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# Risk modelling and management in large-scale, distributed transportation systems

**Keywords**

risk, maritime transport, transportation systems, F-N, RoPax

## Abstract

Large-scale distributed transportation systems can pose various risks in terms of fatalities, environmental pollution, or loss of property. In particular, accident where a vehicle carrying large number of passengers is involved may pose a high risk with respect to human casualties, moreover it will immediately raise a public and political concern. This is an issue in case of maritime transportation systems (MTS), as the biggest ships nowadays can carry up to 8500 people at once (m/s Oasis of the Seas). Thereby lot of effort has been put to increase safety of ships carrying passengers; however the holistic approach to model and manage the risk existing in the MTS is still missing. This paper makes an attempt to fill this gap, by presenting a data-driven model evaluating risk level in the existing MTS and by introducing a systematic methodology for mitigating the risk. Moreover the MTS operating in the Gulf of Finland under non-ice conditions is addressed, where heavy passenger traffic is observed.

## 1. Introduction

A number of studies on improvements of safety to ships carrying passengers have been made; see for example [10], [11], [14], [15], [21], [20], [25]-[27], [31], [3], [34], [39]. One of the outcomes of these studies is the concept of risk-based design (RBD), whereas the major criterion for RBD is the survivability of a ship in damage conditions; see [25]. The survivability model, accompanied by models for accident frequency estimation, along with the accident response models, seems a suitable type of holistic risk model for the design of a ship; see [11], [39]. However, the above-mentioned studies address ship design; and less attention has been paid to a risk-based approach to the design and operation of marine transportation system (MTS). Although a general framework for this purpose is provided by the International Maritime Organisation - see [24] and Figure 2 - few researchers have approached this topic; see [1], [6], [9], [12], [13], [40]. However, the algorithms presented there are either too generalised or the models are based on accident statistics, and therefore the influence of factors contributing to the risk can hardly be measured. Moreover, most of these models utilize the concept of a fault tree (FT) or event tree (ET) assuming binary events, which in some cases may not fully reflect reality. Additionally, FTs and ETs are hampered when comes to handling the uncertainty of the input variables. Furthermore, they allow one-way inference, which in turn significantly limits their applicability in the field of systematic risk assessment, mitigation and finally risk management.

Therefore it is desirable to develop a model that evaluates the risk existing in the MTS in a holistic and proactive way; see [19], [35]. This in turn, will allow an insight into the process of system risk evolution, as well as defining the most significant and sensitive elements of the system that contribute the most to the risk in order to manage the risk in an optimal and systematic way. According to well accepted description of risk management stating the following: “risk management is a systematic approach to setting the best course of action under uncertainty by identifying, assessing, understanding, acting on and communicating risk issues”, see [2].

Hence, this paper makes a contribution to such a model, introducing a novel architecture of a systematic, proactive and transferable model determining the risk existing in the MTS operating in the Gulf of Finland, see *Figure 1*. The risk is expressed in the number of fatalities and is evaluated for a specific ship carrying passengers being struck in an open sea collision. The model focuses on a selected type of ship which is considered a characteristic RoPax for the location being analysed, see *Table 1*. However, the modular nature of the model allows continuous improvement and adaptation to various locations and conditions.

The model is based on a Bayesian Belief Network (BBN), which is a recognized tool for knowledge representation and efficient reasoning under uncertainty; see [3], [5], [19].

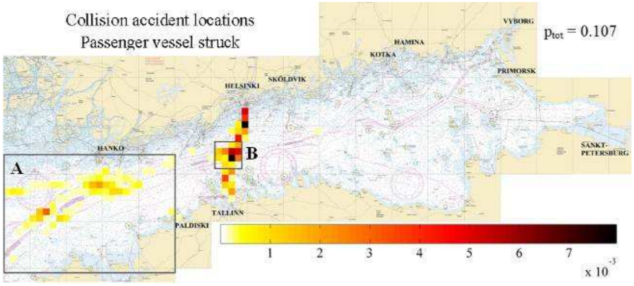

*Figure 1*. Architecture of the analysed MTS with various hazard levels.

