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A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels

A framework for risk assessment for maritime transportation systems—A case study for open sea collisions involving RoPax vessels

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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 considered 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 adopted formal definition of risk. The framework focuses on ship–ship collisions in the open sea, with a RoRo/Passenger ship (RoPax) being considered as the struck ship. 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 risk framework is developed with the use of Bayesian Belief Networks and utilizes a set of analytical methods for the estimation of the risk model parameters.

Finally, a case study is presented, in which the risk framework developed here is applied to a maritime transportation system operating in the Gulf of Finland (GoF). The results obtained are compared to the historical data and available models, in which a RoPax was involved in a collision, and good agreement with the available records is found.

1. 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. Therefore a number of studies on improvements to ship safety have been made; see for example [1–6]. One of the outcomes of these studies is the concept of risk-based design (RBD) for ships carrying passengers [7,8] where the major criterion for RBD is the ability of a ship to survive in damage conditions; see [9,10]. The above-mentioned studies address ship design; however, less attention has been paid to the

risk-based design of ship operations. Although a general framework for this purpose is provided by the International Maritime Organisation – see [11] – few researchers have approached this topic in a holistic manner; see [12–15]. These models rely on accident statistics, and therefore the influence of factors contributing to the risk can hardly be measured. Moreover, most of the models utilise the concept of a fault tree (FT) or event tree (ET) following Boolean logic [16–18], which in some cases may not fully reflect reality, as the events being analysed may take more than just two states. Furthermore FT and ET allow one-way inference, which in turn may limit their applicability in the field of systematic risk mitigation and management. The above limitations have been recognised in the field of Probabilistic Risk Assessment (PRA) in complex socio-technical systems, where alternative, hybrid approaches have been proposed, utilising FT, ET and Bayesian Belief Networks, see for example [19–24]. However, for the domain discussed in this paper, such solutions do not exist.

Therefore, it is desirable to develop a framework that evaluates the risk to ships at the design and operation stage in a proactive

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and systematic way. This would allow an insight to be gained into the process of risk evolution, as well as defining the most significant and sensitive variables that contribute the most to the risk in order to mitigate it in an optimal way, see [25,26].

Hence, this paper introduces a systematic, transferable and proactive framework determining the risk resulting from an open sea collision involving a RoPax. When it comes to describing the evolution of the accident the framework attempts to capture the causality, which makes the framework systematic. Its modular nature allows continuous improvement and adaptation to various locations and conditions, thus making its transferable. The framework is developed using Bayesian Belief Networks (BBNs), as recognised tools for knowledge representation and efficient two-way reasoning under uncertainty, which in turn makes the framework proactive; see [27–29]. Moreover, BBNs allow reasoning in both directions, pointing out the most vulnerable nodes and the most effective ways of improving the outcome of the model. Thus the back-propagation of the probabilities can be utilised in the recommendation phase of risk assessment, see for example [30]. However, this is beyond the scope of this paper. All the above, along with the quantification of the effect of changes in the assumptions on the outcome of the framework – see [31] – make the results which are obtained more credible. Ultimately, the framework communicates to the end-user the level of available background knowledge about the system that is analysed, and how it is distributed across the framework.

Moreover, BBNs allow the adaptation of a formal risk definition following the well-founded idea of triplet given by Kaplan in [32]. Triplet attempts to answer the following questions: what can go wrong in the system?; how likely is it that it will go wrong ?; and what are the consequences if the assumed scenario occurs? This idea has been widely used for risk assessment and management in the maritime, see for example [33,34], which can provide additional justification for its use for the purpose of this study. All the relevant components of risk triplet are discussed here, and a case study is presented that addresses the maritime traffic system (MTS) operating in the Gulf of Finland (GoF) during the ice-free season, considering a specific RoPax as the struck ship.

The paper is structured into six main sections including the introduction. Section 2 explains the use of BBNs to describe the risk in the MTS, with the adopted risk perspective. Section 3 defines the risk framework, and Section 4 describes the elements of the framework. In Section 5, the results obtained are shown, discussed and compared with the available data. Section 6 concludes the paper, focusing on the main findings and limitations of the risk framework.

2. BBNs as reflection of risk perspective

A formal, and well-established definition of risk in decision analysis is "*a condition under which it is possible both to define a comprehensive set of all possible outcomes and to resolve a discrete set of probabilities across this array of outcomes*", see [35]. To define a set of outcomes, knowledge and proper understanding of the system or phenomena being analysed is a prerequisite. This in turn enables scenarios leading to the outcome of interest and their probabilities to be defined. The framework aiming at risk analysis, which is presented in this paper, is developed by means of BBNs. These probabilistic tools allow reflection of the available knowledge on the process being analysed and its understanding in a comprehensive way. First, the aleatory uncertainties inherent to model variables are addressed, by describing variables using distributions obtained in the course of numerical analyses. Second, epistemic uncertainties related to model structure are analysed by performing alternative hypotheses testing. For this purpose, a set of scenarios is developed, with the constant set

of variables, but different, plausible hypotheses governing the links between variables. This is performed for the elements of the model, which, for various reasons, can not be quantified with desired accuracy at the time of analysis. Beside quantification of the uncertainties the framework allows distributing them across the model. By doing this, the crucial areas of the model are pointed, where the limited background knowledge needs to be improved, as it has significant effect on an outcome.

Finally the framework communicates its output in a form of diagram, which presents the cumulative distribution of likelihood for the occurrence of number of fatalities given the scenarios.

By adopting this framework, and BBNs as tools for probabilistic modeling, it is possible to apply modified risk perspective of Kaplan [32], which for this paper reads as follows:

$$R = \{(S, L, C) | BK\} \tag{1}$$

where S stands for a set of scenarios which comprises the same chain of events, described by the same explanatory variables but the variables and their relations can be described by adopting different assumptions (alternative hypotheses). The latter depends on our background knowledge of the process being analyzed – BK, see for example [36]. L is a set of likelihoods corresponding to the set of consequences C, for a given set of scenarios (S) and given combination of anticipated assumptions governing the model parameters.

The above equation makes S, L, C conditional upon BK, which is in line with the formal definition of risk provided in the first paragraph in this section, adapted from [35]. This implies the necessity of quantifying the effect that BK, which for some variable may be limited, has on R.

BBNs as probabilistic tools for reasoning under uncertainty are capable of reflecting the analyzed scenarios along with assigning the associated probabilities. This in turn leads to the quantification of the consequences. Moreover, the BBNs can effectively quantify the effect of limited knowledge and imperfect understanding of the analyzed system on the outcome of the framework.

This section discusses the main features of BBNs, stemming from the formal definition of risk. It also claims the BBNs to be suitable and proactive tools for risk evaluation in an MTS.

2.1. Background knowledge – BK

A clear representation of BK that is available about the given system is relevant for any model which is intended for practical use. This is especially important in the case of risk modelling in MTS, where BK about the system being analysed is limited and unequally distributed across the system. This, in turn, may introduce varying uncertainties depending on the elements of the system. This may result in a situation in which certain areas of the modelled system may lack a sufficient level of BK to satisfy the adopted formal definition of risk. Therefore, it is desirable for a risk framework to communicate the level of BK in order to determine whether the risk results are informative and can be used for decision-making, or should be used with great caution. The latter may be the case if the uncertainties are greater than the margin between the estimated risk and the risk limit. This may lead to some early stage conclusions about the appropriate level of granularity of the problem being analysed or the quality of BK, or the information that is available.

BK can be reflected in a systematic way by constructing a risk framework using BBNs. As a probabilistic graphical model, BBNs allow reasoning under conditions of uncertainty, as well as in the presence of limited data; see [37–39]. Additionally, BBNs can be tested to find the essential variables which have the greatest impact on the output of the framework, and to determine which of these are the most informative; see [40]. For this purpose, a sensitivity analysis and a value-of-information analysis are performed. Moreover, as a

result of the efficient updating of the outcome of the BBNs, given new knowledge on a variable or set of variables, the effect of changes in the predefined relations between variables, called likelihood functions (LFs), can be quantified. In this paper, this is accomplished by performing a so-called influence analysis. This analysis is especially important in the case of LFs which are not based on solid foundations.

All of these analyses allow BBNs-based risk framework to represent the level of available BK about the domain in question in a transparent and systematic way.

2.2. Scenarios – S

A fundamental stage of any risk analysis, and one which affects all the following stages, is scenario identification. This includes proper description of the knowledge about an MTS and its behaviour in a certain situation (e.g. an accident befalling a ship). This means that a risk framework should be capable of reflecting the right variables in the right way, considering the associated uncertainty along with a clear definition of the initial assumptions. Moreover, it should be able to determine the effects of the uncertainties and assumptions on the outcome of the framework, see [25,41–43].

Most of the existing models adopted for risk assessment in maritime transportation are defined in a spatio-temporal, stochastic framework; for a review of the models, see for example [44–48]. However, these models often disregard causal relationships between input variables (e.g. ship size, collision speed, collision angle, relative striking location, and weather) and output variables (e.g. the ship capsizing). These relations are hidden under single probabilities (e.g. the probability of flooding given a collision or the probability of a severe collision) or probability density functions (e.g. a PDF representing the extent of the damage caused by a collision). This way of representing data disregards the causality in the scenario, and therefore substantial elements of risk analysis are missed, i.e. the links among variables and their mutual relationship, see for example [42]. This ultimately increases the uncertainty of the model.

However, some of the above-mentioned shortcomings of the existing models can be addressed by applying BBNs to a risk-analysis framework. First, BBNs allow multi-scenario thinking, which not only focuses on an undesired end event (a collision) but also provides insight into the process of the evolution of an accident. Second, BBNs structure reflects the causality in the process being analysed allowing further knowledge-based decision-making [49,30]. Third, BBNs can efficiently handle the uncertainties about variables and the uncertainties about the relations among variables, and represent those in the outcome.

