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A model for oil spill scenarios from tanker collision accidents in the Northern Baltic Sea

Floris Goerlandt

Aalto University, School of Engineering, Department of Mechanical Engineering
Marine Technology, Research Group on Maritime Risk and Safety
P.O. Box 14300, FI-00076 Aalto, Finland, e-mail: floris.goerlandt@aalto.fi

Floris Goerlandt is a researcher at the Marine Technology Unit of Aalto University, School of Engineering, located in Espoo, Finland. Dr. Goerlandt has obtained his M.Sc. (Tech.) in Electromechanical Engineering with a minor in Marine Technology, at the University of Ghent in Belgium. He subsequently obtained a M.Sc. in Maritime Sciences in a joint program between the University of Antwerp and the University of Ghent, both in Belgium. He received a D.Sc. (Tech.) degree with distinction at the Aalto University, Finland on the topic "Risk analysis in maritime transportation: principles, frameworks and evaluation". In between, he gained broad international experience and technical expertise by working as a hull approval engineer and as a ship surveyor on ships in operation and in construction shipyards, in the Benelux, Norway, Singapore and China.

Dr. Goerlandt is an active researcher in the field of maritime risk and safety. He is a member of the ICES Working Group on Maritime risks in the Baltic Sea and the Applied Risk Management Specialty Group of the Society for Risk Analysis. He has served as delegate to the International Maritime Organization on multiple occasions, and serves as a Guest Editor for the Safety Science Special Issue on Risk Analysis Validation and Trust in Risk Management. He has published over 60 peer-reviewed journal and conference articles on topics related to accident analysis, waterway risk analysis, maritime safety management, tools for risk reduction in ship operations, and foundational issues in risk analysis.

Key words: oil spill, collision, maritime safety, marine environment, risk assessment, Bayesian Network

Abstract

Oil spills from maritime activities can lead to very extensive damage to the marine environment and disrupt maritime ecosystem services. Shipping is an important activity in the Northern Baltic Sea, and with the complex and dynamic ice conditions present in this sea area, navigational accidents occur rather frequently. Recent risk analysis results indicate those oil spills are particularly likely in the event of collisions. In Finnish sea areas, the current wintertime response preparedness is designed to a level of 5000 tonnes of oil, whereas a state-of-the-art risk analysis conservatively estimates that spills up to 15000 tonnes are possible. Hence, there is a need to more accurately estimate oil spill scenarios in the Northern Baltic Sea, to assist the relevant authorities in planning the response fleet organization and its operations. An issue that has not received prior consideration in maritime waterway oil spill analysis is the dynamics of the oil outflow, i.e. how the oil outflow extent depends on time. Hence, this paper focuses on time-dependent oil spill scenarios from collision accidents possibly occurring to tankers operating in the Northern Baltic Sea. To estimate these, a Bayesian Network model is developed, integrating information about designs of typical tankers operating in this area, information about possible damage scenarios in collision accidents, and a state-of-the-art time-domain oil outflow model. The resulting model efficiently provides information about the possible amounts of oil spilled in the sea in different periods of time, thus contributing to enhanced oil spill risk assessment and response preparedness planning.

1. Introduction

Oil spills from maritime activities can have detrimental effects on the marine ecosystem (Lecklin, Ryömä & Kuikka, 2011) and cause economic damage both to ship operators (Negro Garcia et al., 2009) and to coastal communities (Miraglia, 2002). One widely used approach for reducing the adverse effects of possible oil spills is maritime oil spill risk assessment and response preparedness planning, for which the international maritime organization (IMO) has issued a set of guidelines (IMO, 2010). Of particular interest, especially in research communities, are the so-called Tier-III response spills. These are spills of such magnitude, in terms of size and/or geographic area, that large-scale, transnational response efforts are necessary. Typically, such spills would occur from accidents in offshore production facilities such as the Deepwater Horizon or accidents from shipping, either from oil transported by tankers such as the Exxon Valdez, or from bunker oils from cargo vessels such as the Runner-4. It is widely acknowledged that ship collisions and groundings pose a particularly high risk of oil spills, both in open water (Dzikowski & Ślączka, 2014; Sormunen et al., 2015b; Ventikos & Rakas, 2015; Gucma & Bąk, 2016) as in winter conditions (Valdez Banda et al., 2015). Correspondingly, much research in risk assessment and response preparedness planning contexts has been dedicated to estimating the size of oil spills following ship collisions and grounding accidents. In Table 1, an overview is given of the most relevant state-of-the-art models and estimation methods for determining the oil outflow in tanker collision accidents for use in waterway risk analyses and response planning. For each model, some characteristics are listed, pointing to their scope of application and key assumptions and limitations. The following characteristics are evaluated:

C1: scope of the model in terms of tanker size;
C2: model accounts for traffic and impact conditions applicable to specific waterways;
C3: model accounts for both cargo and bunker oil tanks;
C4: model explicitly accounts for uncertainty in the damage scenario;
C5: model accounts for conditions where not all oil from a tank is spilled;
C6: model accounts for the dynamic, time-dependent nature of the oil outflow.

Despite the wide attention to oil spill risk analysis, the current models have some significant limitations, two of which are in focus in this paper as they provide important information regarding response planning.

A first issue is the conservative assumption made in most models of Table 1 that, in case of a collision, all the oil in a cargo tank is spilled to the sea. The use of conservative assumptions in risk analysis is a somewhat controversial issue (Hattis & Anderson, 1999). For response planning, conservative estimates of oil outflow may lead to overinvestments in response vessels and equipment, which on a societal level leads to sub-optimal use of already scarce resources. Hence, improving the oil outflow models is important on that account.

