

A RISK FRAMEWORK FOR MARITIME TRANSPORTATION SYSTEMS

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ABSTRACT

Maritime accidents involving ships carrying passengers may pose a high risk with respect to human casualties. For effective risk mitigation, an insight into the process of risk escalation is needed. This requires a proactive approach when it comes to risk modelling for maritime transportation systems. Most of the existing models are based on historical data on maritime accidents, and thus they can be claimed of being reactive instead of proactive.

This paper introduces a systematic, transferable and proactive framework estimating the risk for maritime transportation systems, meeting the requirements stemming from the formal definition of risk, which is adopted. The framework focuses on ship-ship collisions in the open sea, with a RoRo/Passenger ship (RoPax) being considered as the struck ship. It is developed with the use of Bayesian Belief Network, which effectively propagate the knowledge and understanding of the analysed system through the model. We expect this approach to assist the knowledge-based risk decision-making not only by informing the user about the risk but also about the effect of limited knowledge and understanding of the analysed system, on the risk.

KEYWORDS

Maritime transportation, RoPax safety, Risk analysis, Bayesian Networks, F-N diagram, Ship collision

INTRODUCTION

Maritime traffic poses various risks in terms of fatalities, environmental pollution, and loss of property. In particular, accidents where ships carrying passengers are involved may pose a high risk with respect to human casualties. This paper introduces a framework determining the risk resulting from an open sea collision involving a RoPax. First it covers an identification of the events that follow a collision between two ships in the open sea and second it evaluates the probabilities of these events, concluding by determining the severity of a collision. The introduced framework attempts to capture the causality, when it comes to describing the evolution of the accident, which makes the framework systematic. Its modular nature allows continuous improvement and adaptation to various locations and conditions, thus making its transferable. Finally, the framework is developed using a Bayesian Belief Network (BBN), which is a recognised tool for knowledge representation and efficient reasoning under uncertainty, which makes the framework proactive.

RISK FRAMEWORK DEFINITION

The aim of the proposed framework is to estimate the risk in maritime transportation system, focusing on the probability and consequences of selected accidental scenarios that ultimately lead to the loss of a struck RoPax ship. These scenarios are: 1) in a collision of a RoPax with other ship the inner hull of the RoPax that is struck is breached and consequent flooding is experienced; this can result further in the loss of the ship; 2) the RoPax that is struck has no significant hull damage; however, the ship is disabled and drifts, thus experiencing significant rolling as a result of wave and wind action, which can result further in the ship capsizing. The loss of the RoPax is expected if two consecutive limit states are exceeded, namely crashworthiness and stability. These are conditional upon various events, of which the most relevant are:

1) the striking speed and striking angle for the given ship mass ratios, leading to the rupture of the inner hull of a struck RoPax conditional upon a collision; 2) the extent of damage leading to the significant ingress of water, conditional upon the inner hull being ruptured; 3) the hydro-meteorological conditions contributing to the ship capsizing given the significant ingress of water; 4) the maximum roll angle at which a disabled, intact RoPax capsizes. To obtain the above we use the FEM simulations, a six degree-of-freedom ship motion model, traffic data obtained from a maritime traffic simulator and from Automatic Identification System (AIS), and available data from literature. Subsequently the corresponding probabilities of the limit states being exceeded given the traffic and environmental conditions are evaluated.

Developing the qualitative part of the framework

In this step, the graphical structure of the framework is created. As available accident databases are scarce with respect to the consequences for a RoPax ship that is struck by another ship, we utilise the qualitative part of the existing risk framework for RoPax - see (Konovessis and Vassalos 2008; Vanem et al. 2007) - and confront it with expert knowledge about the domain.

Developing the quantitative part of the framework

The number of probabilities required for a framework depends on its structure, the number of variables and their states. As the framework is developed with the use of a BBN, the former grows exponentially with the latter. To reduce the number of probabilities that need to be determined to evaluate the framework, we use the parametric probability distributions (PPDs) for the variables. These provide simple computation rules for obtaining the required probabilities; see (Drużdzal and van der Gaag 2000).

Validating the framework

The risk framework is validated by performing the following: sensitivity analysis of the

framework, value-of-information analysis, influence analysis, and a comparison of the results obtained with the available data. This stage is important in the context of the reliability and validity of the framework and knowledge distribution and uncertainty analysis in the framework and its output; see for example (Aven and Heide 2009).

RISK FRAMEWORK AGGREGATION

This section describes the methods used to determine the variables and the relations among them focusing on maritime traffic system operating in the Gulf of Finland (GoF). The framework is encoded with a BBN, which is developed by means of an available software packages called GeNIe. The qualitative description of the framework is given in Fig.1, where colours are used to make a distinction between variables, which are obtained from the numerical simulations (blue), taken from the literature (yellow) or based on certain assumptions (grey).