*Table 1*. The characteristics of the analysed RoPax.

| | |
|---|---|
| Length | 188.3m |
| Breadth | 28.7m |
| Draught | 6.0m |
| Displacement | 19610.0t |

## 2. Model and methods

The paper introduces a model fitting an accepted concept of the risk-based rule-making process in the maritime domain, called the Formal Safety Assessment (FSA); see [11] and *Figure 2*. The methodology developed is systematic, proactive and transferable, when comes to estimating the risk of an accident in the open sea in terms of the number of fatalities (step 2). Moreover it determines the most effective and sub-optimal solutions for risk mitigation (step 3), finally allowing decision making (step 5). The cost-benefit analysis (step 4) is omitted in the presented study; however it can easily be included at the further stage.

The risk mitigation measures are proposed based on the systematic analysis of relationship between model's input and output. This is done by utilising the trade-off analysis embedded in the BBN software package GeNIe, which has also been applied for developing the model, see [4]. However, for detailed description of the model the reader is referred to [22]. Whereas this paper limits its content with this respect and only the qualitative and quantitative descriptions of the model is provided, see Figure 8 and *Table 3* respectively.

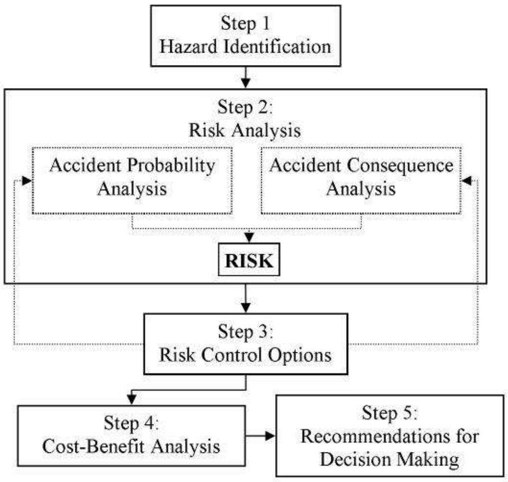

*Figure 2*. General outline of FSA methodology

### 2.1. Model structure

The model for risk evaluation consists of four major parts, as depicted in *Figure 3*: a part estimating the collision relevant parameters; a part evaluating the probability of a ship capsizing as a result of flooding or dead ship conditions (DSC); a part governing the response to an accident, and finally, a part comprising the results of the model.

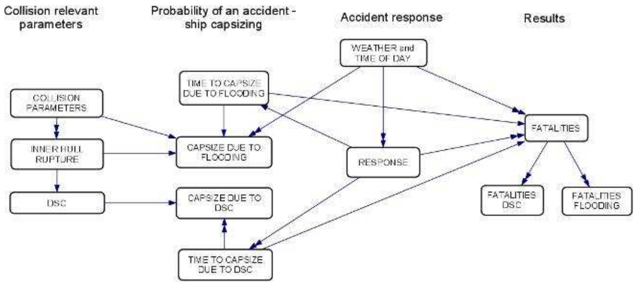

*Figure 3*. A block diagram of the risk model.

The model presented utilises data about traffic composition, ship types, ship sizes, collision angles, collision speed, the time of day of a hypothetical collision and its location. Most of these are determined with the use of the dynamic model of maritime traffic developed by Goerlandt & Kujala, see [7]; however, statistical data are applied as well. As there is lack of data on severe RoPax collisions in general, the study relies on the modelled data, which are considered further as input to a detailed structural analysis of a given RoPax.

The structural analysis is performed for the range of mass ratios of colliding ships: 0.6, 0.8, 1.0, and 1.3, covering more than 80 per cent of maritime traffic in the Gulf of Finland. Therefore the operating conditions of a RoPax are reflected, which is more realistic than drawing conclusions based on an analysis of one mass ratio only; see [21]. The remaining share of mass ratios belongs mostly to values higher than 1.3 (the striking ship mass is 0.8 of the struck ship), which can be assumed to be less critical concerning hull rupture for usual blunt bow shapes, as well as a certain percentage of ratios lower than 0.6 (the striking ship mass is 1.7 of the struck ship), which, however, are not taken into account.