2.3. Likelihood – L

In the field of risk analysis in engineering systems, three methods of interpreting the likelihood are usually followed: the relative frequency, subjective probability and a mixture of these called the probability of frequency; for discussion on these see, for example, [32,50,51]. The BBNs described in this paper combine numbers stemming from the first two concepts, whereby the decision of which to adopt was made with respect to the available knowledge. If the latter permits, the frequentist approach is used, and a repetitive experiment is conducted; otherwise the probabilities are derived through the elicitation of knowledge from experts. The probabilities, as mathematical concepts, follow certain axioms, which in some real-life cases may not hold true; for discussion on the axioms and validity of the given approaches, see, for example, [51,52].

The numbers derived from various sources are combined with the use of BBNs, which encode the probability density function

governing a set of random variables by determining a set of conditional probability functions (CPFs). Each variable is annotated with a CPF, which represents the probability of the variable given the values of its parents in the graph $(P(X|pa(X)) \in P)$. The CPF describes all the conditional probabilities for all the possible combinations of the states of the parent nodes. If a node does not have parents, its CPF reduces to an unconditional probability function, also referred to as a prior probability of that variable.

From a mathematical viewpoint, classical BBNs are 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. Therefore, BBNs representing a set of variables and their dependencies consist of two parts, namely a quantitative (P) and a qualitative (G). Therefore, 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 [27,28]:

$$P(V) = \prod_{X \in V} P(X|pa(X)) \tag{2}$$

In the framework described here, the CPFs were obtained through simulation, a literature study, natural laws and expert opinions. The CPFs are relevant elements of the framework; first, they govern the flow of knowledge through the framework, and second, they constitute a link between the qualitative and quantitative parts of the framework.

3. Risk framework definition

This section describes the five-step procedure according to [53], defining the risk framework as follows:

1. defining what to model;
2. defining the variables;
3. developing the qualitative part of the framework;
4. developing the quantitative part of the framework;
5. validating the framework.

3.1. Defining what to model

The aim of the proposed framework it to estimate the risk in MTS, focusing on selected accidental scenarios that, ultimately, lead to the loss of a struck RoPax ship. These scenarios are (i) 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; (ii) 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 limits are exceeded, namely crash-worthiness and stability.

Subsequently the corresponding probabilities of the limits being exceeded given the traffic and environmental conditions are evaluated on the basis of the model presented here. For this purposes the following general factors are taken into consideration: the composition of the maritime traffic in the sea area being analysed, the collision dynamics, hydrodynamics of the ship and her loading conditions.

Ultimately, the cumulative number of fatalities (N) resulting from an accident is modelled utilising the concept of the rate of fatalities. This rate is determined taking into account time for evacuating a ship and time for a ship to capsize. The number of passengers on board is modelled utilising available data from RoPax operators from the Gulf of Finland. All these, along with the associated probabilities (P) for a given number of fatalities, are
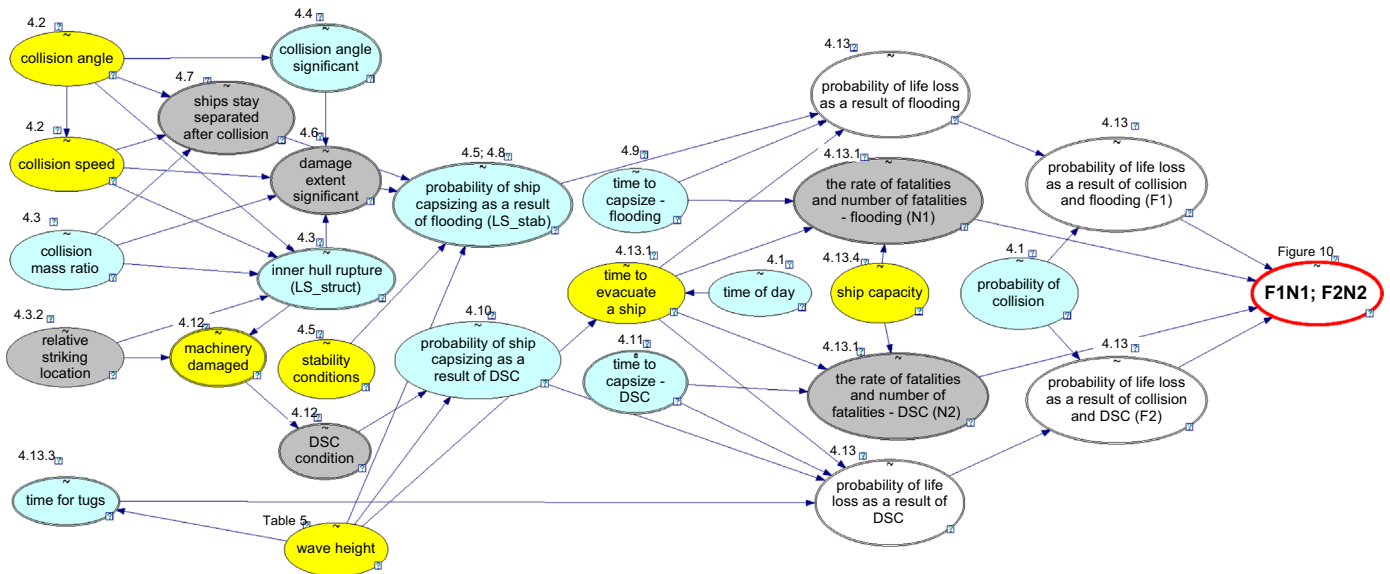
Fig. 1. The qualitative description of the risk framework introduced here. At each variable the reference to a section which describes a given variable is provided. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

finally depicted in a $F-N$ diagram, which can be considered as a risk picture.

3.2. Defining the variables

The framework presented here attempts to reflect the causality in the process of open-sea collision that is being analysed by defining the relevant variables and constructing logical relations between them. Thus the framework consists of four major parts, covering the following areas: (i) collision-relevant parameters; (ii) capsizing-relevant parameters; (iii) the response to an accident; (iv) quantification of the consequences. These are described further in Section 4, and are depicted in Fig. 1. The collision-relevant parameters are obtained from a maritime traffic simulator, which utilizes AIS data and accident statistics for the Gulf of Finland, see Section 4.1. Ship capsizing is conditional upon various events, of which the most relevant are (i) the collision speed and angle for the given ship mass ratios, leading to the rupture of the inner hull of a struck RoPax conditional upon a collision; (ii) the extent of damage leading to the significant ingress of water, conditional upon the inner hull being ruptured; (iii) the hydro-meteorological conditions contributing to the ship capsizing given the significant ingress of water; (iv) the maximum roll angle at which a disabled, intact RoPax capsizes. All these are obtained with the use of finite element simulations, a six-degrees-of-freedom ship motion model, and the available literature.

The response to an accident means the evacuation time or time needed for rescue tugs to arrive to the accident place. The former is modelled adopting the IMO requirements. The latter with the use of maritime traffic simulator and available data about the location of the rescue tugs in the area.

The consequences of an accidents are modelled with the use of a concept of the rate of fatalities, as described in Section 4.13.1.

3.3. Developing the qualitative part of the framework

In this step, the graphical structure of the network is created. As available accident databases are scarce with respect to the consequences for a RoPax ship that is struck by another ship, another source of information must be found. We decided to utilise the qualitative part of the existing ET-based risk framework

for RoPax, see [3,54], and confront it with expert knowledge about the domain.

As the domain under study is wide and multidisciplinary, we divided it into the following sections: (i) ship operations, including the stability of the ship, (ii) the structure of the ship, and (iii) accident response.

Expert knowledge about the domain was elicited through a brainstorming session as well as individual meetings. During the session, the initial structure of the model was presented to the experts for assessment, and was then modified according to their suggestions. The group of experts consisted of 15 researchers and practitioners in the fields of ship design, ship operation and rescue services. Once the structure of the model had been defined, the quantitative part of the model was determined.

3.4. Developing the quantitative part of the framework

The number of probabilities required for a BBN depends on the structure of the network and the number of variables and their states, and it grows exponentially. To reduce the number of probabilities that need to be determined to evaluate the framework, the parametric probability distributions (PPDs) for the variables were used. These provide simple computation rules for obtaining the required probabilities; see [29]. All the PPDs applied in the model are described in detail in Section 4.

A complete list of the model variables and their PPDs is presented in Appendix A in Table A1, which also lists the data sources for the variables.

3.5. Validating the framework

At this stage, the risk framework is validated by performing the following; see also [40]: 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 [55,43].

The lack of BK about the analyzed system leads to uncertainty in the model parameters and affects the hypotheses supporting the model structure. There are numerous ways to address and express the model uncertainty, see for example [56]. The risk

framework introduced here allows for the effect of uncertainties related to BK being evaluated in two-fold. First, by analyzing aleatory uncertainties of the variables. For this, the relevant variables are considered as distributions and the analysis is performed for a range of parameters that these distributions can take. Second, epistemic uncertainties related to model structure are analysed by performing alternative hypotheses testing. For this purpose, a set of models (BBNs) is developed, with the constant set of variables, but different, plausible hypotheses governing the links between variables. In addition to quantifying the uncertainties, the framework allows for their distribution across the model. By doing this, the crucial areas of the model are identified. In these areas the limited BK must be improved, as it has significant effect on the outcome.

If the framework is used for analysing the risk in a specific maritime transportation system, the sensitive variables should be evaluated locally in order to reflect the actual conditions. However, if this is not possible, the framework allows the quantification of the effect of underlying assumptions on the outcome of the framework. The remaining less sensitive variables of the framework can be more generic, as changes to them do not affect the outcome significantly.

4. Risk framework aggregation

This section describes the methods adopted to determine the risk framework, meaning the variables and the relations among them. It also presents the results of the performed case study, which focused on the MTS operating in the Gulf of Finland (GoF). Although the results are valid for the maritime traffic composition and hydro-meteorological conditions prevailing in the GoF, the methods applied are generic and the modularity of the framework makes the approach presented here fully transferable. The framework is encoded with BBNs, developed by means of an available software package called GeNIe; see [57,58]. The qualitative description of the framework is given in Fig. 1, where each variable is annotated with the reference to a section which describes this variable. Moreover, three colours are used to make a distinction between variables which are obtained from the numerical simulations (blue), taken from the literature (yellow), based on certain assumptions (grey) or purely conditional on their parents (without filling).

