in icy waters decreases the weathering rates and thus increases the window of opportunity for use of dispersants.

To be efficient a certain degree of mixing energy is needed. In icy waters where ice dampen the waves the use of vessel thrusters or water jet from MOB-boats\(^3\) has shown sufficient results and opened up for further development of the techniques.

The use of dispersants usually needs special governmental permissions and in some areas the guidelines are against it (e.g. in the Baltic sea) as it means an extra adding of chemical compounds to the water.

\[\text{Man Overboard rescue boat - MOB}\]

![Figure 10: Example of dispersant systems (p.30 [1])](image)

---

\(^3\)Man Overboard rescue boat - MOB
3.5 Response units - Emergency preparedness

The extent and amount of available response units are highly dependent on each specific situation. Arctic oil spill response operations implies that the response units need to be able to operate in the Arctic conditions. This implies properties such as icebreaking capability, low temperature-, low visibility-, darkness operations, extended operability and safe work environment for personnel.

Potential and expected response units that may be needed in an Arctic oil spill response operation or secured in the emergency preparedness are:

<table>
<thead>
<tr>
<th>Unit/resource:</th>
<th>Primary missions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Icebreakers/support vessels</td>
<td>Assisting operation, performing ice management, Figure 11(b) and support recovery vessels.</td>
</tr>
<tr>
<td>Mechanical recovery vessels</td>
<td>Oil spill response vessels equipped with booms, skimmers etc.</td>
</tr>
<tr>
<td>Work boats</td>
<td>Assisting recovery vessels, towing booms, operation of small skimmers, Figure 11(a).</td>
</tr>
<tr>
<td>Equipped &amp; trained personnel</td>
<td>For manual recovery (pails, shovels) and overall unit operation.</td>
</tr>
<tr>
<td>Helicopters</td>
<td>Remote sensing &amp; surveillance, ISB ignition and DS equipment. Emergency transports.</td>
</tr>
<tr>
<td>Aircrafts</td>
<td>Remote sensing &amp; surveillance. DS equipment, Figure 11(c).</td>
</tr>
<tr>
<td>Arctic tanker</td>
<td>Storage, treatment and transport of recovered oil.</td>
</tr>
<tr>
<td>Oil spill response barges</td>
<td>Storage and treatment of recovered oil.</td>
</tr>
</tbody>
</table>

Figure 11: Example of possible response units (p.12 [1], p.5 [7], [23]).
3.6 Contingency planning

Contingency planning is a wide expression and may be defined on several levels. Regarding oil spill contingency plans the purpose may be to either describe the response operation after a minor spill, e.g. from a merchant vessel, or to describe the response operation after a major oil spill. The first should be covered in every vessels’ ‘Ship Oil Pollution Emergency Plan (SOPEP)’ and the later is for instance a requirement prior permit by governments for drilling activities. Governments also have their own contingency plans to protect their territory and be prepared to respond to a potential accident.

In contingency planning conditions and seasons that may occur are considered, spill risks accounted for and areas of special interest or highly sensitive (for instance animal breeding areas) identified. For every identified situation there should be response actions, operation tactics and decision processes established.

Since accidents, conditions and the following response operations are of dynamic nature the objectives and tactics may change over time and the decision process often needs to be reviewed.

Although the contingency plans are more or less extensive the methodology in the decision process is similar, the example below is taken from [5].

1. Gather information and assess the situation.
2. Define response objective(s).
3. Develop strategies to meet the objectives.
4. Select appropriate technique(s), method(s) or tactics to implement the strategy.
5. Evaluate the practicality, feasibility and safety of the strategies and methods or tactics in view of the environmental conditions and the nature of the spill.
6. Prepare an action or response plan.
7. Obtain appropriate approvals, permission or permits.
8. Implement the field response operations plan.

The developed tool presented in Section 4.1 is intended to provide the decision-makers with important information, e.g. to items 4 and 5 above, and thus be a useful tool in the process before and during a response operation.
3.7 Real case - Oil spill in ice

For further insight in practical oil spill response management, oil spill in ice cases have been sought for to be reviewed. Fortunately there have not been that many accidents.

In February 2011 the container vessel Godafoss ran aground at the south coast of Norway close to the Swedish border, see Figure 12. Two bottom tanks where damaged which lead to a following oil spill. The response operation was performed in cold temperatures, short days and light ice conditions. Both Norwegian and Swedish response units were included in the operation.

The response operation, results and lessons learned are presented below.

3.7.1 Godafoss, February 2011

- Godafoss is an Icelandic container vessel, length: 165 m, 14664 GT, build 1995. At the grounding the vessel had approximately 800 tons of heavy fuel oil on board.

- 2011-02-17, 20.00: The vessel Godafoss is reported grounded in Norway, Hvaler (in a National Park) close to the Swedish border.

- Two bottom tanks are quickly found leaking oil, approximately 250 tons oil each. The tanks contain heavy fuel oil of type IF380. The oil is, at an early stage, not assumed to sink when spilled in water (info from SINTEF\textsuperscript{4}).

- 2011-02-18, 00.00: The accident is declared ‘national operation’ and Norwegian Coast Guard, ‘Kystverket’ thereby has the management and responsibility of the operation.

- 2011-02-18, 01.30: Booms are deployed around the vessel to contain oil and prevent it from spreading.

- Approximately 112 m\textsuperscript{3} heavy fuel oil leaked out immediately.

- Oil spill response operation by Norwegian and Swedish response units starts up and continues, see more details in section below.

- 2011-02-23, 07.00: Godafoss is towed off the ground and anchored for inspections and unloading of fuel and cargo.

- 2011-02-29: Godafoss is towed for repair to shipyard in Odense, Denmark.

\textsuperscript{4}SINTEF - Norwegian independent research organization.
Response operation

During the operation Norwegian and Swedish airborne units, satellite pictures, drift buoys, as well as continuously use of vessel installed equipment and hand held devices were used for spill surveillance. However, since surveillance is not a part of the modeling in Section 4.1 further review of the topic is not considered interesting here.

First of all minimizing the spill is high priority. The vessel is investigated, stability secured by unloading cargo and pumping of oil from damaged tanks performed. Parallel actions is to deploy booms around the vessel to reduce oil spreading and as soon as possible start response operations, see Figure 13.

During the response operation the external conditions consisted of low temperatures (down to -20 °C), short days and drifting ice fields with minor ice floes, slush and brash ice.

Well known phenomenons that were confirmed was that oil were captured in drifting low concentrations of ice that were following the ocean current. However if ice field is split up the oil tends follow the ice and spread increases. Ice fields accumulating near shore captures spilled oil and thus ‘protect’ the shoreline from contamination.
Methods considered

During the operation, that mainly were concentrated to mechanical recovery, the use of dispersants and in-situ burning were also considered. However according to important sea bottom resources, oil type and possible lack of mixing energy, the window of opportunity for use of dispersant were considered very short and the response method was considered not to be feasible.

In-situ burning need continuously to overcome the flame point of the oil to be successful. The flame point increases when the oil is emulsified with water. During the beginning of the operation, in-situ burning was considered as an option and burn was tested, however the conclusion was that burning was not possible.

