Prevention of oil spill from shipping by Modelling of Dynamic Risk

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Abstract

To enhance the risk reducing effect of shore based ship monitoring, this paper suggests a new, dynamical approach for risk based ship traffic prioritisation. The philosophy behind this new approach is that risk can be reduced by directing efforts towards ships and areas that have been identified as high priority (high risk), prior to a potential accident. The proposed model separates itself from previous ship prioritisation models by drawing on available dynamic data and by focusing on the ship's surroundings. The model estimates the potential environmental risk of drift grounding accidents for oil tankers in real time and in forecast mode, combining the probability of grounding with oil spill impact on the coastline. Our results show that the potential dynamic risk introduced by an oil tanker sailing along the North Norwegian coast depends significantly on wind and ocean currents as well as tug position and cargo oil type. The results indicate that the risk model is well suited for real time prioritising of oil tankers and coastal segments, and effectively separates low risk and high risk situations. This enables dynamic risk based positioning of tugs, using both real-time and projected risk, for effective support in case of a drifting ship situation.

1 Introduction

The volume of international seaborne trade is growing, and with it the potential risk towards the marine environment is increasing. Global seaborne trade (in tonnes) increased by almost 70% from 1990 to 2004, and oil transportation grew by 30% in the same period (*United Nations Conference on Trade and Development, 2005*). Despite this growth, the number of spill incidents is dropping, and so is the volume of spilled oil (*International Tanker Owners Pollution Federation (ITOPF), 2004*). However the consequences of some rather recent incidents, such as the Prestige accident in 2002 and the Erika accident in 1999, have been particularly grave in terms of both financial loss and local damages to the environment (*ITOPF, 2005*), and they illustrate the need for further improvement. Considering that 25% of the most substandard ships in world fleet are involved in 50% of the severe accidents (*Soma, 2005*) indicates that it is possible to lower the environmental risk by focussing attention on substandard ships, and models have been developed to this end (*Herman, 1995; Andreassen et al., 2003; Degre et al., 2003; Fowler & Sørgård, 2000; UK Department for Environment, 2000; Paris MOU, 2006; United States Coast Guard (USCG), 2006; International Chamber of Shipping/International Shipping Federation, 2006; Eide et al., 2006a)*. Currently, the ParisMOU model forms the basis for a European Union (EU) directive requiring “Mandatory Expanded Inspection” for defined “high risk” vessels (*EU, 2001*). This paper presents a model which separates itself from previous ones by drawing on available dynamic data and by focusing on the ship’s surroundings. The modelling approach incorporates a number of existing operational models (e.g. ship drift model), available databases (e.g. vulnerability data) and technology platforms (e.g. AIS), provided by a number of organizations, resulting in an innovative and comprehensive risk reduction tool for use in improved traffic management (e.g. Vessel Traffic Services (VTS)).

Studies indicate that the risk-reducing effect of a VTS centre is between 20% and 80%, depending on the geography, the traffic density and the resources available to the VTS (*Danish Maritime Authority & Royal Danish Administration of Navigation and Hydrography, 2002*). This indicates that the highest potential for risk reduction may perhaps be found in shore based support systems, such as VTS centres, rather than with ship specific measures. VTS is the central tool for coordination of vessel traffic monitoring and control. The service enables an operator to interact with the traffic, and to respond to situations arising in the VTS area of responsibility. Today, the Automatic Identification System (AIS) transponders aboard the ships enable VTS centres to monitor and track vessels on large stretches of coastline using shore based AIS receivers. AIS is mandated by the International Maritime Organisation (IMO) and included in SOLAS Chapter V (*IMO, 2002a*). From 2002 and onwards, ships above 300 gross ton (GT) carry AIS transponders. The system enables the ships to automatically transmit and receive information (*IMO, 2002b*). The data is carried on ordinary maritime VHF radio frequencies, and contains static and dynamic information such as the ships identity, destination, cargo etc. Static information is transmitted every sixth minute. Dynamic information may be transmitted as often as every 2 seconds, depending on vessel speed and rate of turn. Monitoring far-reaching coastal areas may in turn give the operator an unwieldy number of vessels (e.g. several hundreds) to monitor. Because of the need to effectively monitor large number of vessels, the VTS centres are looking for means enabling them to filter out the unwanted traffic patterns and high risk vessels, in particular hazardous goods traffic (HAZMAT). Such vessels may then be followed up with different risk reducing measures depending on sailing area and traffic pattern. When the global identification and tracking of ships is implemented using Long Range Identification and Tracking (LRIT) technology, the potential for monitoring and filtering would increase further. LRIT is a satellite-based system with planned global cover of maritime traffic from 2008 (*IMO, 2006*). The national level incentives for the monitoring of hazardous goods traffic using VTS and AIS tools and technology is in the European Union set by the EU Directive 2002/59 EC (*EU, 2002*). The Directive establishes a Community vessel traffic monitoring and information system with a view to enhancing the safety and efficiency of maritime traffic, improving the response of authorities to incidents, accidents or potentially dangerous situations at sea. A system called SafeSeaNet (SSN), operated by the European Maritime Safety Agency, is under development and will focus on some of these issues. SafeSeaNet and shore based AIS is regarded as the backbone of the EU traffic monitoring system, and are together with VTS all tools for environmental risk reduction. To enhance the risk reducing performance of VTS centers it is reported that risk based ship prioritization and dynamical risk modelling will be very suitable to implement in the task of improved traffic monitoring (*Eide et al. 2006a*).

The methodology developed in this paper (as part of the Norwegian Research Council project AIS2010 – Innovative use of AIS) will help prevent drift grounding accidents by allowing for a dynamic risk based positioning of tugs along the coast, placing the tugs where they can be most effective. Tugs are often used either in an escort capacity, or as sentinels. The escort function is more effective, but also more expensive (*The Glosten Associates, 2004*) and the described method may bring the tug safety effect close to the escort performance, while keeping the costs at sentinel level simply by giving the tug an opportunity to be in the right place at the right time. The model, although developed with focus on accident prevention, may also be of use in an emergency situation, for effective positioning of contingency resources. As an input to emergency response services (ERS) the model may contribute to reducing tug connection time by predicting ship drift, and possibly enhance traditional ERS services such as strength and stability calculations through environmental input data. The model has been implemented for test application in northern Norway. This area is of particular interest because of the rapid growth in oil transportation in the arctic and sub-arctic regions of the world, such as in Russian and Norwegian arctic waters. In 2002, a total of 4 million tonnes (Mt) of oil was transported along the North-Norwegian coast. In 2004 this number was close to 12 Mt transported by almost 300 vessels (*The Norwegian Coastal Administration*, 2006a). Projections for 2015 indicate that more than 140 Mt of oil will pass through the region annually (equivalent to 1400 tankers carrying 100,000 tonnes) (*Brunstad et al.*, 2004). This growth is increasing the chances of oil spills in environmentally highly vulnerable areas. Drift grounding accidents are a great concern in this region as much of the traffic passes close to shore and is exposed to harsh environmental conditions. Also, both coastline and seabed topography is complex and hazardous. While the occurrence of drift grounding accidents is rare, the expected consequence of such an event is great. Also, although drift grounding accidents are normally the result of a ship loosing manoeuvrability through steering or propulsion failure, drift groundings may also follow events such as collisions or fires. The worst-case scenario came close to realisation in June 2003 when a tanker carrying 102,000 tonnes of crude oil drifted for hours off the North Cape (North of Norway) after suffering engine failure 19 nautical miles from land. The nearest tug was 10 hours away, and the ship is likely to have grounded if not for unusually benign weather conditions which allowed the engine to be repaired in time. Similar “near misses” occur regularly. Although the subject of arctic oil transportation attracts much attention in Norway, the concerns of drift grounding extends to other locations and to other ship types, e.g., carriers of liquefied natural gas (LNG) and chemicals, or passenger ships. Our proposed modelling approach is universally applicable.

This paper first describes the general concept of dynamic risk modelling, with particular focus on drift grounding accidents (Section 2). The modelling concept for other accident types is given in Section 3. Section 4 presents modelling results, and Section 5 presents our conclusions.