The framework captures the accidental scenario, where a RoPax is struck by another ship in the open-sea. The collision is described by collision angle, collision speed and masses of colliding ships and relative striking location along a hull. Potential locations of an accident and collision related parameters are obtained from a maritime traffic simulator. To determine whether the inner hull of a RoPax is ruptured following the collision, the critical speed is calculated with the use of numerical model and then it is compared

with the actual collision speed. If a collision speed is higher than critical speed, a hull rupture is expected. Then the framework estimates whether the damage can cause catastrofic flooding. If this is the case, the model estimates the probability for a ship to capsize along with time to capsize. A RoPax may also capsize even if she is intact, if she is exposed to wave action. Therefore, the probability for a RoPax which is intact but disabled due to post-collision damage to her propulsion is calculated with the use of ship dynamic model. For the probability and time to capsize, a set of stability conditions is considered along with the wave characteristics typical for the GoF. The time needed to evacuate the RoPax is modelled with the use of IMO recommendations, which leads to quantification of the rate of fatalities, given collision and flooding. This, together with the number of people on board, estimates the cumulative probability (F) of a given number of fatalities (N). The framework delivers its output in a form of $F - N$ diagram, which is recognized way of risk visualization.

This section provides description of all variables included in the framework.

4.1. Collision probability

In the case study presented here, 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), developed by Goerlandt and Kujala in [45]. Additionally the accident statistics compiled for the GoF are utilized. The input to the DMTS is taken from the Automatic Identification System (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, as if ice-free conditions were year-round. The annual frequency of such an accident equals 0.1. This means that a collision in which a RoPax is involved would happen every 10 years, if there were ice-free conditions year-round. However, this is not the case for the GoF, therefore more realistic assumptions are made that the ice is present every year and remains there for 3 months. This means that the annual frequency for an open-sea collision in which a RoPax is struck equals 0.07, and the reoccurrence period for such an accident is 14 years.

However, the available accident statistics which are compiled for the GoF reveal that the annual frequency of the collisions between two ships at sea, regardless of ship type and ice conditions is 0.2; see [59]. Then, attributing equal chances of being struck and striking to a ship involved in a collision, the annual frequency for a ship being struck, regardless of her type, given a collision is 0.1. Assuming that the ratio of RoPax ships to the number of other ships navigating in the GoF is 1:10, the annual frequency of a RoPax being struck in a collision yields 0.01. Assuming, period of 3 months, during which the GoF is frozen,
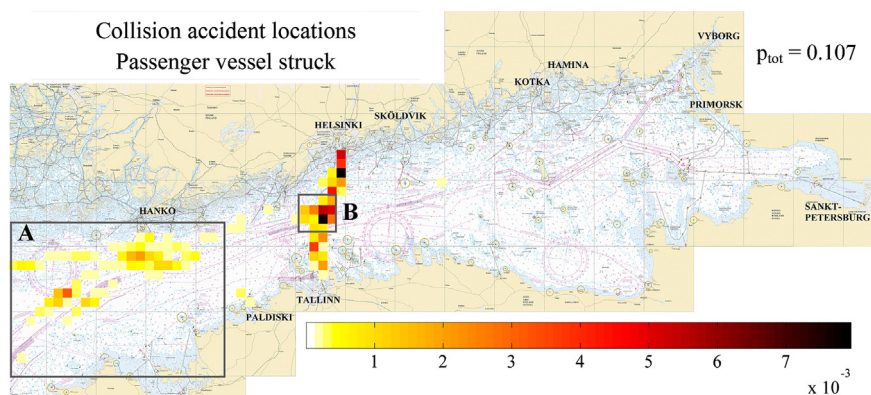

Fig. 2. The modelled locations of an accident in which a RoPax is the struck ship.

the frequency of an open-sea collision, where a RoPax is struck is 0.0075.

Thus, two numbers for the annual frequency of an accident in the open-sea in which a RoPax is struck are obtained, 0.07 from the DMTS, and 0.0075 from the accident statistics. However, both values are burdened with some amount of uncertainty, due to assumptions in the DMTS or simplifications in reasoning from the accident statistics. Therefore it is assumed that the "true frequency" might fall between these two numbers, and they are considered as limits for a uniform distribution estimating the probability of an open-sea collision, where a RoPax is a struck ship; see Eq. (3).

The most likely locations of such an accident are depicted in Fig. 2, and the simplification is made about lack of correlation between time of day and collision:

$$P_{coll} = \begin{cases} \dfrac{1}{0.07 - 0.007}, & 0.007 \leq x \leq 0.07, \\ 0, & x < 0.007 \text{ or } x > 0.07 \end{cases} \quad (3)$$

4.2. 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. These are essential input for the risk framework presented here, as they describe in detail 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, as illustrated in Fig. 3.

The traffic events modelled by the DMTS are based on data which refer to the normal operation of ships, ultimately resulting in safe navigation. Therefore, 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. To fill this gap, a two-step procedure is applied to determine the collision speed. First, the initial value of this parameter is obtained from the DMTS, and then it is considered as the input value for the statistical models, thus arriving at the actual collision speed. There are several different statistical models for estimating the collision speed and collision angle; see [42]. However, only one, proposed by Lützen in [60], takes into account the changes in the initial parameters resulting from evasive action taken by the colliding ships. Therefore, this concept is applied here with the following assumptions:

1. the velocity of a striking ship *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 *B* is approximated by a triangular distribution with the most likely value equal to zero and a maximum value equal to her initial speed;
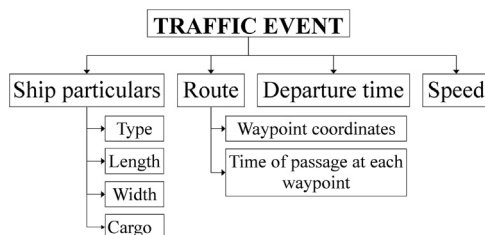3. the initial speed values of *A* and *B* are obtained from the DMTS;

4. the collision angle, defined as the difference in the headings of two colliding ships, is uniformly distributed between 10° and 170°.

Then, applying the four-step random sampling Monte Carlo procedure, the distribution of the actual collision speed is estimated as follows:

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;
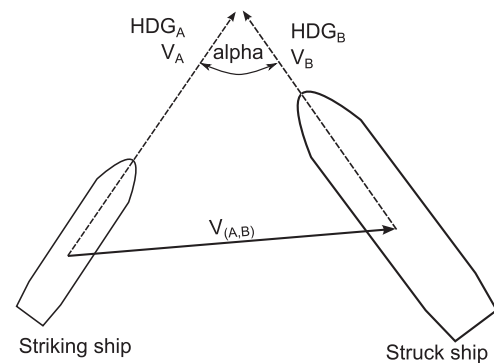
Fig. 4. Definition of collision speed – $V_{(A,B)}$.
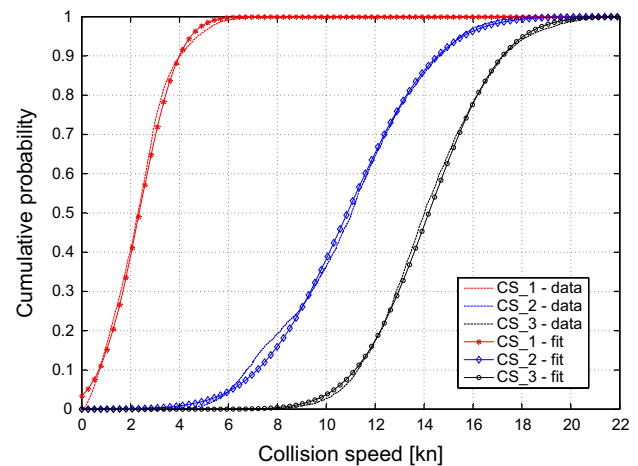
Fig. 5. The CDFs of variable *collision speed* – labelled as *CS* in the graph – conditional upon the *collision angle* adopted in the BBNs developed here.

Fig. 3. Data generated for each simulated vessel, a traffic event [45].

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	$CS-3 = N(14.2, 5.53)$

4. knowing the V_A, V_B and α, calculate the relative speed at which ship A hits ship B, consider it as the collision speed, [61] and store it as $V_{(A,B)}$; see Fig. 4.

For each collision encounter obtained from the DMTS, 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°, 45–135°, and 135–170°. Subsequently, the sub-sets are described with the use of normal distributions, which are the best-fits, see Fig. 5. Finally, these distributions are embedded into the BBNs presented here, as demonstrated in Table 1.

4.3. 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 Eq. (4). The other input is the structural capacity of the ship being analysed, described by the function called *limiting speed* – $V_{rupture}$, which is a speed leading to inner hull rupture. This parameter is evaluated with the use of a numerical model, which is described in this section.

