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A probabilistic model estimating oil spill clean-up costs – A case study for the Gulf of Finland



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ABSTRACT

Existing models estimating oil spill costs at sea are based on data from the past, and they usually lack a systematic approach. This makes them passive, and limits their ability to forecast the effect of the changes in the oil combating fleet or location of a spill on the oil spill costs.

In this paper we make an attempt towards the development of a probabilistic and systematic model estimating the costs of clean-up operations for the Gulf of Finland. For this purpose we utilize expert knowledge along with the available data and information from literature. Then, the obtained information is combined into a framework with the use of a Bayesian Belief Networks. Due to lack of data, we validate the model by comparing its results with existing models, with which we found good agreement.

We anticipate that the presented model can contribute to the cost-effective oil-combating fleet optimization for the Gulf of Finland. It can also facilitate the accident consequences estimation in the framework of formal safety assessment (FSA).

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1. Introduction

As the amount of oil tankers in the Gulf of Finland increases, it raises the public's awareness of the possibility of a large-scale oil accident taking place and leaving this sensitive coastline polluted. However, the economic consequences of said accident have so far not been extensively studied for the Gulf of Finland. This is especially interesting, as the economic cost for an oil accident can be a suitable measure for Cost-Benefit analyses that are commonly used when making decisions about risk control options and future investments, see IMO (2002).

Numerous studies have been carried out on oil spill cost estimations. For the latest review in the field see Yamada (2009). However, the costs of oil spill clean-up operations, which are listed among the top cost categories associated with the total costs of an oil spill have not gained the proper credits yet, see for example Liu and Wirtz (2006, 2009). Moreover, most of the existing models are based on historical data from past oil spills obtained from the IOPCF statistics, which by definition is passive, for the detailed discussion the reader is referred to Psarros et al. (2011). Furthermore, such models are developed with the use of data about spill sizes falling in a certain range, usually with small median value for a spill, see Kontovas et al. (2010), thus applying such models for extrapolation beyond this range is very questionable.

In the scientific literature there are only two models allowing for the estimation of oil spill clean-up costs. One has been proposed by Etkin – Etkin (1999, 2000) – is deterministic but allows rather wide interpretation of the cost factors considered. Another model has been proposed by Shahriari and Frost (2008) it is also deterministic, but with no room for interpretation.

Predictions of both models hold in the context of global oil spill costs, but they have rather low geographical resolution. Therefore, it is not possible to use the models for the purpose of oil-combating fleet optimization or detailed risk management, as the local conditions are not properly reflected.

Moreover, the unique nature of the analyzed sea area of the Gulf of Finland, being classified by the IMO as a Particular Sensitive Sea Area (PSSA), makes it possible for the oil to reach the shore in a very short time with devastating consequences, see for example Lecklin et al. (2011). This means that once the oil spill at sea has occurred, it is almost impossible to prevent it from reaching the coast, see Hietala and Lampela (2007) and Aps et al. (2009). What makes the clean-up operations even more demanding is the fact that the coastline is filled with small islands; making it impossible for the clean-up vessels to navigate in some places even though the sea depth would allow it. Another factor that separates the Gulf of Finland from the larger sea areas is that, according to the HELCOM agreement, use of chemical dispersants or in situ burning are not permitted as oil combating techniques, and the clean-up is mainly performed mechanically, see HELCOM (2012). All these show the complexity of the subject and limitations of existing clean-up cost estimation models. Hence, it is desirable to go to the sources of

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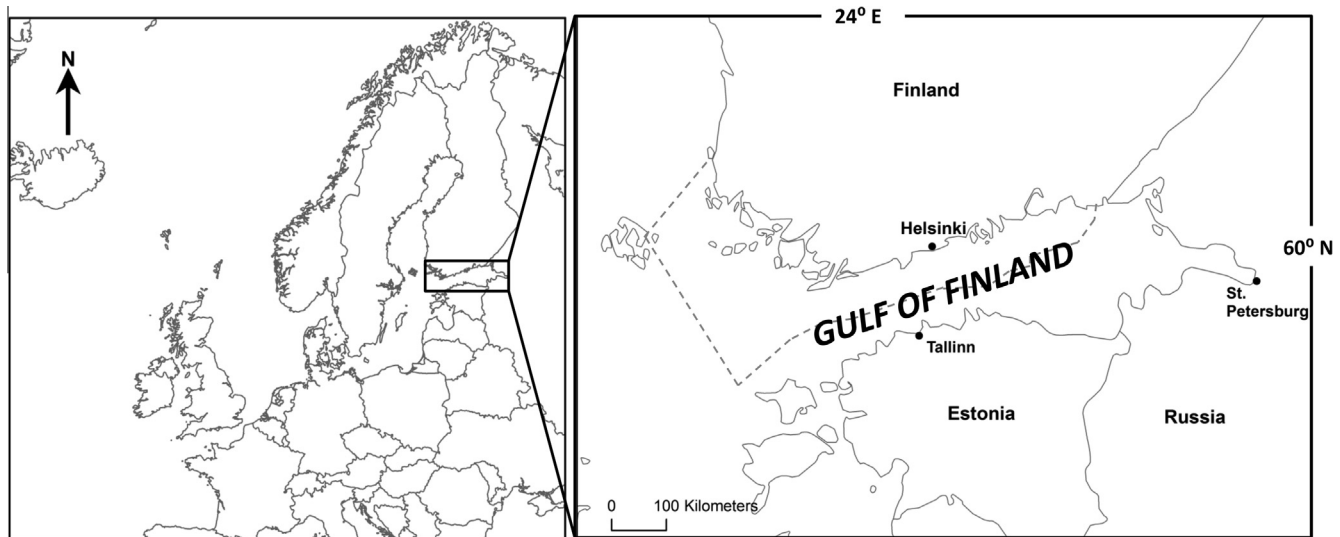


Fig. 1. The analysed sea area – the Finnish response area of the Gulf of Finland.

each of the costs, which together make the total cost of oil spill clean-up operation.