As a result of a collision where the collision speed exceeds its critical value for the given scenario, the probability of the ship flooding and capsizing can be expected. This is modelled for a range of conditions by applying the concept of “a capsize band”. As the band depends on the shape of the ship’s hull, its stability, and the weather conditions - see [27] - the study presented addresses one a RoPax of a given size which is considered a characteristic size for the Gulf of Finland. However, four different sets of loading conditions and resulting damage stability conditions are taken into account, and hence four bands are applied in the model. As the damage stability conditions are affected by the initial stability of a ship, these should be modelled more precisely, with consideration being given to the most frequent loading conditions in the sea area being analysed. Moreover, the probability of there being a significant opening at a critical location, leading to rapid flooding of the car deck, is determined, with consideration being given to the collision speed, collision angle, and dimensions of both ships colliding, thereby providing a realistic case instead of the worst-case scenario; see [24], [27].

Moreover, two means of responding to an accident are considered in this paper. 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, and second, an ordered evacuation of a ship takes place if there is serious flooding following the collision.

Finally the model provides a framework for optimization of the obtained results, considering risk level as an objective. Thereby, the sub-optimal solutions are sought in the searching space defined by the distributions of the input variables. Defining the searching space in this way ensures that the model addresses the same MTS, before as well as after the optimization, with respect to the modelled structure and content of the MTS.

## 2.1. Bayesian Belief Network

A BBN is a probabilistic graphical model, allowing systematical reasoning under uncertainty as well as in the presence of limited data, as there is no such thing for a BBN as ”too little data”. Thereby, a BBN can predicts accurately even with small sample sizes; see [16], [23], [36]. A BBN can consist of either discrete variables, continuous or of both, while the relations among variables in a model are expressed in a probabilistic fashion. Therefore such a model naturally accounts for uncertainties of the input variables and can easily handle lack of knowledge on the modelled domain. BBN is a compact representation of a multivariate statistical distribution function and in fact it is complicated statistical model, for more detailed discussion on BBNs a reader is referred to [17], [33].

Moreover, a BBN allows multi-scenario thinking unlike most of the existing stochastic models, utilising a concept of scenario-approach, defined in a tempo-spatial, stochastic framework, see for example [7], [18], [28], [37]. However being widely spread, the scenario-approach has certain drawbacks, especially if applied for risk analysis of distributed and uncertain systems, such as marine traffic, as discussed by Goerlandt et al. in [8]. Due to their stochastic nature, these models very often disregard relationships between input variables (ship size, collision speed, collision angle, relative striking location, weather) and output variables (ship capsize) hiding them under the probability density functions (e.g.: a pdf representing damage size). Moreover the uncertainty of the model, its variables and results is not always addressed properly; see [9], [38]. Therefore several important elements of risk analysis like links among variables and their mutual relationship as well as uncertainty propagation can be lost.

A classical BBN is a pair N={G,P}, where G=(V,E) is a directed acyclic graph (DAG) with its nodes (V) and edges (E) while P is a set of probability distributions of V. In other words, a BBN encodes 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 conditional probability function (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 conditional probabilities for all possible combinations of the parent nodes states. If a node does not have parents, its CPF reduces to an unconditional probability function, named also a prior probability of that variable. Therefore, a BBN representing a set of variables and their dependencies, consists of two parts namely quantitative (CPFs) and qualitative (model structure). Thereby a network N={G,P} is an efficient representation of a joint probability distribution P(V) over V, given the structure of G following the formula; see also [3], [19]:

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

## 2.2. Risk evaluation

The model that is presented here assumes that a struck RoPax will be lost if either of two accident scenarios, considered high-risk events according to the accident statistics; see [13], takes place:

- the inner hull of the RoPax that is struck is breached and consequent flooding is experienced; this can result further in the loss of a ship;
- the RoPax that is struck has no significant hull damage; however, the ship is disabled and set adrift, thus experiencing significant rolling as a result of wave and wind action, which can result further in the ship capsizing.