Collision probability

The probability of a collision between two ships in the open sea in which the RoPax is struck by another ship is estimated by means of the dynamic maritime traffic simulator (DMTS), presented in our previous work by Goerlandt and Kujala (2011), supported by the accident statistics compiled for the GoF. The input to the DMTS is taken from AIS, augmented with harbour statistics concerning the cargo types that are traded. The model determines the annual frequency of a collision between two ships assuming a RoPax being struck for the whole GoF, given ice-free conditions, which is 0.1. Assuming that the ice is present every year in the GoF, and remains for three months the frequency drops down to 0.07. On the other hand, the accident statistics reveal the accident frequency of 0.01 for the analyzed sea area and ship type. However, the modeled and observed frequencies are burdened with some amount of uncertainty, due to assumptions in the DMTS or simplifications in reasoning from the accident

statistics. Therefore we assume that the "true frequency" falls between these two numbers, and consider them as limits for a uniform distribution, estimating the probability of an open-sea collision, where a RoPax is a struck ship.

Collision parameters

Another item of information derived from the DMTS concerns maritime traffic data in terms of the composition of the traffic, ship types, ship sizes, collision angles, collision speed, and the time of day of a potential collision. They describe in details the tempo-spatial layout of traffic. The DMTS generates a trajectory for each single vessel sailing in the area, called a traffic event, and assigns a number of parameters to this event, e.g. ship particulars, ship speed and course, departure time from a given waypoint. For a detailed description of DMTS the reader is referred to Goerlandt and Kujala (2011). The modelled motion parameters of ships on a collision course (their speeds and courses) do not account for the changes caused by evasive manoeuvres intended to forestall a collision. We adopted a two-step procedure to fill this gap, first, the initial value of ship speed is obtained from the DMTS, and second it feeds the statistical models, which deliver the actual collision speed. There are several different statistical models for estimating the collision speed and collision angle; see (Goerlandt, Stahlberg, and Kujala 2012). However, only one, proposed by Lützen (2001), takes into account the changes in the initial parameters resulting from evasive action taken by the colliding ships. Therefore, this concept is applied here as follows: 1) the velocity of a striking ship V_A follows a uniform distribution for velocities between zero and 75% of her initial speed, then the probability decreases triangularly to zero at her initial speed; 2) the velocity of a struck ship V_B is approximated by a triangular distribution with the most likely value equal to zero and a maximum value equal to her initial speed; 3) the initial values of V_A and V_B are obtained from the DMTS; 4) the collision angle, defined

as the difference in the headings of two colliding ships, is uniformly distributed between 10 and 170 degrees

Then, applying the four-step random sampling Monte Carlo procedure, the distribution of the actual collision speed is estimated: 1) sample the initial speed of a striking ship obtained from the MDTs, then use it as an input to determine the appropriate uniform-triangular distribution; subsequently sample the speed from this distribution randomly, and store it as V_A ; 2) sample the initial speed of a struck ship obtained from the MDTs and use it as an input to the triangular distribution; subsequently sample the speed from this distribution randomly, and store it as V_B ; 3) randomly sample the collision angle α from the uniform distribution; 4) knowing the V_A , V_B and α , calculate the relative speed at which ship A hits ship B, consider it the collision speed, and store it as $V_{(A,B)}$.

For each collision encounter obtained from the MDTs, the above procedure is run repeatedly, and a set of collision speeds given a certain collision angle is arrived at. Then, all the collision speed values that have been obtained are ordered according to the collision angle and are divided into three sub-sets: 10-45 degrees, 45-135 degrees, and 135-170 degrees. Subsequently, the sub-sets are described with the use of normal distributions, which are the best-fits, see Table 1.

Table 1: The continuous probability distributions for variable collision speed, given the collision angle

Collision angle [deg]	Collision speed [kn]
10-45	CS-1=N(2.35; 1.64)
45-135	CS-2=N(10.86, 8.26)
135-170	CS-3=N(14.2, 5.53)

Rupture of the inner hull of the RoPax

The value of the actual collision speed is one of the inputs to a function determining whether the inner hull of a RoPax is ruptured (*ihr*); see the Heaviside function given by Equation 1. The other input is the structural limit state (LS_{struct}) of the ship being analysed described by the function called *striking speed*. The latter is evaluated with the use of a simulation model, which is described here.

$$ihr = \begin{cases} 0 & V_{(A,B)} < LS_{struct} \\ 1 & V_{(A,B)} \geq LS_{struct} \end{cases} \quad (1)$$

The LS_{struct} is a function of the sizes of colliding ships, the striking angle and the relative striking location along the hull of a struck RoPax and is determined using the concept of collision energy, which is evaluated for the reference RoPax; see Table 2. In the case study presented here, the following mass ratios of the colliding ships are considered, with the reference to RoPax: 0.6, 0.8, 1.0, 1.33. Therefore almost 80% of maritime traffic in the GoF is covered. The remaining share belongs mostly to ratios higher than 1.3, which can be assumed to be less critical concerning a hull rupture for the usual blunt bow shapes, as well as a small percentage of ratios lower than 0.6, which, however, are not taken into account.

Table 2: The characteristics of the RoPax vessel that was analysed.