2 Dynamic modelling approach for Drift Grounding

The proposed dynamic model uses input from a wide range of sources, extending beyond previously developed ship prioritisation models, by utilising dynamic information regarding the ships surroundings and environment in addition to the information regarding the ship itself. In general, the dynamic information may be ship position, wind, currents and waves, loading conditions, proximity to land, traffic conditions and available contingency resources. The list goes on, and depends on the type of accident under consideration. The information in this category change over the course of hours or days, and will be used to produce an assessment of the environmental risk level that may change by the hour; a risk model utilising this information is thus *dynamic*. Provided that the right models are available, this concept can draw on a vast pool of information, making it possible to asses risk in close to real-time in an accurate manner, and also predict risk exposure ahead of time. The dynamic factors may impact on both the probability of an accident, and on the consequences of the accident. In general the dynamic risk is a function of location (x and y coordinates) and time (t). As risk (R) is defined as frequency (F) times consequence (C), the dependence on location and time may be modelled through one or both of these factors:

$$R = R(x, y, t) = F(x, y, t) \cdot C(x, y, t) \qquad (1)$$

Drift grounding occurs when a ship loses its ability to navigate, through loss of steering or propulsion, and is forced onto the shoreline before it is either taken in tow or is repaired. In the current context the ship risk, as defined in Equation (1), will vary with both the position (*x, y*) of the ship as well as with time (*t*) by modelling both the frequency and the consequence dynamically (*Figure 1*). Note that the position of the ship is automatically transmitted by AIS.

The type of risk under consideration is the risk of oil spill and subsequent environmental damage. This risk is commonly measured in units of *tons of oil spilled per ship year*, referred to in the literature as pollution risk (Lehman & Sørgård, 2000). However, since the impact of oil spills may vary considerably depending on what, when and where it is spilled, it may be more useful to include some measure on the environmental impact of the oil spill, thus assigning to risk this unit: *oil spill impact per ship year.* This is in the literature referred to as environmental risk (Lehman & Sørgård, 2000). Though this is a less concrete measure in terms of absolute risk levels, it is convenient for comparison between ships. We realise that the proposed unit for R is not informative in any context outside of the specific application of the presented model. However, since the objective is to produce a decision support tool to aid in the prioritisation of ships of the coast, the units used need not be applicable outside this scope. *Table 1* gives an overview of the units associated with the model variables, to be described in the following.

2.1 Accident Frequency Modelling

The frequency of Drift Grounding is modelled to be the product of the frequency of ship drift incidents (F_{drift}) and the probability of grounding given that the ship is adrift ($P_{grounding|drift}$):

$$F(x,y,t) = F_{drift} \cdot P_{grounding|drift}(x,y,t) \tag{2}$$

The failure rates for propulsion and steering are available from the SAFECO project (*Hansson & Kiær, 1997*), with differentiation on ship types, engine types, and ship size. These rates average 0.26 failures per ship-year for all ships but vary significantly for certain segments of the fleet. The failure rates in SAFECO are based on a fault tree analysis, combining failure rates for components and expert judgement. We propose to use the average value of 0.26 failures per ship-year as a first estimate for F_{drift}. However, it should be noted that there are indications that the frequency could change by a factor 5 depending on the ship engine type (e.g. slow speed, medium speed) (*Hansson & Kiær, 1997*) or the number of engines produced of a specific model (*Eide et al., 2006b*).

The probability of the ship grounding given that it is adrift is a function of elements related to its surroundings, elements which are highly *dynamic*. The probability of grounding depends on the ship either being able to repair the problem on its own, or receiving assistance from tugs, and ultimately that either of the solutions can be achieved in time to avoid the grounding. The most general way to describe this is with three probability density functions: the "tug response time"-distribution (f_{TRT}), the "time to shore"-distribution (f_{TTS}) and the "self repair time"-distribution (f_{SRT}). It is clear that f_{TTS} depends heavily on the distance to shore, as well as winds, sea state and currents. Although it might be more difficult to make repairs in bad weather, f_{SRT} is assumed to be a constant distribution, and f_{TRT} is in essence a question of having a sufficiently powerful tug within reasonable distance. The latter is complicated by the tug's performance in bad weather, as well as the time needed to connect tug and tanker in high seas (*The Norwegian Coastal Administration,* 2006b). Other elements might be included such as the probability of emergency anchoring, as done in SAFECO (*Fowler & Sørgård, 2000*), but this is ignored in our model. Given the three distributions, f_{TRT}, f_{TTS} and f_{SRT}, the probability of grounding is found through integration over time as follows. (Note that both variables s and t denote time.)

$$P_{groounding|drift} = 1 - \int_{s=0}^{\infty} f_{TTS}(s) \int_{t=0}^{s} f_{SRT}(t)dtds \tag{3}$$
$$- \int_{s=0}^{\infty} f_{TTS}(s) \int_{t=0}^{s} f_{TRT}(t)dtds + \left(\int_{s=0}^{\infty} f_{TTS}(s) \int_{t=0}^{s} f_{SRT}(t)dtds \right)\left(\int_{s=0}^{\infty} f_{TTS}(s) \int_{t=0}^{s} f_{TRT}(t)dtds \right)$$

Currently a discrete probability function for the self repair time is available from SAFECO (*Fowler & Sørgård, 2000*). The tug response time is determined by four factors: (i) reaction time, (ii) mobilisation time, (iii) sailing time from tug initial position to ship and (iv) time required to connect the ship and the tug. The Norwegian coastal administration (2006b) estimates elements (i) and (ii) to be 1.5 hours each and element (iv) to be 2 hours, totalling 5 hours, but with high uncertainties in this estimate. SAFECO reports a weather-dependent connection time (element iv) of approximately 1 hour (*Fowler & Sørgård, 2000*), illustrating the need for further analysis on this subject. Currently, the following approach is used to estimate the tug response time distribution: First the distance from the tug to the ship is found through AIS. Assuming an average tug speed of 15 knots (28 km/h) gives an estimate of the travel time (iii). Note that this tug speed is in the upper range according to both the Norwegian Coastal Administration (2006b) and LRF (2005a), and that the tug speed should be found specifically in an operational setting, combining AIS data and vessel databases. Furthermore, due to uncertainty in the speed estimate, the travel time is assumed to vary with plus minus 10%, giving a travel time range, with an assumed stepwise, symmetrical distribution. Added to this is a preparation time (reaction time + mobilisation time) of 1.5 hours and connection time of 1.5 hours. This is a rather low estimate for preparation time, and would most likely apply to tug vessels on high alert or already sailing at the time of the alarm.

The time to shore probability density function is being modelled in detail using a ship drift model (*Sørgård & Vada, 1998*). This distribution is based on 500 slightly perturbed simulation runs, and will depend on local currents, weather (wind and waves), proximity to shore and properties of the drifting vessel (e.g. ship type, draft, size, loading condition). The inherent uncertainty in weather prediction and vessel response to its environment will be transferred to the probability density function by perturbations of input data to the ship drift model. The actual wind and ocean current data for the area are obtained from The Norwegian Meteorological Institute (met.no). Ocean current fields in the operational setup of the ship drift model are taken from the operational 3D baroclinic ocean model operated by The Norwegian Meteorological Institute. The model and the operational setup at the Norwegian Meteorological Institute is described in detail in *Engedahl* (1995) and *Engedahl* (2001). The ship drift model is part of a suite of operational emergency trajectory models including an oil fate model and a model for search-and-rescue objects (*Breivik and Allen 2006, Hackett et al 2006*).

2.2 Consequence modelling

The environmental consequence of a drift grounding accident, C, will be modelled in two separate parts. The first part will relate solely to the expected quantity of oil spilled in an accident, i.e. the expected spill size (S). The second part concerns the impact (I) of one tonne of oil on the environment. The consequence model is thus split such as to describe the *quantity* and *quality* of the oil spill separately. Furthermore we model bunker spill (subscript b) and cargo spill (subscript c) separately, with regard to both spill size and spill impact:

$$C = C_c + C_b = S_c \cdot I_c + S_b \cdot I_b = \sum_{i=b,c} S_i \cdot I_i \tag{4}$$

2.2.1 Spill size modelling

The spill size may depend on the ship type, size, and loading condition, and whether the ship is single or double hulled. The model is valid for four accident types; drift grounding, collision, powered grounding and fire & explosion (*Eide et al., 2006b*), and these four accident types account for 95% of all oil tanker spills (Kjellstrøm & Johansen, 2005). There are great differences between the accident types (Sørgård et al., 1999), and the model accounts for these differences. although the details presented here are limited to drift grounding accidents.

