A Bayesian Network Model for Accidental Oil Outflow in Double Hull Oil Product Tanker Collisions

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Abstract: This paper proposes a Bayesian belief network (BBN) model for the estimation of accidental oil outflow in a ship-ship collision where a product tanker is struck. The intended application area for this model is maritime traffic risk assessment, i.e. in a setting in which the uncertainty regarding the specific vessel characteristics is high. The BBN combines a model for linking relevant variables of the impact scenario to the damage extent with a model for estimating the tank layouts based on limited information regarding the ship, as typically available from data from the Automatic Information System (AIS). The damage extent model, formulated as a logistic regression model and based on a mechanical engineering model for the coupled inner-outer dynamics problem of two colliding ships, is implemented in a discretized version in the BBN. The model for estimating the tank layout is applied for a representative set of product tankers typically operating in the Baltic Sea area. The methodology for constructing the BBN is discussed and results are shown.

Keywords: Oil spill, product tanker, Bayesian Belief Network, consequence model, risk assessment

1. INTRODUCTION

Ship-ship collisions are low-probability, high-consequence events which may have a devastating effect on the natural environment in case the struck vessel is an oil carrying tanker. In maritime traffic risk analysis, tanker spills thus are an important object of study.

Several methodologies have been proposed to determine the probability of tanker collisions occurring in a given sea area [1]–[4]. These typically provide a set of scenarios under which vessels encounter each other. These scenarios contain vessel related information such as the main dimensions, sailing speed and encounter angle. These methods are typically based on data from the Automatic Information System (AIS), which is a system where navigational parameters are transmitted from ships to one another and to shore stations, providing a rich source for the study of vessel movements. AIS data does not contain information concerning the ship masses, loading conditions or specific hull shapes. There is thus a high degree of uncertainty related to the vessel characteristics obtained from AIS data.

For the evaluation of the consequences, a link is required between the encounter conditions and the conditions at impact. In particular, collision evasive action prior to collision may change the vessel speeds and the impact angle compared to the encounter angle. For the impact scenario calculations, the impact location along the struck vessel's hull is needed as well. Several approaches have been proposed for impact scenario modeling [5], [6], and while the influence of the assumptions governing the link between encounter and impact conditions on the probability of hull breach is significant, the phenomenon is not well understood and involves high uncertainty [7].

In light of this, for the estimation of accidental oil outflow, a model is needed which can easily account for such uncertain conditions, which is why a BBN approach is selected. A number of models has been presented for tanker oil outflow in collision accidents. Przywarty [8] reports on a simple oil spill model based on the analysis of accident statistics. Montewka et al. [9] proposed a model based on a generic methodology presented by the International Maritime Organization [10]. Smailys and

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Česnauskis [11] presented a more generic method for the determination of the oil outflow when limited information is available about the tanker. Their method only allows for determination of the outflow if the damage extent is known, i.e. there is no link to the impact conditions. van de Wiel and van Dorp [12] have presented a regression model for the evaluation of the damage extent and accidental oil outflow conditional to the impact conditions. Their model has been applied in maritime traffic risk assessment [3] but has the limitation that a predefined tanker layout is assumed, based on the cases presented by the National Research Council [13]. Sormunen et al. [14] present a regression model for damage extent to chemical tankers.

This paper presents a Bayesian network model for the estimation of accidental outflow for product tankers, i.e. tankers with deadweight in the range of 10000 to 60000 tonnes [15]. Such vessels are among the most common in the Baltic Sea region, which presents a pragmatic reason for this limitation in this work. The Bayesian network is learned from calculated spill sizes in a large set of damage cases for a large set of tanker layouts. The impact conditions are linked to the damages extents based on the regression equations presented in van de Wiel and van Dorp [12]. The estimation of tank arrangement and cargo tank volumes is based on a dataset of tankers which operate in the Baltic Sea, to which the procedure proposed by Smailys and Česnauskis [11] is applied for determining bulkhead locations and cargo tank volumes.