A second issue is that all available models shown in Table 1 assume that oil outflow occurs instantaneously. However, state-of-the-art oil outflow models by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a) and Sergejeva et al. (Sergejeva, Laarnearu & Tabri, 2013) clearly show that outflow from damaged tanks is a dynamic process which can, depending on the damage scenario, take a significant amount of time. As the success of response operations depends on the time required to begin oil combating operations (IMO, 2010; Lehikoinen et al., 2013), accounting for the time dimension in oil outflow analysis may also improve response preparedness planning.

Table 1. Overview of key characteristics of state-of-the-art oil spill models for tanker collisions

Model	Reference	C1	C2	C3	C4	C5	C6
M1	(Gucma & Przywarty, 2008)	up to 150 kilotonnes dwt	N	Y	N	Y	N
M2	(Montewka et al., 2010)	up to 150 kilotonnes dwt	N	N	Y	N	N
M3	(van de Wiel & van Dorp, 2011)	up to 150 kilotonnes dwt	Y	Y	N	N	N
M4	(COWI, 2012)	up to 150 kilotonnes dwt	Y	Y	N	Y	N
M5	(Lee & Jung, 2013)	up to 300 kilotonnes dwt	N	Y	N	N	N
M6	(Goerlandt & Montewka, 2014)	between 10 and 60 kilotonnes dwt	Y	N	Y	N	N
M7	(Goerlandt & Montewka, 2015)	up to 160 kilotonnes dwt	Y	Y	Y	N	N
M8	(Goerlandt, Zheng & Montewka, 2015)	Aframax and VLCC	Y	N	Y	N	N
M9	(Valdez Banda et al., 2016)	up to 160 kilotonnes dwt	Y	Y	Y	N	N

Given the above limitations, the overall aim of this paper is to present a new model for oil outflow from tankers, which improves the state-of-the-art by integrating information about designs of typical tankers operating in the Northern Baltic Sea area, information about possible damage scenarios in collision accidents, and a state-of-the-art time-domain oil outflow model. The model is devised as a Bayesian Network model, as such models have favourable characteristics for risk analysis because of their ability to efficiently handle uncertainty and because they are very suitable to account for different types of evidence (data, models and expert judgment). In this sense, the model is intended to be used in connection with other maritime risk management models, e.g. related to the assessment of ecological damage (Lecklin, Ryömä & Kuikka, 2011), accident prevention (Valdez Banda et al., 2016), spill drift models (Jarząbek & Juszkiewicz, 2016) and, of course, response preparedness planning (Lehikoinen et al., 2013).

The remainder of this paper is organized as follows. In Section 2, the evidence base for the model development is described. Section 3 outlines the method applied for the development of the new oil outflow model. In Section 4, the resulting model is presented and a discussion is provided. Section 5 concludes.

2. Evidence base for model development

This section describes the evidence base applied in the model development. It covers some characteristics of the tanker traffic in the Northern Baltic Sea, a selection of representative tankers, a method for determining the cargo tank layout for these vessels, a state-of-the-art time-domain oil outflow model, and damage scenarios used to generate oil outflows.

2.1. Tanker traffic in the Northern Baltic Sea area

The scope of use of the oil outflow model is the Northern Baltic Sea. This is defined here as the sea area composed of the Gulf of Bothnia and the Gulf of Finland, as defined by HELCOM response, see Figure 1. Vertices of the demarcation lines between the areas can be found in HELCOM (HELCOM, 2015). These areas are selected because maritime accidents leading to large oil spills in these areas would require sub-regional cooperation in oil spill response between the relevant contracting parties of the Helsinki Convention. It also corresponds well to the sea areas that are totally ice-covered during normal winter conditions, whereas state-of-the-art risk models for this area currently rely on conservative assumptions related to the amount of oil outflow (Valdez Banda et al., 2016).

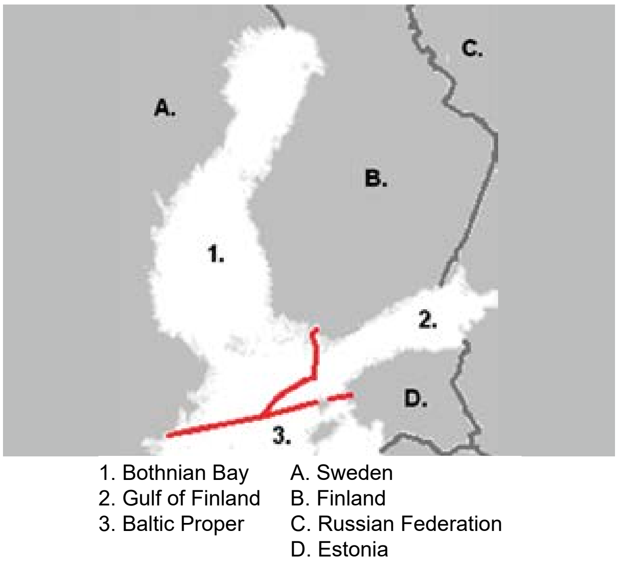

Figure 1. Northern Baltic Sea area: Gulf of Finland and Gulf of Bothnica (HELCOM, 2015)

To construct the model, evidence is required about tankers operating in this area, in particular about their size and cargo capacity, as this affects the amounts of oil potentially spilled in case of a collision. An analysis of tanker traffic in the Northern Baltic Sea is performed based on data from the Automatic Identification System (AIS).