The expected spill size in the event of an accident, *S*, is found by combining the probability of an oil spill given an accident $P^{(s)}$ with the expected oil outflow in the event of a spill *O*. This is modelled for both bunker tanks (*b*) and cargo tanks (*c*), which makes the model applicable also to non-tanker vessels and tanker vessels in ballast:

$$S_i = P^{(s)} \cdot O_i \qquad \text{for} \qquad i = b\,,\, c \tag{5}$$

The volume of oil outflow *O* from cargo and bunker tanks given that there is a spill accident, is modelled as:

$$O_i = \alpha_i \cdot \beta_i \cdot Dwt \qquad \text{for} \qquad i = b,\, c \tag{6}$$

where α_i is the expected outflow rate given as a percentage of the tank content volume (depends on accident type), for both cargo and bunker tanks; β_i is the volume of cargo and bunker oil respectively as a percentage of vessel deadweight tonnage *Dwt.*

Using historical data to model the input values to Equation (5) is not straightforward. Although older data from the SAFECO project, as reported by *Lehmann and Sørgård* (2000), are extensive it is suspected that they are not necessarily representative for today's accident scenarios. New data (*LRF, 2005b*), covering the period 1998-2004, indicate that the long, historical time series used for calculating average oil outflow and pollution probability for crude oil tankers in SAFECO and other sources are outdated, the main reason being the double-hull requirement. The IMO requirements of MARPOL Regulation 13F, as well as other legislation (such as the Oil Pollution Act of 1990), are making single hull tankers obsolete. The decline in the number of single hull tankers is illustrated in *Figure 2* for crude oil tankers above 10 000 GT. Because of these developments, and the fact that statistical data separating on single hull and double hull tankers are not available, this paper relies mostly upon modeled quantities for the assumed oil outflow performance (α_i) factors for collision and powered grounding accidents (*National Academy Press, 1998; USCG, 1998*). Our model differs between single and double hull vessels, but we assume the same outflow performance for both cargo and bunker tanks. This is supported by modelling data reported by INTERTANKO (*Dragos, 2003*) which indicate a difference between single and double hull bunker tanks similar to the cargo tanks. The assumed value for α_i used in the model varies from 20% to 40%. Typical cargo loading condition for crude oil carriers varies between 80% and 97% of Dwt for a laden tanker. *Wijnolst and Wergeland* (1997) reports that utilisation in practice hardly exceeds 95%, but could be as low as 65%. In the modelling we assume a 91% utilisation of cargo capacity (β_c) based on average figures reported by *Behrens et al.* (2003). *Wijnolst and Wergeland* (1997) reports that typically 2.5% of the Dwt is applied for storage of water and bunker oil etc. The fraction of Dwt used for bunker oil (β_b) is assumed to be 2%.

The value of $P^{(s)}$, the probability of spill given a drift grounding accident, is set at 1.6%, given by spill statistics (*LRF, 2005b*) covering the period 1998-2004. In this paper it is assumed that $P^{(s)}$ is the same for both cargo tanks and bunker tanks. It is realised that the values of $P^{(s)}$ should be modelled to differentiate between single and double hull vessels. Modelling results (*National Academy Press, 1998*) indicates that the probability of spill for a single hull tanker could be a factor 4 higher than for a double hull tanker. This difference could be accounted for by applying a multiplication factor γ to the values of $P^{(s)}$, provided that it was known for which ships the statistical $P^{(s)}$ values are valid for; single or double hull vessels. The statistics (*LRF, 2005b*) are quite recent, but it is not known if the vessels contained in the statistics are single or double hull vessels. It is beyond the reach of this paper to analyse this in sufficient detail, and any modelled adjustment of the statistical $P^{(s)}$ values would thus be very rudimentary. It is however believed that this shortcoming is mitigated, at least to some degree, by the modelling of oil outflow (O) in the previous paragraph, in which there is a marked difference in the modelling of single hull and double hull vessels.

2.2.2 Impact modelling

The spill impact (I) per tonne oil depends on the affected area's vulnerability to oil pollution, as well as on the type of oil spilled. For the bunker (b) as well as for cargo (c) spill, the environmental impact factor will then be modelled in two parts: As an environmental sensitivity index (E) and oil type significance index (T):

$$I_i = E \cdot T_i \qquad \text{for} \qquad i = b\,,\,c \tag{7}$$

The first part will incorporate the vulnerability and ecological significance of a selected geographical area, and is independent of oil type. The second part will describe the significance of the oil type spilled. Both E and T are modelled as relative indices, i.e. with little regard for the absolute levels. This is practical as the use of the model will be the relative comparison of ships, and the absolute level of the values for spill impact is of little importance.

With respect to the environmental damage potential, sensitivity has been focused on sensitivity towards petroleum products. As this also includes gas and condensate, it has further been focused on crude oil and oil products as the dimensioning impact factor. This is in line with the *Arctic Monitoring and Assessment Programme (AMAP)* (1998). Two overall criteria have been applied for data compilation (*Moe et al., 2004*): (1) *Vulnerability*; i.e. focus should be placed on those resources considered most vulnerable to oil spill from the sea-borne transportation activity (resources like shallow water benthos, shoreline substrate and communities, fish eggs and larvae (spawning grounds), seabirds and marine mammals may be significantly affected), and (2) *Ecological significance*; this means that effort has been placed on the most important resources within one specific area (e.g. large populations of fish, seabirds, seals). The importance of the various areas for the various species is given factor values reflecting the significance for these areas. By vulnerability we understand a general sensitivity towards exposure of oil, where exposure is a function of behaviour and mode of living, and where negative effects acts over time (restitution capabilities). In this work, the vulnerability values are based upon the MOB model (model for prioritizing environmental resources in acute oil spills in the Norwegian Coast) (*SFT&DN, 1996*), supplied by a wider use of the vulnerability concept from “Particular Sensitive Areas and Acute Oil Pollution” - SMO (*Moe et al., 1999*).

For each resource group (fish, seabirds, etc.) within the 10x10 km area under consideration, factor values of 1-3 (1 = least, 3 = most) has been set for the two parameters above (vulnerability and ecological significance), and multiplied to give a resource specific environmental sensitivity index ranging from 1 to 9. All resource groups within a 10x10 km area contribute to the overall environmental sensitivity index, *E*, by adding up the group specific values. The index values are shown on areas of 10x10 km in *Figure 3*, and are averaged on coastal segments to indicate the potential consequences along practically sized stretches of the coastline. All compilations are given on a seasonal basis.

Different oil types will behave differently in a spill situation. The impact of an oil type will depend on distance to shore, drift pattern (dependents of the local wind and current condition), weathering processes and chemical composition of the oil. Generally, oils with a lower density will be less persistent and have a less severe impact on the environment. However, some apparently light oils can behave more like heavy ones due to the presence of waxes (*ITOPF, 2005*). Statistical oil drift simulations are analysed to evaluate the spread of different oil types. As a first approach, three different oil types where modelled at three different spill locations in the Lofoten – Barents Sea area (north of Norway) (*Figure 4*) to give input values to the quantification of oil type significance index, *T*. In the oil spill model (*Sørgård, 1993*) 20 000 m^3 of oil where spilled during 24 hours as a result of ship grounding. The oil types being modelled was (i) Heavy crude oil, (ii) Medium crude oil and (iii) Light condensate. The category of an oil type will be determined by the density of the oil ρ, according the criteria in *Table 2*. This is similar to the way ITOPF have classified oils into groups according to their density, and the volume of oil and water-in-oil emulsion remaining on the sea surface for the different categories (*ITOPF, 2005*). Results from the spill modelling are indicated by the influence area (sea surface area with more than 5% probability of being hit by oil) in *Figure 4*. The model uses monthly ocean current data (*Martinsen et al., 1992*) and time series of wind data from The Norwegian Meteorological Institute (*Haug & Guddal*, 1981; *Reistad & Iden*, 1998), i.e. more than 40 years time series at 6 hours intervals. By comparing the amount of oil stranded for each spill scenario, a relative significance index (T) valid for the area under consideration was derived for the different oil types (Table 3). The ship specific information about type and volume oil cargo transported is planned to be collected from SafeSeaNet (*The Norwegian Coastal Administration, 2005*).