The resulting Bayesian network model is primarily meant for application in maritime traffic risk assessment, where relatively limited information about the vessels is available and the uncertainty about the impact conditions is significant. It is developed to be compatible with BBN models estimating oil spill related clean-up costs [16], oil combating [17], [18] and environmental impacts of oil spills [19].

This paper is organized as follows: in Section 2, the underlying model rationale in terms of mechanical engineering models is presented and necessary equations for linking impact scenarios to damage extents are given. Section 3 addresses the applied methodology to estimate the tank volumes and bulkhead location based on the limited data of actual tankers. Section 4 presents the methodology for constructing the Bayesian oil outflow model. An example application is shown in Section 5, illustrating the utility of accounting for uncertainty related to the impact conditions. Section 6 concludes.

2. DEFORMATION ENERGY AND DAMAGE EXTENT

2.1. Ship collision damage: phenomenon and model selection

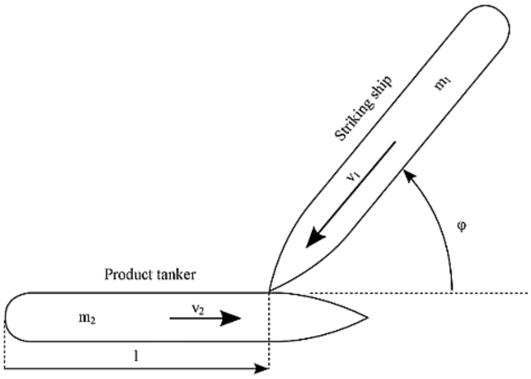
A ship-ship collision is a complex, highly non-linear phenomenon which can be understood as a coupling of two dynamic processes. First, there is the dynamic process of two ship-shaped bodies coming in contact, resulting in a redistribution of kinetic energy and its conversion into deformation energy. The available deformation energy leads to damage to the hulls of both vessels. This process is commonly referred to as "outer dynamics" [20]. Second, there is the dynamic process of elastic and plastic deformation of the steel structures due to applied contact pressure, referred to as "inner dynamics" [20].

A number of models has been proposed to determine the available deformation energy and the extent of structural damage in a ship-ship collision, see Pedersen [21] for an extensive review. One of the few methods explicitly accounting for the coupling of outer and inner dynamics is the SIMCOL model reported by Brown and Chen [22]. This model is a three degree of freedom time-domain simulation model where vessel motion and hull deformation are tracked, from which the resulting damage length and depth can be determined. The method has been applied to evaluate the environmental performance of four selected tanker designs: two single hull and two double hull (DH) tankers of various sizes [13], for which a large set of damage calculations has been performed. The relevant parameters of these damage cases has been transformed in a statistical model based on polynomial linear and binary logistic regression by van de Wiel and van Dorp [12], linking the impact scenario variables to the damage extent and the probability of hull rupture. While more advanced collision energy and structural response models exist [21], this model is suitable as a basis for our purposes. The equations provided in the following section are implemented in the BBN.

2.2. Collision damage extent conditional to given impact scenario

The polynomial regression model by van de Wiel and van Dorp [12] uses a set of predictor variables to link the impact scenario variables to the longitudinal and transversal damage extents. These predictor variables are representative of the impact scenario. An impact scenario can be described through the vessel masses m_1 and m_2, the vessel speeds v_1 and v_2, the impact angle φ, the relative damage location l and the striking ship's bow half-entrance angle η, see Figure 1. An additional variable is used as a scaling factor between the results of the small and the large tankers given in the set of damage cases [13]. This variable is set as the vessel length L or the vessel width B depending on whether longitudinal or transversal damage extents are calculated.

