A model for consequence evaluation of ship-ship collision based on Bayesian Belief Network

Jakub Montewka, Floris Goerlandt, Soren Ehlers & Pentti Kujala
School of Engineering, Aalto University, Finland

Sandro Erceg, Drazen Polic & Alan Klanac
As2con-alveus ltd. Research, development and applications, Rijeka, Croatia

Tomasz Hinz
The Foundation for Safety of Navigation and Environment Protection, Gdansk, Poland

Kristjan Tabri
Technical University of Tallinn, Estonia

ABSTRACT: In this paper, an attempt is made to define a new, proactive model for estimation the ship-ship collision consequences, assuming a RoPax as a struck ship. Therefore two major issues are addressed by this paper, one is an identification of the events that follow a collision between two ships at open sea and another is an estimation of the prior probabilities of the events. The latter are obtained in the course of the numerical simulations, observations and literature survey. Then the model is developed by means of Bayesian Belief Network.

Furthermore the sensitivity analysis of the proposed BBN is performed and results are compared with the available models, thus an initial verification of the results is provided.

Finally the probability of ship loss and human loss given a collision is estimated and the obtained results are discussed.

1 INTRODUCTION

Maritime traffic poses various risks in terms of human casualties, environmental pollution or loss of property. In particular, accidents where RoPax ships are involved may pose a high risk in terms of human casualties. In the publications related to modelling the risk of a RoPax ship (Vanem and Skjong 2004), (Antao and Guedes 2006), (Vanem et al., 2007), (Konovessis and Vassalos 2008), (Guarin et al., 2009), one type of models prevails, which is based on an event-tree concept. Moreover the data used to populate the models are based on the accident statistics, thus can hardly be considered proactive.

Therefore this paper introduces a proactive and transferable model for the probability estimation of ship loss and human loss resulting an open sea collision with respect to a selected type of RoPax ship sailing in the selected location. However the modular nature of the model allows for continuous improvement. The model is based on a Bayesian Belief Network (BBN) and utilises series of logically connected events (nodes). The relations among the nodes are given in a probabilistic way, where the prior knowledge is obtained in the course of numerical experiments, observation, analysis and simulation.

In the model presented, a RoPax loss occurs if one of the two accident scenarios is met:

1. The struck RoPax inner hull gets breached and the consecutive flooding is experienced, which can result further in a ship loss. Therefore the critical striking speed and angle for the given mass ratios are obtained with the use of the finite elements simulations;

2. The struck RoPax has no significant hull damage, however the ship is set disable and is experiencing rolling due to wave and wind action, which can result further in ship capsizing thus ship loss. Thus the probability of RoPax capsizing is calculated with the use of the six degree of freedom ship motion model.

Moreover numerous variables affecting the consequences are taken into account: maritime traffic composition in the analysed sea area, collision dynamics, ship hydrodynamics, weather...
conditions, locations of rescue ships with respect to the probable location of an accident, evacuation time from the ship and time of the day at which an accident is probable to happen.

Finally the outcome of the model is the probability of a struck ship loss given an open sea collision. The following boundary conditions should be observed: a given size, type and loading conditions of the struck ship, specific maritime traffic composition and weather conditions corresponding to the ice-free season in the Gulf of Finland.

2 MODEL FRAMEWORK

The presented model is part of the Formal Safety Assessment concept (FSA), which is commonly accepted and approved by the International Maritime Organisation (IMO) rule-making process (IMO 2002). Thus our focus is on the step 2 of the FSA process, see Figure 1.

Field of our interest depends on numerous related and highly uncertain factors, hence the model presented utilises a BBN, which is recognised tools for knowledge representation and efficient reasoning under uncertainty, see (Madsen et al., 2003).

2.1 Bayesian Belief Network—quantitative and qualitative description

A classical Bayesian Belief Network is a pair $N = \{G, P\}$, where $G = (V, E)$ is a directed acyclic graph (DAG) with its nodes $V$ and edges $E$ while $P$ is a set of probability distributions of $V$. Thus a BBN consists of two parts: a qualitative part (named structure) that is presented as a DAG, and a quantitative part (named parameters) that specifies the dependence relations defined by the structure.

The nodes of a BBN are represented by discrete random variables $X = \{X_1, X_2, \ldots, X_n\}$ whereas edges reflect the relationships among nodes. Each node is annotated with a conditional probability table (CPT), which represents the conditional probability of the variable given the values of its parents in the graph $(P(X \mid pa(X)) \in P)$. The CPT contains all conditional probabilities for all possible combinations of the parent nodes states. If a node does not have parents, its CPT reduces to an unconditional probability table, named also a prior probability of that variable.