In the first case the critical collision parameters, leading to rupture of an inner hull of a struck RoPax, such as the striking speed and striking angle for the given mass ratios, are obtained with the use of finite element simulations. In the second case the probability of the disabled ship capsizing is calculated with the use of the six-degree-of-freedom ship motion model and Monte Carlo simulations.

Additionally, the model presented here takes into account numerous variables that directly affect the consequences, for instance: the composition of maritime traffic in the sea area being analysed, the collision dynamics, ship hydrodynamics and loading conditions, weather conditions, the locations of rescue ships with respect to the probable location of an accident, the time needed to evacuate the ship, the number of passengers on board the ship, and the time of day at which an accident is likely to happen.

The model yields the collision risk, given an open sea collision, presented in the form of an F-N diagram. The results are valid within certain boundaries, defined by: the given size, type, and loading conditions of the ship that is struck, the specific composition of the maritime traffic, and weather conditions corresponding to the ice-free season in the Gulf of Finland.

Additionally, the model evaluates numerous conditional probabilities of intermediate quantities.

## 2.3. Risk mitigation

The model presented in this paper not only allows evaluation of risk in a systematic and proactive way, it also determines the sub-optimal measures to reduce the risk. However due to the model's structure, which is based on conditional probability functions instead of conditional probability tables, the classical Bayesian optimization approach using the utility function cannot be applied here. Thereby, two-fold process is applied, where firstly the trade-off analysis is conducted, which determines the risk levels for each pair of the input variables, given their ranges, see *Table 2*. However, only unconditional input variables are considered. Secondly, using the results obtained, the optimization techniques are applied in order to determine the sets of sub-optimal solutions. The problem presented in this paper can be considered as two-objective optimization problem with numerous constrains, corresponding to the number of input variables. The objective functions can be defined as follows:

$$\begin{aligned} & f_1 = Risk, \\ & f_2 = C/B, \\ & or \\ & f_2 = Feasibility, \\ & or \\ & f_2 = Time, \end{aligned} \quad (2)$$

where the risk level is calculated with the use of the model presented, C/B means cost-benefit ratio of the given solution, while the feasibility addresses the chances for a given solution being implemented and time means how fast the given solution can be applied. However this paper addresses the first step of the risk mitigation process, delivering some results of the trade-off analysis while the further paper will be dedicated to the second step of the optimization process.

*Table 2.* The variables considered an input to trade-off analysis.

| **Variable** | # | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** |
|---|---|---|---|---|---|---|---|---|---|---|
| Collision angle | **1** | / | + | + | + | + | + | + | + | + |
| Collision mass ratio | **2** | + | / | + | + | + | + | + | + | + |
| The probability of collision | **3** | + | + | / | + | + | + | + | + | + |
| Relative striking location | **4** | + | + | + | / | + | + | + | + | + |
| Ship capacity | **5** | + | + | + | + | / | + | + | + | + |
| Stability conditions | **6** | + | + | + | + | + | / | + | + | + |
| Striking location | **7** | + | + | + | + | + | + | / | + | + |
| Time of day | **8** | + | + | + | + | + | + | + | / | + |
| Time to capsize due to flooding | **9** | + | + | + | + | + | + | + | + | / |

## 3. Results

The calculated values of the risk of a RoPax capsizing as a result of flooding are depicted in *Figure 4*, and they fall within the intolerable region for a high number of casualties (F), whereas they stay within the ALARP region or even below for a lower number of fatalities. Additionally the F-N curve based on the available accident statistics on RoPax ships for the North-West European seas is depicted in the same figure for comparison, adapted from [13]. It shall be noted that the statistics based F-N represents risk for all types of accidents, not only collisions. Nevertheless these two curves diverge for higher numbers of fatalities and it can be explained by the fact that in the history of RoPax accidents the most severe were these 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 other ship. The risk values for a RoPax capsizing as a result of DSC are depicted in *Figure 5*, where they stay within the negligible area for the case studied.