Length	188.3 [m]
Breadth	28.7 [m]
Draught	6.0 [m]
Displacement	19710.0 [t]

The available energy for structural deformations is obtained according to the calculation model introduced by Tabri (2010) and improved in Ehlers & Tabri (2012). This model estimates the dynamics of a ship

collision and the share of energy available for ship motions and structural deformations. As a result of the combination of this dynamic simulation procedure and the non-linear finite element method a good estimation of structural damage in various collision scenarios with oblique angles and varying eccentricities of the contact point can be achieved, see also Montewka et al. (2011). The simulated collision scenarios, defined by the striking angles and relative striking locations along the hull of the RoPax are depicted in Fig. 2. For the purpose of collision simulations the LS-DYNA solver version 971 is used and the ANSYS parametric design language is used to build the finite element model of the reference RoPax vessel. A three-dimensional model is built between two transverse bulkheads of the midship section, spaced 26.25 m apart - see Fig. 3- and not accounting for differences in the ship structures present along the length of the ship. Moreover, the translational degrees of freedom are restricted in the plane of the bulkhead locations, whereas the remaining edges are free. The structure is modelled using four noded, quadrilateral Belytschko-Lin-Tsay shell elements with five integration points through their thickness. The characteristic element length in the contact region is 50 mm in order to account for non-linear structural deformations, such as buckling and folding. The element length-dependent material relation and failure criterion according to Ehlers (2010a) is utilised for the simulations. Crashworthiness simulations employing this material model have been found to be sufficiently accurate compared to large-scale experiments; see Ehlers (2010b). Standard LS-DYNA hourglass control and automatic single surface contact (with a friction coefficient of 0.3) are used for the simulations. Moreover, the collision simulations are displacement-controlled. The rigid bow is moved into the side structure of the ship in a quasi-static fashion. Hence, this approach results in the maximum absorption of energy by the side structure alone, which is needed for a comparison and can be considered conservative

and therefore suitable for fast prediction. Moreover, two draughts are considered for the struck ship, which are a function of the maximum variations in draught to be expected for this kind of vessels. Therefore the maximum striking location is positioned close to the first deck and the second striking location is located closer to the tank top, see Fig. 3. Then we assumed that both locations are equally probable and thus take the average response. As a result, the relative energy available for structural deformations as a function of the longitudinal striking location is obtained for a mass ratio of 1.0; see Fig. 4. For mass ratios of 1.33 and 0.6 these curves are scaled with the factors 0.84 and 1.13, respectively, to account for the change in dynamic behaviour. Therefore the values of striking speed for a given mass ratio, striking angle, and striking location along the hull of the struck ship, causing a breach of her inner hull, are evaluated and considered LS_{struct} ; see Fig. 5. Finally the probability of the LS_{struct} being exceeded - $P(ihr)$ - is determined by the framework introduced here, for the case study analysed here, it yields 0.61.

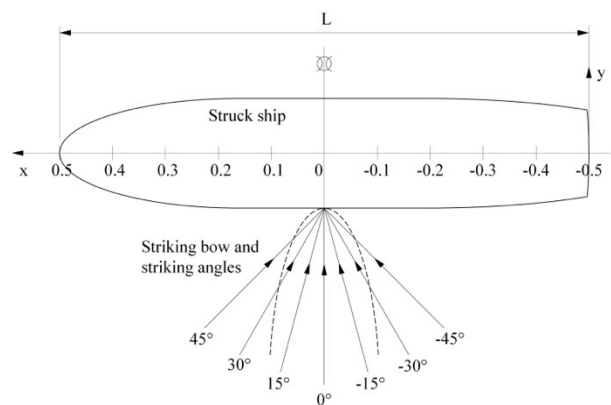


Fig. 2: Relative striking locations and striking angles analysed.

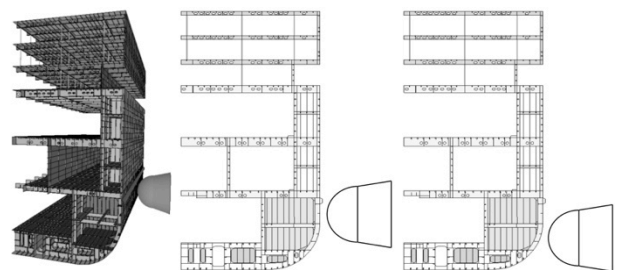


Fig. 3: FEM model and vertical striking locations.

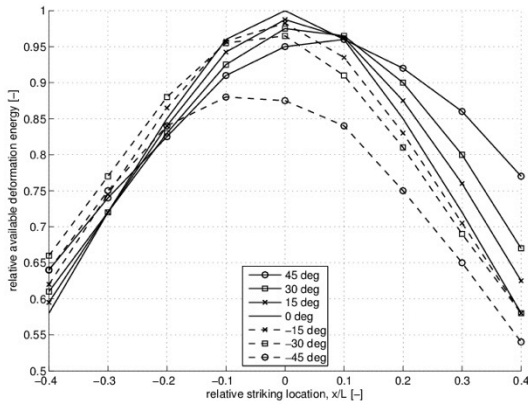


Fig. 4: Relative available deformation energy versus relative striking location and striking angle.