The remaining response option (except natural processes, i.e. leave the oil) were mechanical recovery. Booms were anchored, to prevent spreading, towed by work boats to capture and contain oil for recovery. Vessel installed and free skimmer systems together with crane mounted grabs were used to recover the oil, see Figure 14.
Operation outcome

Estimations of spilled oil volume equals 112 m$^3$ (oil that were pumped from the ship at spill site or at the shipyard excluded), the oil response and recovery distribution ‘oil budget’ is presented in Figure 15.

![Figure 15: Oil budget of the spilled oil](Data: Norwegian Coast Guard)
3.7.2 Key findings, lessons learned

In the continuous work to improve and develop operations a valuable tool is to evaluate and learn from previous operations. Key findings and lessons learned by Norwegian and Swedish Coast Guard concerning spill response from the operation is presented below together with identified areas in need of improvement (excluding highly local subjects).

- Cooperation between Norwegian and Swedish Coast Guard favorable, different units and equipment gave good flexibility.
- Good practice of cooperation agreement in action; Copenhagen agreement.
- Secure heavy booms around the disabled vessel in an early stage to prevent unnecessary oil spill and spreading.
- Large boom systems and sweeping arms to collect oil for mechanical recovery worked good, however systems had some damage from ice and cold temperature during the operation.
- Generally everything takes more time due to low temperature. Problems with some booms and pumps, oil viscosity extremely high.
- Several units did not have enough heating capacity. Problems with disconnecting hoses and equipment.
- Large heating capacity on Swedish ships favorable.
- Several units had problem with ice clogging in cooling systems.
- On deck safety issues and personnel work environment in cold temperatures highlighted.
- Before towing the vessel from accident location. Clean hull, set clear limitations for the voyage and send out emergency warnings to other nations.
- Trajectory modeling for operational purpose of oil in ice drift and spreading needed.
- Remote sensing of oil in ice has potential for research, development and test of new and existing sensors needed.
4 Decision support modeling

4.1 Operational management

To ensure sufficient response preparedness prior drilling operations or opening of new shipping routes as well as gaining knowledge and important information during an ongoing, continuously changing response operation, a fast and up to date response tool for Arctic oil spill would be useful.

A calculation tool or mathematical model is always limited and never gives more accurate results than given by the input. However with a database of statistical information, such as temperature and ice coverage over several years, together with the ability of adding real time input and external experiences the model gets tuned and results are improved.

The results from a decision support tool is intended to give recommendations and guide the decision-makers. With the ability to change various parameters, options and recalculate, the impact on the output will be clear and visible.

4.1.1 Objectives, use and limitations

RAOS is intended to be used by
- Governments
- Oil industry companies including sub-contractors
- Response operation decision-makers and personnel

RAOS is developed to be used in the following situations
- Estimate resources needed in a response operation, e.g. in permit process of industrial activities.
- Provide decision support in case of accident by determine:
  - Response methods available/feasible.
  - Estimate operation performance (given available response units).
- Perform gap analysis for certain locations, circumstances, time periods.

Limitations
- Spill size of Tier 2 and 3 considered\(^5\).
- No spill surveillance or recovery of submerged oil is included in the model.
- Uncertainties of unit/equipment operability and performance in dynamic conditions with large amount of affecting variables.

\(^5\)Definition by IPIECA; [9].
4.1.2 Response tool for Arctic oil spill - RAOS

The model, Figure 16, is here described on a general level to show the different components identified and knowledge needed to be able to perform calculations and produce valuable decision support results.

The input is divided into seven sub-modules where the spill scenario, conditions (statistic or real time), available response units (emergency preparedness) and necessary database knowledge is fed into the model.

Within RAOS several sub-models are needed. The sub-models perform calculations using the information defined by the input and exchange results with other sub-models. The sub-results is then gathered and evaluated to be able to produce valuable output.

The result produced may be a response gap analysis, window of opportunity and/or an estimated response performance.

A full description of input, sub-models and results is found in Appendix A.
4.2 Window of opportunity - Response methods

In operational planning of response operations as well as in gap analysis it is important to achieve the total picture of the situation and the response methods that are available. The concept primary covering this is called ‘window of opportunity’ (WoO) and refers to the available methods, including estimated potential, as a function of time.

One sub-module of RAOS, ‘3. Response, Response methods module’, refers to the calculations of the WoO. The module is presented in this section and further developed in Appendix B. Since external ice and metocean condition continuously changes the evaluation needs to be done with respect to time.

The WoO sub-model is a sub-part of RAOS, thus a complete analysis is beyond the scope of this report. However example of results are presented which are based on fictitious inputs and predefined statistics for specific locations and time.

4.2.1 Objectives, assumption and methods

Objectives

- Estimate expected potential of the response methods; mechanical recovery, in-situ burning and dispersants considering:
  - Change in external conditions.
  - Present results as a function of time.

Assumption

- Affecting variables are separable.

Methods

- Use of earlier defined IceMaster module including external conditions from statistics and weather models.
- Modeling in software GeNie (Bayesian Network).
- Time stepping/result plotting in software Matlab.

---

6Metocean - Variables referring to meteorology and hydrology.
7In sub-parts of the used reference IceMaster.
4.2.2 WoO-model

The modeling is based on the assumption that affecting variables are separable thus the estimated impact from each variable is defined isolated, evaluated and then summarized. A significant advantage is that the model will be easy to update and improve.

A simplified flow-graph of the modeling structure for one response method is found in Figure 17. Affecting variables included in the model are found in Table 1 - 3.

Figure 17: Flow-graph describing WoO model structure.
Mechanical recovery

Table 1: Variables affecting mechanical recovery included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceIndex</td>
<td>[-]</td>
<td>Ice condition, ( f(\text{Ice}, \text{IceConc}, ...) ).</td>
</tr>
<tr>
<td>Visibility</td>
<td>[m]</td>
<td>Visibility at spill site.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration, area; ice rel. water.</td>
</tr>
<tr>
<td>SunHoursPerDay</td>
<td>[%]</td>
<td>Presence of daylight per 24H.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>SeaState</td>
<td>[Beaufort]</td>
<td>Sea state, Beaufort number, 1-12.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type.</td>
</tr>
<tr>
<td>ViscosityOil</td>
<td>[cP]</td>
<td>Oil viscosity, influencing 3 methods differently.</td>
</tr>
</tbody>
</table>

In-situ burning

Table 2: Variables affecting in-situ burning included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_{\text{wind}} )</td>
<td>[m/s]</td>
<td>Wind speed.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration.</td>
</tr>
<tr>
<td>AddIgniterOil</td>
<td>[-]</td>
<td>Availability of additional igniting equipment.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type, defining oil properties.</td>
</tr>
<tr>
<td>( h_{\text{slick}} )</td>
<td>[mm]</td>
<td>Oil slick thickness.</td>
</tr>
</tbody>
</table>

Dispersants

Table 3: Variables affecting use of dispersants included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \nu_{\text{wind}} )</td>
<td>[m/s]</td>
<td>Wind speed.</td>
</tr>
<tr>
<td>SeaState</td>
<td>[Beaufort]</td>
<td>Sea state, Beaufort number, 0-12.</td>
</tr>
<tr>
<td>ActiveAgitation</td>
<td>[-]</td>
<td>Availability of active agitation.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type, defines oil properties.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>ViscosityOil</td>
<td>[cP]</td>
<td>Oil viscosity.</td>
</tr>
<tr>
<td>DSType</td>
<td>[-]</td>
<td>Type of dispersant.</td>
</tr>
<tr>
<td>( T_{\text{water}} )</td>
<td>[°C]</td>
<td>Water temperature.</td>
</tr>
</tbody>
</table>

A full description of input, sub-models and results is found in Appendix B.
4.2.3 Result - Example

In the example below the external conditions are gathered from statistics. Input to the example is found in Table 4, resulting WoO in Figure 18 and a selection of plotted affecting variables in Figure 19.