The 2002 IMO SOLAS Convention, Chapter V Regulation 19, mandates that most vessels over 300 GT on international voyages are to be equipped with a Class A type AIS transceiver. The data transmitted by this system is known as AIS data. AIS is an information exchange platform between vessels and shore organizations and contains, amongst other, time-dependent data about the location, speed, course and navigational status of vessels. The purpose of the system originally was to offer support in collision avoidance decision making, but it is currently also used by Vessel Traffic Services (VTS) for monitoring the traffic in given sea areas, as a support for providing navigational assistance. AIS data has been a rich source of information for scientific research and has been applied to topics ranging from maritime spatial planning (Shelmerdine, 2015) to ship emission estimation (Jalkanen, Johansson & Kukkonen, 2014). For the present study, full-rate AIS data from the winter time periods from 01.11.2007 to 01.05.2013 was used, with data fields as shown in Table 1. The data was extended by Goerlandt et al. (Goerlandt et al., 2017) to include vessel details, including the deadweight, which is particularly important for the purpose of this study as it is needed to formulate a generic cargo tank arrangement for the representative tankers, see Section 2.3.

Table 2. AIS data fields applied in the present analysis

Data field	Unit	Explanation
MMSI number	[–]	A 9-digit code uniquely identifying a vessel
Time stamp	[s]	Time at which the message is recorded, format: yyyy-mm-dd hh:mm:ss
Position	[–]	Longitude and latitude of transmitted message, in WGS-84 coordinate system
Ship type	[–]	A 2-digit code identifying the type of vessel, see (USCG, 2012)
Ship length	[m]	Dimensions from bow to stern, see (USCG, 2012)
Deadweight	[tonnes]	A measure of how much mass a ship can safely carry

This data was analysed to obtain insight on the main dimensions of the tanker vessels operating in the area indicated in Figure 1. In particular, a distribution of the vessel deadweights is sought as it can be related to other main dimensions (length, width, draught, depth) and cargo tank sizes. This is explained further in Section 2.3. The process for determining this distribution is outlined below.

Step I. All AIS data is grouped by ship (using the MMSI number) and chronologically sorted. This results in trajectories of each vessel over the considered time period.
Step II. The trajectories of the vessels are compared to the areas of the Bothnian Bay and the Gulf of Finland, indicated in Figure 1. All ships which have at least one data point in this area are retained for further analysis.
Step III. The resulting set of vessels is narrowed down to cover only oil tankers, using the 2-digit code specifying the ship type.
Step IV. For these vessels, the deadweights are identified form the AIS data, and a histogram is created.

The results are shown in Figure 2. It is seen that tankers operating in the Northern Baltic Sea are mostly Handymax size or smaller. Larger vessels operate in the area as well, but relatively less frequently.

2.2. Representative tankers

As the purpose of the oil outflow model is to be representative for the Northern Baltic Sea area, the results of Section 2.1 are used to select a number of representative tanker designs. The selection is made by balancing two conflicting requirements: keeping the number of tanker designs limited (to keep the model simple) and ensuring that the most relevant tanker designs are appropriately covered (to ensure a reasonable accuracy). Basic tanker data has been added to the AIS database as described in Goerlandt et al. (Goerlandt et al., 2017). The selected set of representative tankers is shown in Table 3, along with the main dimensions and other ship particulars needed for the characterization of cargo tanks, oil outflow model and damage scenario definition described in Section 2.3 to 2.5.

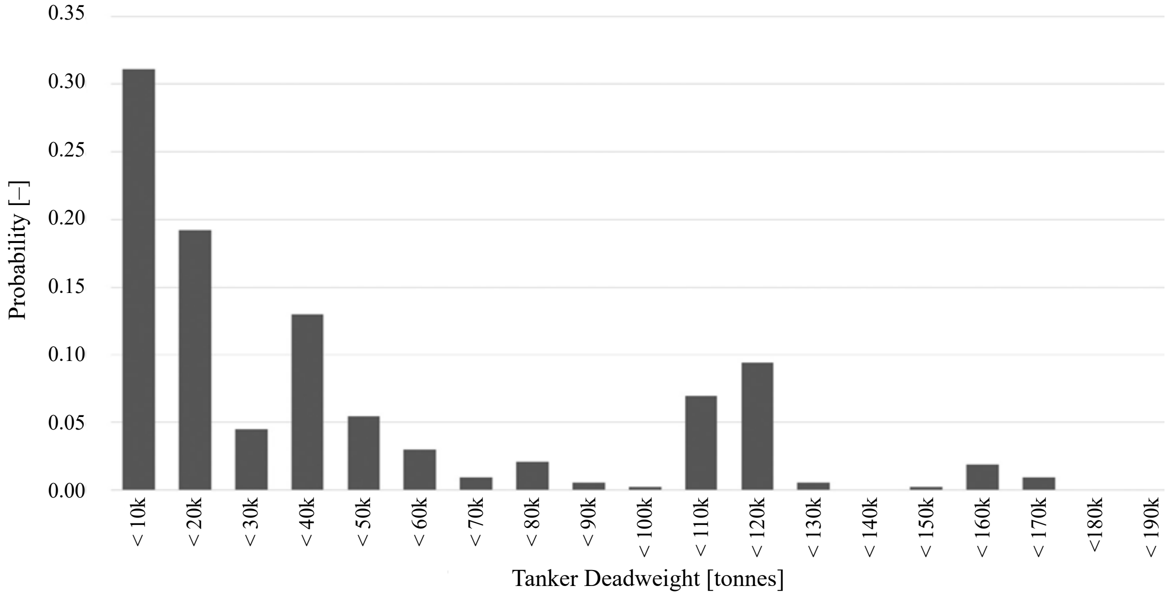

Figure 2. Distribution of deadweights of tankers operating in the Northern Baltic Sea