3 Dynamic modelling approach for other accident types

The model presented in the above chapter is limited to drift grounding accidents. However, the methodology is valid for other accident types as well, and Equation (1) is not limited to drift grounding. There are obviously dynamic factors influencing collision and grounding accident risks, such as proximity to other ships and land respectively. We have considered three additional accident types on a general level: powered grounding, collision and fire & explosion. For drift grounding accidents both frequency and consequence is modelled dynamically. For the three other accident types a more simplified initial approach is suggested, keeping the accident frequency static (invariant with time) while modelling the spill consequence dynamically. This approach is outlined in the following paragraph, but not considered in great detail. Some elements of this approach is identical to the more comprehensive model for drift grounding, and reference is thus made to the chapters which describes this for drift grounding.

For the collision and fire & explosion accident types the simplified modelling approach is to assume an oil spill location in shipping lane with a frequency which do not change with position or time (the probability of an accident occurring is the same all along a route or stretch of coastline). With input from the oil outflow model (Section 2.2.1) we apply the oil drift model (*Sørgård, 1993*) which calculates stranding volumes and shoreline pollution length, depending on weather and wind conditions. Then we apply the environmental impact model (Section 2.2.2). The resulting risk then enables comparison of geographical areas as well as comparison of individual ships. For powered grounding the approach is the same, with the exception of the assumed oil spill location being in the position on the shoreline closest to the current ship position, and that the oil spill impact is tabulated rather than modelled specifically.

4 Modelling Results for Drift Grounding

4.1 Case description and input data

To illustrate the modelling approach for drift grounding described in Section 2 some modelling example cases are presented. All cases are based on the assumption that a loaded Aframax crude oil tanker of 80 000 Dwt (240 meters in length) is identified through AIS at a position off the Norwegian coast (*Figure 5*). The potential risk level, *R*, for this tanker is then estimated from Equation (1) under different circumstances, each set of circumstances is given a case number. For simplicity, not all model variables are altered in these test cases. However, the selected cases are intended to illustrate some central aspects of the model. The different cases are outlined in Table 3. The initial position is left unchanged for all cases. So is the season, which would otherwise impact on the environmental vulnerability. We have used two weather and ocean current situations resulting in two time to shore distributions: one with "fast" drift and one with "slow" drift (*Figure 6*). Both distributions are based on actual simulations using the Ship drift model (*Sørgård & Vada, 1998*), using real weather and currents data from the summer and fall of 2006. The time development of the fast drift situation is illustrated in *Figure 7*. For each of the two weather and ocean current cases we investigate two oil types, one heavy and one light. Furthermore, we use two assumed tug positions: Kirkenes and Hammerfest (Figure 5), resulting in the Tug response time distributions given in Figure 8.

4.2 Results and discussion

The results in *Table 3* clearly demonstrate the great variances in potential accident frequency and environmental risk, depending on the circumstances surrounding the drifting vessel. It is evident that the impact of tug position varies with the drift time to shore: in benign weather conditions the risk is negligible when a tug is available in Hammerfest (case 1), while there is a small risk associated with having the tug as far away as Kirkenes (case 2). As the weather worsens, the difference between having a tug in Kirkenes (case 4) and having a tug in Hammerfest (case 5) is a factor 6. Furthermore, the type of oil carried as cargo has a significant impact on the risks. The factor varies from 6 to 9. The greatest difference in risk is the result of weather and currents. The results show that the risks may differ by as much as a factor 45 (case 2 vs. case 6). It is evident from *Table 3* that all cases 1 to 4 are generally less critical than cases 5 to 8. This is the weather impact. However, case 5 is less critical than case 4, showing that the combined effects of having a tug close by and carrying light oil can compensate for severe weather conditions. Also, case 6 and 7 show that a favourable tug position can nearly outweigh the effect of carrying heavy oil cargo.

Because of the difficulties involved with presenting the risk of environmental damage in stringently defined units, it is proposed to utilise the modelled results on several levels. This means extracting results of the modelling prior to the final result in the risk format *impact per ship year* (i.e. environmental risk). This is illustrated in part in *Table 3* with the inclusion of the *frequency* and *consequence* columns. The increasing result presentation levels will represent results of increasing modelling detail, and of increasing value to specialised users. However, the increase of level will involve a decrease in generality, firmness of definitions, objectivity, possibility of verification and comparability with statistics and other models. It should be noted that the first level output, which is simply the probability of the drift grounding event excluding all consequence considerations (*Table 3*, column *Frequency*), provides a basis for modelling other risks, such as loss of life or property damage. The probability modelling is universal for all consequences. The second level would be the pollution risk level, measured in *tonnes of oil per ship year*, and would be compatible with use of cost-effectiveness criteria such as the Cost of Averting one Tonne of oil Spill (CATS) criteria (*Skjong et al., 2005*). The third and final level, environmental risk, which is expresses in terms of *impact per ship year* is appropriate for comparison of individual ships or geographical areas (*Table 3*, column *Risk*).

The information provided to the users of the dynamic risk model should show an overall risk level and details provided in the calculation steps prior to the final risk calculation. Of particular importance are values that show the VTS operator the reason why a risk level is high, indicating which measures to apply in order to decrease the risk. If applied correctly, the additional information may help determine which risk reducing measures will be most effective for each ship. Also, quantitative risk assessments of this kind make it possible to evaluate the cost effectiveness of different risk reducing measures (*Skjong et al.*, 2005). Risk assessments for ships generated over time (months or years) may be aggregated to provide a periodic risk picture covering selected areas (*Thevik et al., 2001*). This in turn will provide decision makers with a tool to evaluate risk reducing measures of a permanent nature against each other by identifying risk “hot-spots” and subsequently evaluating the costs and effects of available measures (*Harrald et al., 1997*). Such permanent measures might include positioning of permanent tug stations, oil spill emergency response units and adjustment of shipping lanes. However, ship traffic surveillance of the sort proposed in this paper is a risk reducing measure in itself which could be analysed with respect to cost effectiveness.

4.3 Uncertainty

The results obtained with the proposed model must be used with care. The intended use is decision support, not decision making. Ultimately, all decisions must be made by qualified operators, and all decisions should draw on all available information and not any one model alone. The model includes uncertainties, and this section highlights some elements contributing to the inherent uncertainties in the model. No attempt is made to quantify the uncertainty. The uncertainties stem from input data, as well as simplifications and assumptions used in the modelling approach. It is worth noticing that the absolute level of the risk estimate is not a major concern, as the aim of the model is to compare the relative difference between oil tankers. The following sections discus the uncertainties associated with the modelled frequency of drift groundings, and the environmental consequences of drift groundings.

The probability of a ship losing its ability to navigate is kept constant for all crude oil tankers in the proposed model, although it is known that engine failure rates vary. Two studies indicate that the failure rate varies with the type of main engine installed (*Hansson & Kiær, 1997; Eide et al., 2006b*). In further developing the model, this information could be utilised to adjust the value of *P(drift)* to different ship properties. Interestingly, Hansson & Kiær (1997) also suggest that there might be geographical differences in the engine failure rates. It should also be noted that some tankers have two main engines, which significantly reduces the probability of loss of propulsion. Initial numbers suggests that approximately 20% of tankers below 10 000 GT (and above 100 GT) have dual machinery, while only 4% of larger tankers have the same redundancy (*LRF 2005a*). It is important to notice that the failure rate may also depend on maintenance, crew skills and other operational aspects. For instance, it is likely that substandard ships may have a higher failure rate. The probability of drifting could then be modified taking this into account as outlined for instance in Degre et al. (2003) or Eide et al. (2006a).