Thereby a network $N = \{G, P\}$ is an efficient representation of a joint probability distribution $P(V)$ over $V$, given the structure of $G$ following the formula, see also (Madsen et al., 2003), (Darwiche 2009):

$$P(V) = \prod_{X \in V} P(X \mid pa(X))$$ (1)

A BBN adopted in our study consists of the CPTs which are obtained in two ways: either by the means of experiment or literature survey. In order to determine, which factors are essential thus should be modelled with greater caution, the sensitivity analysis is carried out at the initial stage of the model development. Once defined, the most vulnerable nodes were tailored to the specific ship type and location by means of experiments and methods described in the previous sections. The CPTs for the remaining nodes that had lower impact on the outcome of the model were based on the generic data available in the literature.

The qualitative and quantitative descriptions of the BBN developed are given in Figure 2.

2.2 Maritime traffic modelling

One of the inputs for the model presented is maritime traffic data, in terms of traffic composition, ship types, ship sizes, collision angles, collision speed and time of the day of a hypothetical collision. Most of these, except collision speed and angle are obtained from the dynamic model of maritime traffic, see (Goerlandt and Kujala 2011). The dynamic traffic model simulates the trajectory for each single vessel sailing in the area, while assigning a number of parameters to this vessel as illustrated in Figure 3. The input to this traffic simulation model is taken from the AIS, augmented with the harbours statistics concerning the traded cargo types. The results obtained from the simulation cover the following: time and location...
of a hypothetical collision encounter, types of ship, main dimensions, speeds and courses.

Additionally the collision speed and collision angle are modelled using statistical models taking into account the changes of the initial parameters due to collision evasive action, see (Lützen 2001). Whereas the initial speed and angle of ships are obtained from the traffic simulator.

2.3 Collision speed and angle modelling

There are several models to estimate the parameters relevant to a collision scenario, see also (Goerlandt et al., 2011). However most of them are based on the accident statistics and do not take into account the initial speed and angle of colliding ships, except one given by (Lützen 2001). Thereby, this concept is applied in the presented study, as follows:

- The velocity of a striking ship follows a uniform distribution for velocities between zero and 75 percent of an initial speed, then triangularly decreasing to zero;
- The velocity of a struck ship is approximated by a triangular distribution with a most likely value equal to zero and a maximum value equal to initial speed of a ship;
- The collision angle is uniformly distributed between 10 and 170 degrees.

Additionally the actual collision speed is estimated following the adopted five-step procedure: step 1—random sample a striking speed \( V_A \) of a ship \( A \) from an appropriate uniform-triangular distribution; step 2—random sample a struck speed \( V_B \) of a ship \( B \) from an appropriate triangular distribution; step 3—random sample the collision angle—from the uniform distribution; step 4—calculate the relative speed \( V_{\text{rel}} \) at which
ship A hits ship B; step 5—calculate a component of \( V_{AB} \) that is normal to a hull of struck ship B, finally \( V_{AB} \perp \) is collision speed. For the above procedure Monte Carlo simulations are applied, to get the distributions of collision speed and collision angle.

Finally a CPT is obtained, for model variable collision speed given collision angle, see Table 1.

2.4 Probability of inner hull rupture modelling

To determine the probability of RoPax inner hull rupture given a collision, the critical collision speed and angle is evaluated, using the concept of collision energy. Hence, the collision energy is evaluated for the given collision encounters, where the reference RoPax vessel is struck by: a vessel of similar size (mass ratio 1.0); a vessel smaller by 25 percent (mass ratio 1.33); a vessel larger by 25 percent (mass ratio 0.8) and vessel larger by almost 70 percent (mass ratio 0.6). The available energy for structural deformations is obtained according to the calculation model introduced in (Tabri 2010). This model estimate the dynamics of ship collision and the share in energy available for ship motions and structural deformations. As a result of the combination of this dynamic simulation procedure and the nonlinear finite element method a good estimation of structural damage in various collision scenarios under oblique angles and eccentricity of the contact point can be achieved.

For the purpose of collision simulations the solver LS-DYNA version 971 is used. The ANSYS parametric design language is used to build the finite element model of the reference RoPax vessel. The main characteristics of the ship are gathered in the Table 2.

