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Probabilistic Risk Assessment and Decision Support Tools for the Evaluation of Oil Transport in the Gulf of Finland, North-Eastern Baltic Sea

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Abstract: The maritime traffic in the Gulf of Finland (GoF), North-eastern Baltic Sea, is predicted to rapidly grow in the near future, which increases the environmental risks through both direct environmental effects and by increasing the risk of severe oil accident. A multidisciplinary group of researchers has developed a prototype of risk assessment and decision support model, applying Bayesian Networks (BNs), for the evaluation of environmental risks arising from the oil transport. It consists of sub-models on tanker collisions, causation probability (human factor), the resulting leak size, and the efficacy of open sea oil recovery. This meta-model is based on three alternative growth scenarios concerning the maritime traffic of the GoF in 2015 and the probability of a major oil accident given these conditions within four selected areas. The model can be used to compare the effectiveness of some preventive management actions and oil recovery against the accident risk. The multidisciplinary approach developed helps in comparing the risks in different parts of the oil accident cause – effect chain when current knowledge and uncertainty are taken into account. In addition, a user interface for the model has been created and tested for the analysis of spatial ecological risk arising from the oil transport in the GoF. A simplified version of the risk assessment meta-model is used to calculate probabilistic oil accident scenarios. The resulting probability distributions are used as an input in Geographic Information System (GIS) -environment, where probabilistic oil drifting maps are calculated accordingly. In the end, these drift calculations are evaluated against information on the known occurrences of endangered species on the Finnish coastline and conservation value indexes related to them. This allows us to calculate and compare the total risk for endangered species given the conditions selected in the risk assessment meta-model. This approach provides an interesting, alternative viewpoint concerning the decisions on how and where the available risk management resources should be directed.

Keywords: Oil transport, Bayesian networks, Risk analysis, Decision support

1. INTRODUCTION

The Gulf of Finland (GoF) is an ecologically sensitive brackish watered gulf in the easternmost part of the northern Baltic Sea. During the last few years maritime traffic - especially oil transport - has been growing rapidly in the area [Kujala et al.

2009, Kuronen et al. 2009, Hassler 2011], increasing the risk of an oil accident. As the ecosystem of GoF is species-poor and sensitive, a major oil accident could have severe ecological consequences that may extend for over a decade [Lecklin et al. 2011]. For some unique threatened populations living in this area, this type of incident could be a nail in the coffin [Ihaksi et al. 2011]. Thus it is urgent to assess the alternative precautionary strategies of oil spill risk management actions in the GoF. So far the practical risk management measures have focused on post-accidental actions - mainly on the efficient oil recovery organization. The need for sub-regional risk assessment tools and an evaluation methodology targeting the minimization of the oil accident probability in the Baltic Sea is commonly recognized [e.g. Steiner 2004, HELCOM 2007]. Tools could also help in trying to reach the international consensus of the best ways to manage the risks.

Decision analyses and decision support systems provide a quantitative means to study alternative decisions in the presence of multiple aims [e.g. Clemen 1996]. They also help decision-makers in making consistent and justifiable choices when concerning with complex problems. In this paper a risk assessment and decision support model for analyzing maritime oil transport in the GoF is presented. As method, we have applied Bayesian Networks (BNs) as they allow quantitative analysis and integration of different types of data, as well as the decision ranking, taking into account the uncertainty on each level. Consisting of multiple sub-models, this meta-model integrates results from a variety of analyses and models. In addition, a user interface where the produced risk assessment meta-model is utilised, is shortly presented. The first version can be used for the evaluation of spatial risk against endangered species arising from the oil transport.