The probability of a drifting ship running aground is governed by three factors in the current model; drift time to shore, tug response time and self repair time. These are given as probability distributions and will thus express the uncertainty within each factor. Our results are believed to be sensitive to the estimated time to shore distribution. We have, as outlined above, applied a ship drift model forced by ocean currents and winds on a 10x10 km resolution grid. The ocean current model does not necessarily include local effects such as eddies and detailed topography. We have therefore evaluated the effect of grid resolution by modelling drift of particles (trajectory modelling) in 4 km versus 0.8 km grid. The sensitivity modelling was made with the ocean current model SINMOD (*Slagstad & McClimans, 2005*) using boundary conditions form the operational 4 km ocean model, Nordic 4, from the Norwegian Meteorological Institute. The area studied is a part of the north Norwegian coast. Oil-like particles were released along the 12 nautical miles territorial sea line every 12th hour in the simulation period (8th -17th December 2005), and transported (advected) by the surface currents of the model. In addition, Stokes drift which is set to 2.5% of the wind speed in the direction of the wind is added (*Martinsen et al., 1994*). This forcing typically reflects the movement of an oil slick. By applying two different horizontal model resolutions, 0.8 km and 4.0 km to this trajectory model, and forcing it with the same input values, the effect of grid resolution was investigated. The simulations revealed an important difference between the two model cases, although the results should not be interpreted as general trends as only one specific simulation period is considered: The calculated drift time to shore was in general significantly shorter in the 0.8 km resolution case. Also, the calculated total number of particles reaching shore is higher in the 0.8 km case than in the 4 km case, and these particles are distributed more evenly on the coastal segments. The results illustrate that using two different resolutions, may produce significantly different results for particle drift time to shore, at least in coastal areas where the topography and eddies are complex. Of course, when considering ship drift, the wind is a much larger factor than with oil drift (given not calm weather). In addition the effect needs to be investigated for different ocean and weather conditions and for different types of ship drifting.

Besides the uncertainties related to grid resolution, there are other factors contributing to drift modelling uncertainty. For instance, wind measurement itself is uncertain: Wind and wave data presented in Young & Holland (1996) are reported with satellite measurement error. These uncertainties are expected to be no worse than those inherent in other measuring techniques. For wind speeds in the range of 0-15 m/s the uncertainty is in the order of 2 m/s, and for wind speeds above 20 m/s the uncertainty is as much as 20%. Other studies suggest similar uncertainties in measurements (*Meissner et al. 2001, Mears et al. 2001*). In addition, Polar lows represent a particular challenge to forecast systems for arctic regions. Their small spatial scale combined with few observations in Polar Regions heightens the risk that lows may form before they are identified and forecasted. To account for this, a new high-resolution atmospheric and wave forecast system has recently been set up by the Norwegian Meteorological Institute. Both atmospheric and wave forecast models operate on a 10 km grid. In the applied ship drift model, the wind vector uncertainty is set to 2.6 m/s standard deviation, and included in the modelling simulations. This is based on observations and model results from open-ocean conditions (Weather station Mike, see *Breivik and Allen, 2006*). Thus we expect that the contribution from uncertainty in wind is accounted for in the modelling approach. However, there are uncertainties in connection with ship loading condition, hull form and size and superstructure design not necessarily fully taken into account in the modelling approach. Also, there is uncertainty regarding the impact of detail level of wave input data to the model (Sætre & Wettre, 1999).

Adding to the uncertainty in the probability of grounding given drift is the fact that the anchor salvage option has been omitted in the current study. A drifting vessel may drop its anchor in shallow waters in an attempt to stop the ship. In a future extension of the model, anchor salvage should be included by modelling bottom topography, bottom type (sand, rock), and drift speed of vessel. The error introduced by omitting this option in the current model is not believed to be significant.

Perhaps the most critical element in the estimation of probability of grounding given drift is the tug response time. Currently the estimates for preparation time and connection time are crude. Depending on these estimates the response time could shift by several hours, severely influencing scenarios in which the oil tanker is drifting to shore fast. An updated model should account for the status of the tug, if it is sailing, on standby or unmanned as well as the weather conditions in the area, which could influence the connection time as well as the travel time. This is particularly important at high latitudes, with rough weather, darkness, snow and icing situations. The proposed model is also sensitive to the estimated tug speed. Currently, a fixed speed of 15 knots is assumed, but this is optimistic according to both the Norwegian Coastal Administration (2006b) and LRF (2005a). The global average is 12 knots, spanning from 5 to 26 knots (LRF, 2005a), and the Norwegian Coastal Administration (2006b) reports that available tugs in Norwegian waters range in speed from 11 to 15 knots. However, combined tugs and coastguard vessels are available in the area under consideration, and the speed estimate may thus be appropriate for the specific area under consideration. In an operational setting the tug speed should be found specifically by linking AIS data to vessel databases. This will significantly increase the precision of the risk estimates. Also influencing the connection time is the type of equipment installed on the tanker to facilitate towing. Currently, tankers above 20 000 Dwt are required to have a strong point available for tug connection. However, smaller tankers and other ship types have no such requirements.

There are also other uncertainties in the consequence part of the model, such as the oil spill probability and quantity (see discussion above), the vulnerability estimate of affected area and even identifying the affected area (the vessel may potentially hit land on a large stretch of the shoreline) and in the simplification of oil types. These uncertainties will not be discussed further, but it is worth noticing that the sensitivity to model resolution (see above) may also impact the applied estimates of oil type impact, which relies on oil drift modelling. Based on the above, we expect some uncertainty in the estimated risk levels, and a more detailed sensitivity analysis has to be made to quantify the uncertainty. Nevertheless, it is likely that the results are representative as indicators of risks, well suited for the intended use of the model namely relative comparisons of ships and areas (at the same time).

5 Conclusion

The rise in traffic in the arctic and sub-arctic regions of the world leads to an increased risk to these sensitive coastal areas. The regions of North West Russia and Northern Norway are particularly critical with regards to environmental impact from oil spill. There are ongoing international efforts to utilise land based monitoring of vessels and cargo to prevent accidental spills. We have developed a decision support tool which will enhance the effect of traffic monitoring via dynamic risk assessments for drift grounding and strategic tug positioning. Our model supports the VTS centre by providing an answer to the question “What is the environmental risk of a potential drift grounding accident occurring with that ship, at that location, under those weather conditions?” For a VTS operator to effectively identify and track the potentially most critical vessels sailing in this region, it is important to be able to differentiate between those ships which are at risk and those which are not. Only in this way is it possible to focus attention and effectively utilise scarce resources on ships that involve a high environmental risk.

Our results indicate that the model accounts for the main features defining a potential risk from a drifting ship situation in the north of Norway, and effectively separates potentially high risk and low risk situations. The results clearly shows the great difference between “good” and “bad” weather situations (factor 45), i.e. winds blowing towards the shore or from the shore. It is clear that two ships sailing along the coast at the same time may very well experience very different weather conditions, and thus pose very different risks to the environment. Not only may the winds have different directions and force, but due to the curving nature of the coastline (*Figure 5*), the same westerly wind may be blowing from the shore in the east, and towards shore in the west. The same applies to ocean currents. We also see the great effect of having tugs positioned in the right place at the right time, and that this effect depends on the weather conditions. The oil type carried onboard also has a great impact on risk. Aggregating results over time may provide a clear picture of highly exposed and lesser exposed stretches of coastline, and provide valuable decision support on a strategic level.

It is clear from the discussion in the preceding chapter that there are uncertainties in the presented risk estimates. Our sensitivity modelling indicates that the use of high resolution models and data is important in these waters with the challenging topology and local conditions. These results call for a closer investigation into this issue. Nevertheless, it is likely that the results are valuable as indicators of risks, well suited for relative comparisons of ships and areas.

It is concluded that the proposed model facilitates intelligent ship traffic monitoring and intelligent resource management. The model is a decision support tool, aiding in the prioritisation of individual ships, and by extension, the prioritisation of geographical areas. Though only crude oil tankers are considered in detail, the methodology presented is generic. The model gives the opportunity to assess the current risk level as well as a forecasted risk level for each ship (and geographical region), based on a wide range of data sources (e.g. AIS data). The dynamic modelling approach could be extended beyond drift grounding scenarios. The model may also be extended to cater for other ship types such as general cargo, bulk and container. These ship types often carry great volumes of bunker fuel, and are often suspected of having a lower safety standard than oil tankers. By developing models for other accident types and other ship types, the dynamic model tool would have increased value for VTS operators regardless of traffic load or geography. It is important to notice that this model, developed with focus on accident prevention, may also be useful in an emergency situation, as a tool for effective emergency response support and effective oil spill response management.