Three-dimensional model is built between two transverse bulkheads spaced at 26.25 m (see Figure 4) and the translational degrees of freedom are restricted at the plane of the bulkhead locations. The remaining edges are free. The structure is modelled using four nodded, quadrilateral Belytschko-Lin-Tsay shell elements with five integration points through their thickness. The characteristic element-length in the contact region is 50 mm to account for the non-linear structural deformations, such as buckling and folding. The element length dependent material relation and failure criterion according to (Ehlers 2010) is utilised for the simulations. Standard LS-DYNA hourglass control and automatic single surface contact (friction coefficient of 0.3) is used for the simulations. The collision simulations are displacement-controlled.

The rigid bow is moved into the ship side structure in a quasi-static fashion. Hence, this approach results in the maximum energy absorption of the side structure alone, which is needed for a comparison and can be considered conservative and thereby suitable for a fast prediction.

As a result, the relative energy available for structural deformations as a function of the longitudinal striking location is obtained (see Figure 5) for a mass ratio of 1.0. For a mass ratio of 1.33 and 0.6 these curves are scaled with 0.84 and 1.13 respectively to account for the change in dynamic behaviour. Therefore the graphs for critical striking speeds, for a given mass ratio and striking angle, causing the inner hull breach are obtained.

An exemplary graph for a mass ratio 1.0 is presented in Figure 6. The striking speed obtained is a function of striking location along the hull of struck ship.

Finally the CPT for the variable inner hull rupture is constructed, see Table 3.

Table 1. The conditional probability table (CPT) for a collision speed variable, given the collision angle.

<table>
<thead>
<tr>
<th>Collision speed [kn]</th>
<th>Collision angle [deg]</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;7</td>
<td>0–45</td>
<td>0.9987</td>
</tr>
<tr>
<td>7–10</td>
<td>0–45</td>
<td>0.0013</td>
</tr>
<tr>
<td>&gt;10</td>
<td>0–45</td>
<td>0</td>
</tr>
<tr>
<td>&lt;7</td>
<td>45–135</td>
<td>0.3784</td>
</tr>
<tr>
<td>7–10</td>
<td>45–135</td>
<td>0.4837</td>
</tr>
<tr>
<td>&gt;10</td>
<td>45–135</td>
<td>0.1379</td>
</tr>
<tr>
<td>&lt;7</td>
<td>135–180</td>
<td>0.9709</td>
</tr>
<tr>
<td>7–10</td>
<td>135–180</td>
<td>0.0291</td>
</tr>
<tr>
<td>&gt;10</td>
<td>135–180</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2. The analysed RoPax vessel characteristics.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>188.3 m</td>
</tr>
<tr>
<td>Breadth</td>
<td>28.7 m</td>
</tr>
<tr>
<td>Draught</td>
<td>6.0 m</td>
</tr>
<tr>
<td>Displacement</td>
<td>19610.0 t</td>
</tr>
</tbody>
</table>

Figure 4. FEM model and vertical striking locations.
Estimation of the probability of ship capsize due to flooding in damage condition

As a result of a ship-ship collision, where the collision speed exceeds the critical speed for breaching the inner hull (see Figure 6), ship flooding can be expected. Moreover, if the wave height is greater than a critical height, a ship can experience flooding which can contribute to a ship loss.

To determine the probability of ship loss due to flooding a concept of “capsize band” has been recently introduced, see (Papanikolaou et al., 2010). The band begins at the wave height that does not cause capsize \( P_{capsize} = 0 \) and ends at the wave height where a ship loss is expected always \( P_{capsize} = 1 \). The capsize boundaries are symmetrical, around the value of critical wave height, which correspond to \( P_{capsize} = 0.5 \). Another attribute is that the capsize band gets broader with the increase of the critical wave height. For the purpose of this study we assume the damage stability conditions of a RoPax corresponding to the critical wave height of 5.5 m, with a symmetrical bandwidth of 4 m around it, see (Papanikolaou et al., 2010). Moreover the flooding of a car deck and two compartments underneath is assumed. Additionally the hypothetical damage opening is constant regardless of collision scenario, as defined by SOLAS’95 (B-II Reg. 14).

Time to capsize due to flooding was estimated by means of a simulation model by (Spanos and Papanikolaou 2010).

The weather conditions applied in the model are categorised into three groups (see Table 4). These division corresponds to the adopted capsize band, as follows: moderate corresponds to the capsize band, good means no capsize at all, whereas bad stands for sea conditions in which ship will always capsize \( (Weather = Bad) \). Table 4 shows the prior probabilities for the weather conditions, which are obtained from the Global Wave Statistics, see (BMT Ltd 1986).

