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A Bayesian Network for Assessing the Collision Induced Risk of an Oil Accident in the Gulf of Finland

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Supporting Information

ABSTRACT: The growth of maritime oil transportation in the Gulf of Finland (GoF), North-Eastern Baltic Sea, increases environmental risks by increasing the probability of oil accidents. By integrating the work of a multidisciplinary research team and information from several sources, we have developed a probabilistic risk assessment application that considers the likely future development of maritime traffic and oil transportation in the area and the resulting risk of environmental pollution. This metamodel is used to compare the effects of two preventative management actions on the tanker collision probabilities and the consequent risk. The resulting risk is evaluated from four different perspectives. Bayesian networks enable large amounts of information about causalities to be integrated and utilized in probabilistic inference. Compared with the baseline period of 2007−2008, the worst-case scenario is that the risk level increases 4-fold by the year 2015. The management measures are evaluated and found to decrease the risk by 4−13%, but the utility gained by their joint implementation would be less than the sum of their independent effects. In addition to the results concerning the varying risk levels, the application provides interesting information about the relationships between the different elements of the system.

1. INTRODUCTION

The Gulf of Finland (GoF), located in the easternmost part of the Baltic Sea, is considered a challenging area for navigation because of its shallowness, dense Finnish archipelagos, and ice coverage typically present in the wintertime.[1] In the 2000s, maritime traffic, especially oil transportation, grew rapidly in the area, and today, the GoF is one of the busiest sea areas in the world.[2,3] The growth of oil transport and other maritime traffic increases the probability of an oil tanker accident. In the sensitive, brackish ecosystem of the GoF, a large oil spill could have severe and long lasting consequences.[4,5] The need for comprehensive assessment tools that are targeted at minimizing environmental risks was already recognized a decade ago.[6]

We present a Bayesian network (BN) for assessing the environmental risk of oil transportation in the GoF. The model can be used to examine how various future oil transportation and maritime traffic scenarios affect the probability and severity of a collision-induced oil accident in the GoF, and how well the risk can be controlled by certain management actions. The concept was first introduced in Klemola et al.[7] In practice, we integrated information from existing models, previous studies, the literature and experts into a metamodel. The Bayesian network was used as the knowledge integration method. Several parts of the entity are reported in detail in other publications and only referred to in this article.

The current model is the first analysis of a causal chain starting from alternative future traffic flows and consequent accident frequencies, covering the formation of an oil leak and the efficiency of oil destructive measures. The inference leads to the final amount of oil that will drift to the coastal ecosystem annually. This work also covers the accident preventative perspective in risk management, whereas earlier approaches were concentrated mainly on oil recovery from the sea and the

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shores. In this article, a comparison of the risk levels under different circumstances and the results of the decision analysis are presented and the methodology is discussed.

2. MATERIALS AND METHODS

In this study, BNs were used to synthesize information from various sources and perform integrated analysis. Hugin Researcher 7.6 software[8] was used to perform this task. The principle of BN is described in the Supporting Information. More information about the method can be found in many books emphasizing slightly different aspects.[9−11]

BNs have previously been applied in case studies focusing on the potential consequences of oil tanker accidents in the GoF. Goerlandt and Montewka[12] demonstrated their oil outflow model by applying it to two GoF tanker collision scenarios. Juntunen,[13] Aps,[14] and Lecklin[5] and their coauthors applied BNs to evaluate the consequences of an oil spill in the ecosystem. Rahikainen and colleagues[15] recently modeled the joint effects of three stressors, eutrophication, fishery, and oil spills, on the GoF's herring stock. Helle et al.[16] and Lehikoinen et al.[17] modeled the effectiveness of oil recovery, the former from an ecological point of view and the latter from a perspective of maximal efficiency. Montewka et al.[18] upgraded the latter model to evaluate the costs of oil recovery measures. BNs have also been applied to oil spill risk analysis of the other areas, like the Deepwater Horizon Spill response in the Gulf of Mexico.[19]

BNs also have been utilized in the modeling of the mechanisms leading to ship accidents and in analyzing the effects of risk control options on the frequency of accidents in the GoF.[20−25] However, the joint effects of traffic development, preventative management actions and oil recovery measures have not been previously studied.

2.1. Model Structure and Logic.

The model estimates the annual number of ship−ship collisions involving at least one tanker and the amount of postaccident oil in the ecosystem given two hypothetical management actions and current oil recovery procedures. The resulting influence diagram (ID)—a specific form of a BN constructed for the decision analytic purposes−consists of the main model (Figure 1) and two submodels, *Leakage* and *Oil recovery* (Figure 2). The former estimates the amount of oil that leaks into the sea after a tanker collision, and the latter evaluates the amount of leaked oil that the open sea oil recovery vessels can collect. In the model, tanker collision frequency plays a central role. It is recognized that ship groundings also have the potential for an oil spill, but during this study, existing models for estimating the number of groundings were found unreliable in the GoF.[26,27] Thus, while the development of a grounding frequency model is in progress, the only accident type taken into account in this model is collisions, and groundings will be considered in the future.