The relation between the collision speed – $V_{(A,B)}$ – and the limiting speed – $V_{rupture}$ – is given by the following Heaviside function:

$$ihr = \begin{cases} 0, & V_{(A,B)} < V_{rupture} \\ 1, & V_{(A,B)} \geq V_{rupture} \end{cases} \qquad (4)$$

The $V_{rupture}$ quantity is a function of the sizes of the colliding ships, the striking angle and the relative striking location along the hull of a struck RoPax. This quantity 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 sizes of the striking ship are considered with respect to the struck RoPax: a similar size (mass ratio 1.0), a ship that is 25% smaller (mass ratio 1.33), a ship that is 25% larger (mass ratio 0.8) and a ship that is 70% larger (mass ratio 0.6). Therefore the mass ratios that are analysed cover almost 80% of maritime traffic in the GoF. The remaining share belongs mostly to ratios higher than 1.3 and lower than 0.6, which are not taken into account in the numerical analysis. Ratios higher than 1.3 can be assumed to be less critical concerning a hull rupture for the usual blunt bow shapes. However, ratios lower than 0.6 shall not be neglected, thus despite the fact that they are excluded from the numerical analysis, they exist in the risk model. The conservative assumption is made that in any case where the ship masses ratio is lower than 0.6, the inner hull of a RoPax is breached, if the collision speed is higher than 80% of the limiting speed for the ratio 0.6.

$$ihr(ratio < 0.6) = \begin{cases} 0, & V_{(A,B)} < 0.8 V_{rupture} \; (ratio = 0.6) \\ 1, & V_{(A,B)} \geq 0.8 V_{rupture} \; (ratio = 0.6) \end{cases} \qquad (5)$$

The available energy for structural deformations is obtained according to the calculation model introduced by Tabri in [62]. His model estimates the dynamics of a ship collision and the share of
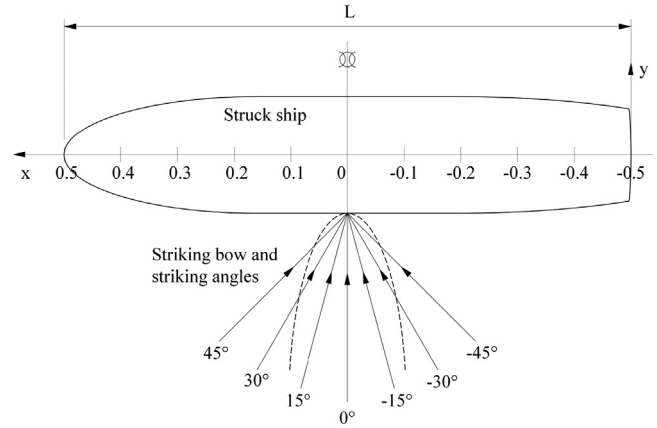
Table 2
The characteristics of the RoPax vessel that was analysed.

Length	188.3 m
Breadth	28.7 m
Average draught	6.0 m
Displacement	19 610.0t

Fig. 6. Relative striking locations and striking angles analysed.

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 [63]. The simulated collision scenarios, defined by the striking angles and relative striking locations along the hull of the RoPax, are depicted in Fig. 6.

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. 7 – 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 [64] are utilised for the simulations. Crashworthiness simulations employing this material model have been found to be sufficiently accurate compared to large-scale experiments; see [65]. 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. Then it as 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. 8. 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 $V_{rupture}$ 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; see Table 3.
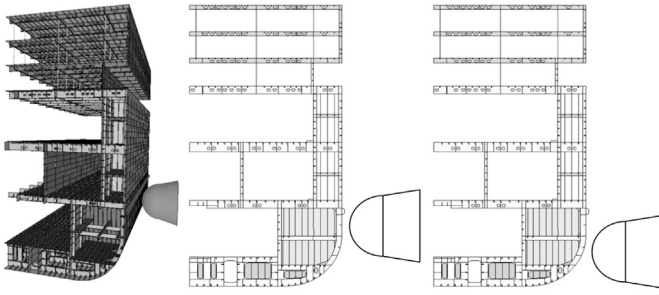
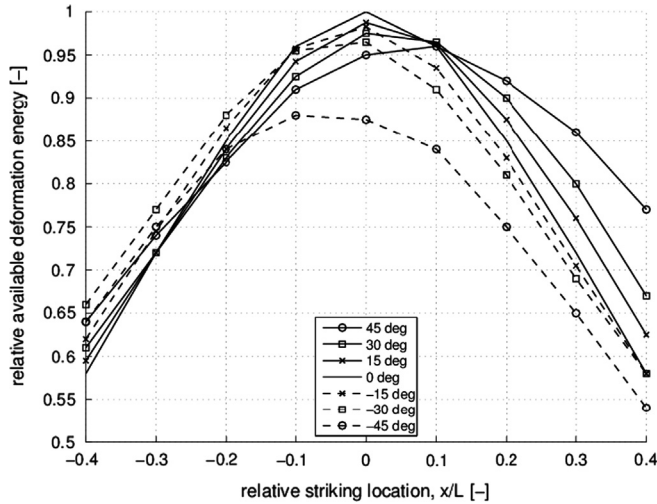**Fig. 7.** FEM model and vertical striking locations.

Fig. 8. Relative available deformation energy versus relative striking location and striking angle.

Finally, the probability of the inner hull rupture given a collision – P_{ihr} – is obtained with the use of the framework introduced here. For the case study analysed here, it yields $P_{ihr} = 0.61$.

4.3.1. Masses of colliding ships

In the case study presented here, the masses of colliding ships are obtained from the DMTS, and then modelled with the use of a log-normal distribution with the following parameters: $\mu = 0.25$ and $\sigma = 0.70$.

4.3.2. Relative striking location

Relative striking location is modelled with the use of a uniform distribution. This means that any location along the hull of a RoPax is equally probable for being hit by the striking ship. Thus, the limits for this distribution are -0.5 (the most aft part of the RoPax) and 0.5 (the most forward part of the RoPax); see Fig. 6.

4.4. Collision angle significant

It is assumed that the collision angles falling in a range between $45°$ and $135°$ may lead to a rupture of the inner hull of a RoPax, and thus they are considered relevant, see also [66]. Therefore the collision angle from this range is referred to as α significant (α_{sign}). This assumption corresponds to the range of striking angles adopted in the FEM-based RoPax crashworthiness experiment, which is described in the previous section.

Table 3
The values of the structural capacity for a RoPax, expressed by limiting speed – in knots – as a function of the relative striking location and striking angle, mass ratio 1.0.

Relative striking location	Striking	angle	(deg)				
	45	30	15	0	-15	-30	-45
-0.4	8.20	8.40	8.50	8.61	8.33	8.07	8.20
-0.3	7.63	7.73	7.73	7.73	7.60	7.48	7.57
-0.2	7.22	7.20	7.16	7.12	7.05	6.99	7.16
-0.1	6.88	6.82	6.76	6.70	6.70	6.71	6.99
0.0	6.73	6.64	6.60	6.56	6.62	6.68	7.01
0.1	6.70	6.68	6.69	6.70	6.78	6.88	7.16
0.2	6.84	6.91	7.01	7.12	7.20	7.29	7.57
0.3	7.07	7.73	7.52	7.73	7.81	7.90	8.14
0.4	7.48	8.01	8.29	8.61	8.61	8.61	8.92

Nevertheless, 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.

4.5. Capsizing of a damaged ship as a result of flooding

As a result of a ship–ship collision in which the collision speed exceeds the limiting speed for a given RoPax in given scenario (size of colliding ship, collision angles and location), the ingress of water can be expected. This, in turn, can bring the damaged ship being analysed towards the boundaries of her stability limit. In the risk framework presented here, it 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, as a function of wave height (H) and ship stability ($stab$); it also takes dynamic time-variant flooding characteristics into consideration, see [67,68]. Within the band a transition between two states, namely "safe" and "unsafe," takes place, according to the logic presented in Eq. (6). The band begins at a wave height that does not cause the ship to capsize ($H_{capsize = 0}$) and ends at the wave height where the loss of the ship is always expected ($H_{capsize = 1}$). The capsize boundaries are symmetrical around the value of the critical wave height ($H_{critical}$), which corresponds to the probability of capsizing equal to 0.5. The band is estimated with the use of a sigmoid function (S). This logic is captured by the following function:

$$P_{capsize}(stab) = \begin{cases} 0, & H < H_{capsize = 0}(stab) \\ S(H_{critical}), & H_{capsize = 0}(stab) \leq H \leq H_{capsize = 1}(stab) \\ 1, & H > H_{capsize = 1}(stab) \end{cases}$$

(6)

For a detailed description of the concept the reader is referred to [6,69].

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. presented in [6]. For the purpose of this study, wave data for the sea area that is analysed is shown in Table 5. Four equally likely stability conditions of a damaged RoPax are assumed, s_i, where $i = 1-4$. They correspond to the following $H_{critical}$ [m] = $[2.0, 2.5, 3.5, 5.5]$, with appropriate bandwidths around each $H_{critical}$, see Table 4. For a detailed description of the ship conditions and method, the reader is referred to [6].

Table 4
The capsize bands and likelihood functions applied in the model.

$H_{critical}$ (m)	Likelihood functions ($P_{capsize}$) and corresponding capsize bands		
	$P_{capsize} = 0$ (m)	$P_{capsize} = S(0,1)$ (m)	$P_{capsize} = 1$ (m)
2.0	0–1.3	1.3–2.8	> 2.8
2.5	0–1.5	1.5–3.4	> 3.4
3.5	0–2.0	2.0–4.8	> 4.8
5.5	0–3.5	3.5–7.2	> 7.2

Table 5
The wave statistics for the Baltic Sea including the GoF, [70].

Wave height (m)	Probability of occurrence
0–1	0.345
1–2	0.390
2–3	0.185
3–4	0.062
4–5	0.015
5–6	0.003

Finally, the conditional probability of a RoPax exceeding her stability limits resulting in ship capsizing is obtained – $P_{capsize}$. For the case study being analysed here, it yields $P_{capsize} = 0.17$.

4.6. Damage extent significant

The damage stability conditions analysed in this paper consider a RoPax experiencing the flooding of certain compartments, which are the main car deck and two of the compartments beneath. However, not every hull breach results in such severe effects, and, 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 following function:

$$des = \begin{cases} 1 & \text{AND}(ihr) = 1, \ \alpha_{sign} = 1, \ V_{(A,B)} > 1.2V_{rupture} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

Here, the collision speed leading to significant damage is taken as 120% of the structural capacity for a RoPax, defined by the limiting speed, introduced in Section 4.3. The collision angle contributing to significant damage is called *collision angle significant* (α_{sign}), and it is introduced in Section 4.4.

In the framework presented here, the conditional probability of such a critical accident scenario is evaluated by a node called *damage extent significant* (*des*), which, for a given case study, yields $P_{des} = 0.15$. As this variable is quantified on the basis of an assumption, the analysis of the effect of a change to the assumption on the response of the framework is conducted at the validation stage.

4.7. 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 occur 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 is governed by a function binding the following variables: *collision speed*, *collision angle significant*, and *collision mass ratio* (*cmr*), through the following Heaviside function:

$$sss = \begin{cases} 1 & \text{AND}(V_{(A,B)} > 1.2V_{rupture}, \ cmr < 1, \ \alpha_{sign} = 1) \\ 0 & \text{otherwise} \end{cases} \quad (8)$$

The probability of such a situation for the case study presented here equals $P_{sss} = 0.94$. As this variable is based on assumptions, an analysis of the effect of changes in the assumptions on the results of the framework is carried out.