Table 4: Pre-defined inputs.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value/Evidence</th>
<th>Comments:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Tuktoyaktuk</td>
<td>North of Canada.</td>
</tr>
<tr>
<td>Years</td>
<td>1999-2009</td>
<td>Interval for statistics.</td>
</tr>
<tr>
<td>SpillDay</td>
<td>240</td>
<td>I.e. beginning of August.</td>
</tr>
<tr>
<td>CalcPeriod</td>
<td>14 days</td>
<td></td>
</tr>
<tr>
<td>Visibility</td>
<td>&gt;900 m</td>
<td>Good visibility.</td>
</tr>
<tr>
<td>WaterTemperature</td>
<td>0 °C</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>35 psu</td>
<td></td>
</tr>
<tr>
<td>OilType</td>
<td>Troll B</td>
<td>Crude oil.</td>
</tr>
<tr>
<td>OilSlickThickness</td>
<td>20 mm</td>
<td></td>
</tr>
<tr>
<td>AdditionalIgniter</td>
<td>Available</td>
<td>E.g. heli-torch.</td>
</tr>
<tr>
<td>DispersantType</td>
<td>Corexit9500</td>
<td></td>
</tr>
<tr>
<td>ActiveAgitation</td>
<td>Available</td>
<td></td>
</tr>
</tbody>
</table>

Figure 18: Window of opportunity output for the example.
4.2.4 Result interpretation and discussion

Interpretation of the result in Figure 18 is for instance that in-situ burning have the greatest potential at the very beginning of the spill. The potential however decreases relatively fast and the oil will no longer be ignitable after eighth days. Thus if the method is thought to be used with success a fast in-situ burning operation is essential.

The three mechanical recovery methods show different potential due variety in potential coupled to oil viscosity. Mechanical recovery using grab show no potential because of the oil viscosity that is below the limit for grab.

The dispersability of the oil shows moderate potential in an early stage which is decreased slightly when the oil is weathered.

Figure 19 shows a selection of plotted affecting variables. For instance the MRIceIndex variable shows that the ice conditions are reduced, i.e. less potential impact, during the calculation period. For different cases the particular variables of interest may be plotted as well as the development of external conditions and oil variables.
4.2.5 Uncertainties

A mathematical model which is intended to describe real phenomenons through mathematical functions includes uncertainties. The uncertainties vary and affect the result differently depending on what is modeled, simplifications and assumptions made and whether the model is used within the limits for validity, to name a few.

In the WoO model identified uncertainties are due to the assumption made that affecting variables are separable, thus treating the variable impact isolated. The Bayesian approach uses statistical data as main input to describe the external conditions, probability is calculated for certain events to occur. This should be kept in mind when interpreting results, estimations of future events are based on historical events.

Statistical data are based on input from different sources where quality and data resolution varies. Sometimes the data in turn are produced by other models.

Impact measures on a specific method by a specific variable is based on different sources ranging from laboratory tests, experts judgments to reasoned assumptions. Concerning Arctic operations and oil spills in ice the number of operations are still limited and the field is under development meaning that broad experience does not exist.

It is important to remember that the results presented from the WoO model at this stage is only for example purposes to show the idea and functions of the model structure and how the decision support tool preferably could be used. Therefore no validity check of the model has been performed and no further guaranties are given.
5 Discussion and conclusions

The need of development and understanding of Arctic oil spill response is stated several times in the report and in the reference material. The Arctic has, and is, facing changing conditions affected by higher mean temperatures and increasing shipping activities.

The research and development on the field have made progress over the years but there is still a lot of work to be done and solutions to be invented to meet the increasing need of efficient response operation following an oil spill in cold climate. E.g. to develop accurate oil in ice drift and spread models, seriously consider how to manage a sub-sea blowout in ice conditions and to develop high performance spill surveillance sensors for cold conditions.

In several areas around the world there are established cooperations between neighboring nation governments, response preparedness groups and other groups of interest. The cooperation means sharing of knowledge, response units, equipment stockpiles and operational support.

In the Arctic there are forces working to unite the Arctic nations to cooperate, the intentions are good however the work takes time and a faster progress would be favorable. Standardized equipments, stockpiles and contingency plans developed by a united organization could highly increase the preparedness and potential for successful response operations.

In any operation, whether it is an united effort or stand alone operation, it is important to have overview of the whole situation to be able to take the right decisions. The proposed model in the thesis is one alternative to start the work in creating a decision support tool which cover the whole operation and at the same time work as common reference when serveral decision makers are involved. The proposed decision support tool, RAOS, and the further developed window of opportunity sub-model is a good start. However, a lot of work still remains.
References


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Appendices

A RAOS - Full description

This Appendix is a complement to the main report as well as an independent document that describes the outline and structure of the proposed decision support tool, response tool for Arctic oil spill (RAOS).

RAOS is described on a general level where the different identified components and knowledge needed to be able to perform calculations and produce valuable decision support results.

RAOS is intended to be used by

- Governments.
- Oil industry companies including sub-contractors.
- Response operation decision-makers and personnel.

RAOS is developed to be used in the following situations

- Estimate resources needed in a response operation, e.g. in permit process of industrial activities.
- Provide decision support in case of accident by determine:
  - Response methods available/feasible.
  - Estimate operation performance (given available response units).
- Perform gap analysis for certain locations, circumstances and time periods.

Limitations

- SS\text{spill} size of Tier 2 and 3 considered\(^8\).
- No spill surveillance or recovery of submerged oil is included in the model.
- Uncertainties of unit/equipment operability and performance in dynamic conditions with large amount of affecting variables.

\(^8\)Definition by IPIECA [9].
A.1 General outline

Input

There are various types of input to the model, real time information (if available), case specific information and several knowledge databases. The inputs are divided into seven categories, see Figure 20.

Sub-models within RAOS

The RAOS calculation model is built up by five sub-models, see Figure 21, that use the input to calculate sub-results as well as exchange sub-results within RAOS to be able to evaluate data and produce an output.

Output - Results

The requested output is presented to the user, see examples in Figure 22. Sub-results may be valuable information and should therefore either be provided in the result or easy to extract.