As of December 2006, an online demonstration application of the dynamic risk model for drift grounding is available for the AIS2010 project participants. Based on the dynamic risk model (Equation (1)) developed by Det Norske Veritas, this demonstrator has been implemented by Christian Mikkelsen Research, with model and data input from met.no, and AIS data from the Norwegian Coastal Administration. This is the first step towards trial implementation with the Norwegian Coastal Administration, and work is proceeding to verify the implemented algorithms and upgrade user interface.

6 Acknowledgment

The preparation of this paper was co-funded by the Norwegian Research Council (contract no. 168157/I30). We sincerely acknowledge J. L. Ervik at the Norwegian Coastal Administration for his support and input during the work with this paper.

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Figures

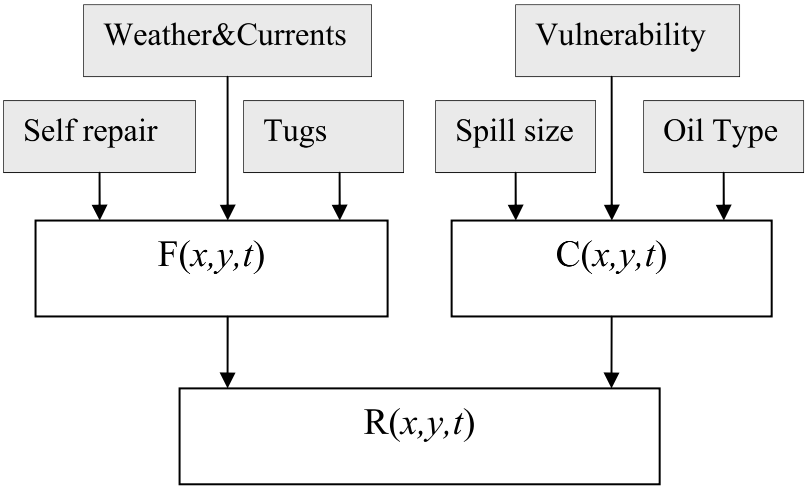


Figure 1: Dynamic drift grounding Risk Model Outline

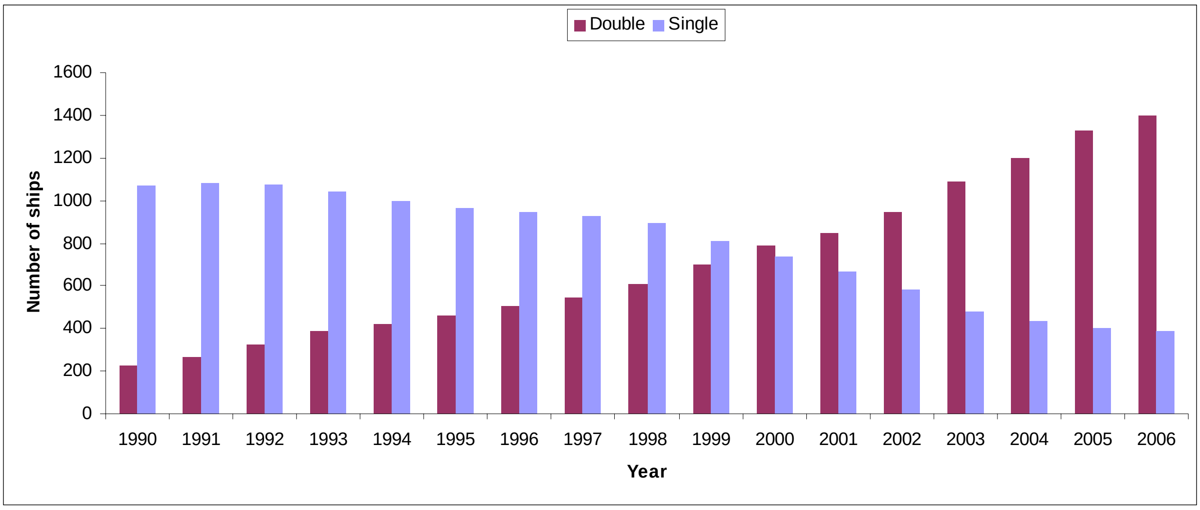


Figure 2: Number of single hull crude oil tankers and double hull crude oil tankers above 10 000 GT. Double hull category includes all varieties of double skinned vessels (e.g. double bottom, double side). Based on data from Lloyds Register Fairplay World fleet database, from 1990 to 2006 (LFR, 2006).

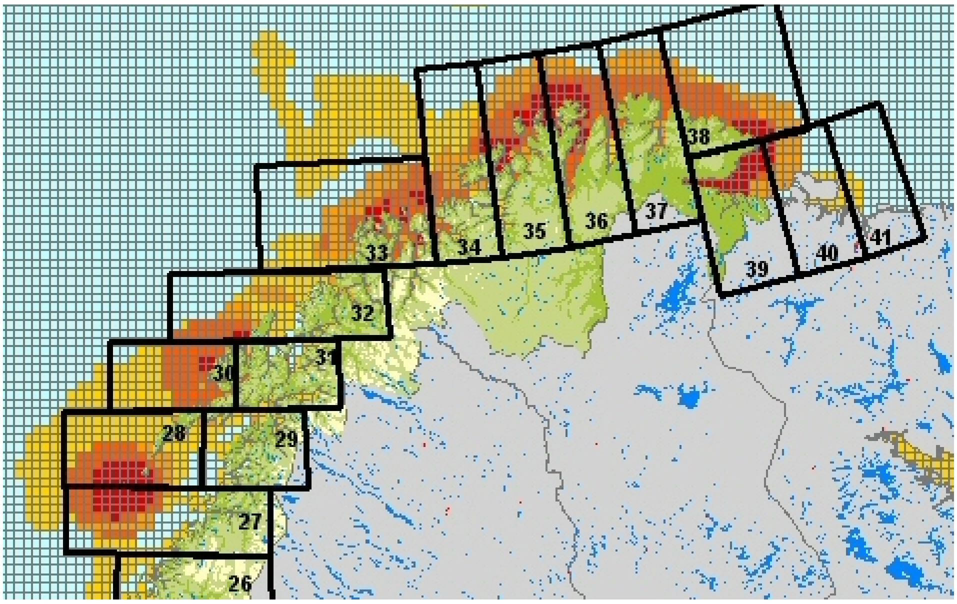


Figure 3: Coastal segments used for summarizing index values, shown in colour codes on 10x10 km squares.

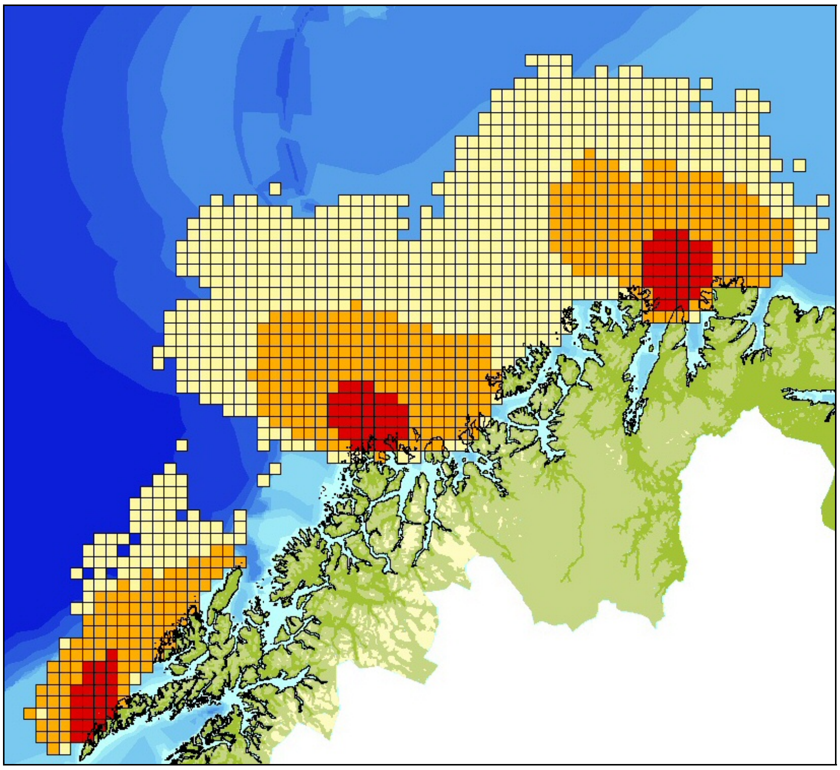


Figure 4: Oil spill modelling for three spill positions in the Lofoten– Barents Sea area, with Light condensate, Medium and Heavy crude showing as red, orange and yellow respectively. The maps is showing the influence area (>5 % probability of being hit by oil). The modelling is made with DNV's oil spill model (Sørgård, 1993).