This paper introduces a probabilistic model for accidental oil spill cleanup-cost estimation for the Finnish response area of the Gulf of Finland – see Fig. 1. For this purpose, we adopt a top-down approach, where the clean-up costs are divided into offshore and onshore and then further broken down to smaller individual cost factors, thereby arriving at a model better suited for the analyzed area. To reflect the causal relationships among different factors affecting the clean-up costs in a probabilistic fashion, the Bayesian Belief Networks (BBNs) are used as a medium to propagate the available knowledge through a model. For this purpose, literature survey and expert knowledge are extensively utilized and systematically organized. In order to validate the model, the case studies are performed, whereby the outcome of the model for given scenarios is compared with the result based on the existing models provided in the literature, with which good agreement is found.

The study does not include any socioeconomic and environmental costs, nor does it include waste management procedures. It is also assumed that the oil spill in the model happens all at once, and only three seasons are considered, leaving winter out of the scope of the analysis. Moreover, we assume, that in the case of an oil spill, only the Finnish fleet capability is used, and no assistance from neighboring countries or EMSA is given.

Nevertheless, the presented model quantifies the costs of oil spill clean-up operations, which can be further utilized for the purpose of oil-combating fleet optimization adopting the cost-benefit analysis. This in turn, can be utilized in the framework of formal safety assessment aimed at enhancing maritime safety – (Hanninen et al., 2013; Goerlandt and Kujala, 2011) – including protection of life and health, the marine environment – (Lecklin et al., 2011; McCay et al., 2004) – and property – (Montewka et al., 2012, 2010) – by using risk analysis and cost benefit assessment.

The remainder of this paper is organized as follows: Section 2 presents methods and describes the probabilistic model. Section 3 shows and discusses the results, which are obtained. Section 4 provides concluding remarks.

2. Methods

2.1. Bayesian Belief Networks

As the oil spill cleanup-cost estimation model consists of many uncertain variables, which very often are of a probabilistic nature,

there is a need to adopt a proper modeling technique to handle these uncertainties. For the purpose of this study, we adopted BBNs, which are recognized tools to represent one's knowledge about a particular situation as a coherent network, see for example Darwiche (2009). Moreover, BBNs allow instantaneous reasoning under uncertainty and allows one to effectively update a model when new knowledge is available. This is an increasingly popular method for modeling uncertain and complex domains, see for example Montewka et al. (2012, 2011), Uusitalo (2007), Aguilera et al. (2011). BBNs are especially used to simulate domains containing some degree of uncertainty caused by imperfect understanding or incomplete knowledge of the state of the domain, randomness in the mechanism or a combination of these circumstances, see Bromley et al. (2005), Montewka et al. (2010), Eckle and Burgherr (2013).

BBNs can also be used as a way to facilitate decision making, see Lehtikoinen et al. (2013). In some types of networks, known as influence diagrams (ID), the decisions are represented by distinctive decision nodes (DNs) that often are guided by the reaction of utility nodes (UNs) to the network. These two types of nodes (DNs, UNs) are used to automatically help determine the decision to make, which gains the highest expected utility (EU), considering the given circumstances.

For the purpose of this study, an influence diagram is used as a way to transmit our knowledge about an analyzed system, its components and their behavior. The use of an ID to develop the cost model allows us to easily determine the oil-combating actions that minimize the total cost of the clean-up operation. The presented model has been developed with the use of Hugin Researcher 7.8 modeling environment.

2.2. Data acquisition

In order to gather data for the model, both literature sources and expert opinions are utilized. Additionally, some of the conditional probabilities needed for the cost model have already been estimated in previous studies regarding the environmental impact of an oil accident in the Gulf of Finland, see for example Lehtikoinen et al. (2013), Partila (2010), Juntunen (2005) and Juntunen et al. (2005).

Usually, when expert solicitation is used as a way of collecting data for BBNs, one should first decide if the expert will be asked to provide both the model structure and the probability distributions, or if expert knowledge is only to be used for the latter. In the case presented in this paper, the structure of the model is based on the

The expert solicitation for this study is completed primarily during a one-day workshop, where fifteen professionals in the field of environmental issues are gathered. As the information regarding the needed costs and oil-combating ships efficiency is highly dependent on a wide range of situational circumstances, the group discussion approach is preferred to the individual interview scenario. This allows the interchanging of opinions between the interview subjects, and, in some cases, leads to a more accurate result than in the case of personal estimations.

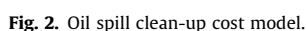
A cost model of oil spill clean-up operations, which is developed here, is depicted in Fig. 2. It consists of four types of variables, connected in a logical way. The variable types are as follows:

- ### 2.3.1. Utility variables

from the offshore clean-up and, secondly, the costs related to the onshore clean-up procedures. The utility variables also dictate the states of the decision variables in such a way that the total costs are minimized. This means that the model can determine the oil-combating strategy, which minimizes the clean-up costs. However, the remaining effects of the oil spill on the environment and society are not considered in this study, and thus, the proposed strategy shall by no means be considered optimal.

The decision nodes in the model consist of booms and oil-combating vessels. These nodes only exist in Boolean states of being sent or not sent to the location of the accident. These decision nodes directly affect the offshore clean-up costs and, indirectly, the onshore clean-up costs. The decision node *Booms* refers to the use of offshore booms, with the aim of keeping the oil close to the oil combating vessels for as long as possible thereby decreasing its spreading rate. The use of onshore booms is not anticipated in this model.

When it comes to oil combating fleet, the decision nodes account for the three largest and the most effective oil-combating vessels in the Finnish Navy: Louhi, Halli and Hylje. There are also two combined nodes encapsulating smaller oil-combating vessels managed by the state-owned company Meritaito Ltd., and ships belonging to the Finnish Border Guard. This division is justified by the fact that the ships owned by the Finnish Border Guard and Meritaito Ltd., are rather small and mostly used in the early stages of the clean-up process, before the larger combating vessels reach the spill location. These ships are grouped into two decision nodes in the model. The node *Finnish Border Guard* refers to three vessels: Uisko, Tursas and Merikarhu, and the node *Meritaito Ltd.* refers to four vessels:



Oili I, Oili II, Oili III and Seili. Due to the size limitations of the model, it is not feasible to include all vessels separately.