Table 3. Main dimensions and ship particulars of representative tankers

Id.	Length L	Width B	Draught T	Depth D	Deadweight DWT	Id.	Length L	Width B	Draught T	Depth D	Deadweight DWT
[–]	[m]	[m]	[m]	[m]	[tonnes]	[–]	[m]	[m]	[m]	[m]	[tonnes]
T1	83.5	13.5	5.3	7.0	3232	T9	228.0	32.2	8.2	18.6	63605
T2	109.1	16.0	5.2	7.5	5565	T10	216.3	38.1	12.7	18.9	82000
T3	122.8	17.2	5.5	9.5	7750	T11	211.3	37.4	12.5	18.5	85000
T4	148.0	21.6	8.6	11.2	15000	T12	243.8	42.0	13.8	21.0	105009
T5	164.4	23.2	9.8	12.3	20610	T13	249.0	44.0	8.2	21.8	115527
T6	159.0	27.0	10.7	15.7	37000	T14	245.7	41.0	14.9	22.4	121000
T7	191.1	33.4	13.1	19.3	40000	T15	243.6	42.2	15.2	21.8	136000
T8	176.5	32.5	12.5	18.6	46000	T16	254.2	45.6	16.2	22.6	151000

2.3. Cargo tank layout model

The methodology for determining the layout of cargo tanks is based on the procedure proposed by Smailys and Česnauskis (Smailys & Česnauskis, 2006), which is aimed at estimating the cargo tank configuration of conventional designs. For the oil outflow model, it is assumed that the breached cargo tanks are located in the midship area. Compared to the foremost and aft most tanks, these are slightly larger so this is a somewhat conservative assumption. The main parameters for determining the cargo tank volumes are shown in Figure 3. L_T, B_T and D_T are the cargo tank compartment length, width and depth, and V_i is the volume of tank i. The double hull width is given the notation w and the double bottom height is denoted with h.

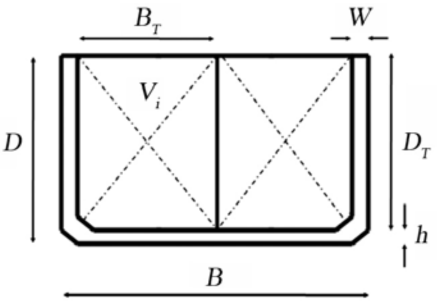

Figure 3. Cargo tank layout and main parameters (based on (Smailys & Česnauskis, 2006))

The volume V_i of a given tank is determined as:

$$V_i = C_i\, L_T\, B_T\, D_T \tag{1}$$

where C_i is a volumetric coefficient, accounting for the actual shape of the tank in comparison with a rectangular prism. Based on the analysis by Smailys and Česnauskis (Smailys & Česnauskis, 2006), C_i can be taken to be approximately equal to 1 for tanks in the midship area. The cargo tank width, depth and length are calculated as:

$$B_T = \frac{B - 2w}{m} \tag{2}$$

$$D_T = D - h \tag{3}$$

$$L_T = \frac{L - L_A - L_F}{n} \tag{4}$$

where m is the number of tanks in the transverse direction, and n the number of tanks in the longitudinal direction. Based on the data presented in Goerlandt and Montewka (Goerlandt & Montewka, 2014), m and n are taken as 2 and 6, respectively, so that all tanks have the same width, B_T, and length, L_T. Based on the analysis by Smailys and Česnauskis (Smailys & Česnauskis, 2006), L_A and L_F are as assigned the values reported in Table 4. The double bottom height, h, and double hull width, w, are determined based on the relevant rules for classification of ships, as in Goerlandt and Montewka (Goerlandt & Montewka, 2014).

Table 4. Values of parameters L_A and L_F for tankers of different deadweights

	below 35k DWT	35k – 50k DWT	50k – 80k DWT	above 80k DWT
L_A	0.24 L	0.22 L	0.21 L	0.195 L
L_F	0.06 L	0.055 L	0.055 L	0.05 L

2.4. Oil outflow model

As seen in Section 1, the state-of-the-art oil spill risk models for tanker collisions assume an instantaneous outflow from all cargo in the damaged cargo tank; however, as shown by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a), oil outflow from a damaged tank is a dynamic process. Moreover, the amount of spilled oil depends significantly on the specific damage scenario.

Several authors have proposed models for the oil outflow process. Tavakoli et al. (Tavakoli, Amdahl

& Leira, 2011a) developed a model based on the Bernoulli principle and the ideal gas law for a side damage in single and double hull cargo tanks. They performed a validation through Computational Fluids Dynamics (CFD) modelling, finding a good agreement. An experimental program (Tavakoli, Amdahl & Leira, 2011b) provided further confirmation. Sergejeva et al. (Sergejeva, Laarnearu & Tabri, 2013) and Kollo et al. (Kollo, Laanearu & Tabri, 2017) developed a model for oil outflow from submerged compartments following collision and grounding damages.

For the current purposes, the best available model is the one by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a). One reason is that it has been most widely validated (using CFD and experiments); the other is that it is applicable for side damages both above and below the waterline.

The model for oil outflow from a double hull tank can be distinguished in three phases. In the 1st phase, the ballast tank is filled with oil from the cargo tank, and (if the damage opening extends to below the waterline) with sea water. This stage terminates once hydrostatic equilibrium is attained between either the oil-water mixture and water, or between oil and water. In the 2nd phase, outflow from and inflow to the ballast tank occurs. Two different states may develop in this phase. In a first state, the hydrostatic oil pressure at the inner opening is greater than the hydrostatic pressure of the mixture of oil and water. In this case, oil will flow from the cargo tank into the ballast tank, increasing the hydrostatic pressure there and subsequently pushing water or oil into the sea. In the second state, seawater flows into the ballast tank and oil or water flows into the cargo tank. This is due to the higher hydrostatic seawater pressure than the pressure of oil and water at the outer opening. In this case, no oil spill occurs. This second phase terminates as soon as a new hydrostatic equilibrium occurs. In the 3rd phase, there are two-ways flows between the sea water and the fluid(s) in the ballast tank (outer hole), and between the oil in the cargo tank and the fluid(s) in the ballast tank (inner hole). The reason for these flows is the difference in fluid densities. The model by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a) consists of a set of differential equations for the flow rates to and from the different compartments, from which the time-dependent volumes and masses of oil spilled form the tanks can be determined by integration.