Figure 1: Impact scenario variable definition



As predictor variables, dimensionless variables x_i are applied as follows:

$$\begin{cases} x_1 = 1 - \exp\left(-\dfrac{e_{k,p}}{\beta_p}\right)^{\alpha_p} \\ x_2 = 1 - \exp\left(-\dfrac{e_{k,t}}{\beta_t}\right)^{\alpha_t} \\ x_3 = Beta\left(l^* + \dfrac{1}{2} \mid 1.25, 1.45\right) - \\ \quad Beta\left(-l^* + \dfrac{1}{2} \mid 1.25, 1.45\right) \\ x_4 = \mathrm{CDF}(\eta) \\ x_5 = CDF(L) \text{ or } CDF(B) \end{cases} \qquad \text{(Eq. 1)}$$

where $e_{k,p}$ and $e_{k,t}$ are respectively the perpendicular and tangential collision kinetic energy, l^* the relative impact location with reference to midship and α_p, β_p, α_t and β_t parameters of a Weibull distribution for the predictor variables involving respectively the perpendicular and tangential kinetic energy. These are given in Table 1, along with the values for the empirical CDF of the bow half entrance angle η and the empirical CDF(L) and CDF(B). We write:

$$l^* = \left| l - \frac{1}{2} \right| \qquad \text{(Eq. 2)}$$

$$e_{k,p} = \frac{1}{2}(m_1 + m_2)\big(v_1 sin(\varphi)\big)^2 \qquad \text{(Eq. 3)}$$

$$e_{k,t} = \frac{1}{2}(m_1 + m_2)\big(v_2 + v_1 cos(\varphi)\big)^2 \qquad \text{(Eq. 4)}$$

Table 1: Coefficients and parameters in predictor variables x_1, x_2 and x_4, from [12]

Parameter	**Value**	**η** [deg]	**CDF(η)** [-]	**L** [m]	**CDF(L)** [-]	**B** [m]	**CDF(B)** [-]
α_p	0.4514	η≤17	0.224	L≤190	0	B≤29.1	0
β_p	589.4	η≤20	0.776	190<L≤261	0.014L–2.68	29.1<B≤50	0.048B-1.4
α_t	0.4378	η>20	1.000	L>261	1	L>50	1
β_t	709.1						

Using these predictor variables, a polynomial regression model is made for respectively the expected damage length y_l and penetration depth y_t:

$$y_l = exp\left(h_l(\boldsymbol{x}|\hat{\beta}^l)\right) \quad \text{(Eq. 4)}$$

$$y_t = exp\left(h_t(\boldsymbol{x}|\hat{\beta}^t)\right) \quad \text{(Eq. 5)}$$

with:

$$h_l(\boldsymbol{x}|\hat{\beta}^l) = \sum_{i=1}^{5} \hat{\beta}_0^l + \sum_{j=1}^{5} \hat{\beta}_{i,j}^l x_j^i \quad \text{(Eq. 6)}$$

$$h_t(\boldsymbol{x}|\hat{\beta}^t) = \sum_{i=1}^{5} \hat{\beta}_0^t + \sum_{j=1}^{5} \hat{\beta}_{i,j}^t x_j^i \quad \text{(Eq. 7)}$$

The regression coefficients for the expressions h_l and h_t are given in Table 2.

Table 2: Regression coefficients of polynomial expressions for h_l and h_t, from [12]

	$\hat{\beta}_{i,j}^l$						$\hat{\beta}_{i,j}^t$					
	i=0	**i=1**	**i=2**	**i=3**	**i=4**	**i=5**	**i=0**	**i=1**	**i=2**	**i=3**	**i=4**	**i=5**
j=0	-2.63						-3.68					
j=1		-0.12	4.67	-1.97	1.16	0.05		6.65	3.99	0.427	0.051	0.044
j=2		5.79	/	16.82	-0.57	/		-3.76	-4.33	/	/	/
j=3		/	-5.76	-53.7	/	/		/	/	-9.29	/	/
j=4		-10.9	0	69.4	/	/		/	/	20.69	/	/
j=5		7.798	4.031	-31.2	/	/		1.83	1.87	-12.4	-0.35	/

Using the above expressions, the damage length y_l and penetration depth y_t can be evaluated based on the impact scenario parameters. Note that m_1 and m_2 have as units tonnes, v_1 and v_2 are in knots, φ in degrees with φ=0 bow-bow collision and η in degrees. Index 1 and 2 denote striking and struck vessel, respectively.