2. METHODS

2.1 Bayesian Networks

Bayesian Networks (BNs) are models for reasoning under uncertainty through computing our updated beliefs about events given observations on other events [Kjaerulff and Madsen 2005]. BNs describe probabilistic relationships between variables that contain a number of mutually exclusionary states of the variable outcome [Jensen 2001, Kjaerulff and Madsen 2005].The relation of a variable to the other variables (nodes) is defined by links (arrows). Every random variable with incoming links has a conditional probability table which contains the information on the probability of a variable being in a certain state depending on the configuration of its parents, i.e. the conditional probability distributions of the variable. The inference within a BN follows the rules of probability calculus. The calculus is explained in detail e.g. by Jensen and Nielsen [2007].

A variety of methods can be used to form probability distributions: simulations and data analyses [e.g. Gilks et al. 1994, Mäntyniemi 2006], as well as interviews of one or more experts [e.g. Uusitalo et al. 2005, O'Hagan et al. 2006] can be used. The advantage of BNs is that both qualitative and quantitative data can be used which makes them remarkably useful in multidisciplinary questions. This possibility is extremely important especially when statistic materials are scarce. BNs including decision and/or utility variable are called Bayesian Influence Diagrams (BID). They can compute the expected utilities of all combinations of decision options given the state of uncertainty at the time of the decision. BNs and BIDs are found to be accessible also to the end-users without earlier modelling experience [Cain et al. 2003]. Both types of networks can have a hierarchical structure, i.e., another network model can be inserted within a model as a sub-class or sub-model. The models including sub-models are called Object-Oriented Bayesian Networks (OOBNs) [Jensen and Nielsen 2007].

2.2 The Object-Oriented Bayesian Influence Diagram (OOBID)

The meta-model presented were developed during the period from 2008 to 2010, thus the current state analysis is based on the statistics of the year 2008 whereas the (probabilistic) future maritime traffic scenarios for the year 2015 are experts' best estimates reflecting the prevailing situation in November 2008. As the model fulfils the definitions of both BID and OOBN, we call it Object-Oriented Bayesian Influence Diagram (OOBID) from now on. It consists of the main model (Figure 1) and two sub-models: *Leakage* and *Oil recovery.* The commercial software Hugin Expert® (Madsen et al., 2005) was used for integrating information from the statistics, calculations, predictions and models, as well as for performing the meta-analysis. The causal OOBID structure of the main model is shown in Figure 1.