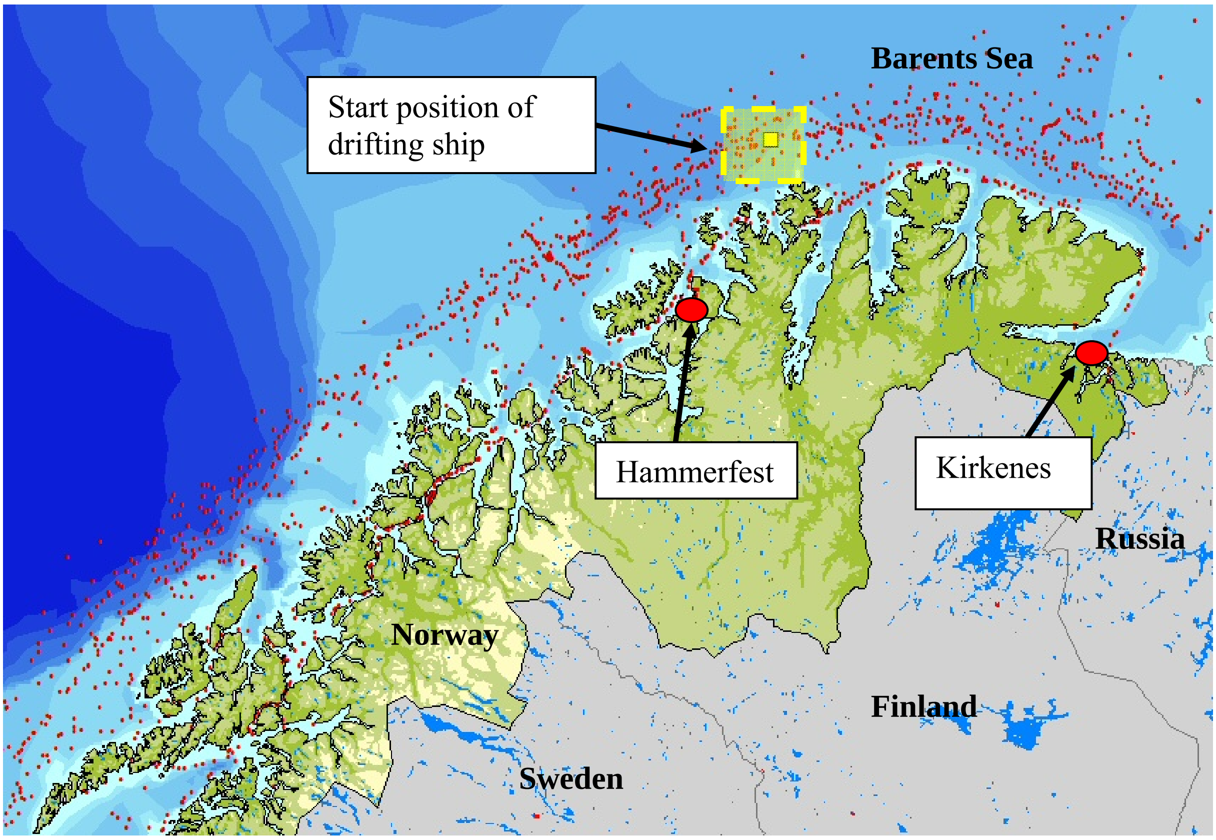


Figure 5: Traffic density maps for oil tankers outside the North of Norway based on AIS data provided by The Norwegian Coastal Administration. The yellow mark is assumed start position of drifting ships (UTM 33: 7958106 North, 864291 East). Also marked are the assumed starting positions for the tug; Hammerfest and Kirkenes. The distance from the tug starting positions to the start position of the drifting ship is 111 km and 307 km respectively.

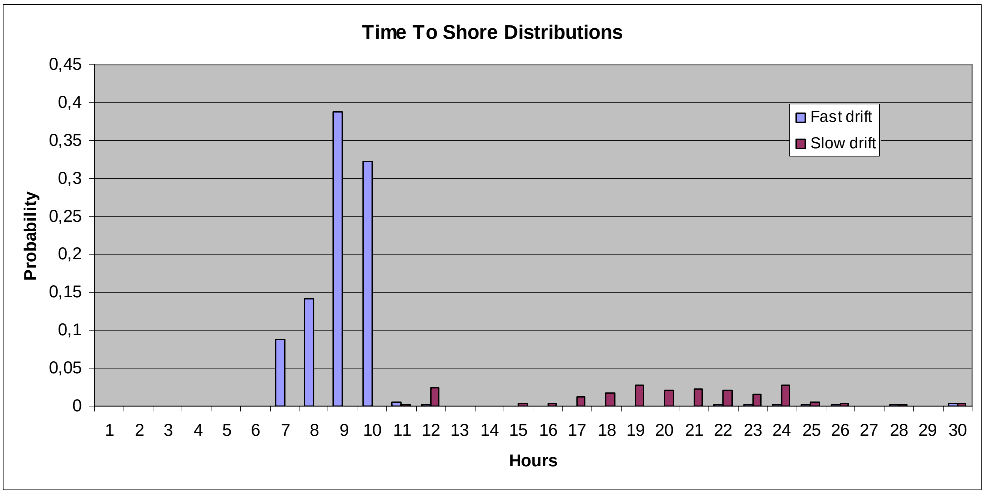
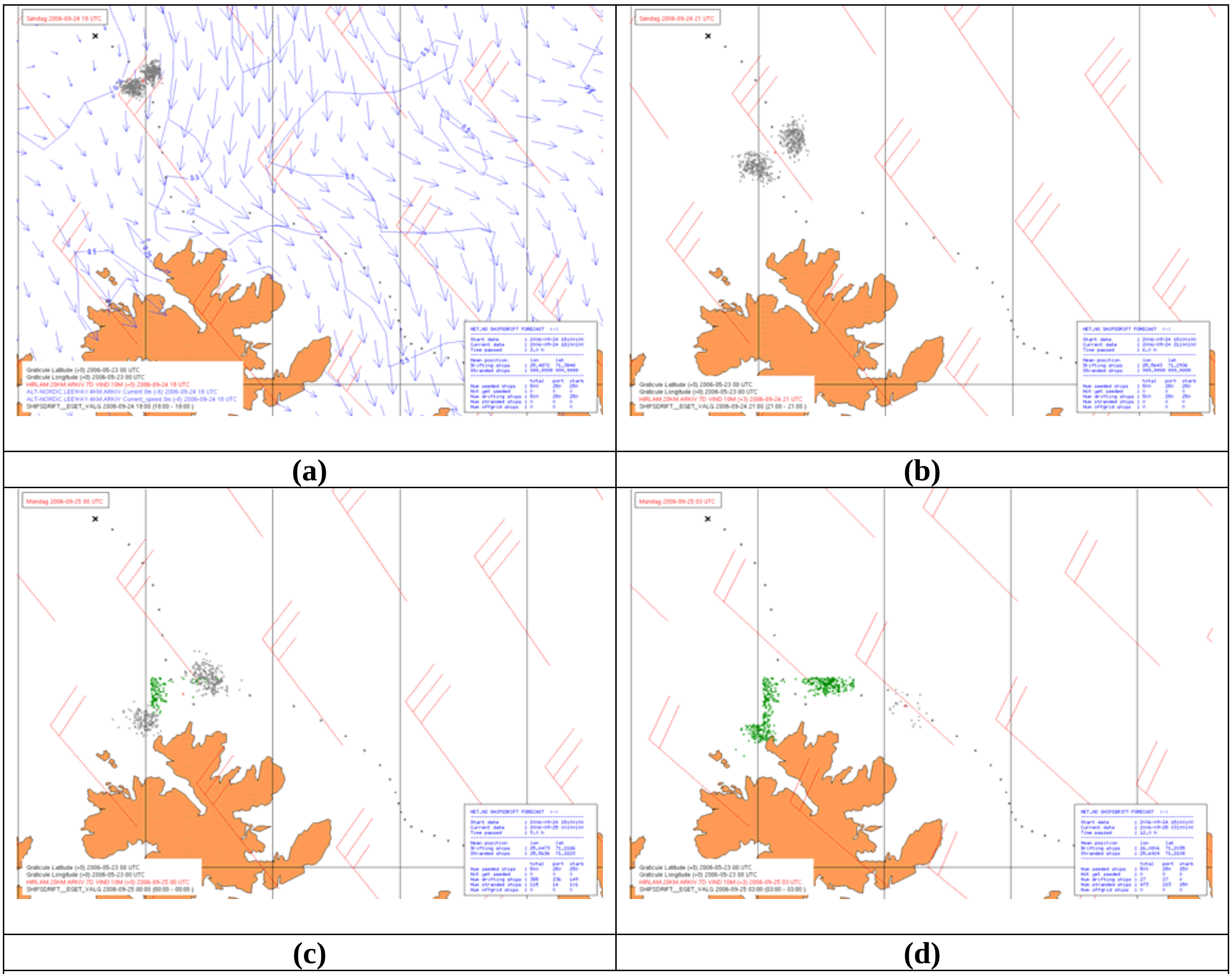