The determination of the maximum and minimum location of the longitudinal damage extent, respectively y_{l1} and y_{l2}, depends on the damage length y_l, but also on the relative damage location l, the ship length L and the damage direction θ:

$$y_{l1} = (1-\theta)y_l + (1-l)L \quad \text{(Eq. 8)}$$

$$y_{l2} = -\theta y_l + (1-l)L \quad \text{(Eq. 9)}$$

Naturally, y_{l1} and y_{l2} cannot exceed the position of the fore or aft perpendicular. The damage direction θ accounts for the phenomenon that the longitudinal damage extent will not necessarily be symmetrical around the impact location. In van de Wiel and van Dorp [12], it is assumed that θ depends on the impact angle φ and the relative tangential velocity v_t as follows:

$$\theta = \begin{cases} 0 & \text{if } \varphi = 0 \\ \left(\frac{1}{2}\left(\frac{\varphi}{90}\right)^{n}\right)^{\exp(m v_t)} & \text{if } 0 < \varphi < 90 \\ \left(1 - \frac{1}{2}\left(\frac{180 - \varphi}{90}\right)^{n}\right)^{\exp(m v_t)} & \text{if } 90 \le \varphi < 180 \\ 1 & \text{if } \varphi = 0 \end{cases} \qquad \text{(Eq. 10)}$$

where $v_t = -v_1\cos\varphi - v_2$, m=0.091 and n=5.62.

The penetration depth y_t is applied to evaluate which longitudinal bulkheads are breached and hence from which tank compartments in the transverse direction oil can spill. Likewise, the longitudinal limits of the collision damage, y_{l1} and y_{l2}, are applied to evaluate which transverse bulkheads are breached and hence from which tank compartments in the longitudinal direction oil can spill.

3. A MODEL FOR ESTIMATING BULKHEAD LOCATION AND TANK VOLUMES

3.1. Aim and tanker arrangement data

The overall aim of the model for tanker tank arrangement is to determine, based on limited data of a given ship, a reasonable estimate for the location of transversal and longitudinal bulkheads and the corresponding tank volumes. As mentioned in the introduction, AIS data typically only contains very crude ship related data such as vessel type, length and width. The model presented below aims to allow estimates of tank arrangements if only these variables are known. The approach is based on a data set containing tank arrangement parameters for 219 product tanker designs which operate in the Baltic Sea. The data is obtained from IHS Maritime [23]. Some abridged tank arrangement data used in the analysis is shown in Table 3. L, B and D represent respectively the vessel length, width and depth. DISPL is the displacement (weight of the ship) and DWT the deadweight (carrying capacity). TT is the tank type, where TT1 signifies a DH tanker with no longitudinal bulkhead, TT2 a DH tanker with one longitudinal bulkhead and TT3 a DH tanker with two longitudinal bulkheads. PST, CT and SBT are the number of port side, center and starboard side tanks. Of the 219 tanker designs, 93% has is tank type 2, 5% tank type 3 and 2% tank type 1, showing that for the product tanker class, the most common configuration is with one longitudinal bulkhead on the center line.