In the main model, two random variables representing the annual number of collisions between two oil tankers (*Tanker−tanker collisions*) and between an oil tanker and another type of ship (*Tanker−other collisions*) are controlled by four decision variables (Figure 1). Two of them, *VTS alarm system* and *Pilot regulation*, cover the actual risk control options (RCOs). The other two serve as "setting nodes" because they are used to specify the zone and traffic scenario in which the analysis is performed.

The collision frequencies are used as input information for the submodel *Leakage*, where given a tanker collision, the probability of an oil leak and the volume of the potential spill are modeled. The spill size (*Oil in water* in Figure 2) is the output information from *Leakage*, which is then used as the input information in the *Oil recovery* submodel. This submodel provides the oil recovery efficiency based on the amount of oil in the water.

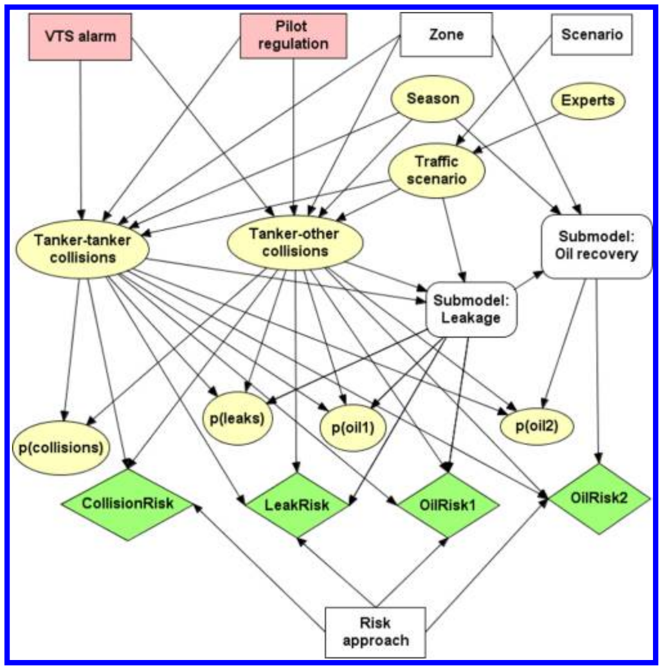

Figure 1. Graphical representation of the main model. The rectangles depict decisions; the purple rectangles are the actual risk control options, and the white rectangles indicate the setting nodes. The yellow oval nodes depict random variables, and the white angulated ovals indicate the submodels. The green diamonds denote the utilities/losses that are used as the alternative decision making criteria.

The decision analytic functions of IDs, such as the value of information analysis and the policy optimization, are based on the expected values derived from the target variables' probability distributions (the variables to be managed) and the corresponding utility functions via the so-called utility nodes. Using the model, the harm caused by the tanker can be evaluated from four different perspectives: (a) the annual number of collisions where at least one oil tanker is involved (*CollisionRisk*), (b) the annual number of oil tanker collisions leading to leakage of cargo oil (*LeakRisk*), (c) the annual amount of oil leaked into the water (*OilRisk*1) and (d) the annual amount of oil that reaches the coast after oil oil recovery actions in the open sea (*OilRisk*2). The negative utility functions of these four risks approaches were formulated in the utility nodes. Model users should select one approach by locking the fifth decision variable and setting the *Risk approach* node to the chosen state before studying the results.

2.2. Main Model.

In this section, we provide a detailed description of the variables, data and probability estimates used in the main model (Figure 1). The section explains key elements of the metamodel, that is, the model features, that enable the reader to follow and evaluate the results and discussion. Detailed reports on the submodels *Leakage* and *Oil recovery* are provided in the Supporting Information.