Figure 6: Time To Shore distribution for drifting ships. Slow drift simulation (10th June 2006); and fast drift simulation (24th September 2006). Note that for the slow drift simulation, a large percentage of the ships do not run aground within the first 30 hours, whereas for the fast drift situation, only very few ships do not ground within the first 30 hours.



(a) (b)

(c) (d)

Figure 7: Simulated drift to shore snapshots. 500 vessels released in position marked x. Figure (a) shows drifting vessels (grey dots) after 3 hours, with currents (blue arrows) and winds (red arrows). Figure (b) shows drifting vessels after 6 hours. Figure (c) shows vessels after 9 hours, drifting vessels marked grey, stranded vessels marked green. Figure (d) shows vessels after 12 hours. Most of the 500 vessels are marked green after 12 hours, indicating grounding.

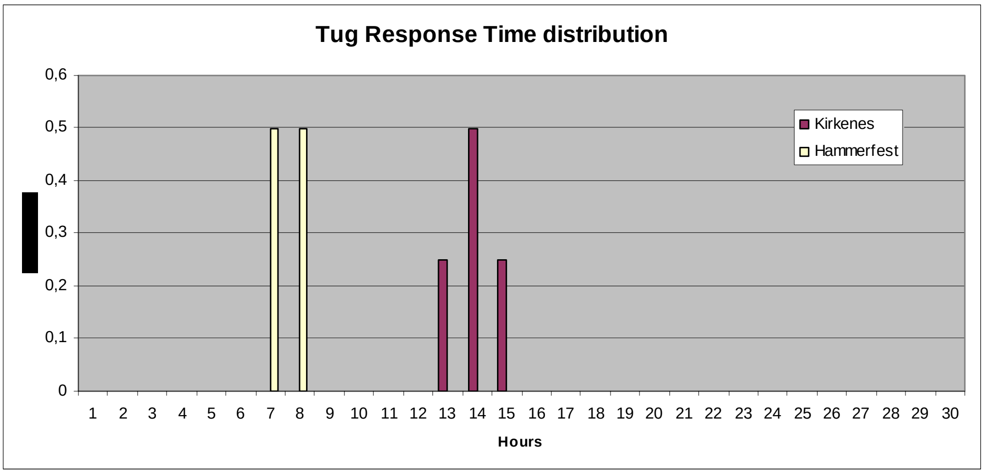


Figure 8: Tug Response Time, from Kirkenes (307 km) and from Hammerfest (111 km). Note that the uncertainty in the time estimate increases with the travel distance.

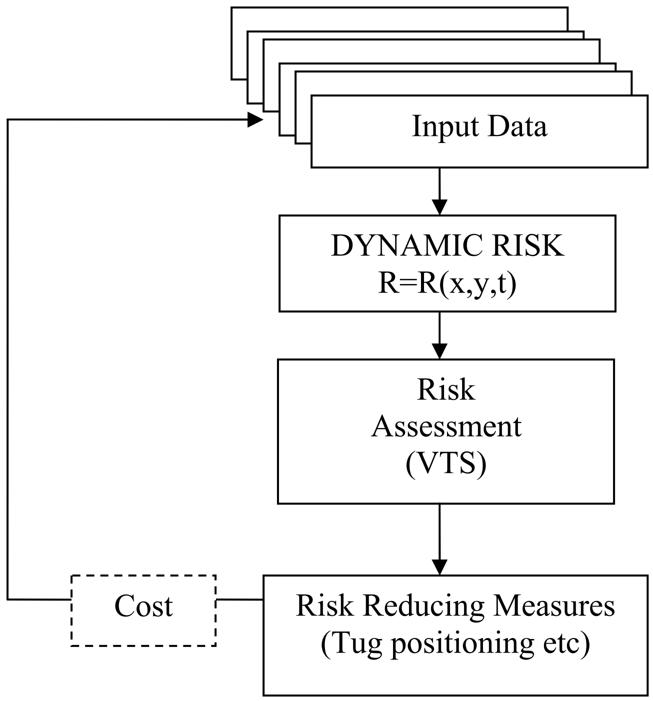


Figure 9: Dynamic Risk evaluation

Tables

Table 1: Unit overview, Equation (1)

$[R]=\frac{oil\_spill\_impact}{ship\_year}$	$[F]=\frac{drift\_grounding}{ship\_year}$	$[F_{drift}]=\frac{drift\_incidents}{ship\_year}$
		$[P_{grounding \mid drift}]=\frac{drift\_grounding}{drift\_incident}$
	$[C]=\frac{oil\_spill\_impact}{drift\_grounding}$	$[S]=\frac{ton\_of\_oil\_spilled}{drift\_grounding}$
		$[I]=\frac{oil\_spill\_impact}{ton\_of\_oil\_spilled}$

Table 2: Example on relative indexing for different oil types based on spill site 2 (Figure 4, middle site). 20 000 m^3 spilled in total. Relative density (ρ) of an oil type is its density in relation to pure water (Criteria are based on ITOPF (2005)).

Oil type category	Category criteria	Volume stranded (m^3)	Relative index (T)
Light condensate	$\rho < 0.85$	1035	1.0
Medium crude	$0.85 < \rho < 0.95$	3903	3.8
Heavy crude oil*	$0.95 < \rho$	7907	7.6

*) including bunker oils

Table 3: Modelling Results. Season: Spring, Initial position of drifting vessel: UTM 33 - 7958106 N, 864291 E. The results illustrate change in weather, difference in cargo type and change in tug position. Unit of risk is impact per ship year.

Wind & Current	**Crude Oil Type**	**Tug position**	**Case Number**	**Frequency**	**Consequence**	**Risk**
Slow drift	Light	Hammerfest	**1**	0.0	258	**0**
		Kirkenes	**2**	0.005	258	**1**
	Heavy	Hammerfest	**3**	0.0	1719	**0**
		Kirkenes	**4**	0.005	1719	**9**
Fast drift	Light	Hammerfest	**5**	0.029	258	**7**
		Kirkenes	**6**	0.17	258	**45**
	Heavy	Hammerfest	**7**	0.029	1719	**49**
		Kirkenes	**8**	0.17	1719	**299**