4.8. Capsize resulting from flooding

The framework developed here assumes that a RoPax will capsize if the collision speed is higher than the limiting speed

for the given ship and given collision scenario, the damage is significant, the two ships that have collided are separate after the collision and the stability limit 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 *ship capsizing as a resulting of flooding*, using the following formula:

$$P_{C-flooding} = \begin{cases} P_{capsize} & \text{AND}(des = 1, \ sss = 1) \\ 0 & \text{otherwise} \end{cases} \quad (9)$$

where $P_{capsize}$ is determined through Eq. (6). The probability of a RoPax capsizing as a result of flooding for the case study presented here yields $P_{C-flooding} = 0.018$.

4.9. 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. This framework recognises this parameter, and for the case study presented, we use a probabilistic model based on the results of numerical simulations by Spanos and Papanikolaou in [10]. The model that is applied here reflects their findings, where 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 following function is adopted to determine *TTC*:

$$TTC \ [\text{min}] = \exp(\lambda) \quad (10)$$

where $\lambda = 0.05$, and the distribution is truncated at $TTC = 180$ min, see [10].

4.10. 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). DSC means "*a condition in which the entire machinery installation, including the power supply, is out of operation and the auxiliary services for bringing the main propulsion into operation and for the restoration of the main power supply are not available*;" see also [71]. This phenomenon is dependent on the ship type, and thus 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 [72]. 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 – P_{C-DSC} – Monte Carlo simulations are applied:

$$P_{C-DSC} = \frac{N_{\phi_c}}{N_s} \quad (11)$$

where N_{ϕ_c} means the number of simulations in which the roll angle that would lead to the ship capsizing was reached, and N_s is the overall number of trials.

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 $P_{C-DSC} = 2.0 \times 10^{-4}$.

4.11. 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. This is considered as an input variable to the risk framework. A log-normal distribution is used for modelling this parameter, where, $\mu=8.0$ and $\sigma=5.7$, as follows:

$$TTC_{DSC} \text{ [min]} = \ln \mathcal{N}(\mu, \sigma^2). \tag{12}$$

4.12. 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 (*ihr*). However an assumption is made about a 50% chance of the main propulsion or the steering gear failing as a result of the collision impact only, even if the inner hull is not ruptured. The probability for machinery damage is calculated with the following formula:

$$P_{md} = \begin{cases} 1 & \text{AND}(ihr = 1, steer-me = 1) \\ 0.5 & \text{AND}(ihr = 0, steer-me = 1) \\ 0 & \text{otherwise} \end{cases} \tag{13}$$

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

$$steer-me = \begin{cases} 1 & \text{If}(Uniform(0, 10) > 8) \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

The probability of the machinery being damaged as a result of a collision for the case study analysed here yields $P_{md}=0.16$. At the stage of the validation of the framework, the effect of the changes in the above assumptions on the results of the framework is examined.

4.13. The probablity of loss of life and 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 following a collision, such a situation is considered as a success. Otherwise, the response is not effective and loss of life (*LL*) can be expected. The following Heaviside function is applied to determine this parameter:

$$LL = \begin{cases} 0, & haz/resp > 1 \\ 1, & haz/resp < 1 \end{cases} \tag{15}$$

For the case study presented here, the loss of life can be expected in 82 out of 100 cases in which a ship is flooded. In the cases in which a ship capsizes as a result of DSC, this ratio is even higher, and equals 98 out of 100.

To obtain the annual probability for loss of life resulting from a ship capsizing as a result of collision, the following conditional functions are adopted:

$$P_{LL|\,capsizing\,|\,collision} = P_{LL}P_{C-flooding}P_{coll} + P_{LL}P_{C-DSC}P_{coll} \tag{16}$$

Additionally, the rate of fatalities with respect to a total number of people on board is derived, which results in a number of fatalities per year. This, together with the probability for the loss of life, determined through Eq. (16), leads to a cumulative density function of the number of fatalities. The latter is called *F–N* and it is considered as an outcome of this framework.

In the following sub-sections, simplified models addressing accident response are introduced. Also an approach for modelling the rate of fatalities is shown.

4.13.1. The rate of fatalities and number of fatalities

In a case where the accident response is not effective ($LL=1$), the number of fatalities (*N*) is estimated. This parameter is one of the most relevant for the risk framework, and should be modelled as accurately as possible. However, as a result of a lack of information regarding the relationship between the assumed explanatory variables, namely *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, conservative assumptions are adopted in this study. Such a choice can be justified by the aim of this paper, which is to introduce a framework for risk assessment, showing its abilities for efficient reasoning and instantaneous updating in the light of new knowledge, rather than delivering the "true numbers" for risk. Thus, *N* is assumed to be inversely proportional to the ratio *haz/resp* and the number of passengers on board as follows:

$$N = (1 - (haz/resp))N_{passengers} \tag{17}$$

where $1 - (haz/resp)$ is considered as the rate of fatalities. Although this assumptions appears straightforward, the results obtained are comparable with the accident statistics, as presented in Fig. 9 and discussed in Section 5.4.

4.13.2. The time needed for evacuation of a RoPax

Assuming an ordered evacuation of a ship in danger, the time to evacuate the ship (*TTE*) is modelled with the use of triangular distributions following the IMO recommendations, and a distinction is made between day and night; see [73]. Additionally, an assumption is made regarding the effect of challenging weather conditions on the evacuation time, in a fashion presented in the following equation:

$$TTE = \begin{cases} T1, & \text{Day and wave height} < 3 \text{ m} \\ T2, & \text{Night and wave height} < 3 \text{ m} \\ T3, & \text{Day and wave height} > 3 \text{ m} \\ T4, & \text{Night and wave height} > 3 \text{ m} \end{cases} \tag{18}$$

where $T1 = [20, 20, 40]$, $T2 = [20, 40, 40]$, $T3 = [20, 40, 60]$, $T4 = [25, 40, 60]$ in minutes.
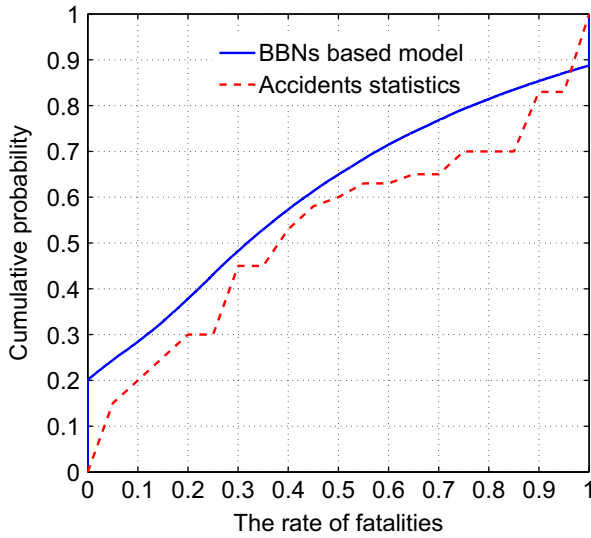
Fig. 9. A CDF describing the rate of fatalities obtained from the model (solid line) plotted against the CDF reflecting historical data from 1987 to 2007 (dashed line).

4.13.3. The time needed for tugs

The time needed for tugs to arrive at the scene is based on the location of the accident relative to the nearest shore rescue station and possible weather conditions. 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, and are depicted in Fig. 2. Thus, the time needed for tugs to reach the scene varies from 1 to 3 h, given good weather conditions. In the event of bad weather this time is increased by a factor of 1.5.

4.13.4. 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 ($N_{passengers}$) is modelled by means of triangular distribution, with a lower limit of 200, an upper limit of 3000 and mode value of 900. The lower limit is an estimate for a ship's crew and a minimal amount of passengers, whereas the upper limit is an estimate of the maximum capacity of RoPax ships cruising in the GoF. The mode value is based on the available data published by ship operators regarding the total monthly volume of passengers transported, see for example [74].

5. Risk framework validation

Once the framework structure and its parameters are defined and the results are obtained, we validate the framework by performing four analyses, to determine the following:

1. the sensitivity of the framework to the stochastic parameters (the sensitivity analysis);
2. the distribution of uncertainty across the framework (the value-of-information analysis);
3. the sensitivity of the framework to changes in the assumptions governing the framework (the influence analysis);
4. the agreement of the framework with the real-world conditions.

5.1. The sensitivity analysis

The sensitivity analysis is performed to identify the essential variables which have the highest impact on the outcome of the model. For this purpose, every conditional and prior probability in the BBNs is systematically varied in turn while keeping the others

unchanged. This allows the effects on the output probabilities computed from the network to be examined, see for example [40].

To determine the sensitivity of an output variable to a given parameter of the model a sensitivity function is estimated for each single variable. This sensitivity function describes outcome of the model as a function of the parameter z, which takes the following form:

$$z = p(Y = y_i \mid \pi) \tag{19}$$

where y_i is one state of a network variable Y, and π is a combination of states for Ys parent nodes. The sensitivity function takes a general form as follows, see [75]:

$$f(z) = (c_1 z + c_2)/(c_3 z + c_4) \tag{20}$$

where $f(z)$ is the output probability of interest given observations, and $c_{1...4}$ are the constants, which are identified based on the model. The first derivative of this function describes the effect of minor changes in a variable on the output and is called the sensitivity value. The sensitivity values were obtained using dedicated tools, which are implemented in the software package GeNIe, used for the development of BBNs presented here.

The results of the analysis indicate that the model is sensitive to changes in the following nodes: *stability conditions*, *collision mass ratio*, *collision probability*, *capsizing as a result of flooding* and *time to evacuate a ship*; see Table 6. In the case study presented here, 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, e.g. *evacuation time*, and thus the effect of those on the output of the framework is determined in Section 5.3. 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 authors' best judgement.

