Uncertainty in maritime risk analysis: Extended case-study on chemical tanker collisions

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Abstract

Uncertainty is inherent to risk analysis; therefore the proper treatment of the former is of high relevance. In the field of risk analysis for maritime transportation system, the effect of uncertainties is rarely discussed or quantified. Therefore, in this paper we reflect on a case-study regarding risk analysis of chemical spill in the Gulf of Finland and analyze the associated uncertainties by adopting a systematic framework.

The risk is assessed as expected spill frequency and spill volumes caused by ship-chemical tanker collisions in the Gulf of Finland (GoF). This is done by applying a collision consequence with a novel approach-to-collision-speed- linkage model and GoF-specific causation factors, based on re-analyzing accident data. The paper also presents a meta-model for assessing collision probability with initial vessel speeds for any given scenario where a chemical tanker is about to be struck by another vessel.

We show that even when we conduct a risk analysis using state-of-the-art methods there is medium-high uncertainty in our model, which becomes apparent only when conducting a systematic uncertainty assessment analysis, emphasizing the importance of uncertainty assessment in quantitative maritime risk analysis. For this purpose a qualitative framework for uncertainty assessment analysis is introduced for general use in the field of maritime risk analysis.

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Keywords

Chemical tankers, ship-ship collisions, spills, Gulf of Finland, risk, uncertainty, sensitivity

Introduction

There are several definitions of risk which generally relate risk with uncertainty regarding (negative) outcomes of possible future events, see e,g, Aven et al.[1] or Kaplan[2] for discussion on the definitions. Several risk studies can be found in the literature where risk of maritime traffic is quantified starting since mid-20th century [3, 4, 5, 6, 7, 8, 9, 10]. Results of such analysis can often be used within a framework that aims at taking decisions to mitigate risks caused by marine traffic such as IMO's Formal Safety Assessment[11] .

Quantitative maritime risk studies rarely discuss the uncertainty of their results or the sensitivity of their results relative to changes in individual parameters of the risk model. Discussions regarding the implications of the simplifications that are made in the modeling process are also usually not discussed at a desired level of detail. Due to lack of this discussion it is unclear how well the model results correspond to reality and which parts of the model need most future research. Lack of knowledge of uncertainty of the results can lead to decision-making based on a false sense of accuracy and trustworthiness of the results which can lead to implementation of sub-optimal or ineffective risk mitigation measures. As Goerlandt et al.[12] show, different assumptions in ship collision damage estimation can change the results drastically.

In this paper chemical tanker traffic in the Gulf of Finland (GoF) is selected as a case study for the risk analysis and uncertainty assessment, which measures risk in terms of expected chemical spills due to tanker collisions with other vessels. The GoF is a heavily trafficked sea that is also classified as a particularly sensitive sea area by the IMO[13] . With the economical rise of Russia, the oil tanker traffic in the GoF has been on the increase[14] and it is feared that sooner or later a catastrophic environmental disaster will occur.[15] [16] The environmental risk posed by oil tankers has been much studied [17, 17, 19, 20, 19, 22], but the risk posed by spills from chemical tankers has so far not attracted much attention from academia or officials. [23]

Chemical tankers carry various kinds of hazardous substances including highly toxic, flammable and/or corrosive chemicals, such as nonylphenol, sulphuric acid and ammonia, but also lighter products, such as ethanol and edible vegetable oils.[24] The amount of liquid chemicals handled annually in the Baltic Sea ports is over 11 million tonnes – and about one half of that (roughly estimated 5.0–6.3 million tonnes) is handled in Finnish ports.[24] Even though the volume of chemical transportation may seem small in relation to oil and oil products, the potential risks relating to chemicals may actually be greater. Firstly, chemicals may be far more toxic than oil, and secondly, the high cargo diversity in chemical carriers poses a special risk in accident conditions, as different chemical cargoes with different reactive properties may be mixed together, forming a chemical mixture significantly more reactive and/or more toxic than its parent compounds.[25]

Aim

This paper presents an extended risk analysis method which is two-fold: Firstly, an improved risk analysis is conducted in terms of expected chemical spills in the different parts of the GoF due to ship-ship collisions. Secondly, the uncertainty related to the different parts of the risk analysis is assessed by a modified framework of Milazzo and Aven's [28]. The obtained results of the study evaluate the impact of the model uncertainty on the trustworthiness of the results and discuss the impact of the uncertainty on the applicability of the results in risk mitigation. The uncertainty analysis also aims at pointing out which parts of the risk modelling need the most improvement.

The reminder of the paper is organized as follows: next section presents risk analysis process, which is followed by the description of the associated uncertainties and their effects on the results of the analysis. The last section discusses the main findings and concludes the paper.

CHEMICAL TANKER RISK ANALYSIS

Methodology of the case study

Besides the uncertainty analysis and discussion, the paper's other aim is fulfilled by addressing several suggestions for improvement compared to the results from Sormunen[23]: Using a more refined spill model as presented by Sormunen et al.[27], adapting GoF-specific causation factors based on the Bayesian network model by Hänninen and Kujala[29] in the ship traffic simulation by Goerlandt and Kujala[30]. Furthermore, this paper presents and applies an empirical distribution for the relationship between ship initial and collision speed. The size range of chemical tankers sailing in the GoF is also examined. The spills resulting from ship-tanker collisions are also linked together with the average toxicity level of chemicals transported in the given area to get a more detailed picture of the risk. The uncertainty of the risk analysis is analysed by evaluating how much change in one variable value changes affect the overall results as well as evaluating how well the phenomena understood as well as assessing how good data is available. The different parts of the analysis are summarized in Figure 1.

The traffic simulation randomly generates ship particulars based on 2007 AIS data from the GoF. The ship particulars contain information such as the physical dimensions of the striking and struck ship, their velocities, angle, etc. The traffic simulation is based on filtering output from Goerlandt and Kujala[30], which gives the collision candidates where the struck ship would be a tanker. The causation factors are extracted specifically for this paper using an adaptation of Hänninen and Kujala's[29] method. The finite element (FE) –based model is described in detail in Sormunen et al.[27], see also Ehlers[31]. Combining these different parts gives the expected collision frequency, spill size and probability for any given area and time span in the GoF. This can be used to express the risk caused by ship-chemical tanker collisions. The risk modeling done here does not aim at including all the different aspects of risk caused by the presence of chemical tankers in the Gulf of Finland: other accident types are left for future research along with the actual effects of the spilled chemicals. Also the economic consequences of accidents and the resulting casualties etc. are not analyzed here.