- Window of Opportunity - Feasible response methods
- Operation/Recovery Performance
- Response Gap Analysis
A.2 Input to the model

In this section input to the model is specified, the main properties are defined together with short description and reference to related sub-models in RAOS. The inputs are divided and presented in the same categories as in Figure 20.

A.2.1 Spill scenario

Spill scenario input is unique for each operation and may change over time, especially if the tool is used during an ongoing operation.

Spill scenario input is used in sub-models: 1. External conditions, 2. Oil Properties.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spill type</td>
<td>On ice, under ice, between floes etc.</td>
</tr>
<tr>
<td>Oil type</td>
<td>Defines oil properties.</td>
</tr>
<tr>
<td>Oil volume/rate</td>
<td>Extent of spill.</td>
</tr>
<tr>
<td>Location</td>
<td>Specifies position.</td>
</tr>
<tr>
<td>Date</td>
<td>Determine season, expected conditions etc.</td>
</tr>
<tr>
<td>Spill duration</td>
<td>Time reference for response operation.</td>
</tr>
</tbody>
</table>

Figure 23: Spill scenario input.
A.2.2 Emergency preparedness

Emergency preparedness refers to the amount and extent of secured (available) response units, the input is unique for each operation. The input may change over time if the tool is used during an ongoing operation, or changed in an iterative process to investigate estimated operation performance for different preparedness.

Emergency preparedness input is used in sub-model: 3. Response.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit type / amount</td>
<td>Airborne, recovery vessel, assisting/supply vessel etc. and amount.</td>
</tr>
<tr>
<td>Location (posted)</td>
<td>Sets location for units respectively.</td>
</tr>
</tbody>
</table>

Unit type is individual for each specific unit (e.g. icebreaker class), the properties for the units are received from Response units & methods input.
A.2.3 Statistics

Statistics refers to information of ice and metocean conditions over several years for locations in the Arctic. Knowledge is here referred to a database describing different oil types and properties.

Statistics input is used in sub-models: 1. External conditions, 2. Oil Properties.

Figure 25: Statistics input.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice conditions</td>
<td>MYI/FYI, type, concentration, thickness, floe size, ridges, drift.</td>
</tr>
<tr>
<td>Metocean</td>
<td>Air/water temperatures, wind speed, ocean currents, visibility.</td>
</tr>
<tr>
<td>Oil properties</td>
<td>Density, chemical composition, viscosity, pour point.</td>
</tr>
</tbody>
</table>
A.2.4 Real time conditions

The real time conditions input is used, if available, to replace corresponding statistical-based information with up to date information (ice conditions, metocean forecasts). On site experiences from crew and personnel may also be added as an input.

Real time conditions input is used in sub-model: 1. External conditions.

---

*Figure 26: Real time conditions input.*

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice conditions</td>
<td>Up to date ice condition parameters.</td>
</tr>
<tr>
<td>Metocean</td>
<td>Up to date metocean parameters.</td>
</tr>
<tr>
<td>Forecasts</td>
<td>Forecasts of above defined properties.</td>
</tr>
<tr>
<td>Experience</td>
<td>On site experiences by crew and personnel, e.g. feasibility of methods.</td>
</tr>
</tbody>
</table>
A.2.5 Response Units & Methods

Response units & Methods is a knowledge based input which define response units, equipment and methods according to operabilities, limitations, capacities and performances. The database is an important key in the tool and needs therefore continuously to be updated and improved.

Units & Methods input is used in sub-model: 3. Response.

---

**Figure 27:** Response Units & Methods input.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit type</td>
<td>Airborne, recovery vessel, assisting/supply vessel etc.</td>
</tr>
<tr>
<td>Performance</td>
<td>Performance, f(Ice conditions, visibility, temperature, oil...).</td>
</tr>
<tr>
<td>Capacities (storage)</td>
<td>Tanks (recovered oil/bunker/fresh water), food &amp; supplies.</td>
</tr>
<tr>
<td>Operational limits</td>
<td>Max/min, f(Ice conditions, visibility, temperature, wind...).</td>
</tr>
<tr>
<td>Needed resources</td>
<td>Needed units &amp; equipment for use of response method.</td>
</tr>
</tbody>
</table>
A.2.6 Infrastructure

Infrastructure defines feasible approach and exit routes as well as Arctic ports and their preparedness, e.g. stockpiles, ability to accept recovered oil, ability to supply response vessels etc.

Infrastructure input is used in sub-model: 4. Logistics.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human populations</td>
<td>Location and size.</td>
</tr>
<tr>
<td>Arctic ports</td>
<td>Location and size.</td>
</tr>
<tr>
<td>Capacities</td>
<td>Abilities to assist and supply operations, stockpiles.</td>
</tr>
<tr>
<td>Approach &amp; exit routes</td>
<td>Seasonal feasible navigational routes in the Arctic ocean.</td>
</tr>
<tr>
<td>Fuel &amp; Supplies</td>
<td>Location, volume/extent of stockpiles (temporary or permanent).</td>
</tr>
</tbody>
</table>
A.2.7 Laws & Regulations

Laws & Regulations describe local differences in general approach to response methods and operations.

Laws & regulations input is used in sub-models: 5. Evaluation & Performance

Figure 29: Laws & Regulations input.

<table>
<thead>
<tr>
<th>Property</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>Nations involved in the operation.</td>
</tr>
<tr>
<td>Area</td>
<td>Areas of special interest/regulations.</td>
</tr>
<tr>
<td>Government</td>
<td>Government to contact for permit processes, e.g. prior use of method.</td>
</tr>
</tbody>
</table>
A.3 RAOS - sub-models

In this section RAOS sub-models, their main objectives, input, output and results are presented. The sub-models are divided in categories according to Figure 21.

A.3.1 1. External conditions

The sub-model handles parameters associated to external conditions such as season, metocean variables and ice conditions. The model evaluates statistics and real time input and produces state variables as function of time. The output is used in other sub-models to evaluate performance and limitations for methods, equipment and units. Included in the sub-model is also an ice management module, output state variables is thus affected by presence of assisting icebreakers.

Input: Statistics/real time conditions, emergency preparedness (assisting icebreakers). Season; Date, Sun hours/day, freeze-up/thaw. Metocean; air/water temperatures, wind speed, ocean currents, visibility. Ice; MYI/FYI, type, concentration, thickness, floe size, ridges, drift.

Output/results: State variables (season, metocean, ice) as function of time.

A.3.2 2. Oil Properties

The sub-model Oil Properties consists of the oil weathering model (OWM) and the oil drift and spread Model (ODSM). OWM determines the fate and behavior of the spilled oil according to time. Input is gathered from oil definition (knowledge & case) and from the Condition sub-model. The weathering process is evaluated and the oil properties (e.g. ignitiability and viscosity) as function of time is the output/result. The ODSM describes the expected drift (movement) and spread (area coverage) of an oil slick as function of time.

Input: Oil definition (chemical composition), spill volume/rate, state variables.

Output/results: Oil properties as function of time, drift and spread as function of time (preferable presented with maps).