In the main model, the setting node *Scenario* defines the maritime traffic and oil transportation scenario on which the analysis will be based. The node has two states: *Baseline* and *Future (2015)*. If *Baseline* is selected, the data (vessel movement

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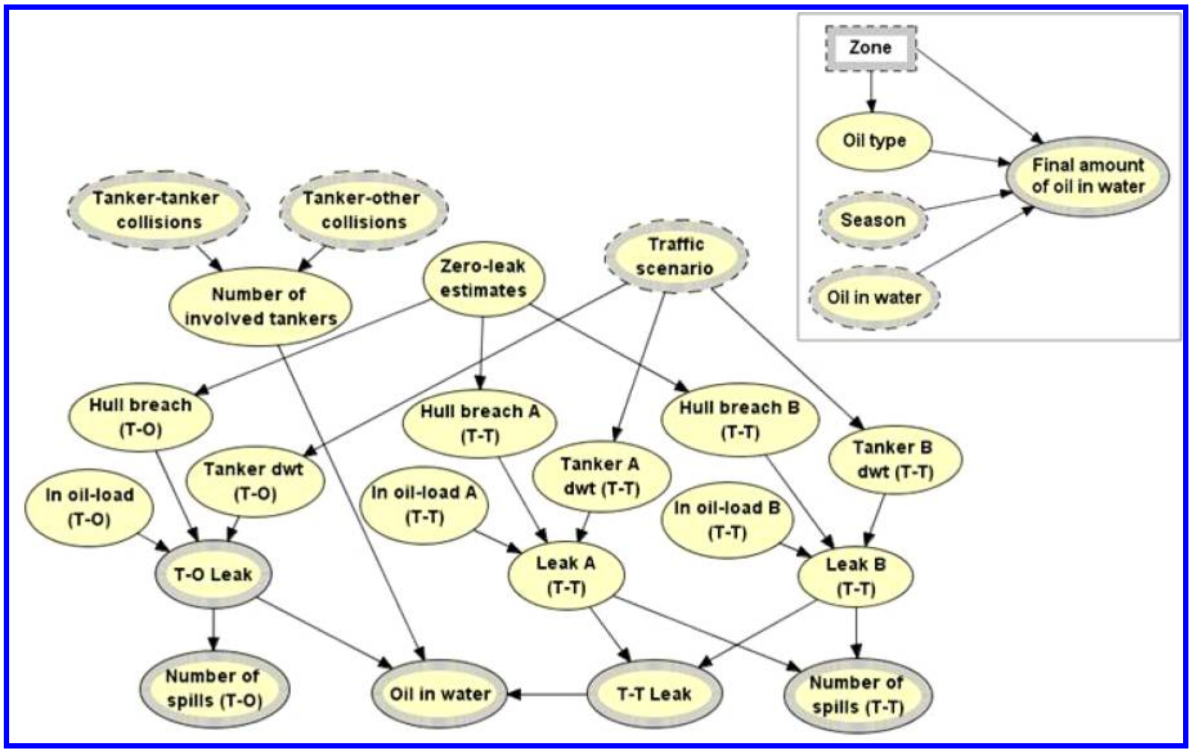

Figure 2. Graphical representations of the submodels *Leakage* and *Oil recovery* (in the box). The variables with broken line borders depict inputs inherited from the main model (Figure 1). The nodes with uniform gray borders are the output variables that pass information further. The original Bayesian network that was used to produce the conditional probability table for the variable *Final amount of oil in water* in the submodel *Oil recovery* is presented by Lehikoinen et al.[17]

data obtained from the Automatic Information System, AIS) and statistics from the years 2007−2008 are used as the starting point.[2] By choosing *Future*, the calculations are based on three alternative traffic scenarios for the GoF with the year 2015 as the focus. The future scenarios were forecasted by the group of four experts (maritime researchers) at the end of 2008. The main drivers behind the scenarios are the expected economic, industrial, and transportation trends presented by Kuronen et al.[2]

The random variable *Traffic scenario* is conditional on *Scenario* and has four alternative states (described in detail by Kuronen et al.[2]): *Baseline* and the three future traffic growth scenarios *Slow*, *Average*, and *Strong growth*. The experts provided their degrees of belief concerning the mutual realization of the future growth scenarios (Table 1). All of the views are given equal weights using a uniform distribution for the node *Experts*. This node enables us to pool the experts' opinions within the ID, thus retaining the information about the differences among them. By modifying the distribution of *Experts*, their weight could be easily updated.

Table 1. Experts' Degrees of Belief for the Mutual Realization Probability of the Three Alternative Scenarios of Maritime Traffic and Oil Transport by the Year 2015[a]

	expert 1	expert 2	expert 3	expert 4	marginal
slow growth	0.33	0.35	0.15	0.15	**0.25**
average growth	0.33	0.50	0.50	0.60	**0.48**
strong growth	0.33	0.15	0.35	0.25	**0.27**

[a]The marginal distribution, shown on the right, is used if none of the traffic scenarios is selected.