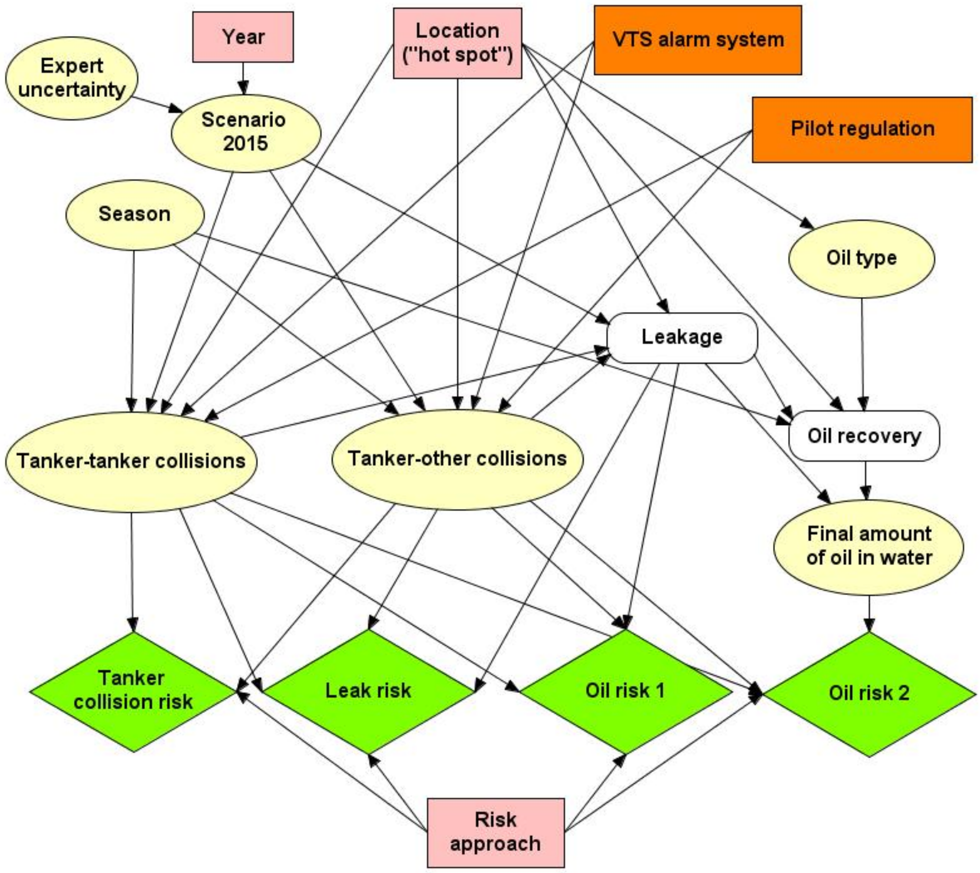

Figure 1. The causal structure of the main model. The rectangles are decision nodes (purple ones for making settings to the model and the orange ones for actual decision analysis) and the ovals random nodes. The white angulated ovals represent the sub-models, the quadrangles are utility nodes.

In the main model, five decision nodes are included: *VTS alarm system*, *Pilot regulation*, *Location*, *Year*, and *Risk approach*. Each combination of the states of these can be formed and analyzed by the user. The development of Vessel Traffic Service (VTS) operations and pilotage were ranked as the most effective measures to prevent an oil accident in the GoF according to a questionnaire study that was made amongst the Finnish maritime experts [Kuronen and Tapaninen 2010]. The variable *VTS alarm system*, having two alternative states *(implemented / not implemented*), describes the implementation of an automatic alarming system for

VTS. The purpose is to create an alarm in a VTS centre if a ship is on a collision course. Another preventive action variable *Pilot regulation* has three alternative states: *no change* from current (2008) regulation, *extending piloting obligations*, and *allowing English* as an official piloting language. *Extending piloting obligations* describes the situation where having a local pilot on-board would be mandatory in all high risk areas. The state *allowing English* describes the situation where 10 % of the ships would have an English-speaking pilot on line service.

The decision node *Location* includes four states representing selected areas in the GoF (Figure 2). They were chosen on the following grounds: 1) an area with crossing traffic (*C1*), 2) an area with a possibility of the collision of two tankers on oil load (*C2*), 3) an accident-prone area according to accident statistics (*C3*), and 4) an area with high ecological values (*C4*). The decision node *Year* allows the user to choose if she / he wants to use the current (*2008*) maritime traffic statistics or future scenarios (*2015*) as a basis for her / his analysis. The decision node *Risk approach* is used for choosing the way the resulting risk is expressed (see p. 4 below). The four expected utility nodes of the OOBID present these particular risk approaches (Figure 1).

The random variables in the main model are named as *Scenario 2015, Expert uncertainty*, *Season*, *Oil type*, *Tanker-tanker collisions*, *Tanker-other collisions* and *Final amount of oil in water* (Figure 1). Three maritime traffic scenarios for the year 2015 (*low growth / average growth / strong growth*) were created based on earlier forecasts, transport statistics from the year 2007 and expert interviews [Kuronen et al. 2009]. Four different expert opinions are included and can be weighted differently (e.g. for the sensitivity analysis) in the variable *Expert uncertainty*. Variable *Season* has three alternative states: spring, summer and fall. Winter is excluded so far, as the winter conditions in the GoF would require traffic models of its own. Also, when it comes to the oil drifting and oil combating, at the present, no models predicting the movements and behaviour of oil in ice conditions, exist. The variable *Oil type* includes alternative states *light / medium / heavy,* based on the viscosity-classification of IVL [2004], reflecting the similar effects on biota within a class. The distribution represents the frequency of oil types the tankers are likely to carry, given the location.