Whereas, selected results of the trade-off analysis are depicted in *Figure 6* and *Figure 7*. Thus the influences of the following two pairs of variables onto the risk level are measured: the probability of collision versus the time to capsize due to flooding and the collision angle versus the time to capsize due to flooding. The presented results concern the risk level for F> 1000 (see *Figure 4*), which falls beyond the acceptable limits of 1E-4 for this particular F, see [30], [38]. Thereby, the optimization process should provide the user with the results leading to risk level less than this limit. Analysing just these two figures one can notice, that decreasing the probability of collision will not take the risk level below the limit values. This can be achieved either by extending the time to capsize above 60 minutes or by making collision angle more than 130 degrees.

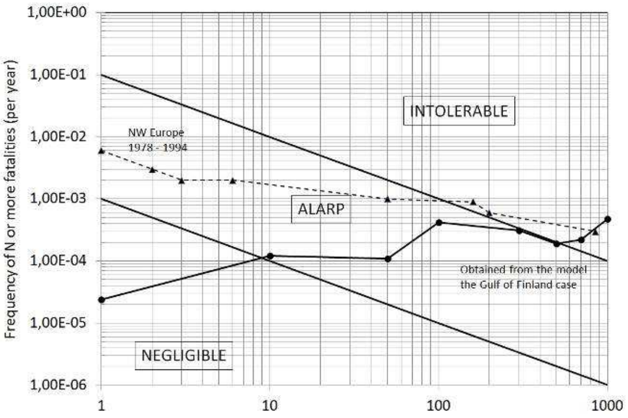

*Figure 4.* An F-N curve for the RoPax analysed here for the ship capsizing as a result of flooding, plotted against the social criteria (F-N flooding).

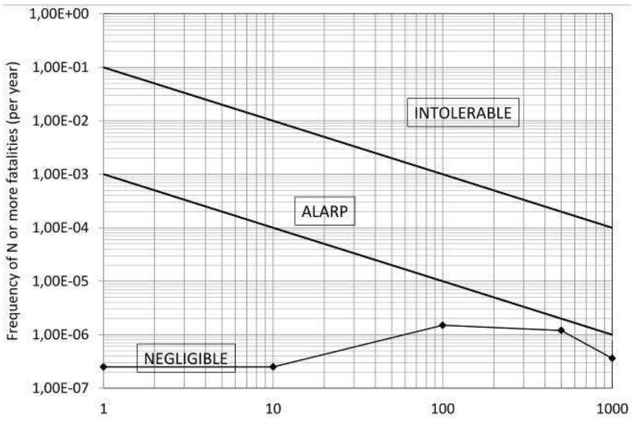

*Figure 5.* An F-N curve for the RoPax analysed here for the ship capsizing as a result of DSC, plotted against the social criteria (F-N DSC).

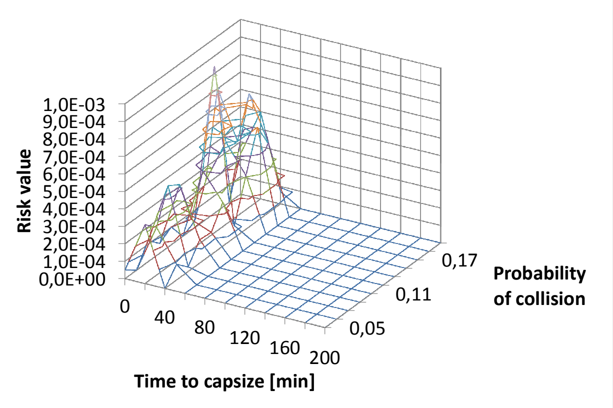

*Figure 6.* Results of trade-off analysis for two variables: the probability of collision and time to capsize due to flooding.

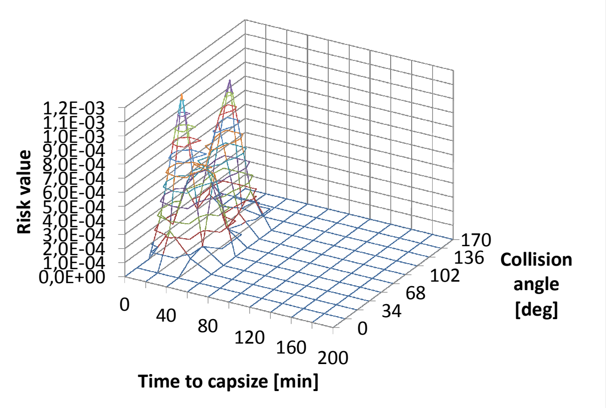

*Figure 7.* Results of trade-off analysis for two variables: collision angle and time to capsize due to flooding.