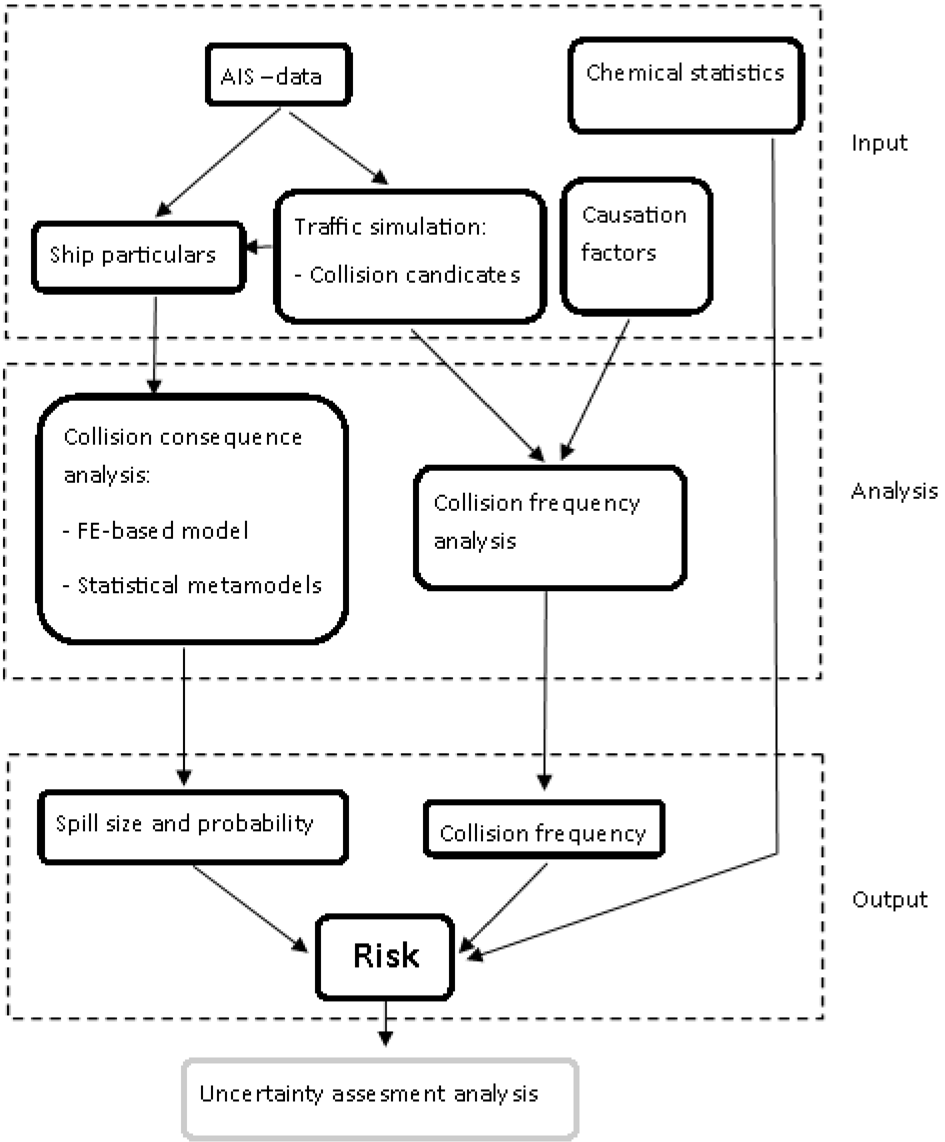

Figure 1. Paper content summary

Traffic simulation

Potential ship-tanker collision situations were obtained by using a real-time ship traffic simulation by Goerlandt and Kujala[30]. The simulation randomly generates ship voyages using a time-variant Poisson- process, where the departure intensity is based on statistics obtained from AIS- data of 2007. The simulation assumes that ship sail blindly and whenever two ships would at least partially occupy the same location at the same time, the ships are counted as collision candidates. From the collision candidates the cases where a tanker was the struck ship were retained and the other filtered out. Furthermore, as tanker traffic to and from Russia is almost exclusively oil and oil products, thus these tankers were also filtered out. [23] The following Figure 2 represents all potential chemical tanker collision candidates from 24 simulation runs where each simulation run represents a whole year of traffic. As the data is based on AIS-data, in which the tankers themselves do not reliably report their type, the tanker type was assessed probabilistically post-hoc based on DWT.[32] Further analysis done for this paper in a Finnish nationwide vessel traffic system called PortNet shows that tankers above 20 000 DWT can be counted as oil- and oil product tankers; thus they are also filtered out. For tankers below 10 000 DWT the probability that the tanker is chemical or gas tanker is 72 % and for tankers 10-20 000 DWT 85 %.[32] However, many tankers are dual certified as oil – and chemical tankers, thus it is difficult to assess with certainty the exact probability of a tanker of certain DWT being chemical or oil.

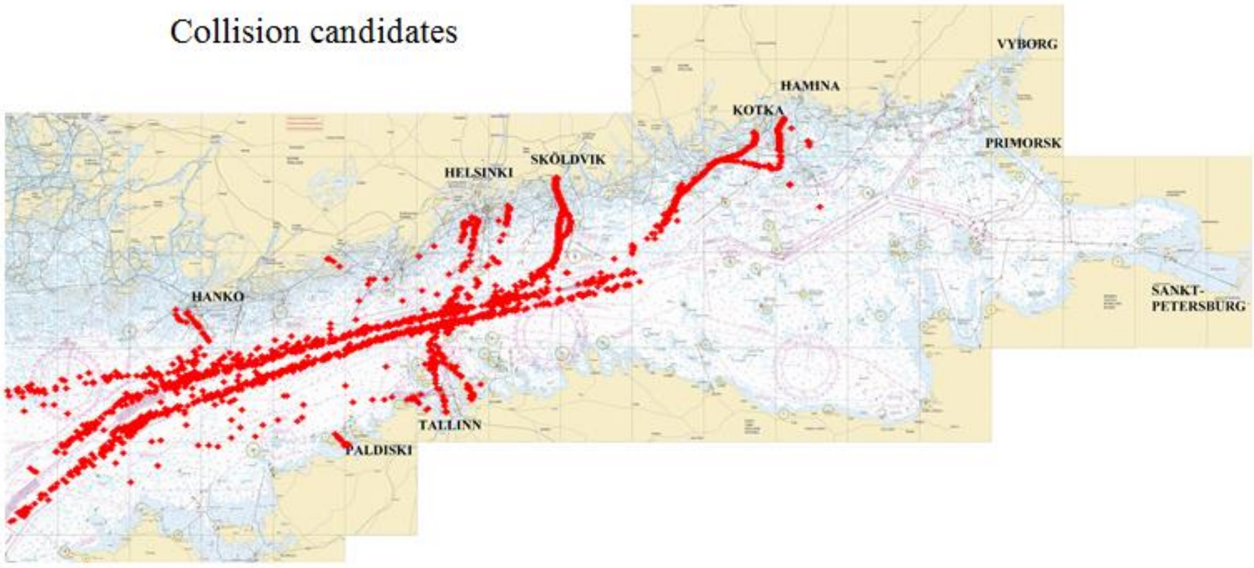

Figure 2. Chemical tanker collision candidate cases *N* = *3657*
map: © Finnish Transport Agency license nr 1803/1024/2010

As the simulation does not specify the type of tanker in advance, each tanker is assigned a probability of being either chemical – or gas tanker or oil or oil product tanker based on the DWT, which was calculated based on ship dimensions reported in the AIS-data, see Sormunen[32] for more details.

Causation factors

Information about the collision candidates needs to be combined with causation factors in order to calculate collision frequency. The causation factor or P_C gives the probability that a collision candidate scenario would actually lead to a collision. It quantifies various technical, environmental, and human factors which might have an effect on not avoiding the collision. The GoF- specific causation factors, derived with a Bayesian network model[29] are presented in Table 1, conditional on striking ship type, collision candidate situation[30] and weather. More in-depth discussion of causation factors can be found in Hänninen and Kujala[29] or Sormunen[32].

Table 1. General causation factors for tankers in different weather states for different encounter situations based on a Bayesian network model by Hänninen and Kujala[29]

		Tanker and				
	Weather	Tanker	Passenger vessel	High Speed Craft	Cargo ship	Other ship type
Head-on	Good	1.006E-05	1.006E-05	1.006E-05	1.006E-05	1.006E-05
	Storm/rain	1.015E-05	1.014E-05	1.015E-05	1.017E-05	1.017E-05
	Windy	1.006E-05	1.006E-05	1.006E-05	1.006E-05	1.006E-05
	Fog	1.006E-05	1.006E-05	1.006E-05	1.006E-05	1.006E-05
Crossing	Good	5.145E-05	5.070E-05	5.100E-05	5.234E-05	5.237E-05
	Storm/rain	7.430E-05	7.147E-05	7.314E-05	7.699E-05	7.715E-05
	Windy	5.144E-05	5.069E-05	5.100E-05	5.234E-05	5.237E-05
	Fog	5.132E-05	5.059E-05	5.088E-05	5.221E-05	5.224E-05
Overtaking	Good	2.058E-04	2.028E-04	2.040E-04	2.094E-04	2.095E-04
	Storm/rain	2.970E-04	2.857E-04	2.936E-04	3.077E-04	3.084E-04
	Windy	2.058E-04	2.028E-04	2.040E-04	2.935E-04	2.095E-04
	Fog	2.053E-04	2.024E-04	2.035E-04	2.088E-04	2.090E-04

The conditional probability of the different weather states depending on the season are as follows:

Table 2. Probabilities of weather states from Hänninen and Kujala[29]

Pr(weather state|season)	Winter	Spring	Summer	Autumn
Good	0.305	0.474	0.666	0.379
Storm/rain	0.1667	0.00775	0.00275	0.0207
Windy	0.501	0.307	0.225	0.496

Fog	0.0268	0.211	0.105	0.104

Collision frequency

Combining the collision candidates and causation factors, the expected number of chemical tankers struck per year for each 5x5 km cell of GoF is obtained according to the following equation:

$$E\left[\frac{tankercollisions}{year}\right]_{ij} = \frac{1}{N_{sim}}\sum_{t=1}^{T} P_{c\,t} \cdot Pr(tanker\ t\ is\ chemical) \qquad (1)$$

for all struck tankers $t = 1,2,\ldots,T$ of collision candidates in the ij:th 5x5 km square

where

N_{sim} the total number of simulation runs, each representing a year of traffic (=24)

$P_{c\,t}$ is the relevant causation factor.