The random variables *Tanker-tanker collisions* and *Tanker-other collisions* describe the distribution for the number of collisions per year, where both vessels are tankers, and where one of the colliding vessels is a tanker, respectively. The approach applied to estimate their distributions is based on the simulations for the geometric collision probabilities, given the location, and on the BN model for the causation probability (human error), given the ships are on a collision course. The process is described in details in Hänninen et al. [2011]. As the existing models for estimating the number of groundings in a certain area have been found unreliable for the conditions in the GoF [Ylitalo 2008, Mazaheri and Ylitalo 2010], only collisions are taken into account at the moment.

The number of expected utility nodes - representing the way the risk is analysed in the model - is four: *Tanker collision risk, Leak risk, Oil risk 1* and *Oil risk 2*. *Tanker collision* risk presents the theoretical expected number for tanker collisions per year. *Leak risk* gives the theoretical expected number for tanker collisions causing an oil spill per year. *Oil risk 1* presents the theoretical expected amount of oil spilled to the sea per year whereas *Oil risk 2* shows the theoretical expected amount of oil remaining in the sea each year when oil recovery efficiency and evaporation are taken into account. The gained values cannot be handled as realistic estimates, as in reality accidents do not occur yearly. However, the theoretical values are proportionally comparable and thus useful for the purposes of the decision analysis, when the efficiency of various actions is estimated and the alternatives ranked accordingly.

As mentioned above, the OOBID includes two sub-models: *Leakage* and *Oil recovery*, the former estimating the amount of oil that is leaked to the sea given a tanker collision and the latter estimating the percentage of the leaked oil that can be removed by oil recovery vessels given the leak size. By integrating existing calculations e.g. competing model results on the probability of zero-leak given a tanker collision, as well as the likely spill size given the dry weight of the colliding tanker and by giving a model user a possibility to change their weights on these (model uncertainty), the *Leakage*-model estimates the likely amount of oil in water in case of a tanker collision. The sub-model *Oil recovery*, in turn, includes large amount of technical and expert knowledge on the Finnish oil recovery vessels and organization in case of an oil accident in the GoF [Luoma 2010, Luoma et al., manuscript]. In the end, the *Oil recovery* -model estimates the percentage of the leaked oil that would likely be removed by Finnish oil recovery vessels given the size of the spill, type of the oil spilled and the random weather conditions (given the season). The final product of the sub-models is the probability distribution for the amount of oil ending up ashore which depends on the amount of oil spilled and its removal percentage.

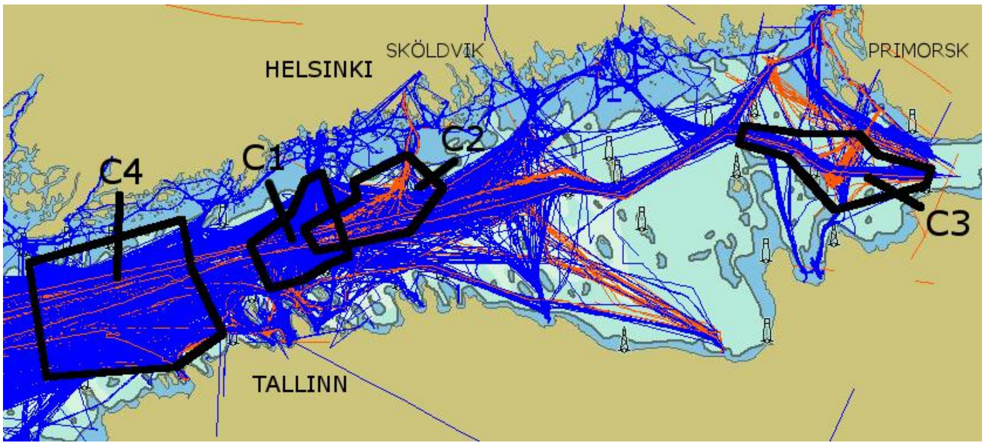

Figure 2. The areas (C1-C4), where the model can be applied, incl. the tanker traffic (plotted in red) and other vessel type traffic (blue) in the Gulf of Finland in July 2010, produced with HelCom WebStat AIS data tool.