A.3.3 3. Response

Response is one of the most comprehensive and important sub-models in RAOS. The sub-model is divided into Response methods module and Response units module. The Response methods module uses the input to evaluate feasibility and expected potentials of the response methods. The output defines the window of opportunity as function of time.
The Response units module determine the operability and performance in accordance to conditions defined by state variables of unit types defined in the emergency preparedness input.

**Input:** State variables (from 1. External Conditions), oil properties (from 2. Oil Properties), response units & methods, emergency preparedness.

**Output/results:** Window of opportunity and corresponding method potential as function of time, unit operability & performance.

**A.3.4 4. Logistics**

The Logistics sub-model uses the input that defines the location of the spill and operation together with knowledge of Arctic ports, navigational routes and current conditions. The model evaluates the distances (sail and flight) to important infrastructure such as ports, flight bases and human populations. The model evaluate feasible approach and exit routes (sail) to the spill location, sail time and icebreaker assistance needed.

Stockpiles and port abilities/capacities are included in the calculation. The result is presented to the user as a summary of possibilities together with constrains/requirements.

**Input:** State variables, infrastructure knowledge.

**Output/results:** Logistic possibilities (ports, land bases, navigational routes), distances, time, needed icebreaker assistance, stockpiles, port abilities/capacities.

**A.3.5 5. Evaluation and Performance**

Evaluation and Performance summarizes all sub-results, evaluates and produce the final result that is presented to the user. Gap analysis and estimation of operation performance in accordance to the emergency preparedness is determined in the sub-model. Laws & Regulation as external input is considered in the evaluation process.

The result is delivered to the user in an easy and accessible way to work as decision support, important and interesting sub-results are provided to the user or easy to extract.

**Input:** Sub-results, Laws & Regulations.

**Output/results:** Response gap analysis, estimated operation performance, sub-results.

45
A.4 Output - Result

The results from the decision support tool, Figure 22, is intended to give recommendations and guide the decision-makers. With the ability to change various input parameters and recalculate, the impact on the output will be clear and visible.

Together with the requested output sub-results will also be interesting in the decision process and should therefore either be provided to the user or easy to extract.

A.4.1 Window of opportunity

The window of opportunity refers to the available response methods, past the spill, for the specific conditions, case and time. The output should be presented in an easy acceptable format where time is an important variable as it strongly affect the response strategy. The output is also affected by on site experience which may be added from crew or personnel through real time updates.

A.4.2 Response performance

The response performance is an estimate based on the overall definition of the conditions, case and the emergency preparedness (which defines the extent of the response force). The output should be used as a guideline and also to indicate and identify possible improvement in the response operation by changing the input of available response units.

A.4.3 Gap analysis

If a gap is found for specific conditions or cases the ruling variables should be provided in the result. Thereby the options are to either improve the operation and response preparedness to overbuild the gap or restrict the operation under the specific conditions or cases where the response gap occurs to ensure environmental protection and personnel safety.
Figure 30: General description RAOS.
B Window of opportunity model - Full description

Important result in the evaluation process of RAOS (described in Section 4.1 and Appendix A) is the window of opportunity (WoO). This appendix describes the modeling of WoO which includes the response methods: mechanical recovery, in-situ burning and dispersants.

The appendix works as a complement to the main report as well as an independent document that describes the modeling of WoO.

First the objectives, assumption and modeling methods are presented which follows by a description of the included variables as well as input data. The presentation is ended with an example of result provided by the model.

Objectives

- Estimate expected potential of the response methods; mechanical recovery, in-situ burning and dispersants considering:
  - Change in external conditions.
  - Present results as a function of time.

Assumption

- Affecting variables are separable.

Methods

- Use of earlier defined IceMaster module including external conditions from statistics and weather models.
- Modeling in software GeNie (Bayesian Network).
- Time stepping/result plotting in software Matlab.

The model is based on the assumption that affecting variables are separable thus the estimated impact from each variable is defined isolated, evaluated and then summarized. A significant advantage is that the model will be easy to update and improve.
B.1 Modeling structure, included variables and input

The evaluation of each method is performed separately, a simplified flow-graph of the modeling structure for one response method is found in Figure 31.

For each response method a set-up of affecting variables are considered and included in the model. The variables are primarily consisting of the external conditions such as ice and metocean parameters together with oil properties. The variable input may be achieved from statistical databases or defined from real time conditions and high performance (short time) forecasts. The input variables are defined through probability distributions and the following calculations are performed with respect to probability (Bayesian Networks).

The impact of each variable on each specific response method is defined from previous performed research experiments, general established practice or reasoned assumptions. Location and modeling timespan are basic input to the model. Due to the model structure, updates and improvements of variable impact as well as adding or removing affecting variables are easily performed.

The primary output is the window of opportunity of the methods, however variables of special interest and their time history are easy extractable from the calculations for analysis purpose.

Model input data - Important remark

The input data to the model relies on results from research as well as reasoned assumptions. It is important to remember that the results presented together with the WoO model are aimed to show the use and functions of the model, thus the results should not be interpreted as necessarily correct.

However the intention is that the model, at this early stage, show reasonable results which point in the right direction in accordance to the change in input variables such as oil behavior and external conditions.

The oil characteristic input data should be provided to the WoO model from another sub-model of RAOS and metocean statistic data updated for locations of interest prior higher level of output results could be expected.
Figure 31: Flow-graph describing WoO model structure.
B.1.1 Mechanical recovery

Eight variables are used to model the potential of mechanical recovery methods, see Table 5, five of them refers to external conditions such as ice and metocean parameters. *OilType* and *ViscosityOil* refers to the spilled oil and one time variable *SpillDuration* is used. The impact of viscosity on the three mechanical recovery methods; brush/band skimmers, rope-mop skimmers and grab are contradicting. Therefore, the calculation of potentials are separated.

Table 5: Variables affecting mechanical recovery included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceIndex</td>
<td>[-]</td>
<td>Ice condition, ( f(h_{ice}, IceConc, ...) ).</td>
</tr>
<tr>
<td>Visibility</td>
<td>[m]</td>
<td>Visibility at spill site.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration, area; ice rel. water.</td>
</tr>
<tr>
<td>SunHoursPerDay</td>
<td>[%]</td>
<td>Presence of daylight per 24H.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>SeaState</td>
<td>[Beaufort]</td>
<td>Sea state, Beaufort number, 1-12.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type.</td>
</tr>
<tr>
<td>ViscosityOil</td>
<td>[cP]</td>
<td>Oil viscosity, (influencing 3 methods differently).</td>
</tr>
</tbody>
</table>

Figure 32: Structure of sub-model considering mechanical recovery.
Ice index

The ice index variable is calculated from external ice and weather conditions and used to determine the degree of toughness for the fleet to manage the current ice conditions. The ice index measure has then been used to classify and compare performance of icebreakers and other vessels and their ability to operate and withstand conditions in the Arctic. Ice index ‘0’ should be interpreted as ‘No icebreaker assistance needed’ and the upper limit of 10 as ‘border of breakable ice’. Parameters which is accounted for are ice loads, turning capability, backing, position keeping etc.