The setting node *Zone* is used to define the geographical area of the analysis. The GoF is divided into five zones, denoted *C1*−*C5* (Figure 3). The collision parameters have been estimated for these zones; thus, the model can also be applied to analyze the differences between the areas. In addition, *Zone* has a sixth state, *All*, representing the entire GoF. The zones have different traffic and navigational and environmental characteristics. Zone *C1* features dense passenger traffic between Helsinki and Tallinn, which crosses the main east−west waterway of the GoF. Within *C2*, the crossings of laden tankers are more common than on average. Zone *C3* contains a narrow waterway to St. Petersburg and a merging of two waterways near shoals. Zone *C4* is an example of a larger area with many crossing and merging waterways. In addition, *C4* includes the Hankoniemi peninsula area, which contains unique habitats and biodiversity.[4,28] Zone *C5* includes a part of the highly trafficked east−west waterway and the traffic of the HaminaKotka port, which is one of the main GoF ports for chemical tanker traffic.[29,30]

The number of collisions per year is expressed as an integer from 0 to 6; the upper limit was selected based on the accident statistics published by Kujala et al.[31] The approach and data for the estimation of the tanker−tanker (T-T) and tanker-other (T-O) collisions are described in the publications of Hänninen and coauthors.[24,32] In brief, the estimation includes two elements: (1) the number of collision candidates given a blind navigation assumption[33] and the traffic properties (e.g., the number of ships) in the area, and (2) a BN model to describe factors affecting the success of evasive maneuvers by the collision candidates. Estimates for the numbers of ships in the studied waterways in the year 2015 are based on traffic data from the year 2008 and traffic multipliers collected from experts

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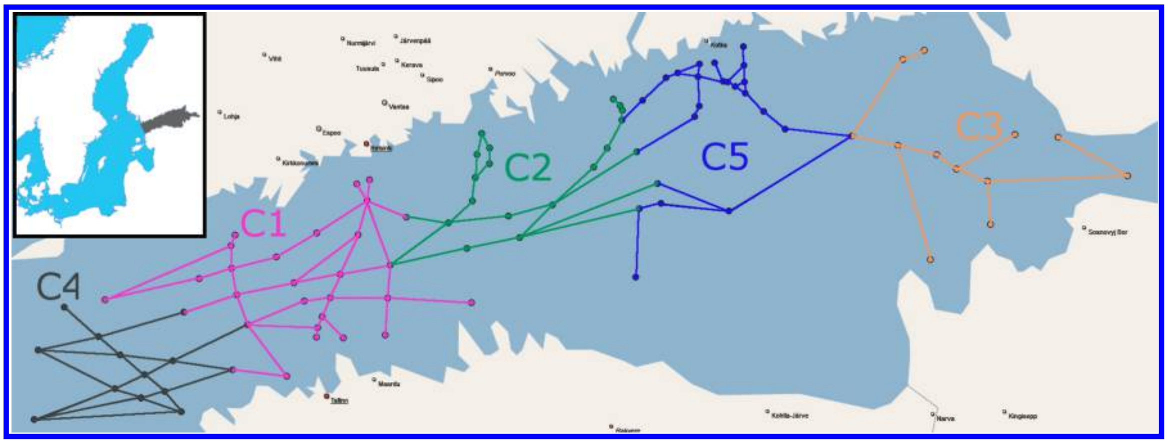

Figure 3. Gulf of Finland (shown as part of the Baltic Sea in the small picture) and the analyzed waterways within the modeled zones C1−C5.

for the three growth scenarios. Based on port-specific growth factors, cargo and oil volume multipliers were estimated for each segment of each waterway. A detailed description of the multiplier estimation method is provided in Hänninen et al.[32]

The selection of the RCOs *VTS alarm system* and *Pilot regulation* is based on the results of a questionnaire study targeted at Finnish maritime experts,[34,35] where the chosen RCOs had been ranked as the most effective measures to prevent an oil accident in the GoF. The *VTS alarm system* (RCO1 hereafter) has two alternative states: *Implemented*/*Not implemented*. When RCO1 is set to implemented, the model describes the situation where an alarm will be given in the Vessel Traffic Service (VTS) if the automated system detects two ships on a collision course. If not implemented, the situation corresponds to the current VTS service practice where the detection depends on the vigilance of the VTS officers only. In our model, implementation of the alarm system decreases the collision probabilities by increasing the probability that the VTS officer detects and warns the ships about the risky situation. The effect of the automated VTS detection on the collision probability is originally estimated in the paper of Hänninen and Kujala.[24]

Another RCO variable, *Pilot regulation* (RCO2 hereafter), includes the states *No change* and *Extended obligations*. In the GoF, it is obligatory to have an external pilot onboard within defined pilotage areas near the coast, unless the ship has an internal pilot, which means that the master or the officer of the watch is familiar with the route and has been granted a route- and vessel-specific Pilotage Exemption Certificate. For ships with dangerous cargo (e.g., oil), using an external pilot is the only option. In the current model, the waterways leading to ports were not included; thus, the state *No change* represents the situation without an external pilot. The option *Extended obligations* implies that the use of an external pilot is mandatory within the entire GoF. The effect of pilot regulation is evaluated by modifying the collision causation model of Hänninen and Kujala,[24] so that given the *Extended obligations*, the probability of having an external pilot onboard is 1. The pilot onboard is evaluated to increase the probability that the danger will be detected on the bridge from 0.80 to 0.97.