## 4. Conclusion

This paper makes a contribution to a holistic risk model for MTS by introducing a novel architecture of a systematic, proactive and transferable model, focusing on a selected type of RoPax ship sailing in the selected location. Unlike the existing models, the solution proposed utilises the BBN and continuous variables, instead of a simple binary format, which is still a common practice, and thus the uncertainties of these variables are incorporated into the model. The approach taken allows the probabilistic relationship among variables and complex dependencies as well as relatively fast and easy propagation of uncertainty through the model. The model gives good prediction even for small data-sets, and updates beliefs instantaneously in the presence of new data.

The results obtained are normalised over the whole maritime traffic, according to the prior probabilities of the ship mass ratios, collision speeds, and collision angles obtained from the analysis of AIS data for the Gulf of Finland. The results are valid within certain, predefined boundary conditions; however, the modular nature of the model allows its continuous improvement and adaptation to various locations. Moreover, the model can be continuously improved and extended to include more hazards and consequences.

Additionally the model is capable of delivering the sub-optimal solution of the risk optimization problem which is tantamount to systematic risk mitigation. Finally the results of risk optimization can serve as a basis for decision makers, clearly showing quantitatively how the given risk reducing measures affect the risk.

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# Appendix

*Table 3*. The quantitative description of the model.

| Factor group | Variable name | Variable symbol | Output states |
|---|---|---|---|
| **Collision parameters** | Collision speed | V(A,B)⊥ | If(α <45, Exp(0.36), If(α >135, Exp(0.36), Triang(0,10,15))) |
| | Collision angle | α | Unif(10, 170) |
| | Striking location | m | If(Unif(0,10)>8,1,0) |
| | Relative striking location | r | Unif(-0.5,0.5) |
| | Collision mass ratio | cmr | Logn(0.2548,0.7014) |
| | Inner hull rupture | ihr | f(r,cmr,V(A,B)⊥) |
| | Machinery damaged | md | If(And(ihr=1,m=1),1,If(And(ihr=0,m=1),0.5,0)) |
| | Collision angle significant | αs | If(And(α<160,α>20),1,0) |
| | Damage extent significant | des | If(And(ihr=1,cmr<1.3,V(A,B)⊥>7,αs=1),1,0) |
| | Ships stay separated after collision | sss | If(And(V(A,B)⊥>10,cmr<1.1),0,1) |
| **Probability of an accident** | Weather | W | Exp(1.1), where W<1 stands for good, 1 <W<2 moderate and W>2 is bad |
| | DSC conditions | DSC | If(md=0,0,1) |
| | Capsizing in DSC | CDSC | If(DSC=1,Unif(1E-4,2E-4),0) |
| | Capsizing due to flooding | Cflood | If(And(des=1,1<W<2),Wmoderate*Unif(0,1),If(And(des=1,W>2,sss=1),Wbad,0)) |
| | Time taken to capsize in DSC | TTCDSC | Logn(5.9948,0.6455)/60 (min) |
| | Time taken to capsize flooding | TTCflood | Exp(0.05) (min) |
| | Probability of life loss | PLL\|flood | Cflood*LLfloodgiven flooding |
| | Probability of life loss given DSC | PLL\|DSCC | DSC *LLDSCgiven DSC |
| | Probability of collision | Pcoll | 0.107 |
| | Probability of life loss given collision and flooding | PLL\|coll\|flood | PLL\|flood*Pcoll |
| | Probability of life loss given collision and DSC | PLL\|coll\|DSC | PLL\|DSC*Pcoll |
| **Accident response** | Time of day | T | Binom(1,0.5); where 1 is day and 0 is night |
| | 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))) |
| | Distance from tugs' base | D | Unif(60,180) (min) |
| | Time for tugs | TT | If(W<1.5,D,1.5D) |
| | Danger of loss of life - DSC | LLDSC | If(E<T T CDSC ,0,1) |
| | Danger of loss of life-flooding | LLflood | If(E<T T Cflood,0,1) |
| | Danger of loss of ship - DSC | SL | If(TT>T T CDSC ,1,0) |
| | Ship capacity | N | Unif(200, 3000) |
| **Results** | Fatalities given flooding | Fflood | If(And(T=1,T T Cflood<5),1,If(And(T=0,T T Cflood <10),1, If(T T Cflood>E, 0, T T Cflood/E))) |
| | Fatalities given DSC | FDSC | If(And(T=1,T T CDSC <5),1,If(And(T=0,T T CDSC <10),1,, If(T T CDSC >E,0,T T CDSC /E))) |
| | Number of fatalities given flooding | NF−flood | Fflood*N |
| | Number of fatalities given DSC | N –DSC | FDSC *N |