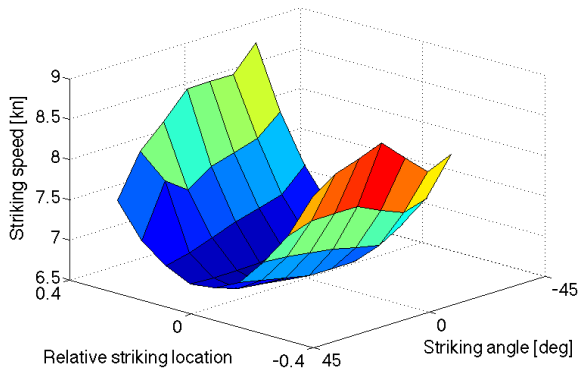


Fig. 5: Striking speed, describing LS_{struct} for a RoPax, as a function of the relative striking location and striking angle, mass ratio 1.0.

Masses of colliding ships

The masses of colliding ships are obtained from the DMTS, and then modelled by a log-normal distribution ($\mu = 0.25$, $\sigma = 0.70$).

Collision angle significant

It is assumed that the collision angles falling in a range between 45 and 135 degrees may lead to a rupture of the inner hull of a RoPax, and thus they are considered relevant. The effect of a change to this assumption on the outcome of the framework and relevant intermediate variables is determined at the validation phase of the framework.

Capsizing of a damaged ship as a result of flooding

As a result of a ship-ship collision, where the collision speed exceeds LS_{struct} for a given ship,

the ingress of water can be expected. This in turn can bring the damage ship towards the boundaries of her stability limit state (LS_{stab}). The latter is developed utilising the concept of a "capsize band", determined on the basis of numerical simulations that consider characteristics of the ship, her loading conditions and environmental properties as explanatory variables. The band is determined for a given ship and it is a function of wave height (H) and ship stability (s_i); it also takes dynamic time-variant flooding characteristics into consideration, see (Papanikolaou 2001; Papanikolaou and Spanos 2007). Within the band a transition between two states, namely "safe" and "unsafe", takes place. The band begins at a wave height that does not cause the ship to capsize and ends at the wave height where the loss of the ship is always expected. The capsize boundaries are symmetrical around the value of the critical wave height (CWH). The band is estimated with the use of a sigmoid function (S). For detailed description of the concept the reader is referred to Papanikolaou et al. (2010). This logic is captured by the following function:

$$capsize(s_i) = \begin{cases} 0, & H < LS_{stab}(s_i) \\ S(CWH), & LS_{stab}(s_i) < H < LS_{stab}(s_i) \\ 1, & H > LS_{stab}(s_i) \end{cases} \quad (2)$$

The framework presented here assumes that the flooding contributing to the loss of the ship occurs if the wave is higher than a critical height and at least the main car deck and two compartments beneath are flooded, which corresponds to the accident scenario adopted in the previous work of Papanikolaou et al. (2009). Wave data for the sea area that is analysed is shown in Fig. 6. Four, equally likely stability conditions of a damaged RoPax are assumed, which correspond to the following CWH [m] = [2.0, 2.5, 3.5, 5.5], with appropriate bandwidths around each CWH , see Table 3. For a detailed description of the ship conditions and the method the reader is referred to (Papanikolaou et al. 2010). Finally, the

conditional probability of a RoPax exceeding her stability limit state is obtained, which for the case study presented here yields 0.17.

Table 3: The capsize bands and likelihood functions applied in the model

Likelihood functions (P_{capsize}) and its capsize bands			
CWH	$P_{\text{capsize}=0}$	$P_{\text{capsize}=(0,1)}$	$P_{\text{capsize}=1}$
2.0 [m]	0 – 1.3 [m]	1.3 – 2.8[m]	> 2.8 [m]
2.5 [m]	0 – 1.5 [m]	1.5 – 3.4 [m]	>3.4 [m]
3.5 [m]	0 – 2.0 [m]	2.0 – 4.8 [m]	>4.8 [m]
5.5 [m]	0 – 3.5 [m]	3.5 – 7.2 [m]	>7.2 [m]

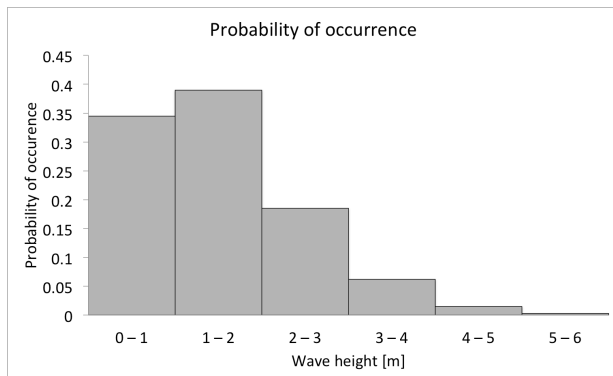


Fig. 6: The wave statistics for the Baltic Sea including the Gulf of Finland, Global Wave Statistics (1986).