The weather and duration of daylight in the GoF are highly seasonal, affecting both navigation[24] and the success of oil recovery operations.[17] In the model, the independent random variable *Season* represents the variability in seasonal weather conditions. Only spring (March, April, and May), summer (June, July, and August) and fall (September, October, and November) are examined. In winter, the collision parameters change remarkably as the ships navigate the narrow channels made by the icebreakers. In addition, little is known about the behavior of oil in ice and the oil recovery process under those circumstances. Thus, making a risk analysis for the icy period will require a separate study (a first attempt toward this model can be found in Valdez Banda et al.[36]). The period 2007−2008 was selected as the baseline state of the model because of the ice-free winter in the GoF. In the current model, *Season* is given a uniform prior distribution. If the variable is not locked, the results of the analysis depict the average conditions during the ice-free periods. *Season* is linked to tanker collision frequencies, and it also affects the oil recovery efficiency in the submodel *Oil recovery* (Figure 1).

The negative utility functions of the four risk approaches are defined as follows:

$$CollisionRisk = -(n_{t-o} + n_{t-t}) \tag{1}$$

$$LeakRisk = -(leak_{t-o} \times n_{t-o} + leak_{t-t} \times n_{t-t}) \tag{2}$$

$$OilRisk1 = -(oil_{t-o} \times n_{t-o} + oil\mathrm{t} - \mathrm{t} \times n_{t-t}) \tag{3}$$

$$OilRisk2 = -final \times (n_{t-o} + n_{t-t}) \tag{4}$$

where $n_{t\text{-}o}$ is the yearly number of T-O collisions and $n_{t\text{-}t}$ is the corresponding number for T-T collisions. Furthermore, $leak_{t\text{-}o} = 1$ if a T-O collision leads to a leakage (and =0 otherwise) and $leak_{t\text{-}t}$ is the corresponding indicator variable for a T-T collision. The factors $oil_{t\text{-}o}$ and $oil_{t\text{-}t}$ represent the amount of oil that is leaked from a T-O or T-T collision, given the leakage. The factor *final* is the final amount of oil that drifts to shores given a random tanker collision leading to a leakage and the open sea oil recovery actions. Because the objective of policy optimization is to minimize the amount of harm, the utilities are expressed as negative values. Four additional random nodes, *p(collisions)*, *p(leaks)*, *p(oil1)* and *p(oil2)*, including the same information than the utility nodes but in the probabilistic form, are added to the main model to enable the user to study the background uncertainty. Their role is demonstrated and discussed in the Supporting Information.

3. RESULTS

The metamodel can be applied to a large numbers of cases, and only selected results are presented here. The expected annual collision and leak frequencies are small fractions. For the

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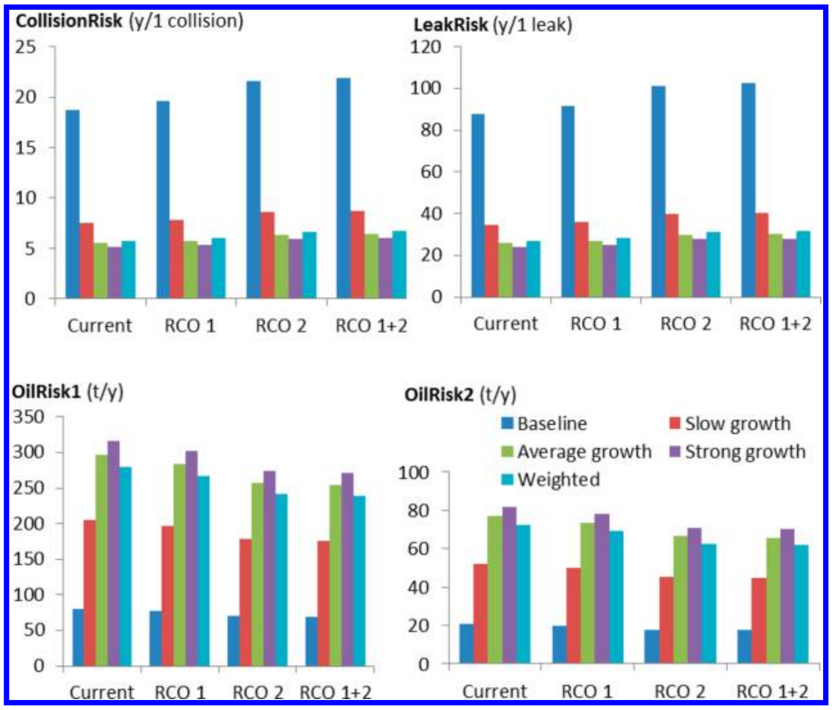