Summing the collision candidates up for each 5x5 km cell in the GoF and multiplying with a relevant causation factor and the probability that the tanker in question is a chemical tanker, the total number of chemical tankers struck per year can be obtained as follows:

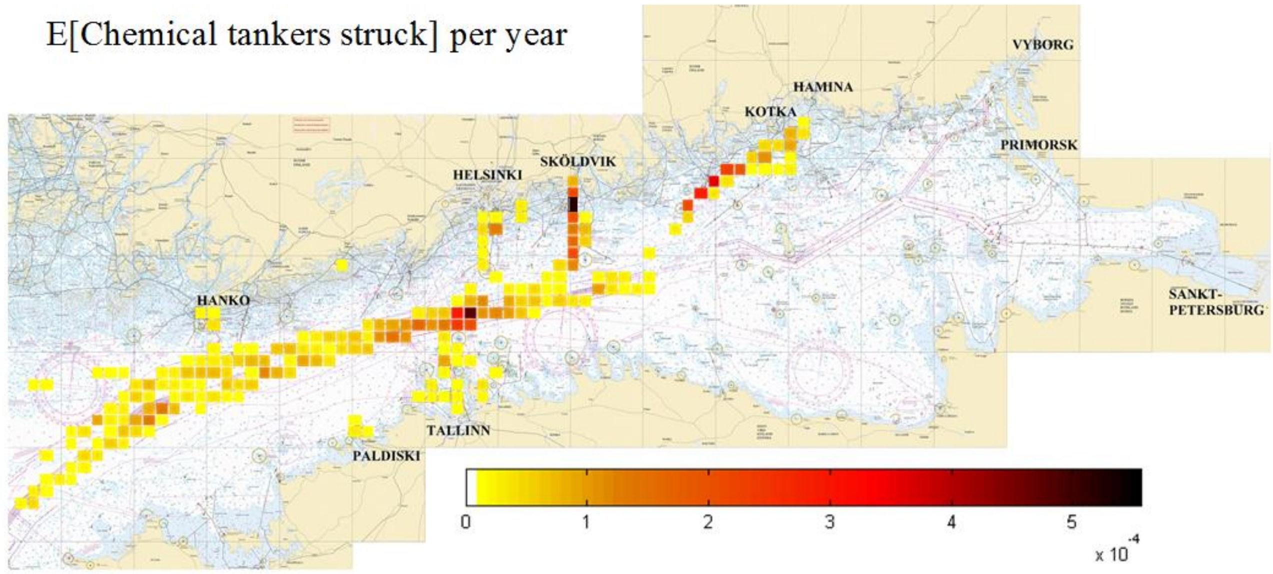

Figure 3. Expected number of struck chemical tankers per year using causation factors by Hänninen and Kujala[29] map: © Finnish Transport Agency license nr 1803/1024/2010

The most risk-prone location is near Sköldvik harbor with an expected 5.55 10^{-4} chemical tankers collision per year. The total number of expected collision in the whole GoF is 0.06 for all tankers and 0.013 for chemical tankers only, meaning one collision on average every 17 / 77 years respectively. Looking at the accident statistics of GoF[33] we find only one case where the struck ship was a tanker. Thus there is not enough data available for a meaningful comparison of the simulation results and the real-life accidents. This is a common problem for high consequence-low probability systems[34]. A more detailed comparison of the effect of different causation factors can be found in Sormunen[32].

Collision consequence analysis

Once the collision frequency is known, this information can be combined with a collision consequence model to obtain the risk expressed in terms of spill sizes in m^3. The discrete spill size estimation model is presented in Sormunen et al.[27] which is used here. This model needs the following input variables:

L_A, L_B: length of striking (A) and struck (B) ship in m

M_A, M_B: mass of striking and struck ship in tonnes

B_A, B_B: Breadth of striking and stuck ship in m

V_A,V_B: velocity of striking and struck ship in knots

W_B: width of the struck tanker in m

W_{DH}: Double hull width of struck tanker in m

β: collision angle in degrees $\in [0; 180]$, where 90° equals a perpendicular, 180 ° a straight head-on and 0° a collision from straight behind.

x_L: relative impact location on struck ship hull [0;1], where 0 is stern, 0.5 amidships and 1 is bow.

Based on the AIS –data, the ships in the simulation have already been assigned masses, breadths lengths, initial speeds and headings. In order to have a reliable estimation of the collision energy (and thus, collision consequence estimate) a reliable model is needed between the approach variables and the collision variables. This is one of the main aims of this paper and is discussed in detail as follows.

Linking the approach/service and collision velocity

In the literature several proposals for estimating collision speed, angle and collision location on struck ship hull can be found. Several of them are summarized in Table 3:

Table 3. Overview of models for collision scenarios (adapted from Goerlandt et al.[12])

Model	β (°)	V_A (kn)	V_B (kn)	x_L [0;1]
Blind navigator	Output from traffic simulation	Output from maritime traffic simulation	Output from maritime traffic simulation	U(0, 1)
Rawson et al. (1998)	U(0, 180)	Truncated bi-normal, lower end: N(5,1) upper end: N(10,1) (min,max) = (2, 14)	same as V_A	U(0, 1)
NRC (2001)	N(90,29)	W(6.5, 2.2)	Exp(0.584)	B(1.25,1.45)
Lützen (2001)	T(0, β_{init}, 180)	Below 0.75$V_{init\,A}$: U(0,0.75$V_{init\,A}$) Above 0.75$V_{init\,A}$: T(0.75$V_{init\,A}$, $V_{init\,A}$)	T(0, $V_{init\,B}$, , $V_{init\,B}$)	Emp
Brown (2002)	N(90,28.97)	W(4.7,2.5)	Exp(0.584)	Emp
Tuovinen (2005)	Emp	Emp	Emp	Emp

Distributions: U = uniform, N=normal, W = Weibull, Exp = Exponential, B= Beta, T= triangular, Emp = empirical

β_{init} is the initial approach angle, in this case taken from the traffic simulation and V_{init} is the initial speed, also taken from the simulation.

Using different proposals for collision speed (V_A,V_B), location (x_L) and angle (β) the collision energy varies much. Therefore the spill probability in case of a collision also varies: According to Goerlandt et al.[12], the simulated spill probability in case of a collision for tankers in the GoF on average is in the range 22-55 %, depending on which estimates are used.

The authors of the proposals point to general problem in form of lack of accurate data, forcing the researchers to make generalizations and assumptions that do not necessary describe the real-life situation well. Also problematic is that most proposals do not link the approach and collision variables. A more in-depth discussion of the different models can be found in Sormunen[32]. For the purposes of this article, the following methods for linking approach speed and angle to their values at time of collision are as follows:

- Uniform distribution for relative collision location on struck ship $x_L \in [0;1[$ from HARDER – damage rules[35] and
- Lützen's[36] proposal: triangular distribution for collision angle β with mode equal to approach angle.
- Self-proposed empirical distribution for collision speeds V_A, V_B based on a more in-depth-analysis of data collected by Tuovinen[37]. This allows for a model to be put forth that links the approach- and collision speeds based on actual accident statistics.

From the accident statistics collected by Tuovinen[37] the following cases were filtered out:

- no design velocity was given
- no speed at moment of collision was given
- vessels collided somewhere else than at open sea, coastal waters or harbor approaches

After the filtering, there were 49 striking ship and 46 struck ship cases where both collision speed and the design velocity were given. In these cases $\frac{collision\ velocity}{design\ velocity}$ is given below in Figure 4.