According to mechanical recovery where managing the ice conditions and maneuverability is essential for ‘success’ the ice index is assumed to impact the potential according to Table 6, also shown in Figure 33.

Table 6: Ice index variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceIndex</td>
<td>[-]</td>
<td>0 1 2 3 4 5 6 7 8 9 10</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>100 100 80 80 60 60 20 0 0 0 0</td>
</tr>
</tbody>
</table>

Figure 33: Ice index impact on mechanical recovery.
Ice concentration

Ice concentration refers to area covered by ice in relation to total water area. Higher ice concentrations may disturb recovery by reducing the access to the spilled oil for the skimmer units. However, higher ice concentrations may also reduce oil drift and spreading significantly. Ice concentration impact on mechanical recovery potential is gathered from [15], [3] and is assumed to affect mechanical recovery according to Table 7, also shown in Figure 34.

Table 7: Ice concentration variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>0</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 34: Ice concentration impact on mechanical recovery.
Visibility

Visibility is essential when tracking oil spill, maneuvering, coordinating vessels to spill concentrations and targeting units for recovery. Operation may proceed with fairly good potential in low to moderate visibility depending on spill tracking. Visibility impact on mechanical recovery potential is assumed according to Table 8, also shown in Figure 35.

Table 8: Visibility variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visibility</td>
<td>[m]</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>20</td>
</tr>
</tbody>
</table>

Figure 35: Visibility impact on mechanical recovery.
Daylight

‘Sun hours per day’ indicate presence of daylight. In ‘no day light’, operation may proceed with good potential in many cases but a reduced recovery potential is assumed. Operation continuous with working lights, however tracking oil drift and spreading as well as coordinate vessels and targeting units may find some difficulties. Sun hours per day impact on mechanical recovery potential is assumed according to Table 9, also shown in Figure 36.

Table 9: Sun hours per day variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>SunHoursPerDay</td>
<td>[%]</td>
<td>Daylight</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 36: Daylight impact on mechanical recovery.
Sea state

Sea state is here defined through the well known Beaufort scale calculated using wind speed input, see Eq. 1.

\[ B = \left( \frac{V}{k} \right)^{2/3} \]  

(1)

where \( B \) is the Beaufort number, \( V \) wind speed in [m/s] and \( k = 0.865 \), [16].

The Beaufort number is rounded to nearest integer. The scale is usually interpreted as a measure of wind and waves in a full developed sea state. However with the presence of ice short waves will be dampened.

Sea state affect the operation by disturbing flow to skimmers, difficulties in maneuvering, safety etc. Sea state impact on mechanical recovery potential is assumed according to Table 10, also shown in Figure 37.

Table 10: Sea state variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeaState</td>
<td>[Beaufort]</td>
<td>0 1 2 3 4 5 6 7 8 9 &gt;10</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>100 100 100 80 50 20 0 0 0 0</td>
</tr>
</tbody>
</table>

Figure 37: Sea state impact on mechanical recovery.
Oil viscosity

The viscosity of the spilled oil varies with time as the weathering processes proceed and temperature possibly changes. Viscosity of different oil grades varies a lot and the variable span is therefore wide. During mechanical recovery the potential for one specific method will increase with e.g. increasing viscosity while another method will show decreasing potential.

Therefore the viscosity impact on mechanical recovery is separated into three according to the different methods; Brushes/band skimmers, rope-mop skimmers and grab. The viscosity limits are assumed according to Table 11 and their impact are shown in Figure 38.

Table 11: Oil viscosity variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viscosity $\text{Oil}$</td>
<td>$\text{[cP]}$</td>
<td>100 → 260000</td>
</tr>
<tr>
<td>Availability – BrushBand</td>
<td>$\text{[cP]}$</td>
<td>100 → 260000</td>
</tr>
<tr>
<td>Availability – RopeMop</td>
<td>$\text{[cP]}$</td>
<td>&lt; 100 → 10000</td>
</tr>
<tr>
<td>Availability – Grab</td>
<td>$\text{[cP]}$</td>
<td>10000 → 260000</td>
</tr>
</tbody>
</table>

Figure 38: Oil viscosity impact on mechanical recovery techniques.
B.1.2 In-situ burning

The modeling of in-situ burning includes six variables, see Table 12. Two of the variables handles external conditions, two variables the oil properties, one time variable and one whether additional ignition equipment is available or not.

Table 12: Variables affecting in-situ burning included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{wind}$</td>
<td>[m/s]</td>
<td>Wind speed.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration.</td>
</tr>
<tr>
<td>AddIgniterOil</td>
<td>[-]</td>
<td>Availability of additional igniting equipment.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type, defining oil properties.</td>
</tr>
<tr>
<td>$h_{slick}$</td>
<td>[mm]</td>
<td>Oil slick thickness.</td>
</tr>
</tbody>
</table>

Figure 39: Structure of sub-model considering in-situ burning.
Ice concentration

Ice concentration refers to area covered by ice in relation to total water area. Low ice concentrations increase the drift and spread of the oil which leads to thinner slick thickness, however in low ice concentrations fire booms are efficiently used to contain the oil for burning. A medium range of ice concentration does not contain the oil efficiently and it reduces the possibility to use fire booms, a slight decrease in efficiency follows. High ice concentrations reduce oil drift and spreading while ice may work as mechanical containment of the oil which is gathered between ice floes. This may lead to favorable amounts of oil with sufficient slick thickness for efficient burn potential.

Ice concentration impact on in-situ burning potential is gathered from burn efficiency review in [3] and assumed according to Table 13, also shown in Figure 40.

Table 13: Ice concentration variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>100 100 100 100 80 80 80 90 90 90 90</td>
</tr>
</tbody>
</table>

Figure 40: Ice concentration impact on in-situ burning.
Oil ignitability

Ignitability of oil is a weathering dependent variable varying with time (spill duration), which is slowed down by higher ice concentrations. The ignitability is extended if additional ignitor equipment is available. Oil ignitability is specific for each oil type.

Ignitability of the Troll B crude is achieved from lab tests preformed by SINTEF in [2], where the oil is considered not ignitable if burn efficiency (BE) is BE%<30%. Ice concentrations tested by SINTEF are 0%, 50% and 90%. In the model ice concentrations between the by SINTEF tested measures are assumed according to: 0-20% in model = 0% in lab, 30-80% in model = 50% in lab, 80-100% in model = 90% in lab. See Table 14 and Figure 41.

According to oil tests performed by SINTEF during the Godafoss accident [19], where the IFO380 oil was tested and found not ignitable in cold conditions the IF380 oil is considered not ignitable in the model.