Figure 4. Upper panels: Expected waiting time (years) between tanker collisions (*CollisionRisk*) and collision induced oil leaks (*LeakRisk*) in the Gulf of Finland (all areas), given the traffic scenario and the risk control options (RCO). Lower panels: the annual expected amount of oil (tons) leaking into the sea (*OilRisk*1) and drifting to the shore (*OilRisk*2) after the open sea oil recovery measures. "Current": neither of the two RCOs is implemented. RCO 1: The VTS alarm system is implemented. RCO 2: extended piloting obligations are implemented. RCO 1 + 2: both RCOs are implemented. The axes are scaled differently for resolution purposes.

readers' convenience, they are presented as their reciprocals, that is, the expected time between two tanker collisions.

For the baseline scenario, the time between two tanker collisions in the GoF is expected to be 19 years if no new RCOs are implemented (Figure 4). The expected time between collisions leading to oil leakage is 88 years, which means that 22% of tanker collisions are estimated to lead to leakages. The annual expected amount of oil ending up in the water from tanker collisions equals 80 tons. After oil recovery actions, the amount decreases to 21 tons. Thus, 74% of the leaked oil is expected to be removed from the sea. For the *Strong growth* scenario with no new RCOs implemented, the corresponding results are the waiting times of 5 and 24 years, and the annual oil amounts of 316 and 82 tons, respectively. The frequency of collisions with an oil leak could thus increase 3.5-fold, and the annual volumes of oil in the ecosystem of the GoF could grow 4-fold compared with the baseline level (Table 2).

The amount that the growing maritime traffic volumes are expected to increase the oil tanker collision induced risk varies spatially (Table 2). In areas C1 and C3 (Figure 3), the risk increases more than in the entire GoF on average, whereas for C2 and C4, the risk is slightly lower. Area C5 is closest to average. The range in the values of Table 2 arises from the results gained using the different risk approaches. The lower limit values represent *CollisionRisk* and *LeakRisk* (for which the levels of increase are nearly identical), the upper limit values represent the approaches *OilRisk*1 and 2 (being close to each other as well). The range is caused by the uncertainty that accumulates along with the additional elements in the system. The overall uncertainty increases, especially when the oil recovery efficiency is involved in the analysis. Particularly for the larger leak sizes and light oil recovery, the efficiency is shown to be highly unpredictable.[17]

Table 2. Increase in Risk by the Year 2015 Given the Future Scenarios[a]

	slow growth	average growth	strong growth	weighted
C1	2.5−2.6	3.6−4.0	3.8−4.1	3.4−3.7
C2	2.0	2.7−2.9	2.9−3.1	2.6−2.7
C3	2.8−2.9	3.6−4.1	3.9−4.3	3.5−3.8
C4	1.7−1.8	2.2−2.5	2.5−2.7	2.1−2.4
C5	2.4	3.3−3.7	3.5−3.9	3.1−3.4
all	2.5−2.6	3.4−3.7	3.6−4.0	3.2−3.5

[a]The numbers are ratios of the risk-approach-specific output to their baseline scenarios. In the column "Weighted", the scenarios are weighted based on the experts' degrees of belief concerning their realization (Table 1). The results are presented separately for areas C1−C5 and for the entire Gulf of Finland ("All"). The ranges arise from the alternative risk approaches.

Independent of the traffic scenario or the risk approach, RCO2 seems to be more than twice as effective as RCO1 at reducing the risks. Compared with the situation where no RCOs are implemented, RCO2 is estimated to reduce the risk by 13% whereas the corresponding risk reduction efficiency of RCO1 is 4%. Because the values remain the same despite the changes in traffic volume or risk approach, it can be stated that the result of the decision analysis is robust against the divergent uncertainties and thus not dependent on the amount of the future traffic and oil transportations, nor the decision making criteria used. Interestingly, implementing both RCOs in parallel reduces the risk by only 14%, which is less than the sum of their individual efficiencies. This is because the VTS alarm becomes useful only when the internal vigilance of the ship is reduced, which is not likely to occur if a pilot is onboard.[24]

As the model is based on the combination of data and expert knowledge and made for analyzing situations that have never

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materialized in the area, it is not possible to evaluate the predictive validity of the output; however, it is possible to evaluate the model behavior and its capability to predict the behavior of the analyzed system.[37] We conducted two types of behavior sensitivity tests. First, the most influential variables for large scale oil pollution (>1000 t/year) in the GoF were searched. One-way sensitivity analysis was conducted using a sensitivity value approach.[38−40] This analysis is described in detail in the Supporting Information. The results showed that the probability of having at least 1000 tons of oil spilled is most sensitive to the probability of whether the T-O collision tanker is in load and the prediction of the tanker collision frequency, which is reasonable because, given no oil or no collisions, there will be no leaks either.