Damage extent significant

Obviously not every hull breach results in such severe flooding, therefore the conditional probability of the damage size (*des*) allowing critical flooding is estimated by considering the mass ratio of the ships colliding, the collision speed and collision angle, adopting the function explained by an equation below. The collision speed leading to significant damage is taken here as 120% of the structural limit state for a RoPax defined by the striking speed, introduced in an earlier section. The collision angle contributing to significant damage is called *collision angle significant* (*cas*) and it is introduced later in the text. The probability of damage resulting in severe flooding, given a

collision is evaluated by a node called *damage extent significant* (*des*), for a given case study it yields $P(\text{des}) = 0.15$.

$$\text{des} = \begin{cases} 1, \text{and}(\text{thr} = 1, \text{cas} = 1, V_{(A,B)} > 1.2LS_{\text{struct}}) \\ 0, \text{otherwise} \end{cases} \quad (3)$$

The analysis of the effect of a change to the assumption on the response of the framework is conducted at the validation stage.

Ships stay separated after collision

A RoPax suffering significant damage resulting from a collision may experience the rapid ingress of water if the opening caused by damage is exposed to high seas. This may be true if two ships that collided remain separated after the collision, instead of the striking ship having her forward part stuck in the side of the struck ship. The probability of these two ships being apart (*sss*), is governed by a function binding the following variables, *collision speed* ($V_{(A,B)}$), *collision angle significant* (*cas*), and *collision mass ratio* (*cmr*), through the following Heaviside function:

$$\text{sss} = \begin{cases} 1, \text{and}(V_{(A,B)} > 1.2LS_{\text{struct}}, \text{cmr} < 1, \text{cas} = 1) \\ 0, \text{otherwise} \end{cases} \quad (4)$$

The probability of ships staying separated for the case study presented here is 0.94. The analysis of the effect of changes in the assumptions on the results of the framework is carried out.

Capsize resulting from flooding

The framework developed here assumes that a RoPax will capsize if the structural limit state for the ship is exceeded, the damage is significant, the two ships that have collided are separate after the collision, and the stability limit state is exceeded for a given stability conditions. Otherwise the ship is not expected to capsize. The probability of this event is evaluated by the node called *capsize resulting*

from flooding and it yields 0.018 given a collision for the presented case study.

Time to capsize because of flooding

The time to capsize (*TTC*) is a relevant factor when it comes to the evaluation of the success of the evacuation of the ship once catastrophic flooding is experienced. The model that is applied here is based on the results of numerical simulations by Spanos and Papanikolaou (2010). The probability of the ship capsizing within 30 min of the damage event equals 0.8 and reaches 0.95 within 60 min. Therefore, the exponential distribution is used to determine *TTC*, with the following parameter, $\lambda = 0.05$, moreover the distribution is truncated at *TTC* = 180min.

The probability of a ship capsizing in Dead Ship Condition

Another type of consequence arising from an open sea collision is a ship capsizing as a result of wave and wind action, where the ship is in dead ship condition (DSC), meaning that the entire machinery installation is out of operation and the auxiliary services are not available. This phenomenon is dependent on the hull shape and weather conditions. Thus for the purpose of this case study simulations are performed to obtain the probability of a RoPax capsizing as a result of DSC using the state-of-the-art, six-degrees-of-freedom (6-*DoF*) ship dynamics model; see Matusiak (2011). The probability of the ship capsizing is assumed to be equal to the probability of a particular angle of roll being exceeded, in this case 60°. To calculate the probability of this roll angle being reached Monte Carlo simulations are applied. The 6-*DoF* model assumes that the overall ship response is a sum of linear and non-linear parts. Such a division is a result of the fact that the linear calculating methods are well known, and the hydro-mechanical radiation and diffraction forces are well presented by linear formulae. The main part of the first-order load is calculated with a linear approximation (added mass, damping coefficient), with the actual heading and placement with respect to

the waves being considered, whereas the following are considered to be the non-linear parts: Froud-Krylov forces, restoring forces, and non-linearity resulting from motion equations. For the case study that is analysed, the probability of a RoPax capsizing, given the collision followed by DSC, yields 0.0002.

Time to capsize as a result of DSC

The ship dynamics model mentioned in the previous section simulates ship motions in the time domain. Thus, for each event associated with a ship capsizing, the time instants of this event are recorded. Monte-Carlo simulations are applied to evaluate the fractions of cases where a ship capsizes, and thus the distribution of the time instants taken a ship to capsize as a result of DSC is obtained and considered an input variable to the risk framework. A log-normal distribution is used for modelling this parameter, where $\mu = 8.0$ and $\sigma = 5.7$, and the results are expressed in minutes.

Machinery damaged

The occurrence of DSC is governed by the unavailability of the ship's main propulsion or steering. The probability of the ship's propulsion and steering systems being damaged as a result of an accident is determined by the node called *machinery damaged*, given a RoPax being hit in the section housing the steering devices or main engine (*steer-me*) and having her inner hull ruptured. However we assume a 50% chance of the ME or the steering gear failing as a result of the collision impact only, even if the inner hull is not ruptured, adopting the following formula:

$$md = \begin{cases} 1, \text{and} (ihr = 1, \text{steer} - me = 1) \\ 0.5, \text{and} (ihr = 0, \text{steer} - me = 1) \\ 0, \text{otherwise} \end{cases} \quad (5)$$

It is assumed, that the length of the section accommodating the propulsion is 0.2 LOA, and thus *str-me* is modelled as follows:

$$md = \begin{cases} 1, \text{if} (\text{uniform}(0,10) > 8) \\ 0, \text{otherwise} \end{cases} \quad (6)$$

The probability of the machinery being damaged as a result of a collision for the case study analysed here yields $P(md) = 0.16$. The effect of the changes in the above assumptions on the results of the framework is carried out.