Table 14: Oil ignitability variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>See Figure 41</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>0h 6h 12h 18h</td>
</tr>
<tr>
<td>IgnitabilityOil</td>
<td>[-]</td>
<td>See Figure 41</td>
</tr>
</tbody>
</table>

It is relatively easy to ignite oil in favorable conditions, however in more severe conditions and for a complete ignition additional igniter equipment such as heli-torch is preferably used. Additional igniter equipment impact on in-situ burning is assumed to extend the ignitability window further with ‘One spill duration unit step’, see Figure 41.
Figure 41: Oil ignitiability, in-situ burning, Troll B oil.
Wind speed

Optimal wind speed for in-situ burning occurs when the flames spread efficiently and oxygen is added without the burn being extinguished. Wind speed limits and impact characteristics is gathered from [3] and impact on in-situ burning potential is assumed according to Table 15, also shown in Figure 42.

Table 15: Wind speed variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{wind}$</td>
<td>[m/s]</td>
<td>0-2</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>90</td>
</tr>
</tbody>
</table>

| $v_{wind}$ | [m/s] | 14-16 | 16-18 | 18-20 | 20-22 | 22-24 | 24-26 | 26-28 |
| Impact     | [%]   | 0     | 0     | 0     | 0     | 0     | 0     | 0     |

Figure 42: Wind speed impact on in-situ burning.
Oil slick thickness

For a successful ignition and burn a sufficient oil slick thickness is needed. The slick thickness varies with weathering stage, oil containment and oil type. The impact of oil slick thickness on in-situ burning potential is gathered from [3] and [15] and assumed to impact in-situ burning according to Table 16, also shown in Figure 43.

Table 16: Oil slick thickness variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_{\text{slick}} )</td>
<td>[mm]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Impact: See Figure 43

Figure 43: Oil slick thickness impact on in-situ burning.
B.1.3 Dispersants

In the modeling of dispersant potential ten variables are included. The potential of the method differs with external conditions, properties of the oil as well as the dispersant type. The included affecting variables are found in Table 17.

Table 17: Variables affecting use of dispersants included in the model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_{wind}$</td>
<td>[m/s]</td>
<td>Wind speed.</td>
</tr>
<tr>
<td>SeaState</td>
<td>[Beaufort]</td>
<td>Sea state, Beaufort number, 0-12.</td>
</tr>
<tr>
<td>ActiveAgitation</td>
<td>[-]</td>
<td>Availability of active agitation.</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>Ice concentration.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>Oil Type, defines oil properties.</td>
</tr>
<tr>
<td>SpillDuration</td>
<td>[h &amp; days]</td>
<td>Time elapsed from oil spill.</td>
</tr>
<tr>
<td>ViscosityOil</td>
<td>[cP]</td>
<td>Oil viscosity.</td>
</tr>
<tr>
<td>DSType</td>
<td>[-]</td>
<td>Type of dispersant.</td>
</tr>
<tr>
<td>$T_{water}$</td>
<td>[$^\circ$C]</td>
<td>Water temperature.</td>
</tr>
</tbody>
</table>

![Figure 44: Structure of sub-model considering dispersants.](image-url)
**Dispersibility and oil viscosity**

The oil viscosity depends on the chemical composition of the oil, external conditions and the degree of weathering. Oil viscosity and ice concentration are influencing the dispersibility of the oil. The rate of the weathering process decreases with higher ice concentrations which affects the oil viscosity and thus the dispersability window of the oil.

Weathering measures (oil viscosity and spill duration) for the Troll B oil is gathered from SINTEF report, [2] (p.91-93) and then linear interpolated for wanted time stamps. Ice concentrations tested by SINTEF are 0%, 30%, 50%, 70% and 90%. In the model ice concentrations between the by SINTEF tested measures are assumed according to: 0-20% in model = 0% in lab, 20-40% in model = 30% in lab, 40-60% in model = 50% in lab, 60-80% in model = 70% in lab, 80-100% in model = 90% in lab.

Dispersibility and oil viscosity measures for Troll B oil is gathered from SINTEF [2] (fig. 5.24 p.57) where the curve fitted function for all ice concentrations is used.

Weathering measures (oil viscosity and spill duration) for the IFO380 oil is gathered from [6] (p.47) and then linear interpolated for wanted time stamps. With missing weathering data considering ice concentration the measures above are assumed to cover all ice concentrations.

Dispersibility and oil viscosity measures for IFO380 oil is gathered from [4] which show very limited dispersability of the oil, especially in cold winter conditions.

As the dispersability and oil viscosity is highly dependent on oil type two examples are presented for model demonstration, see Table 18 and Figure 45.

Table 18: Oil viscosity and ice concentration dispersibility variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>OilType</td>
<td>[ ]</td>
<td>See Figure 45</td>
</tr>
<tr>
<td>ViscosityOil</td>
<td>cP</td>
<td>100 (\rightarrow) 260000</td>
</tr>
<tr>
<td>IceConcentration</td>
<td>[%]</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td>Impact</td>
<td>[%]</td>
<td>see Figure 45</td>
</tr>
</tbody>
</table>

The oil weathering properties (e.g. viscosity) input to the WoO model is meant to be produced in the sub-model 2. *Oil properties of RAOS.*
Figure 45: Oil viscosity and ice concentration impact on oil dispersibility.
Oil dispersability - Oil and dispersant type

Oil dispersability summarizes the impact on oil dispersability coupled to the chemical composition and processes of the oil, dispersant fabric and some affecting external variables. The input to the WoO model is meant to be produced in the sub-model 2. *Oil properties* of RAOS.

Dispersability measures for the Troll B oil with various dispersant types and water salinity is gathered from [2] (p.54) and for the IFO380 oil from [6] (p.31).

For model demonstration, examples are included according to Table 19 and Figure 46. Water temperature is included in the model structure however not included in the example, the used input in the model refers to ‘winter conditions’, about 0°C.

Table 19: Oil dispersability variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{water}}$</td>
<td>°C</td>
<td>Not included in this example.</td>
</tr>
<tr>
<td>OilType</td>
<td>[-]</td>
<td>TrollB</td>
</tr>
<tr>
<td>DSType</td>
<td>[-]</td>
<td>Corexit9500</td>
</tr>
<tr>
<td>Salinity</td>
<td>[psu]</td>
<td>10 35 10 35</td>
</tr>
<tr>
<td>Dispersability</td>
<td>[%]</td>
<td>26.0 48.0 36.7 31.3</td>
</tr>
</tbody>
</table>

![Figure 46: Salinity and dispersant type impact on dispersability of different oil types.](image)
Dispersability and mixing energy

For optimal dispersant efficiency sufficient mixing of oil, dispersant and water is needed which is referred to as Mixing energy. Sufficient mixing energy may be achieved by a certain sea state, however more severe sea states may be needed in the Arctic due to presence of ice which is damping the waves and thus reducing the mixing energy.

Mixing energy impact of sea state and ice concentration is assumed according to Table 20 and Figure 47.

Alternative to natural mixing energy is active agitation by vessels thrusters or MOB-boats, with lacking of natural mixing energy and active agitation is considered available mixing efficiency is assumed to 70%.