We also assume that all the vessels belonging to a decision node are sent to combat the spill if the node is selected.

2.3.3. Independent variables

The independent variables of the cost model are: *Spill size*, *Season*, *Oil type* and *Time for spill to reach shore*. The last is more realistic and more useful from the modeling perspective when expressing the distance from the location of the oil spill to the nearest shore. The independent variables allow users to define them, however the model gives an opportunity to select the closest interval from the pre-set states for the node. In the event that these values are not known, the initial variables have their own probability tables and values, obtained in the course of simulations for the environmental and traffic conditions prevailing in the Gulf of Finland.

The length of polluted coast is not considered in the model, instead we determine the clean-up costs based on the amount of pollution that reach the shore.

2.3.3.1. Spill size. *Spill size* is an independent variable with 10 states, as presented in Table 1. As the cost model does not specify the probability of an accident taking place, nor the volume of the possible oil spill, it is up to the analysts to assign the probability for this variable.

The states of the variable are described as intervals, which are quite large but can be easily modified if necessary. There is one specific amount for the oil spills, of 30 000 ton, which is the largest oil spill considered by the authorities in Finland, and reflects the preparedness level for Finland, see SYKE (2011).

2.3.3.2. Season. It is an independent variable, which exists in three states: spring (Mar.–May), summer (Jun.–Aug.) and autumn (Sept.–Nov.). Winter is excluded for several reasons, first as oil-spill combating during ice season is different than during the other seasons. Second, some of the oil-combating vessels are not capable of operating in ice conditions. Third, there is no reliable prediction model for the movement of oil in ice conditions in the GOF, (Helle et al., 2011). The prior distribution for the variable *Season* is presented in Table 2 and informs about the probability that an accident resulting in an oil spill would occur on the Gulf of Finland specifically during this season of the year. The distribution was gained from the compiled accident statistics of HELCOM between the years 1989 and 2005 – (HELCOM, 2013).

2.3.3.3. Oil type. It is one of the most important factors affecting the cost of the clean-up operation. It affects the cost in a multitude of ways, starting from the way that the spilled oil spreads in water, which affects the time it takes for the spill to reach the shoreline. In addition, heavier oil has the tendency to sink; this in turn affects the possible recovery percentage of the oil-combating vessels. The oil type also affects the efficiencies of the combating vessels, due to the fact that some oils are less likely to adhere to the brushes used by the combating vessels.

In the presented model, this variable exists in three states: *light*, *medium* and *heavy*. The probabilities for each state are given in

Table 1
The states of variable *Spill size*.

Spill size [t]	Spill size [t]
0–0.001	15,000–30,000
0.001–500	30,000–30,001
500–1000	30,001–50,000
1000–5000	Above 50,000
5000–15,000	

Table 2
The probability distribution table for variable *Season*.

Season	Probability
Spring	0.39
Summer	0.28
Autumn	0.33

Table 3
The probability distribution table for variable *Oil type*.

Oil type	Probability
Light	0.2
Medium	0.4
Heavy	0.4

Table 3. They are based on an estimation made by experts from the Finnish Environment Institute considering the oil tankers traffic in the Gulf of Finland, see for example Juntunen et al. (2005).

2.3.3.4. Time for spill to reach shore. For the Gulf of Finland, it is estimated that an oil slick would arrive ashore quite quickly. In the case of an accident taking place in the middle of the sea, it could take between one to nine days for the oil to reach the shoreline, see for example Andrejev et al. (2011), Viikmäe and Soomere (2013) and Soomere et al. (2011). Therefore the variable is set to consist altogether of ten intervals, ranging from zero to ten days. We assume, the prior distribution for this variable follows the Gaussian distribution, with $\mu = 5$ days and $\sigma = 2$ days. However, if the spill takes place in Finnish waters of the Gulf of Finland, it is estimated that it would take a maximum of three days before the oil reaches the shore, (Hietala and Lampela, 2007). This means that in the case of a study only considering the clean-up operations taking place in Finnish waters, the probabilities should be higher for the first three intervals. It should also be noted that this variable gives only the first stranding time of the oil, and a large part of the oil slick may actually still be floating around in the sea, arriving at the shore later.

2.3.4. Conditional variables

Variables of this type are dependent on one or more other variables, called parents. The relations between a conditional variable (child) and its parents are established through a conditional probability table (CPT). A CPT for the model presented here is determined in two fold. First, mathematical functions are adopted when applicable to specify the relations between variables. Second, simulations are performed and the results are incorporated to the model. In this section, all the conditional variables are listed and their origin is explained.

2.3.4.1. Wave height. The variable *Wave height* is conditional on the variable *Season*, and is divided into four different intervals, as

Table 4
The probability distribution table for variable *Time for spill to reach shore*.

Day	Probability
0–1	0.02
1–2	0.04
2–3	0.08
3–4	0.12
4–5	0.16
5–6	0.16
6–7	0.12
7–8	0.08
8–9	0.04
9–10	0.01

Table 5The conditional probability table (CPT) for variable *Wave height*.

Season	Spring	Summer	Autumn
<i>Wave height (m)</i>			
0–1	0.89	0.88	0.52
1–2	0.11	0.11	0.39
2–3	0.00	0.01	0.08
Above 3	0.00	0.00	0.01

presented in Table 5. The probability distributions, which are adopted for this variable, are based on field measurements performed in the Gulf of Finland, see Kahma and Pettersson (1993). As the Gulf of Finland is quite narrow, the highest measured significant wave height is 5.2 m, which has been recorded only twice in the history until 2013, see Marita Mustonen (2013). However, a wave height of approximately two meters already makes it almost impossible for the current Finnish oil-combating vessels to carry out oil-recovery operations.