The model provides the following marginal probability of RoPax capsizing due to flooding in damage condition:

\[
P_{capsize(flooding|collision)} = 1.7 \times 10^{-2}
\]  

Table 3. The conditional probability table (CPT) for inner hull rupture variable, given two variables collision mass and collision speed.

<table>
<thead>
<tr>
<th>Collision mass [-]</th>
<th>Collision speed [kn]</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;0.8</td>
<td>&lt;7</td>
<td>0.8</td>
</tr>
<tr>
<td>&lt;0.8</td>
<td>7–10</td>
<td>1.0</td>
</tr>
<tr>
<td>&lt;0.8</td>
<td>&gt;10</td>
<td>1.0</td>
</tr>
<tr>
<td>0.8</td>
<td>&lt;7</td>
<td>0.1</td>
</tr>
<tr>
<td>0.8</td>
<td>7–10</td>
<td>1.0</td>
</tr>
<tr>
<td>0.8</td>
<td>&gt;10</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0</td>
<td>&lt;7</td>
<td>0.0</td>
</tr>
<tr>
<td>1.0</td>
<td>7–10</td>
<td>1.0</td>
</tr>
<tr>
<td>1.0</td>
<td>&gt;10</td>
<td>1.0</td>
</tr>
<tr>
<td>1.3</td>
<td>&lt;7</td>
<td>0.0</td>
</tr>
<tr>
<td>1.3</td>
<td>7–10</td>
<td>0.5</td>
</tr>
<tr>
<td>1.3</td>
<td>&gt;10</td>
<td>1.0</td>
</tr>
<tr>
<td>&gt;1.3</td>
<td>&lt;7</td>
<td>0.0</td>
</tr>
<tr>
<td>&gt;1.3</td>
<td>7–10</td>
<td>0.0</td>
</tr>
<tr>
<td>&gt;1.3</td>
<td>&gt;10</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 4. The prior probabilities for the variable weather.

<table>
<thead>
<tr>
<th>Variable instance</th>
<th>Wave height [m]</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>0–3</td>
<td>0.920</td>
</tr>
<tr>
<td>Moderate</td>
<td>3–6</td>
<td>0.077</td>
</tr>
<tr>
<td>Bad</td>
<td>&gt;6</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Furthermore, a complement of this number is the probability of survive given the collision and consecutive flooding.

2.6 Estimation of the probability of ship capsizing in Dead Ship Condition

Another type of the consequence arising from a collision addressed by this paper is ship capsizing due to wave and wind action, whereas the ship is in dead ship condition (DSC). DSC means “a condition in which the entire machinery installation, including the power supply, is out of operation and the auxiliary services such as compressed air, starting current from batteries etc., for bringing the main propulsion into operation and for the restoration of the main power supply are not available”, see also (BureauVeritas 2005). To determine the probability of ship capsizing and the time to capsize in DSC, the simulations are performed with the use of the state-of-the-art ship dynamics model. Whereas the probability of ship capsizing is assumed equal to the probability of exceeding a particular angle of roll, which in this analysis means 60°. Thus, the ship dynamics in waves is estimated by means of six-degree of freedom ship motion model LAIDYN, which assumes that the overall ship response is a sum of linear and nonlinear parts, see (Matusiak 2011).

To calculate the probability of reaching the intended roll angle \( P_{\text{capsize}} \) the Monte Carlo simulations are applied. Hence the probability of ship capsize in DSC is obtained by means of the formula:

\[
P_{\text{capsize}} = \frac{N_{\text{capsize}}}{N_{\text{sims}}}
\]

where \( N_{\text{capsize}} \) means a number of simulations where the intended angle was reached and \( N_{\text{sims}} \) is a number of all simulations. The probability of a RoPax capsizing given the analysed conditions yields:

\[
P_{\text{capsize DSC-weather}} = 1.20 \times 10^{-4}
\]

2.7 Sensitivity analysis of the model

To determine how sensitive the results of the model are to variations of the parameter of the model, the parameter sensitivity analysis is carried out. The parameters analysed are the entries of the given CPT. In the analysis presented the influence of all variables on the model outcome, which is a two-state node “Potential Fatalities”, is performed. For this purpose the following sensitivity function

\[
f(t) = \frac{c_1 t + c_2}{c_4 t + c_4}
\]

where \( f \) is an output probability of interest, given observations and \( c_1, ... , c_4 \) are the constants. Whereas the effect of minor changes in the original parameter on the output is given by the sensitivity value, which is computed based on the first derivative of the sensitivity function. Hence, the results of the sensitivity analysis are depicted in Figure 7, where the maximum absolute value of the sensitivity function for the selected nodes are presented. The nodes that obtained the highest values of the sensitivity function are depicted only.