2.3 The user interface for spatial risk assessment

A first version of a spatial risk assessment tool (here called a user interface) has been developed for the analysis of risks due to oil transportation in the GoF when the areal distribution of ecological values is taken into account. It is presented in detail by Jolma et al. [2011]. The user interface integrates a compressed version of the OOBID presented above with 1080 probabilistic oil drift simulations and spatial data on the known occurrences of threatened species on the Finnish coastline. The oil drifting scenarios were simulated in the Finnish Environment Institute by using the probabilistic model SpillMod [Ovsienko 2002]. The scenarios are covering the potential spreading of oil, given the accident location (centres of the areas C1-C4), season (the weather statistics from the years 1996-2001), oil type and the amount of oil in water after the open sea recovery, the probability distributions for these coming from the OOBID. When integrating the resulting map layer with the one including the information on the occurrences of threatened species – or more closely, the conservation value indexes given to these by Ihaksi et al. [2011], the software calculates cell-specific risks. The term “risk” is defined in this case as a product of probability of something undesirable to happen and the harm caused if it becomes true. Thus, the risk in cell *x* is the product of the probability that the cell would be oiled and the sum of the conservation values of the populations living in cell x (Figure 3). The Geoinformatica software [Jolma 2007] was used when creating the user interface.

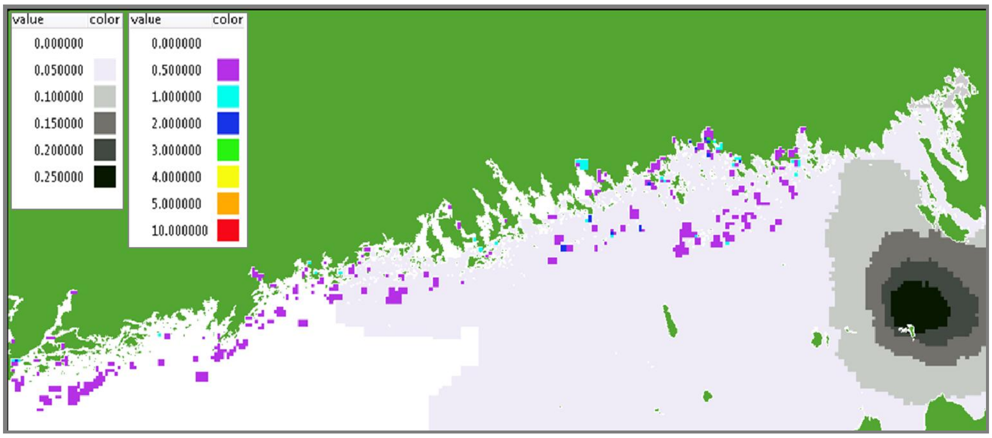

Figure 3. An excerpt from a risk map, where the land areas (dark green), the oil drift simulation result layer (gray scale cells, probabilities shown in the legend) and the risk layer (colored cells, risk values shown in the legend) are shown. The values describe the level of the cell-specific contamination probability (P_{cont}) and the risk against the threatened species (sum of conservation values * P_{cont}).

3. RESULTS

As the OOBID provides for studying a countless number of scenarios and settings, only general examples of the results that can be gained are presented in this paper. Comparison of the two management actions included in the model shows that implementation of the extended piloting maximizes the values of utility nodes (where the harm is given as negative values) compared with the VTS alarm system. The most optimal decision is naturally implementing both the more effective VTS alarm and the compulsory piloting in the GoF. With the implementation of these management actions, it is possible to decrease the expected risk by about 18 % (mean, range 15 – 22 %) regardless of the risk approach and traffic scenario used (see Figure 4).