2.3.4.2. Evaporation. This variable reflects the fraction of an oil spill that evaporates into the air, and is expressed as a percentage of the initial spill size. The rate at which the oil evaporates depends, among other factors on the oil type in question, the weather circumstances, such as wind and wave height, as well as the prevailing temperature. Evaporation is also affected by the initial spreading rate of the oil, since the larger the surface area is, the faster light components will evaporate – see for example Yamada (2009). However, this particular dependency is not taken into consideration here. In order to calculate the CPT we use the following equation, see Juntunen (2005):

$$\text{Evaporation} = f_1(\text{oil type}) \cdot f_2(\text{wave height}) \cdot f_3(\text{season}) \quad (1)$$

where *Evaporation* is the fraction of an initial spill that evaporated (%) and the following factors are used to determine this parameter:

- f_1 (light oil) = 0.8; f_1 (medium oil) = 0.3; f_1 (heavy oil) = 0.15;
- f_2 (wave height < 1 m) = 0.9; f_2 (wave height = 1–2 m) = 1; f_2 (wave height = 2–3 m) = 1.1; f_2 (wave height > 3 m) = 1.2;
- f_3 (spring) = 0.8; f_3 (summer) = 1.1; f_3 (autumn) = 0.9.

2.3.4.3. Amount to be recovered. This variable quantifies the amount of oil that is still left in the water after considering the possible effect of the evaporation. The variable exists in 17 states ranging from 0 (all of the oil has evaporated) to 50,000 cubic meters.

2.3.4.4. Effect of booms. This node quantifies the time that oil-combating fleet may gain by utilizing the offshore booms, which prevent the oil spill from spreading quickly. The probabilities for this variable are elicited from the experts, and are presented in Table 6. The highest probability is associated with a situation when oil-combating vessels would gain between 1 and 12 h if the booms are placed.

Table 6The CPT for variable *Effect of booms*.

Time gained (h)	Booms placed	
	Yes	No
0–1	0.2	1
1–12	0.4	0
12–24	0.3	0
24–72	0.1	0

2.3.4.5. Time for vessel to arrive. This variable refers to the time that it takes for an oil-combating vessel to reach the place of an oil spill. The states are defined in six intervals of hours, as follows: 1–12; 12–24; 24–72; 72–168; 168–288; above 288.

The time it takes for a vessel to arrive at the location of the accident is simulated using an external model that studies the efficiency of the oil-combating vessels in the Gulf of Finland, see (Lehikoinen et al., 2013). Their model considers six different hot spots, which are locations in the Gulf of Finland where an accident is more likely to happen. In the model, the initial locations of the combating vessels are also predetermined. By considering both the initial location and the end location, the distance that the combating vessel has to travel is determined. Using this distance and speed of the vessel, the time needed for a ship to arrive on the scene is calculated.

As the oil spill clean-up cost model presented here is independent with regards of location and therefore does not use the same hot spots as the model presented in Lehikoinen et al. (2013). The variable *Time for vessel to arrive* is simulated separately for each hot spot. Then the obtained probability tables are put together and their average value is calculated and considered an input for clean-up costs model.

The last state for this variable is 288 h or more and is used only in the rare case that none of the combating vessels are sent to the location of the accident, either implying that it would be more cost efficient to let the entire oil slick arrive to the shore or that there is not enough time for the vessels to gather any oil before the oil slick reaches the shore. As the probability table obtained is very large, we abstain from showing it here.

2.3.4.6. Time to collect the oil. This variable is dependent on the *Time for spill to reach shore*, *Time for vessel to arrive* and *Effect of booms* and represents how many hours the combating vessels can operate before an oil slick reaches shore. The variable is divided into seven intervals of hours, as follows: 0–6; 6–24; 24–72; 72–120; 120–168; 168–240; 240–500. The CPT for this variable is calculated by adopting the following expression:

$$\text{Time to collect oil} = \begin{cases} 0 & \text{if } 24 \cdot C15 < C12 \\ 24 \cdot C15 + C17 - C12 & \text{otherwise} \end{cases} \quad (2)$$

where C15 is Time for spill to reach shore (days); C12 is Time for vessel to come (hours); C17 means Effect of booms (hours).

The equation assumes that if the oil slick reaches the coastline before the oil-combating vessels are able to reach it, the time they have to collect oil will be zero. Otherwise, the time the vessels have to collect oil will be the time it takes for the spill to reach the coast, subtracted by the time it takes for the vessel to reach the location. In a case when booms are used, the effect of these will be added to this time. Since the CPT for this variable is extensive it is not presented here.

2.3.4.7. Oil-combating efficiency. This variable indicates the amount of oil being collected by the oil-combating vessels in one hour. The CPT for this variable is obtained using the model studying the efficiency of the oil combating fleet of Finland, see Lehikoinen et al. (2013). In their model, the variable is dependent on factors such as wave height, oil type, the time the combating vessels have to operate, their tank size and the rate at which they can fill and empty their tanks. The simulations that are created with the use of aforementioned model are done separately for each of the oil-combating vessels over a range of external factors. The oil-combating efficiency decreases when the wave height increases. Louhi is the only combating vessel still able to collect some oil still when the waves are higher than two meters, while all other vessels are

ineffective in such conditions. When multiple vessels are sent to the oil spill, their respective efficiencies are added together and their CPTs are combined.

We assume it is unlikely that any of the vessels are able to collect light oil, as it does not tend to adhere to the brushes used. Therefore, all vessels are given the lowest possible oil-combating efficiency for this type of oil, regardless of other parameters.

Depending on the size of an oil spill, the oil-combating vessels may have to empty their tanks one or several times during the course of the operation, and the time that this procedure takes is subtracted from the total time that they have to operate before the oil slick reaches the shore.

The *Oil-combating efficiency* node has a total of 20 states and results in an extensive CPT, which is not shown here.

2.3.4.8. Number of vessels sent. The *Number of vessels sent* exists in 11 states, ranging from 0 to 10, indicating the number of combat-ing vessels sent to the location of the accident.