Accident response

Two means of responding to an accidental collision to a RoPax are considered in this framework. First, a ship salvage operation with the use of tugs is considered in a case where a ship that has been in a collision experiences DSC but no flooding occurs. Second, an ordered evacuation of a ship takes place if there is serious flooding following the collision. If the response time ($resp$) is shorter than the hazard exposure time (haz), namely the time to capsize as a result of flooding or DSC, such a situation is considered a success. Otherwise the response is not effective and loss of life (LL) can be expected and the following Heaviside function is applied to determine this parameter:

$$LL = \begin{cases} 0, & \frac{haz}{resp} > 1 \\ 1, & \frac{haz}{resp} < 1 \end{cases} \quad (7)$$

For the case study presented here, the following conditional probabilities for LL are arrived at: $P(LL_{flooding}) = 0.82$ and $P(LL_{DSC}) = 0.98$.

The time needed for evacuation of a RoPax

The time to evacuate the ship (TTE) is modelled with the use triangular distributions following the IMO recommendations. The effect of challenging weather conditions on the evacuation time is modeled in a fashion presented in Equation (8).

$$TTE = \begin{cases} T1 & \text{Day_and_wave_height} < 3m \\ T2 & \text{Night_and_wave_height} < 3m \\ T3 & \text{Day_and_wave_height} > 3m \\ T4 & \text{Night_and_wave_height} > 3m \end{cases} \quad (8)$$

where: $T1 = [20,20,40]$, $T2 = [20,40,40]$, $T3=[20,40,60]$, $T4=[25,40,60]$, expressed in minutes.

The time needed for tugs

The time needed for tugs to arrive at the scene is based on the weather conditions and the location of the accident relative to the nearest shore rescue station. The probable locations of an open sea collision in the GoF in which a RoPax is expected to be involved are obtained from the DMTS. Thus the time needed for tugs to reach the scene varies from 1 to 3 hours, given good weather conditions. In the event of bad weather this time is increased by a factor of 1.5.

The number of passengers on board the ship

In the case study presented here, the number of passengers on board the ship during a collision ($N_{passenger}$) is modelled by means of uniform distribution, with a lower limit of 200 and an upper limit of 3000. The lower limits is an estimate for a ship's crew and a minimal amount of passengers where the upper limit is an estimate of the maximum capacity of RoPax ships cruising in the GoF.

The number of fatalities

In a case where the accident response is not effective ($LL = 1$), the number of fatalities (N) is estimated. However, as a result of a lack of information on the relationship between the assumed explanatory variables: *time to capsize*, *evacuation time*, *number of passengers on board the ship* and the response variable N , it is difficult to define a precise model predicting N . Therefore, we decided to adopt here conservative assumptions, where N is proportional to the ratio $haz/resp$ and the number of passengers on board, as follows:

$$N = N_{passengers} haz/resp \quad (9)$$

RISK FRAMEWORK VALIDATION

We validate the framework by performing: 1) the sensitivity analysis, 2) the value-of-information analysis, 3) the influence analysis, 4) the convergence analysis.

The sensitivity analysis

It finds the essential variables, which have the highest, impact on the performance of the model. The results indicate that the model is sensitive to the changes in the following nodes: *stability conditions, collision mass ratio, collision probability, capsizing as a result of flooding, and time to evacuate a ship*. We attempt to tailor these variables to the specific ship type and location, and evaluate them as accurately as possible using the methods described in the previous sections. However, certain variables could not be determined without ambiguity thus the effect of those on the output of the framework is determined in following section. The distributions for the nodes with a lesser impact on the outcome of the framework are based on the generic data available in the literature, natural laws and the author's best judgment.

The value-of-information analysis

It indicates the variables among which the probability mass of the output is scattered. For this purposes the concept of entropy is utilised. The results reveal that the uncertainties of the output variables are mostly explained by the distributions of the variables named *capsizing as a result of flooding, collision probability, stability conditions, time to evacuate a ship, inner hull rupture, and collision mass ratio*. The remaining variables are less informative.

The influence analysis

It quantifies the effect of alternative assumptions on the outcome of the framework. The proposed framework allows very effective influence analysis to be performed, as the updating process of a BBN is instantaneous. The following variables are subject to this

analysis: *stability conditions, collision angle, collision angle significant, damage extent significant, ships stay separated, machinery damaged, and time to evacuate a ship*. The framework is evaluated for the number of possible combinations of the given input parameters, and a set of results expressed in a form of F-N diagram is obtained. Where F is the frequency of N or more fatalities. Then the medians and standard deviations of F for each N are determined, and a 95% confidence band around the mean value is obtained. The results of the analysis are depicted in Fig.7.