Due to the growing amount of traffic, there is a large increase in the expected risk level from the year 2008 to 2015. The average change, regardless of the risk approach used, is likely to triple in every area. The area in the easternmost part of the GoF (C3) has the largest expected risks (Figure 4).

The results of the user interface are mainly still forthcoming**.** However, when the spatial harm component – in this case a potential harm for the threatened species – is included in the context of risk assessment, relative weights of the areas C1-C4 are changing. For example, in the area C3 (the accident-prone area according to accident statistics) the probability of an oil accident is two to three times higher than in the area C4 (the area with high ecological values). However, when the potential oil drifting and the harm to known endangered species populations on the Finnish coastline is taken into consideration, the area C4 is seven times more risk-prone than C3.

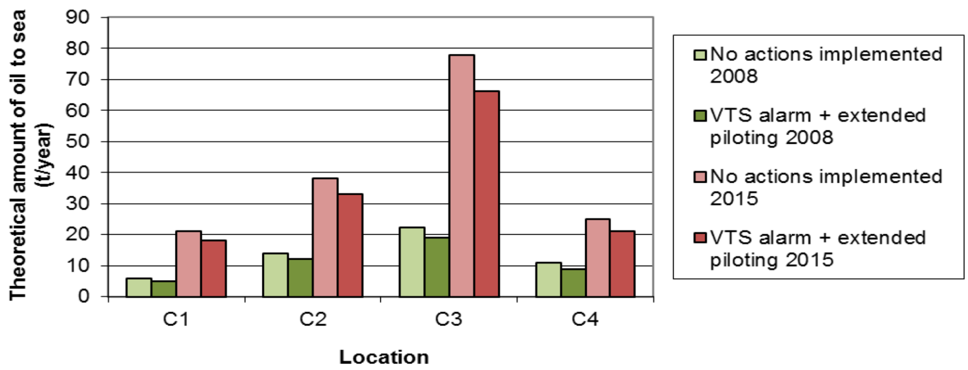

Figure 4. *Oil risk 1* (i.e. theoretical amount of oil (tons) heading to the sea yearly) in four areas (C1-C4) in 2008 and 2015 with and without the actions implemented (Luoma et al., 2011).

4. CONCLUSIONS AND OUTLOOK

According to the OOBID risk assessment model, the traffic growth is likely to triple the risk of an oil accident in the GoF till the year 2015. Management actions decreasing the probability of human errors, like VTS alarm system and compulsory piloting management actions could decrease the risk level. However, the results presented are only indicative on how the tool could be utilized in choosing optimal risk control options. The modeling of the effects of preventive actions on the maritime traffic risks needs to be further developed.

The OOBID will be further developed together with the potential end users to make it more useful. In addition, it needs to be improved to cover the whole GoF. In the future, a grounding model will be included and more management actions to be added and compared. The costs of implementing management actions should also be included in the analysis to enable the assessment of the cost-effectiveness.

Although the OOBID still needs improvements, we see that the approach allows an effective, diverse analysis of oil transport risks and potential management actions in the light of uncertainty about the future development of maritime traffic, other variables and parameters. This kind of trans-disciplinary probabilistic approach can help in creating a more holistic view of the process and the related risks. The contents and structure of BNs are relatively easy to update whenever more information will be available. Updating the model to be used for other sea areas is possible as well.

The results of the user interface are still forthcoming but the preliminary impression is that it is useful and effective a tool. The risk can be seen not only as the probability of something negative to happen but also as the product of this and the harm caused by the outcome. Thus an important question, when it comes to the future analyses, is: when ranking the alternative risk management actions, should we weight those that would minimize the probability of an accident or those decreasing the likely magnitude of its' harmful effects (i.e. the development of the oil combating)? What would be the most optimal combination of actions in the light of prevailing uncertainty? Should we base our decision ranking on the analysis that, in addition, takes into account the uneven spatial distribution of the harm likely caused by the accident? And further on: whose harm and losses should be taken into account and how to evaluate the value of nature compared with the value of real property?

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