5.2. The value-of-information analysis

The value-of-information analysis identifies the most informative variables, with respect to the output variable, determining the variables among which the probability mass of the output is scattered. For this purpose the concept of entropy is utilised, which is a measure of the randomness of a variable; the higher the randomness, the higher the entropy. The entropy $H(X)$ of a discrete random variable X, consisting of a number of states x, is defined as follows; see [76]:

$$H(X) = - \sum_x p(x) \lg p(x) \tag{21}$$

In a model, where the outcome variable is conditionally dependent on a number of parental variables, the conditional entropy $H(X|Y)$ needs to be applied. This is a measure of the uncertainty of X given an observation of Y and is estimated using the following formulae; see [76]:

$$H(X \mid Y) = \sum_y p(y) H(X \mid Y = y) = H(X) - I(X; Y)$$

$$I(X; Y) = \sum_{(x,y)} p(x, y) \lg \frac{p(x, y)}{p(x) p(y)} \tag{22}$$

Table 6
Results of the sensitivity analysis.

Variable name	Maximum absolute sensitivity value
Stability conditions	0.02
Collision mass ratio	0.02
Collision probability	0.01
Capsizing as a result of flooding	0.002
Time to evacuate a ship	0.0001

Table 7
Results of the value of information analysis.

Variable name	Mutual information
Capsizing as a result of flooding	0.60
Collision probability	0.30
Stability conditions	0.30
Time to evacuate a ship	0.15
Inner hull rupture	0.10
Collision mass ratio	0.06

Table 8
Influence analysis set-up.

Variable name		Definitions adopted
Stability conditions	s	s1; s2; s3; s4
Collision angle	α	Uniform(10,170); triangular(10,90,170)
Collision angle significant	α_{sign}	Uniform(45,135); uniform(20,160)
Damage extent significant	des	$1.2L_{struct}$; $1.4L_{struct}$
Ships stay separated	sss	$f(des_i, \alpha_{sign})$, where $i = 1,2,3$
Machinery damaged	md	0.1; 0.16; 0.25
Time to evacuate a ship	TTE	T1; T2; T3; T4 – see Section 4.13.2

where $I(X;Y)$ is the mutual information, which explains the reduction in the entropy of a variable X by observing a variable Y. Thereby, the variable Y to be observed next is the one that has the maximum value of $I(X;Y)$. The results of the value-of-information analysis with respect to the model output are gathered in Table 7. They 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.

However, neither of these two analyses can be performed on a model that contains either PPDs or a continuous variable. Thus, the variables needed to be discretized prior to the analyses.

5.3. The influence analysis

The two analyses above provide an insight into the given BBNs, comprising the given variables linked with certain likelihood functions (*LFs*). However, if these functions are determined ambiguously, as a result of unavailability of knowledge or limited understanding of a given phenomenon (e.g. *collision angle*) or limited resources (e.g. *damage extent significant*, *ships stay separated*, *evacuation time*), changes in the *LFs* may also affect the results of the sensitivity and value-of-information analysis. Thus, the influence analysis is performed, which aims at the quantification of the effect of changes in the assumptions on the outcome of the framework and other relevant variables. The proposed risk framework allows very effective influence analysis to be performed, as the updating process of BBNs is instantaneous. In the case study presented here, the following variables are subject to the influence analysis: *stability conditions*, *collision angle*, *collision angle significant*, *damage extent significant*, *ships stay separated*, *machinery damaged* and *time to evacuate a ship*.

The parameters and the various definitions of them adopted for the influence analysis are presented in Table 8. Then the framework is evaluated for the number of possible combinations of the given input parameters, and thus a set of results $(F-N)$ is obtained. 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. 10.
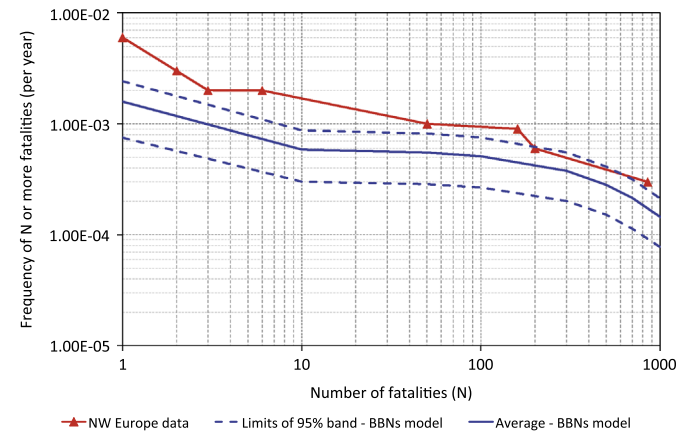
5.4. The agreement of the framework with the real-world conditions

Once the framework is defined and the results are obtained, 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–N graph that was obtained is compared with the graph based on the accident statistics; see Fig. 10. The latter is obtained from the available accident data on RoPax ships for the North–West European seas and is adapted from [18]. The obtained F–N graph contains the accumulated values of the risk of a RoPax capsizing as a result of flooding or DSC, whereas the accident-based graph covers all kinds of accidents (collision, grounding, fire). In general, an F–N can be considered as a suitable risk picture reflecting the definition of risk as "an R set" given by Eq. (1), as it

Fig. 10. A risk picture obtained with the use of the risk framework developed in this paper, for the Gulf of Finland (in blue), plotted against the historical data (1978–1994) on the risk to RoPax ships in European waters (in red). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

comprises the probability of various levels of consequences (N) along with the associated uncertainties expressed as a 95% confidence band. The results obtained show a good level of agreement 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 cases were those accidents associated with the ship capsizing as a result of the car deck flooding. However, none of the recorded capsizing accidents were caused by a collision with another ship. Moreover, it should be noted that the statistics-based $F-N$ 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, the following three intermediate quantities are validated with the available data presented in [7,5,13,77]:

1. the conditional probability of the loss of a RoPax as a result of flooding: $P_{C-flooding}$;
2. the probability of serious damage given an open sea collision: P_{des};
3. the rate of fatalities: $1 - (haz/resp)$.

The probabilities that are obtained with the use of the risk framework presented here are continuous variables, following certain, non-parametric distributions. However, for the purpose of the validation and visualisation of the results, the average values are used where necessary; see Table 9. The rate of fatalities is taken as a distribution and compared with the distribution obtained from the accidents statistics.

The average value of $P_{C-flooding}$ obtained from the framework is close to the results obtained from the model based on global statistics, and to the results of analysis for the specific RoPax as presented in [5,7]. However, the value of $P_{C-flooding}$ delivered by the risk framework introduced here is different from the results for a

Table 9
Risk framework verification, comparison of various models.

Parameter	Value	Limitations	Reference
$P_{C-flooding}$	1.80×10^{-2}	valid for the specific RoPax vessel and location of this study	
	1.76×10^{-2}	accidents statistics-based model	[5]
	1.89×10^{-2}	valid for the specific RoPax vessel, supported by accidents data	[7]
	4.20×10^{-2}	valid for the specific RoPax vessel and location (the Atlantic Ocean)	[13]
P_{des}	1.50×10^{-1}	valid for the specific RoPax vessel and location of this study	
	1.60×10^{-1}	accidents statistics-based model	[5]

specific RoPax operating in the Atlantic Ocean, as shown in [13], but still of the same order of magnitude. The average value of P_{des} is in line with the corresponding probability of serious damage given open sea collision, according to historical data, as compiled in [5].

Also, good agreement is found between two distributions describing the rate of fatalities, as depicted in Fig. 9. The distribution obtained from the data is discreet, as it is based on 31 cases, as compiled in [77]. The distribution obtained from the model is continuous. The agreement between these two can be seen especially for the rates between 0.3 and 0.5 and for the rate 0.9. According to the accidents statistics [77] the probability of the rate of fatalities falling in the range (0.95–1), given accidental flooding, is 0.15. The BBNs-based model delivers a number of 0.16 for the same range. Otherwise, the model presented here tends to slightly overestimate this parameter for rates lower than 0.95. However, for precise calculation of this parameter, one may adopt models simulating ship evacuation processes, which need detailed description of ship interior, see for example [78–80]. Another possibility is to use generic models, for instance [81,82], which require high-level description of the arrangement of escape routes onboard a ship. The results obtained from those models can be used for detailed validation of the simplified approach proposed here.

Despite the simplifications adopted in the framework, the results of the validation show that the presented BBNs-based model provides sound estimations for all three parameters. As these parameters are of high importance for the analyzed phenomena, the above findings provide a basis for beliefs about reliable output of the model. Ultimately the framework delivers risk predictors for the analyzed scenarios which are in good agreement with the available historical data.

6. Conclusions

This paper presents a framework for risk analysis and assessment in maritime transportation systems, following the formal requirements adopted and reflected by Eq. (1). The framework is systematic, proactive and transferable. It utilises BBNs as medium to express and propagate the background knowledge that is available about the system being analysed. The BBNs applied here combine discrete and continuous variables. This allows probabilistic relationships among the variables and complex dependencies as well as fast propagation of information through the framework. Moreover, the processes of incorporation of new knowledge or new data into the framework and the quantification of the effect of changes in the assumptions on the outcome are very efficient, as the BBNs allow for instantaneous updating. This, together with the sensitivity analysis and the value-of-information analysis, increases the credibility of the results which are obtained, as the distribution of knowledge, on which the framework is developed, is presented. This, in turn, may help in determining the areas of the framework which are either unknown or not understood well enough, and have significant effects on the outcome of the framework, meaning that they need to be treated with caution.

Then, the framework is used for a case study, evaluating the risk for an MTS operating in the GoF during the ice-free season considering an open-sea collision, where a RoPax is struck by another ship and the RoPax is lost as a result of hull rupture and consecutive flooding, or as a result of post-accidental propulsion failure and exposure to high waves, resulting in capsizing. This means that the other collision scenarios, such as a RoPax is a striking ship and suffers significant damages to her bow leading ultimately to water ingress, are not considered here. Moreover, the distribution of mass ratios of striking and struck ships accounts for 80% of traffic in the GoF. The cases where the mass of a striking ship is larger than 1.7 times that of a struck ship, which accounts for less than 5% of the traffic in the area, are not considered in the numerical analysis. However, these ratios are included in the risk framework, and their effects are conservatively estimated; extrapolating findings for other ratios.