The main parameters for the problem are shown in Figure 4. In addition, a number of parameters are required in the estimation of the oil outflow, for which the values suggested by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a) are shown in Table 5.

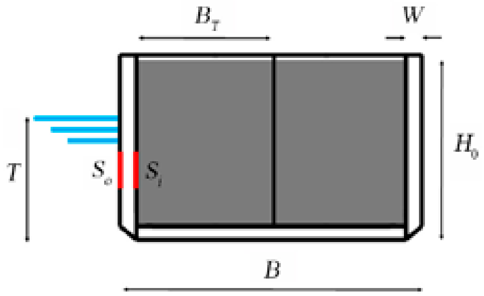

Figure 4. Tank geometry, initial oil and water levels and damage definition (based on (Tavakoli, Amdahl & Leira, 2011a))

Table 5. Adopted parameter values for oil outflow model by Tavakoli et al. (Tavakoli, Amdahl & Leira, 2011a)

Parameter	Symbol	Value	Unit
Sea water density	ρ_{sw}	1025	[kg/m^3]
Oil density	ρ_{oil}	860	[kg/m^3]
Atmospheric Pressure	P_{atm}	1013.25	[kPa]
Gravitational acceleration	g	9.81	[m/s^2]
Discharge coefficient	C_d	0.6	[–]

2.5. Damage scenarios

To determine oil outflow scenarios, a description of a set of damage cases is required. In the current model, these damage scenarios are based the statistics given in the IMO guidelines (IMO, 2003). Taking these damage scenarios as basic inputs for the oil outflow model has the advantage that they cover all plausible types of damage caused by a ship-ship collision (Lützen, 2001); however, it has also been argued that for specific sea areas, the IMO statistics may not be representative (van de Wiel & van Dorp, 2011). In fact, various impact scenario models have been suggested for use in specific sea areas in a maritime waterway risk analysis context (Goerlandt, Ståhlberg & Kujala, 2012). For oil outflow in winter conditions, Goerlandt et al. (Goerlandt et al., 2017) have made an analysis of impact conditions in different operational contexts (independent navigation and different ice breaker assistance operations), but given the lack of comprehensive models for ship collision damage assessment in ice conditions, the estimation of damage following those impact scenarios is currently not feasible. The state-or-the-art in ship collision damage assessment in ice conditions only concerns ship impact with icebergs (Liu & Amdahl, 2010) and ship-ship impacts under a perpendicular angle in level ice conditions (Nelis, Kujala & Tabri, 2015).

Table 6. Definition of damage scenarios (based on (IMO, 2003))

Longitudinal damage extent Y [m]			Vertical damage extent Z_V [m]			Vertical position of damage Z_L [m]		
Y_1	Very small	0.01 L	$Z_{V,1}$	Very small	0.05 D	$Z_{L,1}$	Very low	0.05 D
Y_2	Small	0.05 L	$Z_{V,2}$	Small	0.1 D	$Z_{L,2}$	Low	0.25 D
Y_3	Medium	0.1 L	$Z_{V,3}$	Medium	0.3 D	$Z_{L,3}$	Medium	0.5 D
Y_4	Large	0.175 L	$Z_{V,4}$	Large	0.6 D	$Z_{L,4}$	High	0.75 D
Y_5	Very large	0.25 L	$Z_{V,5}$	Very large	0.9 D			

Damage scenarios resulting from the IMO damage statistics are therefore taken here as a basis for the oil outflow model, with the intention of assigning the probability of a damage scenario on the basis of expert judgment rather than on the results of models such as the one by Pedersen and Zhang (Pedersen & Zhang, 1998) for open water conditions. Based on the findings of a risk analysis of winter navigation by Valdez Banda et al. (Valdez Banda et al., 2016), it is reasonable to assume that damage in collision accidents in ice conditions is typically small and most of the time does not result in hull breach. For the purposes of this paper, the probabilities of the different damage scenarios in the traffic and operational conditions of the Northern Baltic Sea are not further considered.

The damage scenarios applied in the model are based on the IMO guidelines and are defined in Table 6. It is assumed that the damage takes a rectangular shape, as defined in Figure 5, which is compatible with the corresponding parameters of the oil outflow model of Section 2.4. In case two tanks are breached, it is assumed that the tanks are damaged symmetrically. In addition, all scenarios assume that the cargo tank bulkhead is breached, i.e. no-spill scenarios are not retained. It is also assumed that the damage extent is the same at the outer hull and at the outer cargo tank bulkhead. Finally, in case the damage extents resulting from the scenarios of Table 6 go beyond the limits of the tank, these tank limits are taken as new boundaries of the damage, as in IMO (IMO, 2003). These assumptions are made to ensure that the oil outflow model of Section 2.4 can be evaluated.

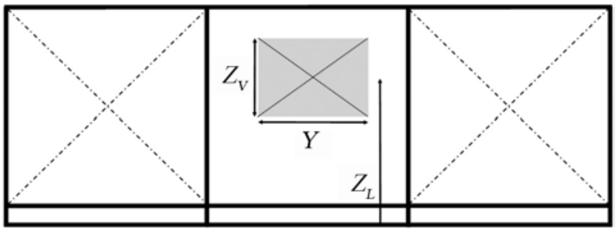

Figure 5. Definition of a damage scenario: side view of a damaged tank, parameters as in Table 6 (based on (IMO, 2003))

3. Method for model development

The probabilistic oil outflow model is developed using Bayesian Networks (BNs) as a modelling approach. This chapter briefly outlines BNs as a modelling approach, and describes how the evidence base introduced in Section 2 is integrated into the resulting model.