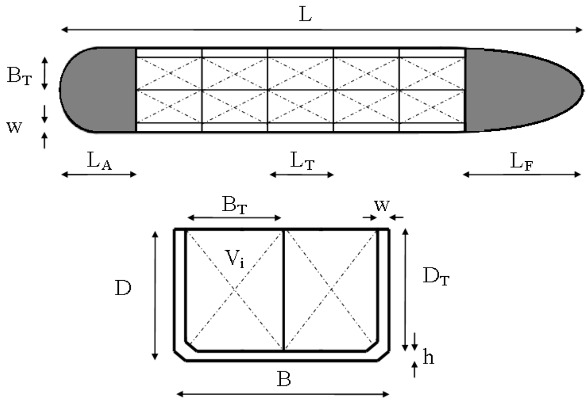
Table 3: Basic information concerning tanker layout, excerpt from [23]

	L [m]	**B** [m]	**D** [m]	**DISPL** [tonnes]	**DWT** [tonnes]	**TT**	**PST**	**CT**	**SBT**
Ship 1	127.6	20.8	11	18179	13781	2	6	/	6
Ship 2	134.8	22	12.8	23838	18008	2	7	/	7
Ship 3	147.2	24.5	13.4	27502	19831	1	/	8	/
Ship 4	160	24.6	13.5	29842	23400	3	5	5	5

3.2. Methodology for finding bulkhead locations and tank volumes

The methodology applied in this paper is to a large extent based on the procedure proposed by Smailys and Česnauskis [11], but is for the analysis in Section 4 calculated on the tanker database set as outlined in Section 3.1. The main parameters relevant for the determination of the tank volumes and the location of the transverse and longitudinal bulkheads are shown in Figure 2. L_A and L_F are the horizontal distance from the aft perpendicular to the aft cargo tank compartment and the horizontal distance from the fore perpendicular to the frontmost cargo tank compartment. L_T, B_T and D_T are the cargo tank compartment length, width and depth and V_i the volume of tank i . The double hull width is denoted w and the double bottom height has notation h.

Figure 2: Definition of tank dimensions and ship parameters



The volume V_i of a given tank is determined as:

$$V_i = C_i B_T L_T D_T \tag{Eq. 11}$$

where C_i is a volumetric coefficient, accounting for the actual shape of the tank in comparison with a rectangular prism. Values for this factor are given in Table 4, taken as averages of an analysis by Smailys and Česnauskis [11]. The tank length, width and depth L_T, B_T and D_T are determined as:

$$L_T = \frac{(L - L_A - L_F)}{n} \tag{Eq. 12}$$

$$B_T = \frac{(B - 2w)}{m} \tag{Eq. 13}$$

$$D_T = D - h \tag{Eq. 14}$$

where n is the number of tanks in the longitudinal direction and m the number of tanks in the transversal direction. It is thus assumed that all tanks have the same width B_T and length L_T. Values for L_A and L_F are given in Table 4, taken as average values reported by Smailys and Česnauskis [11]. The double bottom height h and double hull width w are determined based on the relevant rules for classification of ships [24].

Table 4: Basic information concerning tanker layout, based on [11]

Layout	Cargo tank	10k-35k DWT	35k-50k DWT	50k-60k DWT
TT1	Front	0.7	0.74	0.74
	Middle	1	1	1
	Aft	0.91	0.92	0.92
TT2	Front	0.72	0.75	0.75
	Middle	1	1	1
	Aft	0.91	0.92	0.92
TT3	Front outer	0.68	0.7	0.7
	Front internal	0.84	0.85	0.85
	Middle	1	1	1
	Aft internal	0.93	0.94	0.94
	Aft outer	0.84	0.85	0.85
	L_A	0.24 L	0.22 L	0.21 L
	L_F	0.06 L	0.055 L	0.055 L

The above information can be used to determine the set of positions of the longitudinal and transversal bulkheads, respectively noted LBH and TBH, as follows:

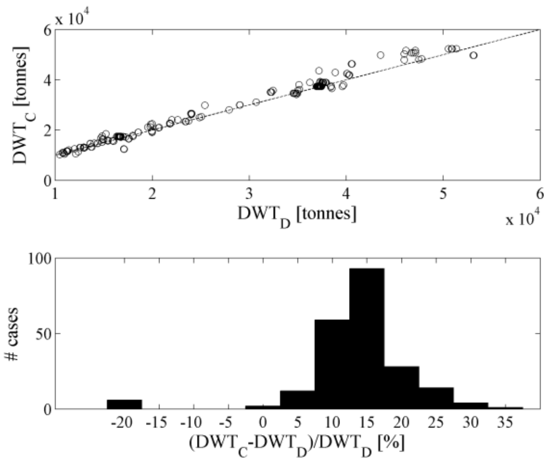
$$TBH = \{L_A + kL_T \mid k = 0 \ldots n\} \tag{Eq. 15}$$

$$LBH = \{w + kB_T \mid k = 0 \dots m\}$$ (Eq. 16)

3.3. Validation

As the procedure to determine tank arrangement is based on a series of simplifying assumptions, the methodology presented in Section 3.2 is validated by comparing the total cargo tank volume as calculated with the DWT as available from the data of the 219 tankers, see Table 3. Figure 3 shows a comparison between the DWT as available in the tanker database (DWT_D) with the DWT as calculated from the cargo tank volume (DWT_C), assuming an oil density of 0.9 tonne/m^3. It is seen that the calculation procedure generally overestimates the cargo tonnage. The histogram shows that the cargo tonnage is overestimated by ca. 15% on average, ranging from an underestimate of ca. 20% to a maximum overestimate of ca. 35%. Overall, the procedure thus leads to a conservative estimate for the possible oil outflow, especially for the larger vessels.

Figure 3: Comparison of DWT_C and DWT_D



While important for the evaluation of the oil outflow, it is not possible to validate the methodology in terms of bulkhead locations as the detailed tanker layouts are not available. A limited study by Smailys and Česnauskis [11] indicates reasonable agreement for this aspect as well. Nonetheless, some uncertainty is inevitable in this model aspect.

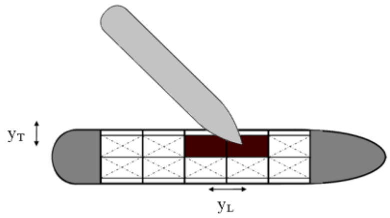
3.4. Determining the oil outflow volume

In actual collision cases, the damage location can be at a range of vertical positions above or below the waterline. Calculations show that the spilled volume can significantly vary depending on the vertical position of the damage [25]. However, there is considerable uncertainty regarding the impact location in accident scenarios. None of the available impact scenario models [5] account for this factor and the vertical damage location will amongst other depend on the striking vessel’s depth, bow shape, loading condition (draft and trim) and on the presence of a bulbous bow. None of these parameters can be derived with a reasonable degree of accuracy based on information available in AIS data and uncertainty related to such factors is high in risk assessment of maritime transportation.

Other factors affecting the oil outflow are e.g. the damage opening size, the ship stability and wave conditions. Various combinations of these can affect the spilled volume of oil, but in maritime traffic risk assessment, there typically is high uncertainty concerning these conditions.

To minimize uncertainty, the assumption is made that all cargo of the breached cargo compartments is spilled, see Fig. 4. This is a conservative estimate which is also applied by e.g. van Dorp and Merrick [3]. The determination of which cargo components are breached is based on a comparison of the penetration depth y_t with the position(s) of the longitudinal bulkhead(s) LBH, respectively the maximum and minimum location of the longitudinal damage extent (y_{l1} and y_{l2}) with the positions of the transversal bulkheads TBH.

Figure 4: Definition of oil outflow given a damage extent



4. BAYESIAN BELIEF NETWORK MODEL FOR OIL OUTFLOW

4.1. Model construction rationale

The definition of the BBN is based on an integration of the model for the collision damage extent conditional to impact scenarios with the oil outflow model conditional to tanker layout.