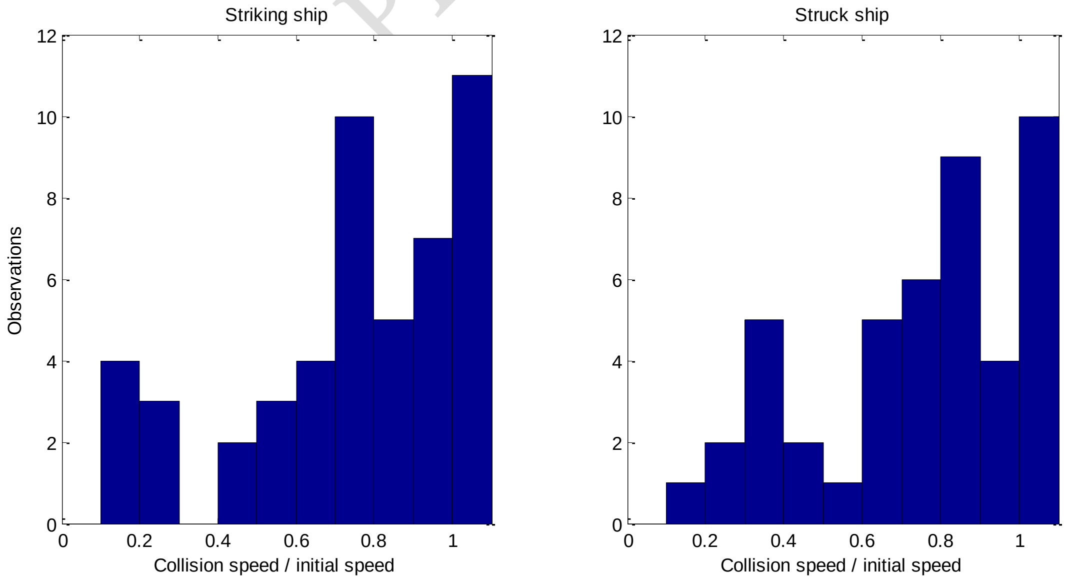

Figure 4. Collision velocity / design velocity[32]

The only proposed model in literature where the approach speed and the collision speed are linked is the one by Lützen[36]. However, according to results of the two-sample Kolmogorov- Smirnov test the sample cannot be assumed to come from the distributions that Lützen proposes.[32] Furhtermore, no known statistical distribution fits Tuovinen's data, therefore an empirical distribution function was used to evaluate the relationship between initial and collision speed with the following bins and bin counts:

Table 4. Collision velocity / design velocity based on Tuovinen's[37] data

Pr(collision velocity /design velocity)				
Fraction	Striking	Struck	Cumulative striking	Cumulative struck
0-0.1	0	0	0	0
0.1-0.2	0.082	0.022	0.082	0.022
0.2-0.3	0.061	0.044	0.14	0.067
0.3-0.4	0	0.11	0.14	0.18
0.4-0.5	0.041	0.044	0.18	0.22
0.5-0.6	0.061	0.022	0.24	0.24
0.6-0.7	0.082	0.11	0.33	0.36
0.7-0.8	0.20	0.13	0.53	0.49
0.8-0.9	0.10	0.20	0.63	0.69
0.9-1	0.14	0.089	0.78	0.78
1	0.22	0.22	1	1

For the purposes of this paper, the "design velocity" is replaced by the speed obtained from the traffic simulation. As such, this approach makes simplifications; also all ships regardless of size etc. are grouped together due to limited data. Also for the same reason note the lack of observations in certain bins in the empirical distribution function.

Using the initial values from the traffic simulation and the approach described here, the following histograms in Figure 5 present the most important collision variables for tankers < 20 000 DWT. Tankers to and from Russia are also excluded based on the low volume of liquid bulk chemicals to Russia, see Sormunen[32] for details.

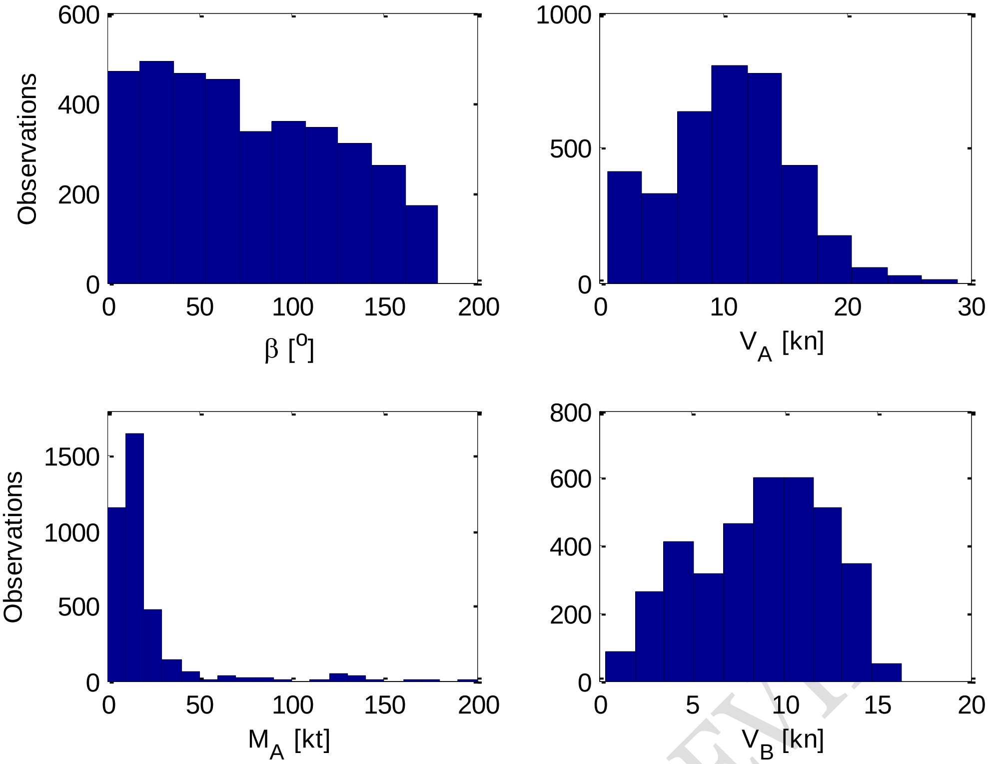

Figure 5. Collision variables for potential chemical tankers

Penetration depth in collision

The collision consequence model used here is the one presented by Sormunen et al.[27] by analyzing the effect of different bulb sizes and double hull widths. The model is based on finite element (FE) method results of the relationship between collision energy, striking ship bulb size, truck tanker double hull width and the resulting perpendicular penetration depth into the side structure of the tanker. To calculate this, the following equations are used:

$$\delta_{\perp} = \frac{E_{\xi}}{\frac{1}{3}F_B\left(82.457\,\frac{W_{DH}}{2} - 31.7\right)}m \;= \frac{E_{\xi}}{F_B(13.743\;W_{DH} - 10.567)}\;m, \qquad (2)$$

where $\delta_{\perp}$ is the perpendicular displacement in meters, W_{DH} is the double hull width of the struck tanker in meters, F_B is the bulb factor and E_{ξ} the perpendicular collision energy in mega joules according toPedersen and Zhang's [38] [39] collision energy model. The penetration length along the struck ship hull δ_{η} is calculated using basic trigonometry

$$\delta_\eta = \frac{\delta_\perp}{\tan(\beta)}. \tag{3}$$

F_B is determined according to L_A - the striking ship length in m.

$$F_B = \begin{cases} 0.8, & if\ L_A < 90 \\ 0.4\dfrac{L_A}{180} + 0.6, & if\ 90 \le L_A < 270 \\ 1.2, & if\ \ L_A \ge 270, \end{cases} \tag{4}$$

and double hull width according of IMO MARPOL Annex I oil tanker regulations[40]

$$W_{DH} = \begin{cases} 0.4\ m + 2.4\dfrac{DWT}{20\ 000}\ m, & if\ DWT < 5000\ tons \\ 0.5\ m + \dfrac{DWT}{20\ 000}\ m, & if\ DWT \ge 5000\ tons, \end{cases} \tag{5}$$

with an absolute minimum width of 0.76 m and a maximum required width of 2 m. This is done due to the fact that many chemical tankers are double-certified as oil tankers as well (Sormunen, 2012). When determining whether the double hull is pierced or not, W_{DH} temporarily becomes

$$W_{DH\ for\ comparison} = \begin{cases} 0.85\ W_{DH}, & if\ L_A < 90 \\ \left(0.3\dfrac{L_A}{180} + 0.7\right) W_{DH}, & if\ 90 \le L_A < 270 \\ 1.15\ W_{DH}, & if\ \ L_A \ge 270, \end{cases} \tag{6}$$

if $W_{DH\ for\ comparison} < \delta_\perp$, then the double hull is considered to be pierced and the location of the bulb at the end of the collision is overlaid with a two-dimensional model of the tanker to see which tanks (if any) are breached in the collision[3]. An illustration of this is given in Figure 6.