However, rather than providing exact predictions for leak frequencies, the main purpose of the model is to compare the proportional risk levels under uncertain future circumstances and study alternative ways to control the risk. Therefore, value of information (VOI) analysis[41,42] was used to discover which factors in the ID have the most important impact on the analyzed RCOs. VOI of a variable measures how much the expected utility in the model would increase if the state of that variable were observed before making the decision. The utilities of the present model are not described in monetary terms; thus, we use the VOI analysis in this context only to search for the most important variables in our inference to evaluate the model and understand the system.

Without locking any of the variables in the model, the only factors that have a minor VOI when choosing the RCO implementations are related to leak formation (the variables *hull breach* and *in oil load*), which is reasonable, as no costs for the implementation of RCOs have been defined. Thus, the implementation is either justifiable (in the case that even one oil accident can be prevented) or insignificant (no additional costs will be caused anyway). If any utility is gained from implementing an RCO depends on whether the predicted tanker collisions will lead to oil spills or not. Collisions do not form risks if any approach other than *CollisionRisk* is selected.

Extreme conditions testing[37] was applied to check the model's consistency with reality under extreme conditions, where the behavior of the modeled system is predictable. In this case, it was applied by locking sets of boolean (true-false) variables (*In oil load* and *Hull breach* nodes) or quantitative variables (numbers of collisions and leak size variables) into their false- or zero-states and checking that this produces zero-pollution with $p = 1$. Based on the above-described model evaluations, we can state that our ID succeeds in modeling the behavior of the analyzed system rationally.

4. DISCUSSION

Based on the results, it seems that compared with the VTS alarm system, obligatory piloting is over twice as effective an option to decrease the collision-induced risk of an oil accident in the GoF. This result was shown to be robust against the uncertainty arising from the development of future maritime traffic and the increasing number of elements included in the model. Interestingly, the joint effectiveness of these two RCOs were less than the sum of their individual effects. A logical explanation for this finding is that the pilot onboard already increases the internal vigilance of the ship, which decreases the utility provided by the VTS alarm.[24] Based on these findings and the fact that the analyzed RCOs are not the only options to manage the oil accident risks in the GoF, we recommend that the presented model be complemented with some additional RCOs. The value of information (VOI) analysis showed that, from the decision analytical perspective, the most crucial uncertainty about the system is the one related to the formation of the leakage. Thus, we suggest that alternative solutions to reduce the leak probability in the case of a tanker accident be analyzed as well as measures aiming to decrease the probability of both collisions and groundings.

Alternative traffic development scenarios for the year 2015 were forecasted at the end of 2008. Based on recent data, in 2012, the volumes of oil transportation and ship traffic in the GoF were between the slow and average growth scenarios.[43,44] The national shares of the oil transport have developed differently than envisioned in the scenarios, concentrating even more on oil export from Russia. In the model, this result would slightly affect at least the relative risk-proneness between the analyzed areas.

Based on the latest observations, tankers between 200 000−300 000 dwt visited the GoF during the years 2010−2013.[45] In the model, the evaluated growth in tanker sizes by the year 2015 was negligible. It would be interesting to examine how the observed increase in tanker sizes actually affects the analyzed total risk. For a fixed amount of oil, the number of tankers decreases, which reduces the frequency of ship encounters. In contrast, it should be determined if evasive maneuvers are more likely to fail or hull breaches to occur in the case of larger ships. Additionally, the volume of potential spills might be larger. Furthermore, when tanker groundings are included in the analysis, it will be interesting to study the following risk estimates compared with those from collisions alone. Although grounding is the most common accident type in the GoF,[31] collisions more often lead to leakages, and the volume of these accidents is typically larger.[46]

The analysis indicated that obligatory piloting (RCO2) more efficiently decreases the number of collisions than the VTS alarm system (RCO1). In reality, international conventions state that coastal countries cannot regulate piloting outside their territorial waters, which makes RCO2 an unrealistic option. From a decision analytic perspective, a cost-effectivity analysis should be performed before choosing between those two actions. Presumably the implementation of RCO2 would be so expensive compared with RCO1 that the latter would outweigh the former anyway. In addition, some supplementary measures could be implemented in parallel. Still, as the results showed, it is important to analyze the potential synergies of all of the alternatives under consideration to find the most (cost-) effective set of the management actions.