3.1. Bayesian Networks

Bayesian Networks (BNs) represent a class of probabilistic graphical models, defined as a pair $\Delta = \{G(V, A), P\}$ (Koller & Friedman, 2009), where $G(V, A)$ is the graphical component and P the probabilistic component of the model. $G(V, A)$ is in the form of a directed acyclic graph (DAG), where the nodes represent the variables $V = \{V_1,\dots, V_n\}$ and the arcs (A) represent the conditional (in)dependence relationships between these. P consists of a set of Conditional Probability Tables (CPTs) $P(V_i \mid Pa(V_i))$ for each variable V_i, $i = 1,\dots,n$ in the network. $Pa(V_i)$ signifies the set of parents of V_i in G: $Pa(V_i) = \{Y \in V \mid (Y, V_i) \in A\}$. Thus: $P = \{P(V_i \mid Pa(V_i)), i = 1,\dots,n\}$. A BN encodes a factorization of the joint probability distribution (JDP) over all variables in V:

$$P(V) = \prod_{i=1}^{n} P(V_i | Pa(V_i)) \tag{5}$$

Bayesian networks are used extensively in risk analysis (Fenton & Neil, 2012), as they have favourable characteristics. For instance, compared to event trees, more complex dependencies between events and risk-influencing factors can be accounted for. The CPTs and the prior probabilities assigned to the parent variables, allow to account for uncertainties concerning events and/or risk-influencing factors. Finally, the CPTs and prior probabilities can be based on various evidence types, including data, expert judgment and engineering/statistical models. Hence, BNs have been used in applications related to oil spill risk analysis, such as oil spill modelling (Goerlandt & Montewka, 2015), response fleet optimization (Lehikoinen et al., 2013) and ecological impact analysis (Lecklin, Ryömä & Kuikka, 2011).

3.2. Method for BN oil spill model development

The developed BN for time-dependent oil outflow from collision damage in double-hull tankers operating in the Northern Baltic Sea has a simple network structure, shown in Figure 7. The amount of oil outflow to the sea is dependent on the main influencing factors, such the tanker size (which affects the cargo tank dimensions), the number of tanks breached, and the dimensions and vertical position of the hull damage, as evident from the oil outflow model outlined in Section 2.4.

The main task required to develop the BN model is to determine the CPTs of the nodes representing the outflow after a given period of time. The method for calculating the entries for these CPTs is shown in Figure 6. Essentially, for each tanker the damage scenario is determined and the corresponding oil outflow is evaluated as a function of time. These outflow time series are sampled for selected time periods and the corresponding amount of oil is saved into the related element of the CPT.

4. Results and discussion

4.1. Resulting model and example scenario

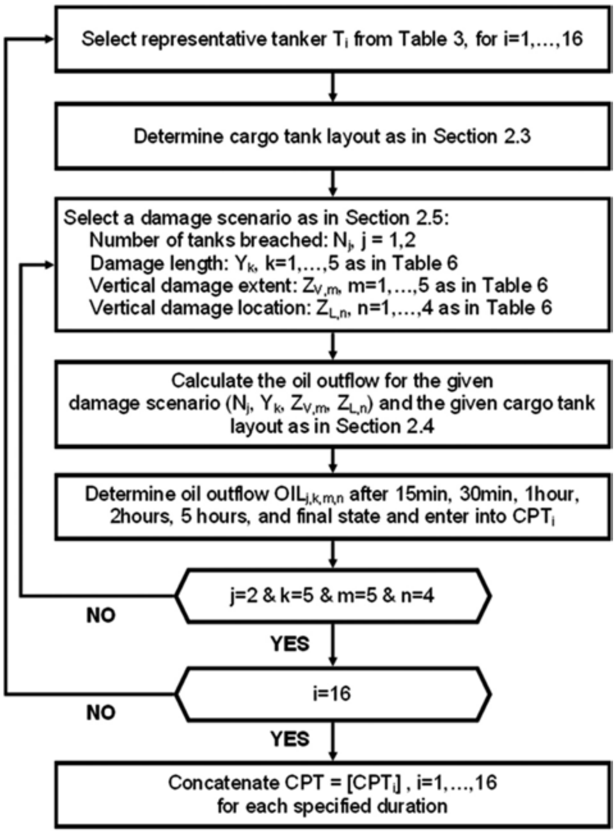

Figure 6. Procedure for determining the CPTs of the nodes representing the oil outflow after given time periods based on parent nodes

The resulting Bayesian Network model for oil outflow from tankers is shown in Figure 7. The five parent nodes are *Tanks Breached*, *Longitudinal Damage Extent*, *Vertical Damage Extent*, *Vertical Damage Position*, and *Tanker size*. The six child