2.3.4.9. Reduced oil combating efficiency. This variable estimates the oil-combating efficiency of the vessels used in the operations, and is expressed in cubic meters per hour. We assume that the efficiency of a vessel is smaller if she operates in a group, when compared to individual operation. This may be due to the fact that the ships have to follow certain path when conducting group work; they need to perform evasive manoeuvres to avoid collisions with each other and they cannot navigate freely. This assumption implies that the group efficiency is smaller than the sum of all individual efficiencies of oil-combating ships involved. As no studies have been conducted on how multiple vessels operate together and how other joining vessels affect the performance of the fleet operating in the scene, it is difficult to provide a reliable estimate for this parameter. In this paper, we assume that this parameter depends only on the number of vessels joining the operation, meaning that with each joining vessel, the overall efficiency of the fleet is reduced by 2%. As this factor is based purely on assumption, we conduct the sensitivity analysis, which reveals an important effect of this variable on the outcome, which is mostly due to its additive nature.

If a factor of 2% is applied for each of ten ships involved in the oil-combating operations, the ultimate fleet efficiency is 80% and the total clean-up costs increases by 10%. If a factor 4% is applied, the fleet efficiency is reduced by 40%, and the clean-up costs increases by 25%, compared to the situation where the combating efficiency of ships is not reduced. However such drastic reduction of the fleet efficiency does not seem realistic, thus our choice for this parameter can be indirectly justified and its effect quantified.

The nature of BBNs allows an efficient updating of this factor in light of new knowledge and evidences.

2.3.4.10. Amount of oil recovered offshore. This variable quantifies the amount of oil that is expected to be collected before the oil slick reaches the shore. It indicates the amount of oil that the combating vessels will collect by multiplying the vessel's reduced oil-combating efficiency with the time they have at their disposal. The variable has 13 states ranging from 0 to 50,000 m³, and its CPT is obtained using the following expression:

$$\text{Amount of oil recovered offshore} = \begin{cases} C3 & \text{if } C8 \cdot C12 > C3 \\ C8 \cdot C21 & \text{otherwise} \end{cases} \quad (3)$$

where C8 is Time to collect oil (hours); C21 is Reduced removal efficiency (m³/h); C3 stands for Amount to be recovered (m³).

2.3.4.11. Amount of oil washed ashore. This variable expresses how much oil is still left in the water after the oil-combating vessels

have collected as much oil as possible in the time frame given. This variable contains 23 states, ranging from 0 to 50,000 m³, and its CPT is obtained through the following conditional expression:

$$\text{Amount of oil washed ashore} = \begin{cases} 0.01 \cdot C3 & \text{if } C3 \leq C5 \\ C3 - C5 & \text{otherwise} \end{cases} \quad (4)$$

where C3 is Amount to be recovered (m³); C5 means Amount of oil recovered offshore (m³).

The expression means that if the amount of oil recovered at sea is higher or the same as the amount to be recovered, there is no significant spill reaching the shore – we assume that 1% of the amount to be recovered is washed ashore. Otherwise, the fraction of what is left from the offshore clean-up is assumed to pollute the coast.

2.3.4.12. Amount of waste – mechanical/manual removal. We estimate that the oil mixture that reaches the shore and needs to be collected there contains 10% oil, 40% water and 50% other substances and materials; see for example Kaakkois-Suomen (2009). The amount of waste that needs to be collected is divided between the mechanical and manual clean-up methods. Their respective shares are determined based on m/t Prestige case, thus we assume 60% of the remaining spill being treated with mechanical methods and 40% is left for manual operations. Both nodes *Amount of waste mechanical removal* and *Amount of waste manual removal* exist in 21 states defined in intervals from 0 to 50,000 m³, and the CPTs are obtained by solving the following equations:

$$\text{Waste (mechanical)} = \text{Amount of oil washed ashore} \cdot 0.6/0.1 \quad (5)$$

$$\text{Waste (manual)} = \text{Amount of oil washed ashore} \cdot 0.4/0.1 \quad (6)$$

2.3.4.13. Time for mechanical/manual removal. A previous study regarding waste management in the case of an oil spill accident in the Gulf of Finland suggests 5 m³/h as the efficiency for mechanical removal, when one machine is used, see for example Partila (2010). The same study specifies the manual removal efficiency in the range of 50–100 l per hour per person, with the higher value assumed for the present study, see also Shikida (1999). The number of people used in the calculations is 500, from which 350 would be cleaning at the same time.

The CPTs contain 26 states ranging from 0 to infinitive; the parameters expressed in hours are obtained by dividing the amounts of waste to be removed mechanically/manually by the adopted efficiencies.

2.3.4.14. Shoreline clean-up costs. This variable is dependent on the following variables: *Machine cost*, *Manual cost* and *Boat cost*.

2.3.4.15. Machine costs. The costs associated with the mechanical removal of oil at the shore are the cost of the machine used and the cost of hiring two people to operate it. During the workshop, the participants agreed that using a machine to remove the oil would cost about 130 euro per hour. The *Machine cost* contains 34 intervals and is only dependent on the *Time for mechanical removal*.

2.3.4.16. Manual costs. This group of costs is similar to the *Machine cost*, but it is divided into 36 intervals as the costs are higher than for mechanical removal. This variable accounts for the equipment and personnel costs. The latter includes the costs of feeding, lodging and personal hygiene of people working at the site, which altogether are estimated to be 20 euro per person per day. The individual salaries depend on the type of people working, as there is a large difference between hiring firemen, volunteers or other third-party workers. We make a rough estimate of 30 euro per

hour, assuming six hours of working time per day. The cost of equipping the personnel is dependent on the complexity of equipment, and varies between 50 and 145 euro, see Partila (2010), however we adopt a value of 50 Euro and assume that the basic equipment fulfils the necessary requirements. Any added quantities will be grouped as additional costs. To calculate the overall manual removal cost and the corresponding CPT the following formulae is applied:

$$\text{Manual costs} = \begin{cases} C25 \cdot 350 \cdot 30 + \frac{C25}{6} \cdot 20 & \text{if } \frac{C25}{6} < 1 \\ C25 \cdot 350 \cdot 30 + \frac{C25}{6} \cdot 20 + 25,000 & \text{otherwise} \end{cases} \quad (7)$$

where C25 stands for Time for manual removal.