The purpose of a decision analysis is not only to find the best single decision but also to help make informed decisions.[47−49] We show that BNs are powerful tools for synthesizing knowledge, logic and rules originating from divergent sources. They provide tools to think about issues that are too complex to be analyzed by human brains alone. This method is suitable for integrating large amounts of multidisciplinary knowledge and, thus, can be utilized for the integrated analysis of environmental risks and their management.[15,50,51] In addition, BNs have a type of Lego-brick characteristic, which enables building large entities piece by piece because two BNs containing an identical node can be easily linked. The integration starts a two-way information flow between the elements, which may provide interesting insights into how these subsystems are interrelated in the real world, which also

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enables an effective synthesis of the work performed in separate projects that use the method.

A novel idea in the presented ID is to use a decision node as a setting variable to adjust the decision making criterion to be applied. This approach allows for study of the VOI as well as ranking the decisions using different decision making criteria, which also serves as a type of a sensitivity analysis. We constructed a decision node, *Risk approach*, for selecting one of the four alternative utility nodes to be used for the calculation. Without this setting node, the presented model structure would perform a multicriteria analysis with equally weighed criteria. However, this approach is not meaningful in the present case. In the case of using parallel utility nodes, they should adopt the same unit. Otherwise, their mutual proportioning does not make sense. If all four utility nodes were used in parallel, the annual numbers of tanker collisions or oil leaks would have been proportioned to the annual oil tonnages ending up in the sea. If this type of synthesis was our objective, different states of the target variables should be given points on a common scale to show how they behave with mutual weighting. Thus, the multicriteria approach is not reasonable in this case; it was more relevant to study the sensitivity of the decision analysis against the longer chain of inference and the increasing uncertainty that follows when the originally missing elements are added.

A common constraint of the current interactive BN software is that they are not capable of full joint modeling of the continuous and discrete variables.[52] For this reason, all of the variables of the presented model are handled as discrete—even those clearly continuous by nature. The more classes we can assign to the variable, the more accurately the underlying continuous probability distribution can be approximated. In contrast, each additional class interval adds computational complexity to the model, increasing the amount of conditional probability distributions (CPD) to be defined for the child variables. Thus, the discretization requires trade-offs between these two aspects.[53]

Several techniques for automated and intelligent discretization of continuous variables exist, covering both static and dynamic approaches.[54−56] Tools for applying them are included in many BN software packages, but their use should be considered case by case, and expert supervision is recommended to ensure that the discretization is in line with the model objectives.[53] In the presented BN, the class boundaries of the tanker's size were recommended by the leak modelers based on the tanker traffic statistics of the GoF. Furthermore, the discretization of the spill size and the following postrecovery amount of oil in water were based on the results of the leak size and oil spill recovery efficiency models, respectively. The need for a zero-leak state is a special feature of this particular research problem because tanker collisions do not always lead to leaks. Because it is not technically possible in Hugin to include true zero states for an interval variable, an insignificantly small value was used to represent the upper boundary of the zero-state interval (Supporting Information Table S1). This solution leads to a minor flaw: when the model is locked to a zero-leak state, the resulting risk level is not dead zero if the risk approaches *OilRisk*1 or 2 are applied.

This paper presents one possible approach for the systematic analysis of oil accident risk and its management in the GoF. In our analysis, the inference ends up in the amount of oil drifting to the shores annually. This information may not be directly comparable to the final harm caused to the coastal ecosystem. The model also includes other variables that have an effect on the impacts of oil spills on the ecosystem, such as season and oil type.[5] The direction that the oil will likely drift under different weather conditions is closely related to the environmental harm because the most vulnerable habitats and species are not evenly distributed along the coastline.[4,14,57] This necessitates a connection between the BN and the locations of the vulnerable species and habitats, which is an approach that was presented by Jolma et al.[58]

Selecting an appropriate approach to value the environment in the risk analyses is not a simple task.[4,59] Society should define the risk level that it is willing to accept (willingness to accept) and delineate how much it is ready to pay (willingness to pay) for oil and not exceed that risk level.[60,61] Successful risk management depends on political will prevailing.[62] Thus, public discussions about the acceptable risk levels in the GoF are needed. We conclude that conducting a comprehensive environmental risk assessment requires integrating much larger entities than was performed in the present study. In this study, we found a workable methodology and developed a platform upon which new elements can be added when striving for a holistic environmental risk assessment for the GoF.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

List of abbreviations used; table presenting all the model variables with their sources of input; information on the Bayesian networks; descriptions of the submodels; results and discussion concerning the background uncertainty. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

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