Table 20: Mixing energy variable definition.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Unit</th>
<th>Discretization/Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>SeaState</em></td>
<td>[Beaufort]</td>
<td>0 1 2 3 4 5 6 7 8 9 &gt;10</td>
</tr>
<tr>
<td><em>IceConcentration</em></td>
<td>[%]</td>
<td>0 10 20 30 40 50 60 70 80 90 100</td>
</tr>
<tr>
<td><em>ActiveAgitation</em></td>
<td>[-]</td>
<td>‘Available/NOT Available’, see Figure 47.</td>
</tr>
<tr>
<td><em>Impact</em></td>
<td>[%]</td>
<td>See Figure 47.</td>
</tr>
</tbody>
</table>

Figure 47: Mixing energy impact.
B.1.4 Complete WoO model structure

Figure 48: Window of opportunity, Bayesian network flow graph.
B.2 Output example

The model provides the user with plotted results where the response methods estimated potential during the prevailing conditions are presented. The affecting variables for each method are easy extracted for analysis purpose and each method may be plotted separately.

B.2.1 Input

Input to the model consists of external conditions, spill specific input and availability of certain equipments.

There are mainly two input options concerning external conditions. Either statistics for a certain location and time period are used or, if the current conditions (real time calculation) are known, they are directly defined as input.

The spill specific input defined by the user consists of OilType, DispersantType, whether ActiveAgitation and AdditionalIgniter are available.

As the model are intended to be a part of a more comprehensive model some additional variables are, at this stage, needed to be defined such as; Salinity, Visibility, WaterTemperature, OilSlickThickness. For a static case calculation (one specific time stamp) SpillDuration needs to be defined.

B.2.2 Calculations

A static case calculation may be performed directly in the software GeNie where the inputs are defined and the network is updated.

For calculations over time, result plotting and analysis the software Matlab (or similar) is preferably used. Inputs are defined directly in a Matlab-script which in turn call for the model, perform the calculations over time, save results and produces the output.
B.2.3 Result

(Same example as in main report, Section 4.2.3)
In the example below the external conditions are gathered from statistics. Input to the example is found in Table 21, resulting WoO in Figure 49 and a selection of plotted affecting variables in Figure 50.

Table 21: Pre-defined inputs.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value/Evidence</th>
<th>Comments:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Tuktoyaktuk</td>
<td>North of Canada.</td>
</tr>
<tr>
<td>Years</td>
<td>1999-2009</td>
<td>Interval for statistics.</td>
</tr>
<tr>
<td>SpillDay</td>
<td>240</td>
<td>I.e. beginning of August.</td>
</tr>
<tr>
<td>CalcPeriod</td>
<td>14 days</td>
<td></td>
</tr>
<tr>
<td>Visibility</td>
<td>&gt;900 m</td>
<td>Good visibility.</td>
</tr>
<tr>
<td>WaterTemperature</td>
<td>0 °C</td>
<td></td>
</tr>
<tr>
<td>Salinity</td>
<td>35 psu</td>
<td></td>
</tr>
<tr>
<td>OilType</td>
<td>Troll B</td>
<td>Crude oil.</td>
</tr>
<tr>
<td>OilSlickThickness</td>
<td>20 mm</td>
<td></td>
</tr>
<tr>
<td>AdditionalIgniter</td>
<td>Available</td>
<td>E.g. heli-torch.</td>
</tr>
<tr>
<td>DispersantType</td>
<td>Corexit9500</td>
<td></td>
</tr>
<tr>
<td>ActiveAgitation</td>
<td>Available</td>
<td></td>
</tr>
</tbody>
</table>

Figure 49: Window of opportunity output for the example.
**B.2.4 Result interpretation and discussion**

Interpretation of the result in Figure 49 is for instance that in-situ burning have the greatest potential at the very beginning of the spill. The potential however decreases relatively fast and the oil will no longer be ignitable after eighth days. Thus if the method is thought to be used with success a fast in-situ burning operation is essential.

The three mechanical recovery methods show different potential due variety in potential coupled to oil viscosity. Mechanical recovery using grab show no potential because of the oil viscosity that is below the limit for grab.

The dispersability of the oil shows moderate potential in an early stage which is decreased slightly when the oil is weathered.

Figure 50 shows a selection of plotted affecting variables. For instance the *MRIceIndex* variable shows that the ice conditions are reduced, i.e. less potential impact, during the calculation period. For different cases the particular variables of interest may be plotted as well as the development of external conditions and oil variables.
B.2.5 Uncertainties

A mathematical model which is intended to describe real phenomenons through mathematical functions includes uncertainties. The uncertainties vary and affect the result differently depending on what is modeled, simplifications and assumptions made and whether the model is used within the limits for validity, to name a few.

In the WoO model identified uncertainties are due to the assumption made that affecting variables are separable, thus treating the variable impact isolated. The Bayesian approach uses statistical data as main input to describe the external conditions, probability is calculated for certain events to occur. This should be kept in mind when interpreting results, estimations of future events are based on historical events.

Statistical data are based on input from different sources where quality and data resolution varies. Sometimes the data in turn are produced by other models.

Impact measures on a specific method by a specific variable is based on different sources ranging from laboratory tests, experts judgments to reasoned assumptions. Concerning Arctic operations and oil spills in ice the number of operations are still limited and the field is under development meaning that broad experience does not exist.

It is important to remember that the results presented from the WoO model at this stage is only for example purposes to show the idea and functions of the model structure and how the decision support tool preferably could be used. Therefore no validity check of the model has been performed and no further guaranties are given.
C IceMaster summary

This is coarse summary made within the exploratory study of the project where the outline of the reference IceMaster is presented.

C.1 General functions and objectives

The Transatlantic IceMaster is a SSPA developed decision support and planning tool for Arctic offshore operations. The conditions for offshore operations that the Arctic climate bring sets high demands on operational planning. The significant seasonal variations mean that the Arctic area is often closed for operations during the winter period due to ice and weather conditions. Therefore the main questions prior operations are concerning the extent of a safe drilling season and operational limiting conditions for the used icebreaker fleet. For the estimated operational window (summer period) additional questions are raised concerning needed units and how to tackle e.g. ice management during the operation.

The Transatlantic IceMaster is a risk-based model which can be used for planning of operations taking into account the environmental conditions, operational goals, emergency preparedness and operational fleet among others as important keystones for a safe and successful operation. The idea is to cover the total operation, be prepared to tackle upcoming conditions, complete the operational objectives and return safely to port before the operational limiting conditions are exceeded.

C.2 Input and output data

The model is build on different inputs where statistics concerning ice conditions and weather is used together with data describing the specific operation and the included units (icebreakers, drilling vessels etc.). The model also use qualitative data from previous operations including experiences from crew on the ability to tackle different conditions as well as up to date observations from the operational area.

The output represents a wide range of data that is intended to be used as guidance for decision making, e.g. operational time window for a drilling season at a specific location.

C.3 Modeling method

The modeling is based on Bayesian Network which link different modules together. Within the modules the Bayesian approach together with MATLAB based programming defines the variables. For instance the ability for a specific icebreaker fleet to be able to perform sufficient ice management is calculated through definition of so called Ice Breakability Index and Icebreaking Capability which in turn is calculated from the input data describing the specific operation and included vessels.