Additionally, four stability conditions of a RoPax that is struck are anticipated, and it is assumed that they are equally likely. This needs further investigation, as this is a sensitive parameter of the framework introduced.

The 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. Despite the simplifications and the assumptions made in the framework, the results obtained are promising, and they show good agreement with the available statistical or modelled data on RoPax accidents operating around Europe.

However, this paper does not claim any "true numbers" for risk in the Gulf of Finland, as the aim of the analysis presented is to demonstrate the abilities of the framework for knowledge-based risk assessment and proper reflection of uncertainties which are inherent to any risk analysis. Further studies are desirable in order to cover missing accident scenarios (e.g. grounding or fires on board RoPax) and to improve the areas of the framework which are relevant, but about which proper background knowledge is lacking (e.g. the number of fatalities resulting from a collision, the extent of the damage resulting in catastrophic flooding or the collision speed and angle). Additionally, the framework allows the effect of risk control options to be studied. Both direction reasoning make it possible to propagate the outcome backwards, which can be utilised in a recommendation phase, pointing out the most effective ways to make improvements. This is, however, beyond the scope of this paper.

Nevertheless, the risk framework introduced here can be considered as a contribution to a concept of holistic risk modelling which can be utilised at the stages of either ship design or operation.

7. Supplementary data

The model presented here is available from the data library PANGAEA at: http://doi.pangaea.de/10.1594/PANGAEA.818516.

Table A1
Description of variables in the model.

Factor group	Variable name	Variable symbol	Expression governing variable	Primary data source
Collision parameters	The probability of collision – per year per area	P_{coll}	Unif(0.07, 0.007)	[45,59], A
	Collision speed	$V_{(A,B)}$	If($\alpha < 45$, $N(2.35,1.64)$, If($\alpha > 135$, $N(14.2, 5.53)$, $N(10.86,8.26)$))	[45,60], S
	Collision angle	α	Unif(10, 170)	[60]
	Striking location	m	If(Unif(0, 10) > 8, 1, 0)	A
	Relative striking location	r	Unif(-0.5,0.5)	A
	Collision mass ration	cmr	Logn(0.2548,0.7014)	[45]
	Limiting speed	$V_{rupture}$	$F(r, cmr, \alpha)$	N
	Inner hull rupture	ihr	If($V_{A,B} > V_{rupture}$, 1, 0)	C
	Machinery damaged	md	If(And($ihr = 1, m = 1$),1, If(And($ihr = 0, m = 1$),0.5,0))	A
	Collision angle significant	α_{sign}	If(And($\alpha < 135, \alpha > 45$),1,0)	[66], N
	Damage extent significant	des	If(And($ihr = 1, cmr < 1.3, V_{(A,B)} > 7, \alpha_s = 1$), 1, 0)	C, A
	Ships stay separated after collision	sss	If(And($V_{(A,B)} > 10, cmr < 1.1, \alpha_s = 1$), 0, 1)	C, A
Ship capsizing	Weather	W	exp(1.1), where $W < 1$ stands for *good*, $1 < W < 2$ *moderate* and $W > 2$ is *bad*	[70]
	DSC conditions	DSC	If($md = 0$,0,1)	C, A
	Capsizing in DSC	C_{DSC}	If($DSC = 1$,Unif(1E-4,2E-4),0)	N
	Capsizing as a result of flooding	$C_{flooding}$	If(And($des = 1, 1 < W < 2$),$W_{moderate}$*Unif(0,1), If(And($des = 1, W > 2, sss = 1$),W_{bad},0))	[6]
	Time taken to capsize in DSC	TTC_{DSC}	Logn(5.9948,0.6455)/60 (min)	N
	Time taken to capsize flooding	TTC_{flood}	exp(0.05) (min)	[6]
	Probability of loss of life – flooding	$P_{LL|flood}$	$C_{flooding}$*LL_{flood}	C
	Probability of loss of life – DSC	$P_{LL|DSC}$	C_{DSC}*LL_{DSC}	C
	Probability of loss of life given collision and flooding	$P_{LL|coll|flood}$	$P_{LL|flood}$ *P_{coll}	C
	Probability of loss of life given collision and DSC	$P_{LL|coll|DSC}$	$P_{LL|DSC}$*P_{coll}	C
Accident response	Time of day	T	Binom(1,0.5); where 1 is day and 0 is night	A
	Evacuation time	E	If(And($T = 1, W < 1$), Triang(20, 20, 40), If(And($T = 0, W < 1$), Triang(25, 40, 40), ,Triang(25,40,60)))	[73]
	Distance from tugs' base	D	Unif(60,180) (min)	[45]
	Time for tugs	TT	If($W < 1.5$,D,1.5D)	C, A
	Danger of loss of life – DSC	LL_{DSC}	If($E < TTC_{DSC}$, 0, 1)	C
	Danger of loss of life – flooding	LL_{flood}	If($E < TTC_{flood}$, 0, 1)	C
	Ship capacity	N	Triang(200, 900, 3000)	[74], A
	The rate of fatalities – flooding	F_{flood}	If(And($T = 1, TTC_{flood} < 5$), 1, If(And($T = 0, TTC_{flood} < 10$), 1, If($TTC_{flood} > E$, 0, $1 - TTC_{flood}/E$)))	C, A
	The rate of fatalities – DSC	F_{DSC}	If(And($T = 1, TTC_{DSC} < 5$), 1, If(And($T = 0, TTC_{DSC} < 10$), 1, If($TTC_{DSC} > E$, 0, $1 - TTC_{DSC}/E$)))	C, A
Results	Number of fatalities given flooding	N_{flood}	F_{flood}*N	C
	Number of fatalities given DSC	N_{DSC}	F_{DSC}*N	C

Acknowledgments

Appendix A. Detailed lists of all variables included in the model and their sources

Table below contains all the variables included in the model. The equations governing these variables are provided along with the primary sources of data. If a variable is obtained through literature study, the relevant materials are referred to. If a variable is labelled with *C* it is simply conditional upon parent nodes only. If a variable is annotated with *A* it allows assumptions. If a variable is obtained through numerical analysis it is labelled with *N* and with *S* if it is based on simulation.

References

[1] Mains C. Updated damage statistics on collision and grounding. Report 1-11-D-2001-01-1, Germanisher Lloyd, 2001.

[2] Papanikolaou A, Eliopoulou E. On the development of the new harmonised damage stability regulations for dry cargo and passenger ships. Reliab Eng Syst Saf 2008;93:1305–16.

[3] Konovessis D, Vassalos D. Risk evaluation for RoPax vessels. Proc Inst Mech Eng Part M: J Eng Maritime Environ 2008;222:13–26.

[4] Mermiris G, Konovessis D, Vassalos D. First-principles collision risk analysis of a RoPax vessel. In: Proceedings of 4th international ASRANet colloquium, 2008.

[5] Guarin L, Konovessis D, Vassalos D. Safety level of damaged RoPax ships: risk modelling and cost-effectiveness analysis. Ocean Eng 2009;36:941–51.

[6] Papanikolaou A, Mains C, Rusås S, Szalek R, Tsakalakis N, Vassalos D, et al. Goalds - goal based damage stability. In: Proceedings of the 11th international ship stability workshop. Wageningen: MARIN; 2010. p. 46–57.

[7] Konovesis D, Vassalos D. Risk-based design for damage survivability of passenger ro-ro vessels. Int Shipbuild Prog 2007;54:129–44.

[8] Papanikolaou AE. Risk-based ship design methods, tools and applications. Berlin, Heidelberg: Springer; 2009.

[9] Santos TA, Guedes Soares C. Numerical assessment of factors affecting the survivability of damaged ro-ro ships in waves. Ocean Eng 2009;36:797–809.

[10] Spanos D, Papanikolaou A. On the time dependent survivability of RoPax ships. In: Proceedings of the 11th international ship stability workshop. Wageningen:MARIN; 2010. p. 143–7.

[11] IMO. Guidelines for formal safety assessment (FSA) for use in the IMO rule-making process. MSC/Circ.1023; MEPC/Circ.392, 2002.

[12] Vanem E, Puisa R, Skjong R. Standardized risk models for formal safety assessment of maritime transportation. In: ASME 28th international conference on ocean, offshore and arctic engineering (OMAE 2009). 2009. p. 51–61.

[13] Otto S, Pedersen PT, Samuelides M, Sames PC. Elements of risk analysis for collision and grounding of a roro passenger ferry. Mar Struct 2002;15:461–74.

[14] Vanem E, Skjong R. Collision and grounding of passenger ships - risk assessment and emergency evacuations. In: Snaj, editor. Proceedings of the 3rd international conference on collision and grounding of ships, 2004. p. 195–202.

[15] Kobylinski L. Stability and safety of ships: holistic and risk approach. Reliab Risk Anal: Theory Appl 2008;1:95–105.

[16] Gerigk M. A method of risk and safety assessment during the ship salvage using the hazard, release and consequence analysis. J KONBiN 2010;13:165–176.

[17] Antao P, Guedes Soares C. Fault-tree models of accident scenarios of RoPax vessels. Int J Autom Comput 2006;3:107–16.

[18] Konovessis D, Vassalos D, Mermiris G. Risk analysis for RoPax vessels. WMU J Maritime Affairs 2008;7:109–31.

[19] Martins MR, Maturana MC. Application of Bayesian belief networks to the human reliability analysis of an oil tanker operation focusing on collision accidents. Reliability Engineering & System Safety 2013;110:89–109.

[20] Groth K, Wang C, Mosleh A. Hybrid causal methodology and software platform for probabilistic risk assessment and safety monitoring of socio-technical systems. Reliab Eng Syst Saf 2010;95:1276–85.

[21] Trucco P, Cagno E, Ruggeri F, Grande O. A Bayesian belief network modelling of organisational factors in risk analysis: a case study in maritime transportation. Reliab Eng Syst Saf 2008;93:845–56.