As the equipment cost depends on the number of people working – in our case 500 as previously mentioned – and the equipment cost is 50 euro per person the total equipment cost amounts up to 25,000. In the case of small spills this is quite a lot, and, in reality, there most likely would be fewer people working to remove the oil manually. In order to make the model more realistic, the conditional function is added to the equation which states that if the clean-up operation takes less than one effective work day of six hours, the equipment costs are not considered, whereas the personnel costs remain. If the operation is calculated to take more than one day, all costs are added together. When calculating the salaries paid per day, it is considered that only 350 people will be working at the same time and this is multiplied by the number of hours the operation takes and with the 30 euro salaries per capita. The other personnel costs are obtained by multiplying the estimated 20 euro per capita by the number of days that the operation will take, which is obtained from the node *Time for mechanical/manual removal*.

2.3.4.17. Boat cost. This is the last of the factors considered in the *Shoreline clean-up cost* node. It is assumed that the boats will be operating as long as the mechanical removal is taking place. The manual removal may take considerably more time, as the removal method covers the more sensitive areas of the shore, and, at this stage the assistance of the oil-recovery boats is most likely unnecessary. In Table 7, the costs for each boat type are presented, as well as the share that each boat type has of the total boat fleet. The costs are based on the discussion at the workshop.

According to the experts' panel an average boat cost is about 250 euro per hour, and there are approximately 50 oil-recovery boats located along the Finnish shore of the Gulf of Finland at any given time. Considering that all of these boats would be sent to collect oil and help to protect the coastline with booms, we arrive at a total hourly *Boat cost* of 12,500 euro. By using this cost and multiplying it by the time from the *Time for mechanical removal*, we calculate the probability table for the *Boat cost*, which has 28 states in total, defined as intervals.

2.3.4.18. Offshore clean-up costs. This variable is dependent on the following variables: *Air surveillance cost*, *Cost of emptying tanks*, *Combating cost*, *Preparation cost* and *Booms*.

Table 7
Oil recovery boat data.

Class	Cost (euro/h)	Share of total (%)
E	230	0.34
F	330	0.39
C	160	0.27

2.3.4.19. Air surveillance cost. This node is estimated by using the hourly cost of the Dornier surveillance aircraft: 7000 euro per hour. The aircraft will make its two-hour surveillance runs three times per day, which means that the total daily cost amounts to 42,000 euro. The number of days during which runs are completed is taken from the *Time to collect the oil*, since it is assumed that surveillance of the movements of the oil slick is required as long as the oil-combating vessels are operating. The probability table is calculated with the following expression:

$$\text{Air surveillance cost} = \begin{cases} 42,000 & \text{if } \frac{C8}{24} < 1 \\ \frac{C8}{24} \cdot 42,000 & \text{otherwise} \end{cases} \quad (8)$$

where C8 is *Time to collect oil* (h).

Eq(8) specifies that even if the oil-combating vessels have less than one day to recover the spilled oil, the air surveillance will still take place, as it must estimate the damage and make sure that the authorities are well-informed about the location and the trajectory of the oil slick. In this case the air surveillance cost will automatically be 42,000 euro. Otherwise, the daily air surveillance costs are multiplied with the number of days the operation takes.

2.3.4.20. Cost of emptying tanks. This node refers to the cost arising from the combating vessels emptying their full tanks during the operation so that they can return to the oil slick to continue the oil-combating operation. This can be accomplished by either setting up containers onshore on the mainland and/or islands, or sending a separate oil tanker to the location, where she will wait for the vessels to have their tanks filled. The latter alternative is assumed here, and during the workshop, the experts agreed that it would cost between 10,000 and 15,000 euro per day to rent a coastal tanker. In the cost model, the average of these two limits are used as the daily tanker cost. The probability table is obtained using the following conditional expression:

$$\text{Cost of emptying tanks} = \begin{cases} 12,500 & \text{if } \frac{C8}{24} < 1 \\ \frac{C8}{24} \cdot 12,500 & \text{otherwise} \end{cases} \quad (9)$$

where C8 means *Time to collect oil* (h).

2.3.4.21. The Combating cost. This variable expresses the total operating cost of the oil-combating vessel fleet used in the offshore clean-up. This node is determined by the previous nodes *Time to collect the oil* and *Daily vessel costs*. The *Daily vessel cost* has a CPT containing possible combinations of combating ships, with the exact daily costs for each of the ships, as illustrated in Table 8. In the case of more than one vessel being sent to the location, their respective daily costs are added together in the *Daily vessel cost*.

2.3.4.22. Preparation cost. This node indicates the costs that arise from the combating vessels being on stand-by. These costs include maintenance costs, and depend largely on the type of combating vessel and how extensively she is used for purposes other than oil combating:

Table 8
Daily costs for the oil-combating vessels.

Response vessel	euro/day	Response vessel	euro/day
Halli	11,800	Uisko	55,200
Hylje	14,900	Oili I	2700
Louhi	25,000	Oili II	2700
Merikarhu	55,200	Oili III	2700
Tursas	55,200	Seili	11,000

- Halli, Hylje and Louhi are each estimated to cost approximately 0.25 million euro per year in order to be prepared.
- The combating vessels of Meritaito Ltd have a total annual preparedness cost of 2 million euro.
- The oil combating vessels of the Finnish Border Guard do not have any preparedness costs that would fall under the responsibility of the oil combating operations, as the vessels are mostly used for other purposes.

2.3.4.23. Booms. If the decision node *Booms* is activated, an additional cost of 966,000 euro is added to the total offshore clean-up costs. This cost was obtained by adding together all separate costs for the offshore booms that are involved in the disposal of the oil-combating operations, from which the costs of type one RO-BOOM 200 is 510 euro/m and costs of type two RO-BOOM 150 is 420 euro/m. Halli is equipped with 600 m of each type, Hylje has 800 m of the first type and one of Meritaito ships Linja has 200 m of the second type.