| | | | |
|---|---|---|---|
| | Fatalities flooding | Fflood | Nflood*N |
| | Fatalities DSC | FDSC | NDSC *N |

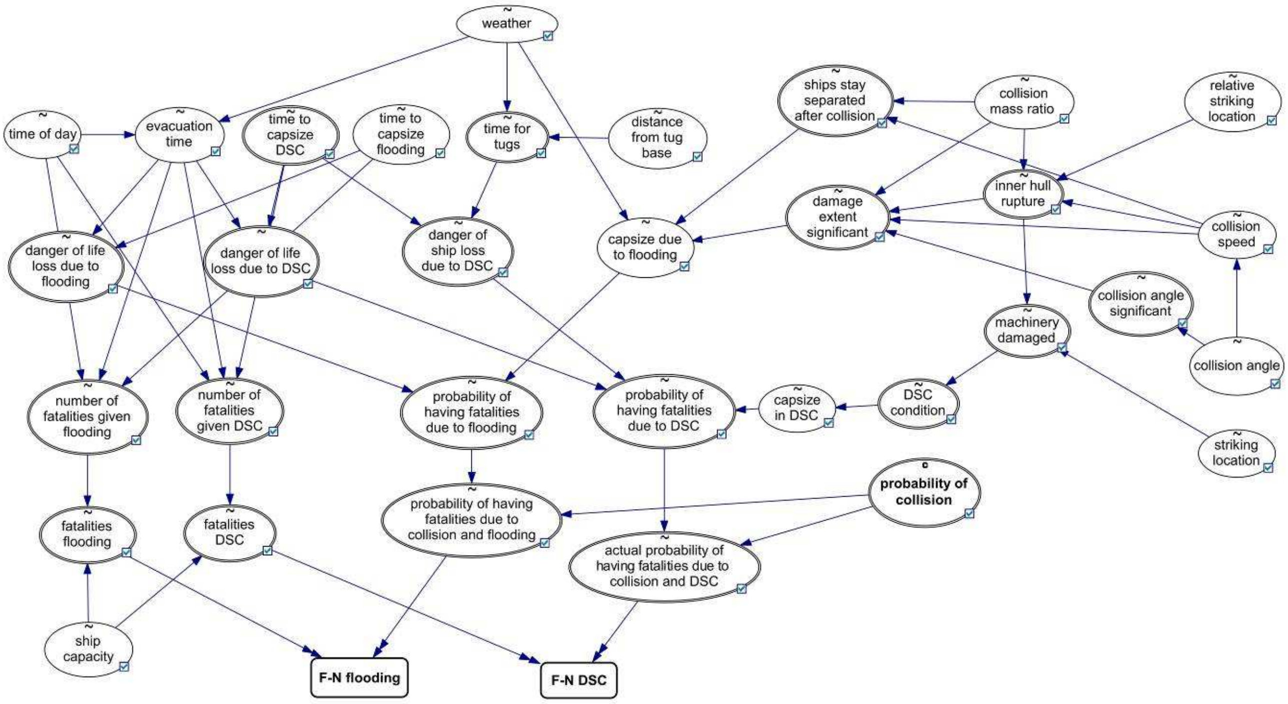

*Figure 8*. The qualitative description of the model.