[22] Vinnem J, Bye R, Gran B, Kongsvik T, Nyheim O, Okstad E, et al. Risk modelling of maintenance work on major process equipment on offshore petroleum installations. J Loss Prev Process Ind 2012;25:274–92.

[23] Gran B, Bye R, Nyheim O, Okstad E, Seljelid J, Sklet S, et al. Evaluation of the risk OMT model for maintenance work on major offshore process equipment. J Loss Prev Process Ind 2012;25:582–93.

[24] Leva, M. C., Friis-Hansen, P., Ravn, E. S., & Lepsoe, A. (2006). SAFEDOR: A practical approach to model the action of an officer of the watch in collision scenarios. In European safety and reliability conference; Safety and reliability for managing risk; ESREL 2006 (pp. 2795–2804). Francis, London.

[25] Grabowski M, Merrick JRW, Harrold JR, Massuchi TA, van Dorp JD. Risk modeling in distributed, large-scale systems. IEEE Trans Syst Man Cybern Part A: Syst Hum 2000;30:651–60.

[26] Szwed P. Risk factors and theory building: a study to improve passenger vessel safety. WMU J Maritime Affairs 2011;10:183–208.

[27] Madsen A, Lang M, Kjrulff U, Jensen F. The hugin tool for learning Bayesian networks. In: Nielsen T, Zhang N, editors. ECSQARU 2003, LNAI 2711. Berlin, Heidelberg: Springer-Verlag; 2003. p. 594–605.

[28] Darwiche A. Modeling and reasoning with Bayesian networks. 1st ed. Cambridge University Press, New York, USA; 2009.

[29] Drużdzel M, van der Gaag L. Building probabilistic networks: "Where do the numbers come from?" guest editors' instruction IEEE Trans Knowl Data Eng 2000;12:481–6.

[30] Montewka J, Weckström M, Kujala P. A probabilistic model estimating oil spill clean-up costs – a case study for the gulf of finland. Mar Pollut Bull 2013;76:61–71.

[31] Zio E, Apostolakis G. Two methods for the structured assessment of model uncertainty by experts in performance assessments of radioactive waste repositories. Reliab Eng Syst Saf 1996;54:225–41.

[32] Kaplan S. The words of risk analysis. Risk Anal 1997;17:407–17.

[33] Ulusçu ÖS, Özbaş B, Altıok T, Or İ. Risk analysis of the vessel traffic in the strait of Istanbul. Risk Anal 2009;29:1454–72.

[34] van Dorp JR, Merrick JRW. On a risk management analysis of oil spill risk using maritime transportation system simulation. Ann Oper Res 2011;187:249–77.

[35] Stirling A, Gee D. Science, precaution, and practice. Public Health Rep 2002;117:521–33.

[36] Montewka J, Goerland F, Kujala P. On a risk perspective for maritime domain. J Pol Saf Reliab Assoc 2013;4:101–8.

[37] Myllymäki P, Silander T, Tirri H, Uronen P. B-course: a web-based tool for Bayesian and causal data analysis. Int J Artif Intell Tools 2002 369–87.

[38] Kontkanen, P., Myllymaki, P., Silander, T., & Tirri, H. (1997). Comparing predictive inference methods for discrete domains. In Sixth International Workshop on Artificial Intelligence and Statistics (pp. 311–318).

[39] Uusitalo L. Advantages and challenges of Bayesian networks in environmental modelling. Ecol Model 2007;203:312–8.

[40] Hänninen M, Kujala P. Influences of variables on ship collision probability in a Bayesian belief network model. Reliab Eng Syst Saf 2012;102:27–40.

[41] Merrick JR, Van Dorp JR. Speaking the truth in maritime risk assessment. Risk Anal 2006;26:223–37.

[42] Goerlandt F, Ståhlberg K, Kujala P. Influence of impact scenario models on collision risk analysis. Ocean Eng 2012;47:74–87.

[43] Aven T. A conceptual framework for linking risk and the elements of the data-information-knowledge-wisdom (DIKW) hierarchy. Reliab Eng Syst Saf 2013;111:30–6.

[44] Pedersen PT. Review and application of ship collision and grounding analysis procedures. Mar Struct 2010;23:241–62.

[45] Goerlandt F, Kujala P. Traffic simulation based ship collision probability modeling. Reliab Eng Syst Saf 2011;96:91–107.

[46] Li S, Meng Q, Qu X. An overview of maritime waterway quantitative risk assessment models. Risk Anal 2012;32:496–512.

[47] Mazaheri A, Montewka J, Kujala P. Modeling the risk of ship grounding—a literature review from a risk management perspective. WMU J Maritime Affairs http://dx.doi.org/10.1007/s13437-013-0056-3, 2013;12.

[48] Montewka J, Krata P, Goerlandt F, Kujala P. Marine traffic risk modelling—an innovative approach and a case study. Proc Inst Mech Eng Part O: J Risk Reliab 2011;225:307–22.

[49] Montewka J, Ehlers S, Tabri K. Elements of risk analysis for LNG tanker maneuvering with tug assistance in a harbor. In: 11th international symposium on practical design of ships and other floating structures, vol. 2. Rio de Janeiro, Brazil: PRADS. 2010. p. 1563–72.

[50] Apostolakis G. The concept of probability in safety assessments of technological systems. Science 1990;250:1359–64.

[51] Aven T, Reniers G. How to define and interpret a probability in a risk and safety setting. Saf Sci 2013;51:223–31.

[52] Winkler RL. Uncertainty in probabilistic risk assessment. Reliab Eng Syst Saf 1996;54:127–32.

[53] Langseth H, Portinale L. Bayesian networks in reliability. Reliab Eng Syst Saf 2007;92:92–108.
[54] Vanem E, Rusås S, Skjong R, Olufsen O. Collision damage stability of passenger ships: holistic and risk-based approach. Int Shipbuild Prog. 2007;54:323–37.
[55] Aven T, Heide B. Reliability and validity of risk analysis. Reliab Eng Syst Saf 2009:1862–8.
[56] Paté-Cornell ME. Uncertainties in risk analysis: six levels of treatment. Reliab Eng Syst Saf 1996;54:95–111.
[57] Laboratory DS. GeNIe Documentation. University of Pittsburgh. Availalble from: ⟨http://genie.sis.pitt.edu/wiki/GeNIe_Documentation⟩, 2011.
[58] Drużdzel M. Genie: A development environment for graphical decision-analytic models. In: Association AMI, editor. Proceedings of the annual symposium of the American Medical Informatics Association (AMIA), 1999, Washington, DC. p. 1206.
[59] Kujala P, Hanninen M, Arola T, Ylitalo J. Analysis of the marine traffic safety in the gulf of finland. Reliab Eng Syst Saf 2009;94:1349–57.
[60] Lützen M. Ship collision damage [Ph.D. thesis]. Technical University of Denmark, Department of Mechanical Engineering, 2001.
[61] Weng J, Meng Q, Qu X. Vessel collision frequency estimation in the singapore strait. J Navig 2012;65:207–21.
[62] Tabri K. Dynamics of ship collisions [Ph.D. thesis]. Aalto University, School of Science and Technology, Espoo, Finland, 2010.
[63] Ehlers S, Tabri K. A combined numerical and semi-analytical collision damage assessment procedure. Mar Struct 2012;28:101–19.
[64] Ehlers S. Material relation to assess the crashworthiness of ship structures [Ph.D. thesis]. Aalto University, School of Science and Technology, Espoo, Finland, 2010.
[65] Ehlers S. The influence of the material relation on the accuracy of collision simulations. Mar Struct 2010;23:462–74.
[66] Ståhlberg K, Goerlandt F, Ehlers S, Kujala P. Impact scenario models for probabilistic risk-based design for ship–ship collision. Mar Struct 2013;33:238–64.
[67] Papanikolaou A. Benchmark study on the capsizing of a damaged ro-ro passenger ship in waves. Issued for comments to: the ITTC specialist committee on the prediction of extreme motions and capsizing, 2001.
[68] Papanikolaou A, Spanos D. Benchmark study on numerical codes for the prediction of damage ship stability in waves. In: Proceedings of the 10th international ship stability workshop. Hamburg: Germanischer Lloyd; 2007.
[69] Schreuder M, Hogström P, Ringsberg J, Johnson E, C.-E. J. A method for assessment of the survival time of a ship damaged by collision. J Ship Res 2011;55:86–99.
[70] BMT Ltd, Global Wave Statistics, BMT Ltd, London, 1986.
[71] BureauVeritas, Rules for the classification of steel ships. Technical Report, Bureau Veritas; 2005.
[72] Matusiak J. On the non-linearities of ships restoring and the Froude–Krylov wave load part. Int J Naval Archit Ocean Eng 2011;3:111–5.
[73] IMO, Guidelines for evacuation analysis for new and existing passenger ships, MSC.1/Circ.1238, 2007.
[74] TALLINK, Tallink exceeded the milestone of 900 000 passengers in June, 2013.
[75] Chan H, Darwiche A. When do numbers really matter? J Artif Intell Res 2002;17:265–87.
[76] Hugin Experts A/S, HUGIN API reference manual. Technical Report Version 7.4, Hugin; 2010. Available online: ⟨http://download.hugin.com/webdocs/manuals/api-manual.pdf⟩.
[77] Jasionowski A, Vassalos D, Scott A. Ship vulnerability to flooding. In: 3rd international maritime conference on design for safety, Berkeley, California, 2007.
[78] Ginnis AI, Kostas KV, Politis C, Kaklis PD. Velos: a VR platform for ship-evacuation analysis. Comput Aided Des 2010;42:1045–58.
[79] Roh M-I, Ha S. Advanced ship evacuation analysis using a cell-based simulation model. Computers in Industry 2013;64(1):80–9.
[80] Vanem E, Skjong R. Designing for safety in passenger ships utilizing advanced evacuation analyses—a risk based approach. Saf Sci 2006;44:111–35.
[81] Łozowicka D. Organization of evacuation from passenger ships–a concept of safety enhancement. Zesz Naukowe 2012;32:110–4.
[82] Łozowicka DH. Problems associated with evacuation from the ship in case of an emergency situation. Int J Autom Comput 2006;3:165–8.