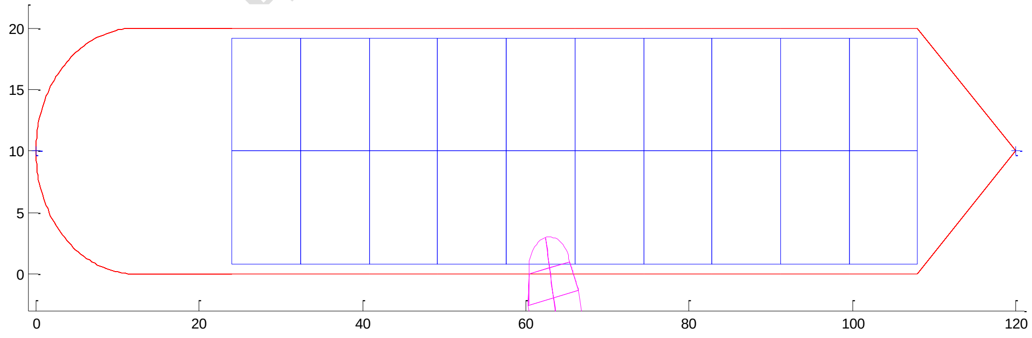

Figure 6. Virtual 120 m long example tanker layout as seen from above generated in MATLAB with penetrating bulb shown (Adapted from Sormunen[32])

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[3] Due to the limitation of the FEM –analysis if the impact location is less than 10 % of ship length from ship aft or fore are counted as no-spill cases.

Furthermore, the following assumptions are done[32]:

- All chemical tankers have 20 equal-sized tanks in 2 row
- Total tank size in m^3 is approximately 1.11 DWT according to statistics of Sormunen[32]
- All tankers are assumed to be 98 % laden when struck[4]
- Full content of any breached tank ultimately ends in the sea due to relative large hole size and wave action.
- Tanks are located between 20 % of tanker length from aft to 10 % of tanker length from fore

The resulting perpendicular collision energy, relative non-dimensional damage length and depth relative to ship length and width (0-1) and spill sizes are illustrated in Figure 7.

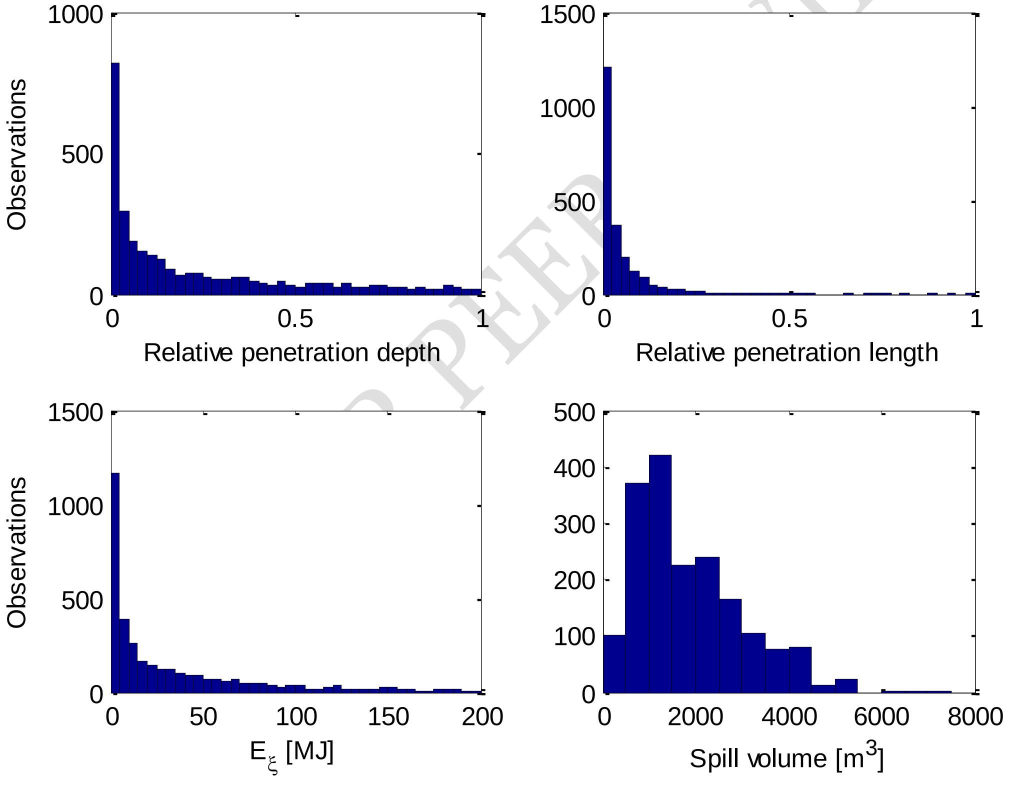

Figure 7. Collision consequence model results

In the histograms the following cases are not shown: 4 % of the cases had collision energy of more than 200 MJ and 16.8 % of the cases the relative penetration depth (W_B / $\delta_\perp$) exceed 1. These cases

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[4] This estimate is a conservative estimate which is commonly practice in risk analysis in case of incomplete information

are, however, included in the analysis. The simulated spill volumes ranged between 120 – 7400 m^3 with a mean spill of 1859 m^3 and median spill of 1566 m^3.

Chemical tanker spills

For describing the risk caused by ships colliding into chemical tankers the expected number of spills can be used as a measure. For 5x5 km squares of the GoF the spilled chemical volume per year is calculated as follows:

$$E[chemical\ spill\ volume]_{ij} = S_{ij} =$$

$$\frac{1}{N_{sim}} \sum_{t=1}^{T} P_{c\,t} \cdot Pr(tanker\ t\ \ is\ chemical) \cdot \frac{N_{t\ tanks\ breached}}{N_{total}} \cdot 1.11\ DWT_t \tag{7}$$

for all struck tankers $t = 1,2,\ldots,T$ of collision candidate situations in the ij:th square where N_{sim} the total number of simulation runs, each representing one year of traffic in the GoF, $P_{c\,t}$ is the relevant causation factor, DWT_t is the DWT of the t :th struck tanker and N_{total} is the total number of tanks per tanker (=20) and $N_{t\ tanks\ breached}$ is the number of tanks breached of tanker t, calculated according to the spill model by Sormunen et al.[27].

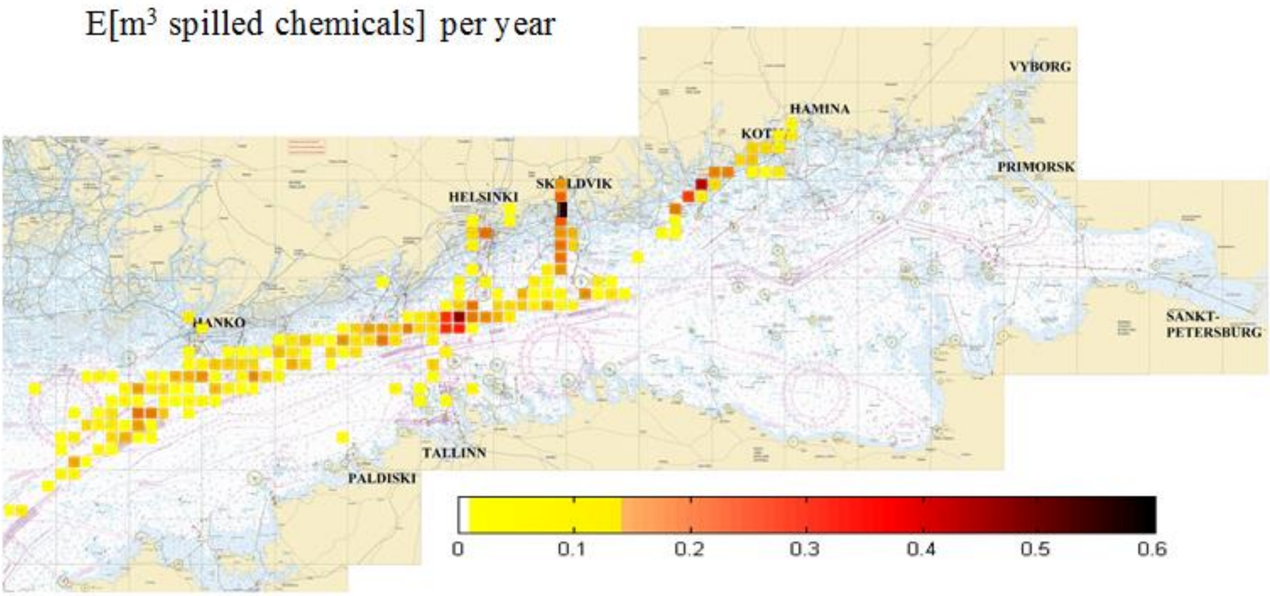

Figure 8. Risk using the causation factors by Hänninen and Kujala[29]
Map: © Finnish Transport Agency license nr 1803/1024/2010

The total expected spill volume per year is 12.6 m^3. The maximum expected spill value per square is near Sköldvik with 0.58 m^3 expected chemicals spilled per year. Even though these numbers are not that informative, the point of making the risk map is to show the relative distribution of the risk in the GoF. This can be used e.g. for calculating optimal placement of chemical recovery vessels, i.e. minimizing average distance to potential accident sites in a similar manner as done in Sormunen (2011). For chemical tankers a spill occurred in 49.8 % of the simulated cases versus 42.3 % for all tankers. Combining this with the expected collision return period of 77 / 17 years for chemical tankers / all tankers respectively, this means that a chemical spill will happen on average once every 156 years and a spill of any kind due to a ship ramming a tanker once every 40 years.