For each ship, the tank layout is generated according to the procedure in Section 3.1 and 3.2. Subsequently, the impact scenario variables, discretized as shown in Table 4 and Fig. 5, are probabilistically sampled per combination, based on which the CPTs for the regression variables x_1, x_2, x_3 x_4 and θ, the damage extent variables y_L and y_T and the oil outflow is computed as explained in Section 2.2 and 3.4. For each combination of parent node variable classes, 100 samples are generated, from which the probability distribution over the child node variable classes are computed.

As for the ship specific parameters as shown in Table 3, the deadweight is selected as parent node for the oil outflow volume. The other ship parameters are linked to the deadweight through the Greedy Thick Thinning Bayesian learning algorithm. The CPT results for the oil outflow for each ship design are aggregated in the respective DWT classes. The complete BN aggregates the probability distributions for each individual ship, accounting for the DWT classes.

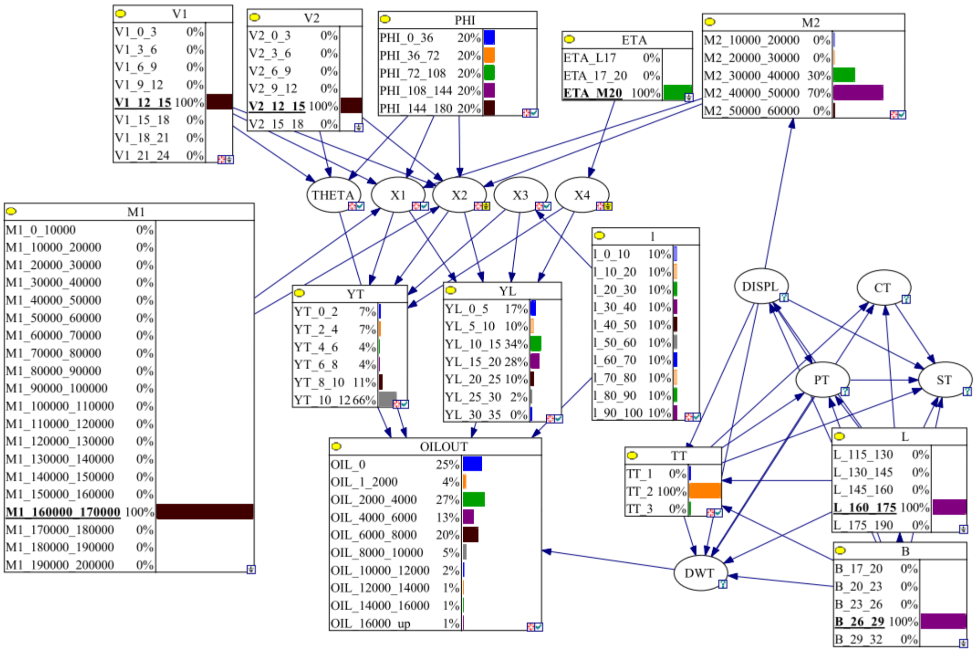
Table 4: Discretization of the impact scenario and oil outflow nodes in the BN

Variable	Discretization	Variable	Discretization
v_1	0, 3, 6, 9, 12, 15, 18, 21, 24	x_1	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1
v_2	0, 3, 6, 9, 12, 15, 18	x_2	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1
φ	0, 36, 72, 108, 144, 180	x_3	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1
η	< 17, 17-20, > 20	x_4	0.224, 0.776, 1
l	0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1	y_L	0, 2, 4, 6, 8, 10, 12
m_2	10k, 20k, 30k, 40k, 50k, 60k	y_T	0, 5, 10, 15, 20, 25, 30, 35
m_1	0, 10k, 20k, 30k, 40k, 50k, 60k, 70k, 80k, 90k, 100k, 110k, 120k, 130k, 140k, 150k, 160k, 170k, 180k, 190k, 200k	OILOUT	0, 2k, 4k, 6k, 8k, 10k, 12k, 14k, 16k, > 16k
θ	0, 0.2, 0.4, 0.6, 0.8, 1		
DWT	< 15k, 15k, 22k5, 30k, 37k5, >37k5		