3 RESULTS AND DISCUSSION

In the course of the analysis presented, we assume an accident scenario, where a RoPax ship of a given structure and size, sailing in the Gulf of Finland is struck by another ship of certain mass, with certain collision speed and angle. Then the probability of human loss and/or a ship loss is estimated by means of newly developed model, see Table 5. Additionally, all the marginal probabilities are depicted in Figure 2.

Furthermore the model estimates the probabilities of other variables which are considered important from the viewpoint of maritime traffic risk analysis, for instance: collision speed, ship sinking due to flooding given a collision and the inner hull rupture given a collision, see Table 6.

At the present stage of the model development, a structural analysis is performed for the following mass ratios: 0.6, 0.8, 1.0, 1.3, thus covering almost 80 percent of maritime traffic in the
Gulf of Finland. The remaining 20 percent belongs mostly to ratios higher than 1.3 (which means that the striking ship becomes smaller and lighter, thus the speed required to rupture the inner hull increases), however some percent of ratios lower than 0.6 is not taken account. The latter is an issue, as the critical collision speed in these cases may be significantly smaller than values adopted in the present analysis, which may increase the probability of ship loss.

The probability of ship capsizing following a collision is estimated using a concept of “capsize band”. In the model presented only one band is applied, which corresponds to specific damaged stability conditions. However, the size of the opening which affects flooding is assumed constant regardless of a collision scenario, according to the SOLAS recommendations.

Finally, we compare the obtained results with the statistical data and results obtained from existing models. Thereby the probabilities per collision, of a RoPax loss (capsizing) following a hit by other ship while under way, based on different sources are as follows:

- \( P_L \) = \( 1.73 \times 10^{-2} \) — by the model introduced in this paper, valid within certain boundary conditions,
- \( P_L \) = \( 4.20 \times 10^{-2} \) — valid for an arbitrary passenger RoRo vessel, see (Otto et al., 2002),
- \( P_L \) = \( 1.89 \times 10^{-2} \) — statistics based model, data refers to any RoPax vessel, the boundary conditions unknown, see (Konovesis and Vassalos 2007),
- \( P_L \) = \( 1.76 \times 10^{-2} \) — statistics based model, data refers to any RoPax vessel, the boundary conditions unknown, see (Guarin et al., 2009).

<p>| Table 5. The conditional probabilities of consequences given a collision for a given RoPax. |</p>
<table>
<thead>
<tr>
<th>Consequences given a collision</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential ship loss</td>
<td>0.017</td>
</tr>
<tr>
<td>Potential fatalities</td>
<td>0.016</td>
</tr>
</tbody>
</table>

<p>| Table 6. The selected marginal probabilities obtained from the model. |</p>
<table>
<thead>
<tr>
<th>Collision speed</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt;7)</td>
<td>0.78</td>
</tr>
<tr>
<td>(7–10)</td>
<td>0.17</td>
</tr>
<tr>
<td>(&gt;10)</td>
<td>0.05</td>
</tr>
<tr>
<td>Inner hull rupture</td>
<td>Probability</td>
</tr>
<tr>
<td>yes</td>
<td>0.41</td>
</tr>
</tbody>
</table>

4 CONCLUSIONS

In this paper, we introduced a novel, proactive and transferable model for the probability of ship-ship collision consequences estimation, with respect to a selected type of RoPax ship sailing in the selected location. In the analysis the ship loss and human loss are considered the consequences of a collision scenario. The results obtained form the model are valid within certain, predefined boundary conditions, however due to modular nature of the model it can be used for any ship type and geographical locations.

The presented results are normalised over the whole maritime traffic, according to the prior probabilities of the ship masses ratio, collision speed and collision angle obtained from the AIS data analysis for the Gulf of Finland.

In the light of the sensitivity analysis performed, the most sensitive nodes of the model refer to the weather conditions, the probability of ship sinking due to flooding, the parameters describing a collision scenario (a mass ratio, a collision angle, a collision speed) as well as the probability of intact, however disable ship capsizing.

Notwithstanding all the assumptions and simplifications made, the model results are comparable with the results obtained form the existing models and accident statistics.

ACKNOWLEDGEMENT

The authors appreciate the financial contributions of the following entities: Merenkulun säätiö from Helsinki and the city of Kotka. Risto Jalonen from Aalto University is thanked for his invaluable comments.

REFERENCES