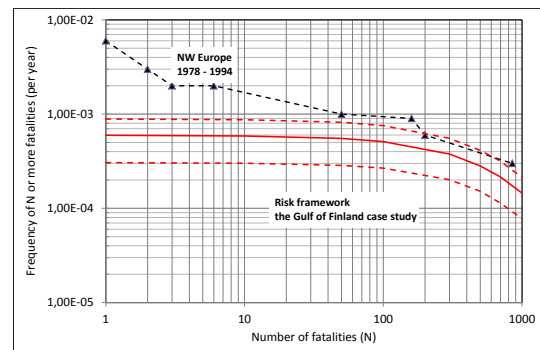


Fig. 7: A risk picture obtained here (in red), plotted against the historical data (1978-1994) on the risk to RoPax ships in European waters (in black).

Convergence analysis

Once the framework is defined and the results are arrived at, they are compared with the available data on the risk and severity of open-sea collisions in which RoPax ships were involved. First, the F-obtained N diagram containing the accumulated values of the risk of a RoPax capsizing as a result of flooding or DSC, is compared with the diagram based on the accident statistics; see Fig. 7. The latter is obtained from the available accident data on RoPax ships for the North-West European seas and is adapted from Konovessis, Vassalos, and Mermiris (2008). The results obtained show a good level of convergence of the modelled data with the observed data for higher numbers of fatalities. This can be explained by the fact that in the history of RoPax accidents the most severe ones were those accidents associated with the ship capsizing as a result of the car deck flooding. Moreover, it should be noted

that the statistics-based FN represents the risk of all types of accidents, not only collisions, which may be a reason for the divergence of plots for a smaller N. Second, two intermediate quantities, i.e. the conditional probability of the loss of a RoPax as a result of flooding - $P(C_{flood})$ - and the probability of serious casualties given an open sea collision - $P(des)$ - are validated with the data from literature as presented in Fig. 8. The probabilities that are obtained with the use of the risk framework presented here are continuous variables, following certain, nonparametric distributions; however, for the purpose of the validation and visualization of the results, the average values are used. The average value of $P(C_{flood})$ obtained from the framework – 1 - is close to the results obtained from the model based on global statistics – 2 - and to the results of analysis for the specific RoPax- 3 – see Konovesis, Vassalos (2007) and Guarin et al. (2009). However, the value delivered here is different from the results for a specific RoPax operating in the Atlantic Ocean - 4 – see Otto et al (2002) - but still of the same order of magnitude. Then, the average value of $P(des)$ from this model – 1 - is in line with the corresponding probability of serious casualties given open sea collision, according to historical data – 2 - as compiled by Guarin, Konovessis, Vassalos (2009).

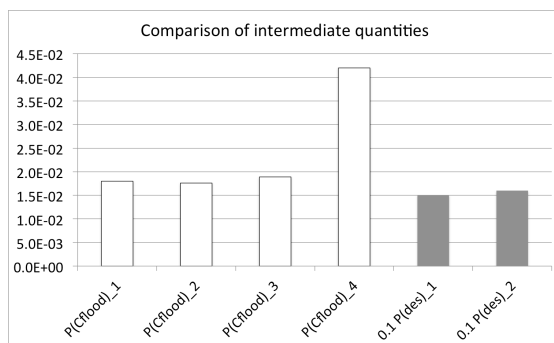


Fig. 8: Risk framework validation, comparison of various models

CONCLUSIONS

This paper presents a systematic, proactive and transferable framework for risk analysis and assessment in maritime transportation systems.

It utilizes BBN as a medium to express and propagate the knowledge that is available about the system being analyzed. This let us determine the areas of the framework which are either not known or understood well enough, and have significant effects on the outcome of the framework, meaning that they need to be treated with caution. Here the framework is used for a case study, evaluating the risk for an maritime traffic system operating in the GoF during the ice-free season, considering an open sea collision, where a RoPax is struck by another ship. The obtained results are valid within certain, predefined boundary conditions, but the modular nature of the risk framework allows its continuous improvement and adaptation to various conditions. However, we do not claim any "true numbers" for risk in the GoF, as the aim of the analysis is to demonstrate the abilities of the framework for knowledge-based risk assessment. Despite of the simplifications made in the framework, the results obtained are promising, and they show good convergence with the available data on RoPax accidents around Europe. The introduced risk framework can contribute to a concept of holistic risk modelling which can be utilised at the stages of either ship design or operation.

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REFERENCES

- Aven, Heide. 2009. "Reliability and Validity of Risk Analysis." *Reliability Engineering and System Safety*: 1862–1868.
- Global Wave Statistics, BMT Ltd, London, 1986
- GeNie Documentation, DSL, University of Pittsburgh, 2011.
- Druzdzel, van der Gaag. 2000. "Building Probabilistic Networks: "Where Do the Numbers Come from?" Guest Editors' Instruction." *IEEE Transactions on Knowledge and Data Engineering* 12: 481–486.