4.2. Results and example application

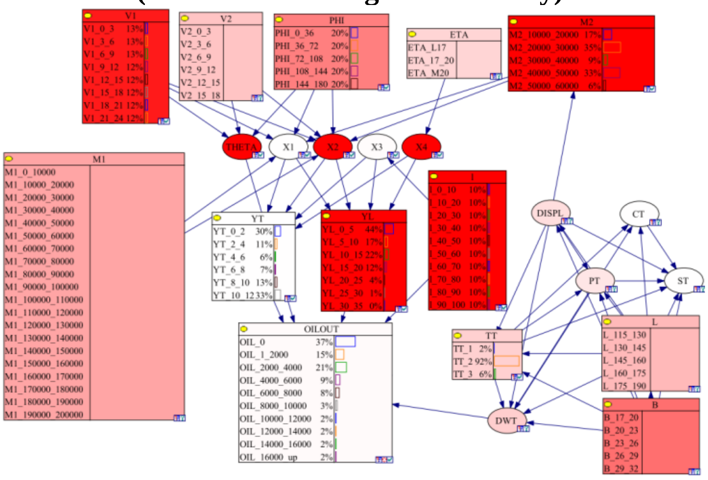
The resulting BBN is shown in Fig. 5. The variable OILOUT is the output of the model, providing the estimate of the oil outflow in ship-ship collisions. Note that the variable x_5 of Eq. 1 is not implemented as for the considered ship sizes, this predictor variable always has value 0, see also Table 1.

Figure 5: Resulting BBN oil outflow model for product tanker collisions



The example application shows a scenario where a relatively large product tanker is hit by a large vessel (e.g. a suezmax bulk carrier or tanker), both at cruising speed. The resulting oil outflow ranges from 0 to more than 10000 tonnes. The relatively large range of probable oil outflows is due to the significant sensitivity of the oil outflow results to the values of the relative damage location and the impact angle, as illustrated in a sensitivity analysis in Fig. 6. In risk assessment of maritime transportation, vessel masses (M1 and M2) and impact speeds (V1 and V2) can be estimated rather well, whereas there is high uncertainty regarding damage location l and impact angle PHI as the process from encounter to impact is poorly understood. The BBN approach shows its value in making such uncertainty explicit rather than providing a potentially uninformative expected value estimate.

Figure 6: Sensitivity analysis of BBN, in relation to OILOUT (darker shades: higher sensitivity)



The presented model provides an extensive insight in possible oil outflows in ship-ship collision accidents involving a product tanker. However, several limitations should be noted. First, the oil outflow is only considered as a direct result of the ship-ship collision. Potentially occurring explosions, subsequent progressive structural failures and ship capsizing or sinking could lead to bigger oil outflows than calculated using the above outlined procedure. The results from the model should be evaluated in light of this additional outcome uncertainty. Second, no distinction is made between the type of spilled oil, which however is important for calculating costs [16] and environmental effects [19].

5. CONCLUSION

This paper has presented a BN model for the evaluation of accidental oil outflow in double hull product tanker collisions. The main intended application area for this model is risk assessment of maritime transportation. For such applications, uncertainty related to the specific tanker layouts is high as only very generic data on the vessels operating in the area is available. Furthermore, the uncertainty related to the exact conditions at impact, conditional to encounter scenarios is high. The application of BBNs provides a platform for consistent reasoning under such uncertainty.

The model integrates results from two models found in the literature. A first model provides an estimate of tanker layouts when only limited data is available for a given ship. This model is applied to a set of tanker layouts which are representative for the Baltic Sea area. A second model provides a link between impact conditions in ship-ship collisions and the resulting damage extent.

Based on a large set of simulated damage cases and oil outflows, a Bayesian Belief Network is constructed, to probabilistically evaluate the possible oil outflows conditional to impact scenarios. The resulting network provides a reasonable, relatively conservative estimate of spill sizes.

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