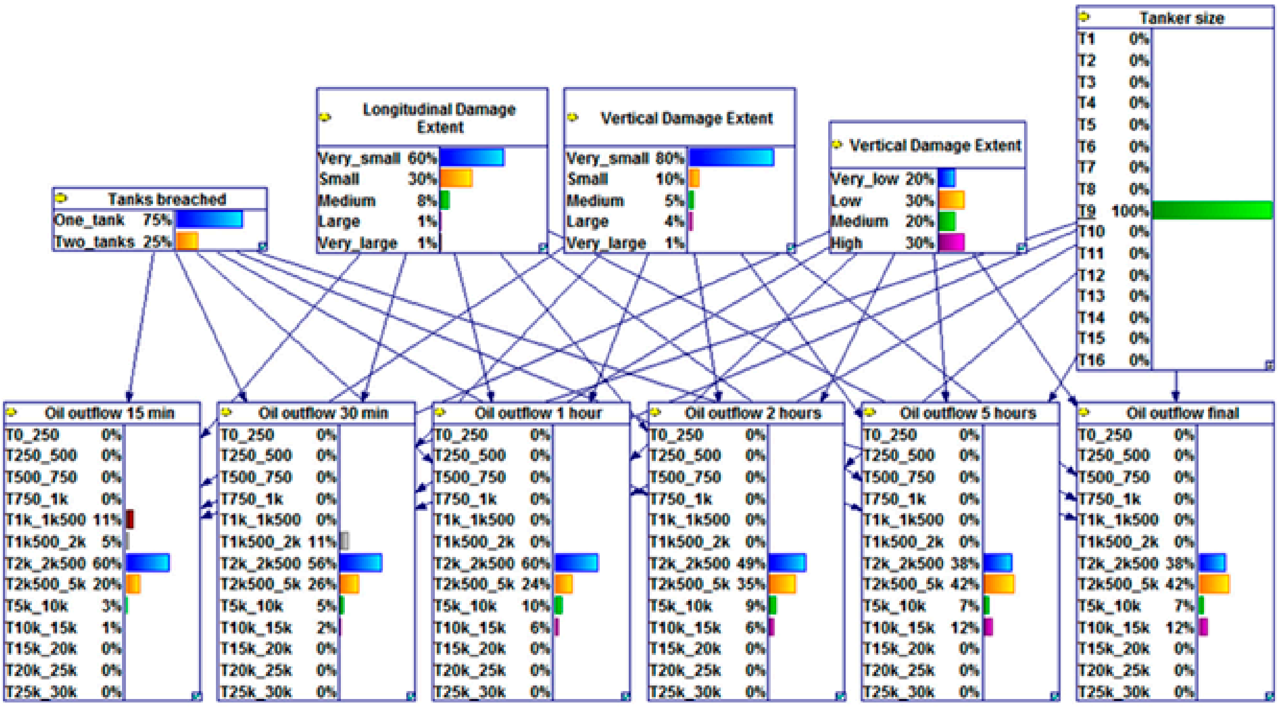

Figure 7. Resulting Bayesian Network model for oil outflow applied to a selected scenario

nodes relate to the amount of oil spilled to the sea after a given amount of time: *Oil outflow 15 min*, *Oil outflow 30 min*, *Oil outflow 1 hour*, *Oil outflow 2 hours*, *Oil outflow 5 hours*, *Oil outflow final*. The different states of these variables are indicated in Figure 7, where for the parent nodes reference is made to Table 3 and Table 6.

As an illustration, the model is ran for a scenario where a tanker T9 (see Table 3 for particulars), is involved in a collision accident. The uncertainties about the damage size (number of tanks breached, longitudinal damage extent, vertical damage extent, vertical damage location) are expressed using knowledge-based probabilities, which are, for illustrative purposes, set as in Figure 7. The resulting oil outflows are also shown, from which it can be observed that the most likely spill size ranges from 2000 m^3 – 2500 m^3 to 2500 m^3 – 5000 m^3 as time progresses. In this case the oil outflow is a time-dependent process that seems to stabilize after about 5 hours.

4.2. Validation of the developed oil outflow model

In order for the developed model to be useful for oil spill risk analysis and preparedness planning, it should be a reasonable representation of the described phenomenon. As oil spills are rare phenomena, and due to the probabilistic nature of the model, a direct comparison with observations is not a feasible validation method. Such an approach can give an indication that the model gives plausible spill ranges, and has in that sense been applied by Goerlandt and Montewka (Goerlandt & Montewka, 2015). However, accident case descriptions where the spilled amount of oil is accurately measured as a function of time, are not available. Hence, another method to validate the developed model is applied. The framework proposed by Goerlandt (Goerlandt, 2015) consists of a set of tests to which the model can be applied, along with a series of questions related to the completeness of the uncertainty and bias descriptions relating to the model construction and the intended application.

Due to space limitation, it is beyond the scope of this paper to provide a comprehensive model validation. Some elements of the validation framework are assessed, providing a confirmation of the plausibility of the results.

A first test concerns the model behaviour. This test requires that the model outputs respond to variations of inputs as the real system would be expected to respond. Such a behaviour test is a form of criterion validity, and has been applied, for example, in Goerlandt and Montewka (Goerlandt & Montewka, 2014) and Goerlandt and Montewka (Goerlandt & Montewka, 2015). In Table 7, the expected oil outflows for the different time periods are shown for the different tanker sizes of Table 3, for damage scenarios with probability values as in Figure 7. The expected oil outflow is calculated as follows:

$$E\left[\mathrm{OIL}_{T_k,t_n}\right]=\sum_{i=1}^{13}P\left[\mathrm{OIL}_{S_i,t_n}\right]\cdot E\left[\mathrm{OIL}_{S_i,t_n}\right]$$
$$k=\{1,4,7,10,13\};\ n=1,\ldots,6 \qquad (6)$$

where T_k is the k-th tanker design, S_i is the i-th state of the oil outflow, and t_n the n-th time period. $E[.]$ denotes the expectation value, and $P[.]$ the probability of a given state. The expectation value of a given oil outflow state is calculated at the midpoint of the intervals for the oil outflow model elements of Figure 7.

From Table 7, it is seen that for small tankers, the oil outflow occurs very rapidly, so that the final outflow is reached almost instantaneously. In contrast, for larger vessels the oil outflow also begins very quickly after the damage has occurred, but the larger the vessel, the longer it takes before the final outflow state is reached. It is also obvious that for larger tankers the volumes of spilled oil are significantly larger than for smaller vessels. These behaviours are in line with an intuitive understanding of the oil spill phenomena, confirming the plausibility of the model.