Adding all these individual cost factors gives the *Offshore clean-up costs*, and adding these to the *Onshore clean-up costs*, we can obtain the total clean-up cost for an oil spill. These two utility nodes have negative values, as they symbolize costs, and when the model optimizes the decision nodes, it will do so by minimizing the total costs.

3. Results and discussion

In this chapter, we present the results of the developed oil spill cleanup-costs model applied for two case studies. The costs for the two scenarios of an accidental oil spill are compared with the available models estimating costs of an oil spill in order to perform a crude validation of the proposed approach. We use two available models, one by [Etkin \(1999\)](#), which is deterministic but allows for rather wide interpretation of the cost factors considered. Another model we use has been proposed by [Shahriari and Frost \(2008\)](#), and is purely deterministic, with no room for interpretation. Therefore, in the presented results, Etkin's model may deliver several results for the same scenario, as the model's parameter may take different values.

The two following accidental scenarios are considered, which are assumed to occur in the Gulf of Finland during ice-free season:

1. a spill of 5000 tons of medium oil;
2. a spill of 30,000 tons of heavy crude oil.

3.1. Scenario 1, oil spill of 5000 tons of medium oil

A comparison of the results of the probabilistic model presented in this paper with the two other models for oil spill cleanup-costs estimations are depicted in [Fig. 3](#). As for the calculations completed using the equation adapted from [Etkin \(1999\)](#), the relevant factors used along with oil type and spill size are the following:

Shoreline oiling modifier: –59%	(moderate)
Oil type: +40%	(light/heavy fuel)
Clean-up methodology factor: +61%	(mechanical manual only)
Spill size modifier factor: 1	(spill size of 5000 ton)
Resulting clean-up cost in euro	12.1M

In this case Etkin's model delivers one number as an outcome, and the parameters are defined without much ambiguity.

When it comes to the calculations using the equation provided by [Shahriari and Frost \(2008\)](#), the density used for the oil is 0.895 kg/m³ and the preparedness level given for the Baltic Sea is 3.

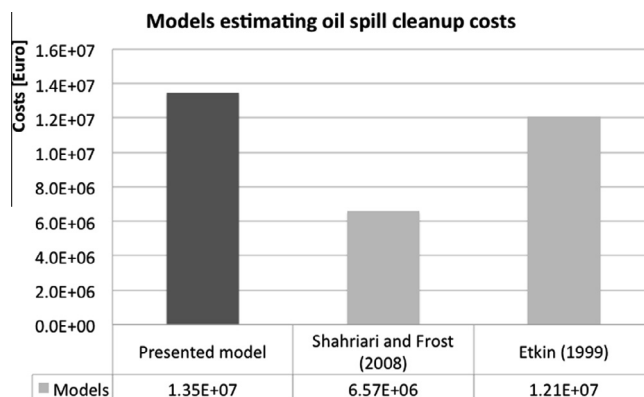


Fig. 3. Resulting oil spill clean-up costs for scenario 1.

3.2. Scenario 2, oil spill of 30000 tons of heavy crude oil

In the second scenario we analyze the clean-up costs for a spill of 30,000 tons of heavy oil. The size of the oil spill is chosen to symbolize the largest oil spill that the Authorities in Finland can hypothetically deal with. The results, which are obtained with the use of three models, are depicted in [Fig. 4](#).

In the calculations completed using the equation by [Etkin \(1999\)](#), the other factors along with oil type and spill size are the following:

Shoreline oiling modifier: +127%	(major)
Shoreline oiling modifier: –59%	(moderate)
Oil type: +52%	(heavy crude)
Clean-up methodology factor: +61%	(mechanical manual only)
Spill size modifier factor: –86%	(spill size larger than 15,000 ton)
Resulting clean-up cost in euro	144M for major shoreline oiling 46M for moderate shoreline oiling 95M – mean value of the above two

In this case, at least one parameter in Etkin's model cannot be determined exactly. This results in an outcome featuring a large spread.

The additional values used in the equation by [Shahriari and Frost \(2008\)](#) are 0.93 kg/m³ as the density of heavy oil, and 3 for the preparedness level.

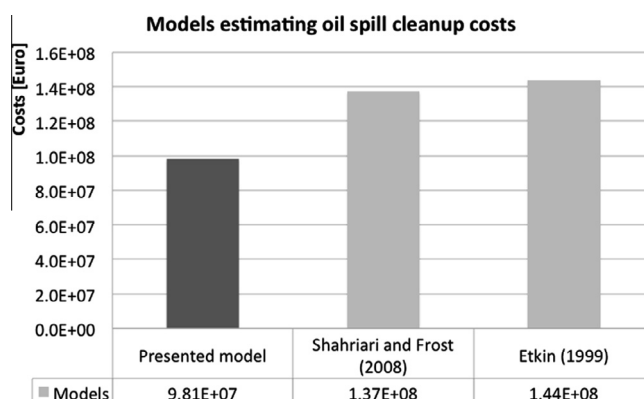


Fig. 4. Oil spill clean-up costs for spill scenario 2.

3.3. Discussion

As the analyzed scenarios are hypothetical, and there has been no record of the clean-up costs of a significant oil spill in the Gulf of Finland made available to us, we do not possess any data to confront our model with. Therefore, we are forced to compare the obtained results with the models, which claim to be supported by empirical data. The proposed model shows good agreement with two existing models. Despite the extensive use of experts' knowledge in development, which involves numerous assumptions, we managed to obtain a model that provides promising results. In case of a relatively small spill (5000 tons), the presented approach is in line with the model by Etkin and both models deliver results almost double those obtained with the use of Shahriari & Frost's model, see Fig. 3. In case of a large spill (30,000 tons), our probabilistic model provides results very close to a mean value of possible outcomes of Etkin's model, and somewhat below the result provided by the Shahriari & Frost's model – see Fig. 4.