Chemical spill toxicity

The level of toxicity of different bulk liquid substances varies from harmless to extremely toxic. Thus in order to properly assess the risk caused by chemical spills due to collisions, the differences in transported chemicals in different parts of the GoF needs to be taken into account. According to IMO classification, noxious liquid substances carried in bulk are classified into different categories according to their level of toxicity based on the GESAMP[41] evaluation. It indexes the substances according to their bioaccumulation; biodegradation; acute toxicity; chronic toxicity; long-term health effects; and effects on marine wildlife and on benthic habitats. The categories are from the most hazardous to the least hazardous X, Y and Z with an additional category N/A, which includes all substances that are not deemed hazardous for human health or the maritime environment. The GESAMP categorization is very comprehensive, but different chemicals having very different toxicity mechanisms, environmental fate and other physico-chemical properties may end up to same MARPOL category. The MARPOL-categories do not assign any number to describe the difference between category X,Y or Z but for the sake of comparison, here the different categories are arbitrarily given the following risk multipliers: $X = 3$, $Y = 2$, $Z = 1$ and $N/A = 0$. Other toxicity scoring systems exist [24] [42] [43] [44] [45] that allow a numerical comparison of the relative hazard level difference between chemicals but these unfortunately do not cover the full range of transported bulk liquid substances and thus cannot be used in quantitative risk analysis on this scale.

Looking at the GoF, the only harbours with significant liquid bulk chemical transport volumes are Sköldvik, Kotka and Hamina, thus GoF was divided into 2 areas: I) Sköldvik and the area west of it and II) the area east of Sköldvik (i.e. HaminaKotka). Note that transports from area II) pass though area I) according to the traffic simulation and thus affect the statistics there as well.

Table 5 summarizes the average volume share of chemicals in different categories in the GoF.[5] It is assumed that all chemicals and gases transported through Finnish GoF harbours go to or come from outside the GoF.

Table 5. Average of 2008 and 2010 chemical transport volume by MARPOL-category based on TraFi's PortNet to Finnish GoF harbors

Category	Share of total volume
X	2.75 %
Y	74.34 %
Z	16.10 %
N/A	6.81 %

The risk factor $\bar{M}_m$ is the average risk multiplier for the given area $m \in$ [I, II], calculated as the sum of the risk multipliers (X= 3, Z=2, Y =1, N/A=0) multiplied with the relevant share of the chemical category in question in the area. Multiplying each S_{ij} with the relevant $\bar{M}_m$ we obtain the risk R per square ij:

$$R_{ij} = S_{ij}\bar{M}_m \tag{8}$$

which for western GoF is $\bar{M}_I =$ 1.73 (west of red line in Figure 9) and for eastern GoF $\bar{M}_{II} =$ 1.89. Multiplying spill volume with the average risk factors, the following risk map is obtained:

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[5] Due to confidentiality agreement the authors cannot specify the X,Y,Z, N/A percentual share of transportation volumes in more detail, only the risk multipliers $\bar{M}_m$

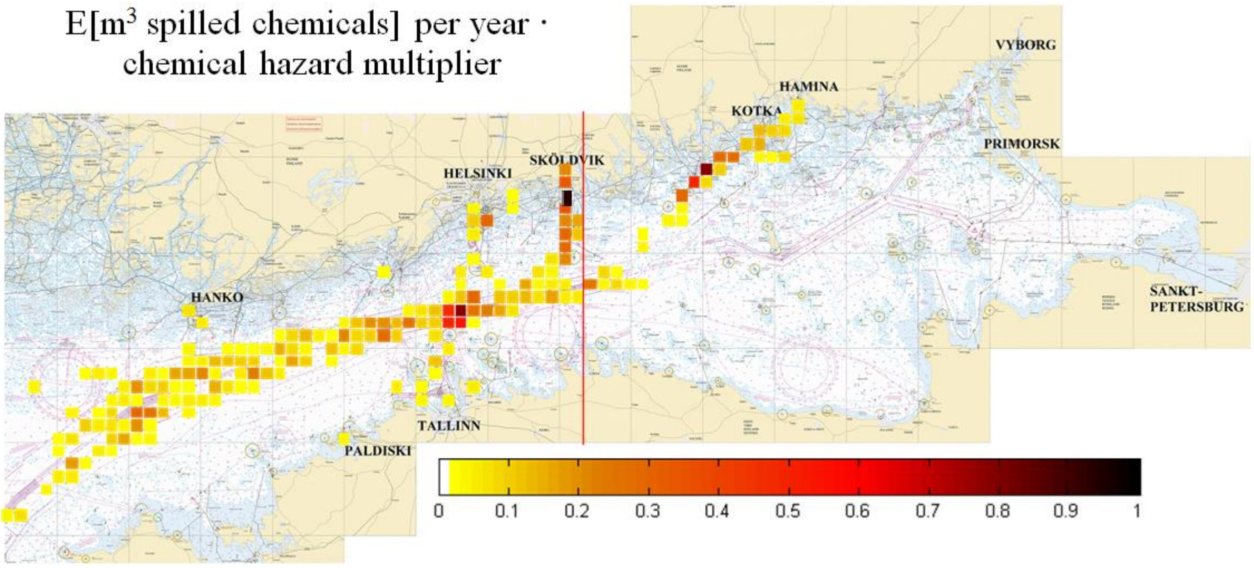

Figure 9. Chemcial spill risk map weighed according to average hazard level of chemicals in the area
Map: © Finnish Transport Agency license nr 1803/1024/2010

The map above is practically identical to the map showing the expected spill values visually but the relative risk level of the eastern part of GoF (east of the red line) becomes higher due to the fact that the chemicals carried to HaminaKotka are on average more hazardous.

When summing together the expected spill volume west of the red line (~25.7 E) the expected yearly spill volume totals 10.52 m^3 and east of the line 2.12 m^3 – a ratio of 4.96:1 in favor of the western part. When multiplying the numbers with the risk factors, the numbers are 18.21 and 4.0 respectively, meaning that the ratio is now only 1:4.54.

STATISTICAL METAMODELING FOR ASSESSING COLLISION CONSEQUENCES

As the code for running the collision consequence model by Sormunen et al.[27] is quite long, sensitivity analysis of the collision variables is difficult. Also the length of the code makes it difficult for others to use the model presented here, limiting its application in practice. These challenges can be overcome by making a metamodel (i.e. a model of a model) for estimating the spill probability for a given accident scenario involving a ship striking a chemical tanker.

In this paper, a metamodel based on the ships' approach variables taken from the traffic simulation are used for estimating spill probability for tankers of maximum 20 000 DWT. For similar metamodels for larger tankers and for estimating spill probability using the simulated collision variable values, see Sormunen et al. [27] and Sormunen[32]. In this case 80 % of the 3657 simulated cases were randomly selected for training the logistic regression model and the remaining 20 % were kept for validation purposes.