A second test concerns the evaluation of the model in relation to its nomological network. In this test, the developed model and its characteristics are placed in context with similar models available in literature. This allows the identification of similarities and

Table 7. Model behaviour test: expected oil outflow at different times for selected representative tankers

Tanker ID	$E\,[\mathrm{OIL}_{Tk,\,t1}]$ [m^3]	$E\,[\mathrm{OIL}_{Tk,\,t2}]$ [m^3]	$E\,[\mathrm{OIL}_{Tk,\,t3}]$ [m^3]	$E\,[\mathrm{OIL}_{Tk,\,t4}]$ [m^3]	$E\,[\mathrm{OIL}_{Tk,\,t5}]$ [m^3]	$E\,[\mathrm{OIL}_{Tk,\,t6}]$ [m^3]
T1	225	225	225	225	225	225
T4	950	950	950	950	950	950
T7	1580	1948	2390	2568	3108	3108
T10	2154	2541	3406	3919	4856	5056
T13	7108	8423	9673	12000	13150	13350

differences between the models, which help confirm the plausibility of the developed model. A detailed comparison with the available models is beyond the current scope, but comparing the contents and structure of the developed BN model with the characteristics of the state-of-the-art models of Table 1 shows a favourable comparison in almost all respects. The range of tankers considered is suitable for the Northern Baltic Sea tankers, the model can account for location traffic conditions through a modification of the environment prior to the damage scenarios. The BN accounts explicitly for uncertainties and introduces an improvement compare to the assumption that all oil is spilled. The developed model is the first one to explicitly account for the time-dependency of the spill. Some other models are somewhat more realistic in that they account for bunker spills, but as these are typically much smaller than cargo tank spills this is a justifiable limitation.

Finally, the model validation focuses on the uncertainties underlying the model construction, and the importance of deviations between results due to assumptions and underlying evidence. The explicit focus on uncertainties deriving from the model has been identified as an important issue in risk model validation (Goerlandt, 2015 Flage et al., 2014) and in mari-time waterway risk analysis (Sormunen et al., 2015a).

To assess the uncertainties, a method proposed by Goerlandt and Reniers (Goerlandt & Reniers, 2016) is applied. This method considers the different elements of the evidence applied in the risk model or analysis, and makes a qualitative rating of the strength of evidence. For data, the quality and amount are considered. For models, an assessment is made of the empirical validation and theoretical viability. Expert judgments are assessed in relation to the intersubjective agreement of the experts. Finally, assumptions are rated in relation to the agreement among peers and the influence that deviations from the assumption may have on the outcome of the analysis. For details about the rating scheme and the interpretation of the scales, see (Goerlandt & Reniers, 2016). The evidence assessment is shown in Table 8, where a simple traffic light colour scheme indicates strong (green), medium (yellow) or poor (red) strength of evidence, and grey indicates that the category is not applicable.

The evidence assessment shows that the tanker traffic and representative tankers are based on strong evidence: much relevant data of high quality is available. The cargo layout model in itself shows good agreement with actual tanker layouts, but the modelling assumption that midship cargo tanks are breached is somewhat conservative as aft and forward tanks are a bit smaller. Also, only cargo tanks are considered, i.e. spills from bunker tank breaches are not accounted for. The oil outflow simulation model is in itself a theoretically and empirically sound model, but quite stringent assumptions are necessary for the calculations. For instance, the vessel is assumed to be stationary, and wave effects are excluded. Also factors related to cold climate and spills in ice conditions, which may affect the geometry of the opening and the viscosity of the oil are not taken into account. The case for damage scenarios is the same. The data upon which the damage scenarios are built is quite extensive, but based on relatively old accidents. The assumption that damage has a rectangular shape and that this shape is the same for the outer hull and the cargo tank bulkhead is not very realistic in actual collisions and this may have quite important effects to the outflow dynamics.

To sum up, the validation of the developed oil outflow model shows that the outputs are reasonable, based on state-of-the-art models with an overall rather high evidence strength. However, the application of the model should be made carefully, accounting for the possible deviations from assumptions in specific cases, for example for spills occurring in ice conditions or involving bunker tanks. These limitations are possible paths for further research and model development.

Conclusions

A new model for oil outflow from tankers is developed for vessels typically operating in the Northern Baltic Sea. The model extends the state-of-the-art primarily by explicitly accounting for the

Table 8. Strength of evidence assessment of the evidence underlying the BN model

Evidence		Data	Model	Judgement	Assumption
E1	Tanker traffic in the Northern Baltic Sea	🟩	▨	▨	▨
E2	Representative tanker dimensions	🟩	▨	▨	▨
E3	Cargo layout model	▨	🟩	▨	🟨
E4	Oil outflow simulation model	▨	🟩	▨	🟥
E5	Damage scenarios	🟨	▨	▨	🟥

dynamic nature of oil outflow, thus diminishing the conservative bias in the model compared to the common assumption that all oil from a breached tank is spilled. It also enables probabilistic statements on the spill volumes after given periods of time, which is important in oil spill preparedness and response planning. The model is implemented using Bayesian Networks as a modelling tool, and various evidence types are integrated to build the probability tables. In particular, representative tankers for the Northern Baltic Sea are determined based on a traffic analysis using AIS data, a cargo tank layout model and a time-domain oil outflow simulation model are implemented, and a set of damage scenarios are defined. The resulting BN model is subjected to selected validation tests, indicating its plausibility. This follows also from the relatively good evidence base underlying the model construction. Nevertheless, an uncertainty assessment highlights several opportunities for further model improvement.

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