However, if we take a closer look at the alternatives proposed by the models, we arrive at more coherent results, as depicted in Fig. 5. The first alternative involves the time that an oil spill takes to reach the shore. In the model by Etkin, the level of shoreline oiling expresses this, which for the analyzed spill size can be either moderate or major. By adopting these two values as extremes, we arrive at the clean-up costs, which are described by a band. The same applies for our probabilistic model, where we can fix a certain time after which an oil spill reaches the shore. For the low band, in our case, we assume the original distribution of this variable, as presented in Table 4, whereas for the upper band we use a time period of 3 days, after which an oil spill washes ashore. Our model makes it possible to calculate an average from the band, however it is not specified if Etkin's model allows such a manipulation. The averages for these two models are presented in Fig. 5.

The model by Shahriari & Frost delivers a band already, but it is not possible to calculate the average value from the band, as this is not the intention of the model.

However, the Shahriari & Frost model's predictions hold in the context of global oil spill costs, but it has very low geographical resolution. Thus straightforward comparison of their results with the results obtained from our model does not appear fully justified. Such a comparison can serve as a crude indicator for our model, which lacks data from the past oil spill clean-ups to be validated.

The presented model assumes that in the case of oil spill, only the Finnish fleet capability is utilized, and there is no assistance from the neighboring countries. This may hold in the case of smaller spills, whereas a large spill may imply the use of oil-combating ships from neighboring countries as well as from the European Maritime Safety Agency, see for example EMSA (2012). We expect this assumption affecting the share of offshore and onshore costs when the model is used to predict cleanup-costs for large spills. In the reality, more oil-combating units are going to be involved, which increases the offshore costs. At the same time, the amount of oil collected at the sea increases, which significantly reduces the costs related to on-shore clean-up, see also SYKE (2012). Ultimately we can expect the total clean-up costs to be lower than predicted by our model, and the share of offshore and onshore costs will differ.

The model developed here has several features that the other two models lack.

- Firstly, it accounts for the effect of season on the clean-up costs, mainly through the variable called *Wave height*. This variable determines the probability for the operability of oil-combating ships, which in association with the location of a spill from the shore (*Time for spill to reach shore*), allows one to define the fraction of spill which cannot be recovered from the sea and therefore arrives ashore.
- Information about the onshore and offshore clean-up costs is the second feature of our model that competitors are missing. For scenario 1, the onshore costs are ten times higher than offshore, yielding 12.3 M euro and 1.2 M euro, respectively. This seems to be in line with the findings of Etkin and those of Finnish Environmental Institute, whose claims, supported by historical data and experience, state that the offshore costs account for up to 15% of the total clean-up costs, see also Etkin (1999) and SYKE (2012). However, for scenario 2, the presented model tends to underestimate this ratio, which is now as low as 5%. This may raise a concern about the applicability of the model for predicting costs for larger spills, as already discussed.
- Third, our model reflects the oil-combating capacity for the Finnish oil-combating fleet, which narrows its geographical applicability, but also serves as a tool for cost-effective oil-combating-fleet optimization or the choice of clean-up strategy, see for example Lehtikoinen et al. (2013). Therefore, the model can facilitate the accident consequences estimation in the framework of formal safety assessment (FSA).

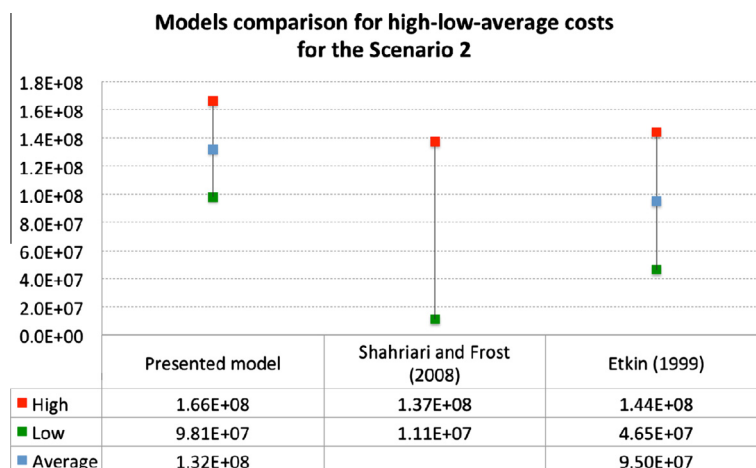


Fig. 5. Comparison of three available models determining the costs of oil spill clean-up operations – scenario 2.

4. Conclusions

In this paper we presented our development of an accidental oil spill cleanup-costs model, suited for a particular sea area, being very sensitive and heavily trafficked with the oil tankers at the same time. We have extensively utilized experts' knowledge and relevant information from the literature and available materials. To combine these types of information in a systematic way, we adopted BBNs, which allowed us to develop a probabilistic model, which suits our needs better than its deterministic competitors. Moreover, the applied technique allows for updating of the model in light of new knowledge, which is especially important in event of any change in the oil-combating fleet, which is analyzed here.

The model allows a user to select the location of an oil spill, its size, type of oil and season, however winter is out of scope of this analysis. Based on this information along with the number and type of anticipated oil-combating ships, the model delivers the total costs of clean-up operations, which can be broken down to offshore and onshore costs. Despite its geographical limitations, the model features several novelties compared to its competitors, which have been discussed in the previous section. The obtained results are compared with the existing models, and good agreement is found.

Notwithstanding all assumptions, the obtained results are promising, and the structure of the model gives insight into the total costs breakdown, pointing out the most relevant variables.

We anticipate that the model can contribute to the cost-effective oil-combating fleet optimization or the choice of clean-up strategy. Finally, the model arrives at the costs of clean-up operations, which may be found a suitable measure for Cost-Benefit analyses in the framework of FSA aimed at risk analysis and risk management for maritime.

However, further research should focus on developing a model estimating costs of clean-up operations in ice-covered waters.

Supplementary data

The model presented here is available from the data library PANGAEA at: <http://dx.doi.org/10.1594/PANGAEA.816576>.

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