The logistic regression model has the following form[46]:

$$\Pr(spill\ in\ case\ of\ collision|X) = \frac{1}{1+e^{-z}}, \qquad (9)$$

where X are the given approach variables for the two ships and $z = b_0 + b_1x_1 + b_2x_2 + \ldots . + b_nx_n$, taken from the SPSS analysis results summarized in Table 6:

Table 6. Logistic regression result table from SPSS using approach variables

Independent variables x_i	Estimate b_i	Significance	e^b
Constant x_0	-1.900	0.000	0.150
Double hull width (W_{DH})	-1.888	0.000	0.151
Collision in tank compartment (θ)	2.936	0.000	18.842
Velocity (V_{Ainit})	0.075	0.000	1.078
Length (L_A)	0.006	0.000	1.006

The new variable θ is 1 if $0.2 \leq x_L < 0.9$, 0 otherwise, indicating whether the impact point on the tanker hull was where the cargo tanks are located or not. Note that the θ – variable is included in this model in the training and validation data due to the fact that it is crucial for the model accuracy even though the actual value θ is only known after the collision has happened as the following models show. All of the values in the *Significance*- column are practically 0, meaning that all x- variables in the model are statistically significant. From Table 6 we get $z = -1.900 + 0.006\, L_A - 1.888\, W_{DH} + 2.936\, \theta + 0.075\, V_{A\, init}$

If $\Pr(spill\ in\ case\ of\ collision|X) < 0.5$, then the case is predicted as a no-spill collision and vice versa. This logistic regression model predicts the same results as the discrete model by Sormunen et al. (2013) in 75.3 % of the cases in the training data set and in 77 % of the cases in the validation data set.

Table 7. Confusion matrix for the training data set when including θ

		Logistic regression model results		
		No spill	Spill	Correct classification %
Sormunen et al.	No spill	898	570	61.2
(2013) model results	Spill	153	1305	89.5
Correct classification %		84.5	69.6	

Looking at the confusion matrix, it seems that if the logistic regression predicts “no spill”, then there is 84.5 % chance that this prediction is correct whereas vice versa the accuracy drops to ~70 %. The sensitivity analysis using this logistic regression gives the following results: given everything else equal, if the value of one of the independent variables x increases by 1, then the spill probability changes by the multiplier given in the e^b - columns in Table 6. The most important variables in determining spill probability in case of collision are:

1. If the collision happens in the tank compartment (θ =*1*), having a spill is 18.8 times higher than otherwise.
2. If W_{DH} increases by one meter, then the spill probability decreases by a multiplier of 0.151.
3. Each knot increase in the initial striking ship velocity increases the spill probability by a factor of 1.078. In the same manner, when the length of the striking ship increases by one meter, the spill probability becomes 1.006 times higher.

If θ is not generated for the calculations in advance - that is, it is not known in advance whether the collision will happen in the cargo compartment or not - then the following equation is to be used

$$\Pr(spill\ in\ case\ of\ collision|X) = \Pr(\theta = 0)\frac{1}{1 + e^{-z_{\delta=0}}} + \Pr(\theta = 1)\frac{1}{1 + e^{-z_{\delta=1}}}, \qquad (10)$$

where $\Pr(\theta = 0) = 0.3$ and $\Pr(\theta = 1) = 0.7$ when applying the assumptions of this paper.

Applying this calculation the correct classification percentage is 62.4 % for the training and 62 % for the validation data sets. Removing the θ – variable altogether from the logistic regression model gives the following estimates:

Table 8. Logistic regression result table from SPSS using approach variables

Independent variables x_i	Estimate b_i	Significance	e^b
Constant x_0	2.053	0.000	7.793
Double hull width (W_{DH})	-2.803	0.000	0.061
Velocity (V_{Ainit})	0.058	0.000	1.060
Length (L_A)	0.004	0.000	1.004

The prediction accuracy drops to 63.4 % of the cases in the training data set and in 61.8 % of the cases in the validation data set.

Table 9. Confusion matrix for the training data set when not including θ

		Logistic regression model results		
		No spill	Spill	Correct classification %
Sormunen et al. (2013) model results	No spill	865	603	58.9
	Spill	468	990	67.9
Correct classification %		64.9	62.1	

From the confusion matrix it can be seen the logistic regression correct classification this time is around 60 % which is not very good as even pure “coin-flipping” gives a ~50 % correct classification. This means that predicting spill / no spill based on approach variables only - without knowing whether the collision will happen in the tank compartment - is not really meaningful due to the low prediction accuracy.

UNCERTAINTY DISCUSSION AND RECOMMENDATIONS FOR FUTURE RESEARCH

The results presented in this paper are subject to uncertainty due to the different models’ simplifications and generalizations. It is still uncertain exactly which tankers carry chemicals, which carry gas and which carry oil or oil products, especially since many tankers are double-classified for oil products as well as bulk chemicals. This needs more research. Only if cargo manifests for each and every tanker sailing in the GoF would be investigated could the classification be made in a reliable manner.

In order to improve the risk analysis results, the following suggestions are made for future research: The traffic simulation should be improved so that it can simulate ship sailing in ice conditions as well as developing a more realistic model for estimating how ship encounter scenarios develop into collision scenarios. The link between the approach and the collision variables such as speed and angle require more detailed data and modeling. One of the biggest challenges involves determining the causation factor (or equivalent) in an accurate manner due to the high degree of complexity and variability of the socio-technical system in question and further in the accident occurrence within such a system. Also the traffic simulation should be re-coded to assign tanker type and cargo in advance. Furthermore, the collision consequence model by Sormunen et al.[27] contains several simplifications (quasi-static assumption, indestructible bulb, assumption of linear penetration resistance regardless of ship bow form and/or deformation, assuming that is stern/bow collision lead to no spill) which should be addressed with future research. The need for future research is underlined by the fact that the calculated penetration perpendicular depth exceeded struck tanker width in 16.8 % of the cases which intuitively sounds as much but might not be so as in this paper the tankers are relatively small. Also other common accident types such as groundings should be included in the analysis and their results compared.

The numerical division of chemical hazard level to a scale of 0-3 is a major simplification: Generally, this classification will not describe what the effects for humans or water environment are or what chemicals are most hazardous e.g. to fish species. The impact of a spill depends on the behaviour of the chemical or chemicals in question. It can be concluded that the most harmful chemicals for human health have quite opposite properties to those that are most hazardous for water biota. For human health, the most hazardous chemicals are those that are very reactive, form either very toxic or irritating (or explosive) gas clouds, and also have possible long-term effects, such as carcinogenic effects. From the environmental point of view, the most hazardous chemicals are those that sink, have a high solubility, possibly stay at the water column, are persistent, bioavailable and very toxic and can have possible long-term effects. [24, 44, 45] For future research it is proposed that a comprehensive quantitative risk scoring mechanism is developed for all hazardous liquids transported in bulk which is lacking at the moment.

As already mentioned the main results of the risk analysis such as collision frequency cannot be directly verified for the GoF given the available statistics[33], a common problem for high consequence – low frequency accidents[34]. However, an uncertainty analysis is possible and is done as follows based on categorizing and analysing the simplifications and assumptions of the model that were already mentioned in this chapter. The framework for this uncertainty assessment analysis (UAA) is based on the approach taken by Milazzo and Aven[28]. This UAA combines the results of the sensitivity analysis (i.e. how much change in one variable value changes the overall results) with the epistemic uncertainty (i.e. how well is the phenomena understood/ how good data is available) and takes their average to obtain a so-called importance score. Inspired by this approach, the authors propose a framework for assessing uncertainty related to this kind of risk analysis, see results in Table 10. This is done in order to assess the overall uncertainty regarding the model as well as to highlight where future research is needed most. The classification for degree of uncertainty goes as Milazzo and Aven[28] propose:

Low (L) if one or more of the following conditions are met:

– the assumptions made are seen as very reasonable

– much reliable data is available

– there is broad agreement/consensus among experts

– the phenomena involved are well understood; the models used are known to give predictions with the required accuracy

High (H) if one or more of the following conditions are met:

– the assumptions made represent strong simplifications

– data is not available or is unreliable

– there is lack of agreement/consensus among experts

– the phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions

Medium (M) if conditions between those characterizing low and high uncertainty.

The way Milazzo and Aven[28] define the L-M-H classification seems to be so that the L/ H classes are not mutually exclusive, which means that the class definitions have some degree of ambiguity. Also it is difficult to assess what exactly is e.g. a "very reasonable" assumption, leaving a degree of subjectivity (and uncertainty) in the uncertainty assessment analysis itself.

The authors propose adding a "sensitivity uncertainty" category to the UAA that is not found in Milazzo and Aven[28]. Sensitivity uncertainty is defined as the uncertainty about the effect of local changes in parts of the model to the overall risk measure. This is usually connected to limitations regarding possibilities to carry out detailed sensitivity analysis e.g. if the modelling technique used has significant limitations when it comes to efficient sensitivity analysis. In this case this especially applies for the traffic simulation due to the structure of the algorithm. Using other methods there might not be such uncertainty if the technique allows for thorough sensitivity analysis.