- Ehlers. 2010a. "Material Relation to Assess the Crashworthiness of Ship Structures." *Aalto University*. Aalto University.
- Ehlers. 2010b. "The Influence of the Material Relation on the Accuracy of Collision Simulations." *Marine Structures*: 462–474.
- Ehlers, Tabri. 2012. "A combined numerical and semi-analytical collision damage assessment procedure". *Marine Structures* 28 (1): 101–119.
- Goerlandt, Stahlberg, Kujala. 2012. "Influence of Impact Scenario Models on Collision Risk Analysis." *Ocean Engineering* 47: 74–87.
- Goerlandt, Kujala. 2011. "Traffic simulation based ship collision probability modelings." *Reliability Engineering and System Safety* 96: 91–107.
- Guarin, Konovessis, Vassalos. 2009. "Safety Level of Damaged RoPax Ships: Risk Modelling and Cost-effectiveness Analysis." *Ocean Engineering* 36 (12-13) (September): 941–951.
- Konovessis, Vassalos. 2008. "Risk Evaluation for RoPax Vessels." *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment* 222 (1) (January 1): 13–26.
- Konovessis, Vassalos. 2007. "Risk-based Design for Damage Survivability of Passenger Ro-Ro Vessels." *International Shipbuilding Progress* 54 (2-3): 129–144.
- Konovessis, Vassalos, Mermiris. 2008. "Risk Analysis for RoPax Vessels." *WMU Journal of Maritime Affairs* 7 (1) (April): 109–131.
- Lützen. 2001. "Ship Collision Damage." *Technical University of Denmark*. Technical University of Denmark.
- Matusiak, On the non-linearities of ships restoring and the Froude-Krylov wave load part. *International Journal of Naval Architecture and Ocean Engineering* 3 (2011) 111–115.
- Montewka, Goerlandt, Ehlers, Kujala, Erceg, Polic, Klanac, Hinz, and Tabri. 2011. "A Model for Consequence Evaluation of Ship-ship Collision Based on Bayesian Belief Network." In *Sustainable Maritime Transportation and Exploitation of Sea Resources*, edited by Enrico Rizzuto and C. Guedes Soares, 721–728. Taylor & Francis Group.
- Otto, Pedersen, Samuelides, Sames. 2002. "Elements of Risk Analysis for Collision and Grounding of a RoRo Passenger Ferry." *Marine Structures* 15 (4-5) (July): 461–474.
- Papanikolaou. 2001. "Benchmark Study on the Capsizing of a Damaged Ro-ro Passenger Ship in Waves." Issued for Comments To *International Towing Tank Conference*.
- Papanikolaou, Mains, Rusås, Szalek, Tsakalakis, Vassalos, Zaraphonitis. Goals - goal based damage stability, in: *Proceedings of the 11th International Ship Stability Workshop*, 2010, MARIN, Wageningen, pp. 46–57.
- Papanikolaou, Spanos. 2007. "Benchmark Study on Numerical Codes for the Prediction of Damage Ship Stability in Waves." In *10th International Ship Stability Workshop*. Germanischer Lloyd, Hamburg.
- Tabri. 2010. "Dynamics of Ship Collisions." *Aalto University*. Aalto University.
- Vanem, Rusas, Skjong, Olufsen. 2007. "Collision Damage Stability of Passenger Ships: Holistic and Risk-based Approach." *International Shipbuilding Progress* 54: 323–337.

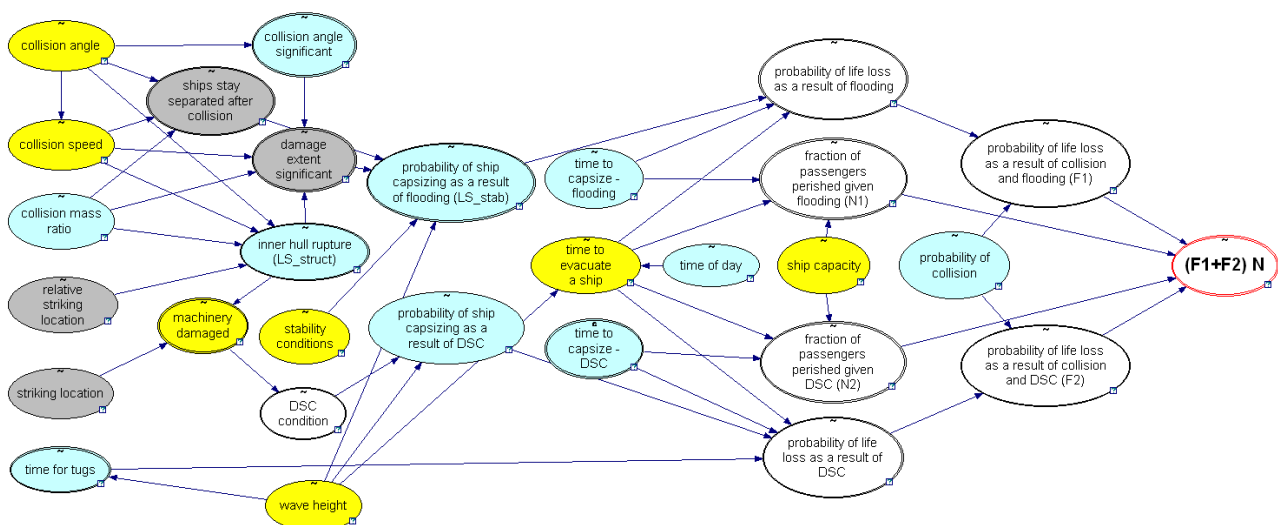


Fig. 1: The qualitative description of the risk framework introduced here.