We define sensitivity as the expected change in risk metric output conditional to parameter value or model part conceptual change. The sensitivity uncertainty is assigned as unknown (U) if there is too little information available to make an assessment. The importance score is based on the average of the epistemic uncertainty, sensitivity and sensitivity uncertainty taken together.

Table 10. Risk model uncertainty assessment analysis matrix

Model part	Epistemic uncertainty	Main reasons	Sensitivity	Main reasons	Sensitivity uncertainty	Main reasons	Importance
AIS-data grouping for traffic simulation	M	Routes grouped separately for each departure/destination but data gaps exist	L	Subjective assessment	H	Subjective assessment	M
Traffic simulation	M	Sampling procedure done as time-variant Poisson process but not including traffic scheduling	M	Subjective assessment	U		M
Collision candidate estimation	H	Major simplifications regarding navigator actions	H	See Goerlandt and Kujala[47]	U		H
Chemical tanker separation from other tankers	M	Data incomplete and determination post-hoc based on tanker DWT	H	Major changes in expected spill return periods usings differnet filtering assumptions	L	Subjective assessment	M

Causation factors	H	Understanding and modelling human errors subject to major simplifications, phenomenon not understood in detail	H	Direct multiplier of risk, major variance in different estimates[32]	L	Sensitivity discussed in Hänninen and Kujala[29]	M
Collision angle	H	Evasive manoeuvring models make major simplifications, phenomenon not well understood	M	See Sormunen[32]	L	Effect of collision angle on collision energy reasonably well understood	M
Collision location on the struck ship hull	L	Uniform distribution assumption reasonable according to accident data	H	If collision in tank compartment, spill probability much higher	H	Actual effects of collision damage due to end/rear collisions unknown	M
Collision velocity	H	Link between collision angle and velocity missing, turning decreases speed but effects unknown. Link between approach and collision velocity subject to major assumptions	M	See logistic regression models here and in Sormunen et al.[27]	L	Relationship between collision velocity and collision energy quite well understood	M
Collision damage model	H	Major simplification regarding with respect to both damage length and collision energy	M	Subjective assessment	H	Subjective assessment	H
Chemical hazard level	H	No official quantitative hazard score exist, no interaction modelled, different chemicals toxic for different species	H	Multiplier of whole risk	U		H

The reasoning with the sensitivity uncertainty assessment is basically an assessment of how much the authors know about this specific part of the model and we had in many cases to resort to heuristics, i.e. a subjective assessment. As can be seen in Table 10, the importance and the epistemic uncertainty is medium-high for most cases.

Conclusions

This paper presents the risk measured as expected number of tanker collisions and spill volume per year in the GoF for chemical tankers. The most risk-prone locations are the lane to Sköldvik and the area between Helsinki and Tallinn due to the high number of vessels crossing each other's paths.

The total number of expected collision in the whole GoF is 0.06 for all tankers and 0.013 for chemical tankers only, meaning one accident on average every 17 / 77 years respectively. Using the chemical tanker filtering in Sormunen[32], where also some tankers above 20 000 DWT are assumed to be chemical tankers, the chemical tanker collision return period decreases to one on average every 45 years.

In this paper, using the collision consequence model by Sormunen et al. [27] a collision leads to a spill in 49.8 % of the cases for chemical tankers versus 42.3 % for all tankers in the simulation. Combining this with the expected collision return period of 77 / 17 years for chemical tankers / all tankers respectively, this means that a chemical spill will happen on average once every 156 years and a spill of any kind due to a ship ramming a tanker once every 40 years. The total expected chemical spill volume per year is 12.6 m^3 versus 28.8 m^3 when using the filtering in Sormunen[28]. The chemicals carried to and from eastern part of the Finnish GoF were found to be on average slightly more hazardous than chemicals carried elsewhere in the GoF.

It was noted that different models for ship speed, angle and collision velocity give different estimates for spill probability in case of collision. A model that links approach and collision speed was presented based on re-analysis of statistic collected by Tuovinen[37]. It was also pointed out that models presented in literature mostly do not link approach variables and collision variables.

The collision consequence model by Sormunen et al. [27] can be used relatively reliably for estimating spill probability: Using the impact variables a spill prediction accuracy of more than 90 % can be achieved[27]. However, using the approach variables only, the prediction accuracy is quite low (62-63%) unless the value of θ is known (75-77 %). The reference point is that by randomly guessing "spill" or "no spill" for the cases presented here a correct classification percentage of 50 % should be achieved, meaning that an accuracy of ~60 % is not very good.

The UAA of Milazzo and Aven[28] was found to be useful as a starting point for systematically assessing and presenting the uncertainty of this risk analysis despite the somewhat subjective nature of the evaluation. The authors propose adding a category called "sensitivity uncertainty" to the UAA as in some cases the sensitivity of the whole model to changes in individual parts is not fully known due to practical limitations. Looking at the uncertainty matrix in Table 10, the uncertainty and importance is medium-high despite using best data available and state-of-the –art models. That means that using this approach, getting the exact spill frequency at the exact locations and the resulting exact spill volume distributions cannot be done reliably at the present moment. Also since the risk output is a function of all the sub-models, uncertainty of one part propagates through the system.

This means that it is of special importance to research more in-depth the model parts with high importance. Alternatively a different risk approach could be adopted altogether in order to model the risk more reliably: Risk could be defined and foremost taken as the uncertainty regarding (negative) outcomes rather than what it is in this case, where risk revolves mainly around describing expected outcomes and their probabilities (plus the uncertainty of the values). See e.g. Aven[48] for a discussion on the topic. A "bottom-up" approach is also viable for reducing risk in many cases; that is, analysing potential chains of events that lead to accidents and then installing barriers or changing practices to prevent mistakes or failures on a lower level from escalating into an accident, see e.g. Sklet et al.[49]. If the current approach is kept, priority should be given to the parts of the model that score "high" on the importance score in Table 10 as they affect the outcome of the risk analysis most, see Table 10.

For decision-making purposes this means that risk analysis results in cases similar to the results presented here should not be used without critical reflection and evaluation of the findings and the effects of the uncertainty in the model. This also depends on the scope and aim of the decision-making: Is the decision- maker interested in collision frequency, geographical distribution of the risk or consequences in case of spill? The more detailed the need for information regarding risks, the bigger a role the uncertainty plays. However, despite the uncertainty the risk analysis results here should correlate with the underlying "actual" risk as the traffic patterns and volumes, ship sizes, etc. are taken straight from actual shipping data and serves as a useful starting point for future improvements and analysis. When putting the results of the extended risk analysis done here into the framework of Stirling and Gee[50], we are nevertheless still in the most desired area – "risk" – as we have well-defined outcomes and some basis for probabilities. Note thought that the impact of potentially spilled chemicals on the marine environment and human health could not be precisely determined.

Knowledge about likelihoods	Knowledge about outcomes		
	Outcomes well defined		Outcomes poorly defined
Some basis for probabilities	**Risk**	Incertitude	Ambiguity
No basis for probabilities	Uncertainty		Ignorance

Figure 10. Formal definitions for risk, uncertainty, ambiguity and ignorance[50]

The results of this study can be used as part of a larger risk analysis framework for improving safety in the Gulf of Finland and in updating the results of Sormunen[23] as the risk analysis done here gives an idea of what size of chemical spills are to be expected in the GoF. where, how often and how toxic the spill is expected to be. Also the effect of changes in double hull width, collision angle and impact velocity are analyzed- information that can be used in e.g. evaluating tanker construction regulations or changing traffic recommendations in order to mitigate risk. Knowledge and awareness of risk and the effects of different risk control options allows for proactive risk mitigation before accidents happen instead of reactive mitigation – something that this paper contributes to.

Finally the authors recommend that uncertainty assessment should be made a standard part of risk analysis as these affect decision-making. Without a systematic and relatively easy to interpret UAA it is complicated for outsider decision-makers to understand the limitations of the models found in literature. Not doing so can lead to sub-optimal or ineffective decisions being taken regarding how to mitigate risk at sea.

In this case the degree of uncertainty and the propagation of uncertainty throughout the whole model only becomes apparent after applying a systematic manner of assessing the uncertainty. If this would not have been done the true extent of the uncertainty would not have been detected which could have led to problems regarding decision-making because the “true” collision and spill frequency and size may deviate substantially from our results.

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