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A Model for Risk Analysis of Oil Tankers

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Abstract

The paper presents a model for risk analysis regarding marine traffic, with the emphasis on two types of the most common marine accidents which are: collision and grounding. The focus is on oil tankers as these pose the highest environmental risk. A case study in selected areas of Gulf of Finland in ice free conditions is presented. The model utilizes a well-founded formula for risk calculation, which combines the probability of an unwanted event with its consequences. Thus the model is regarded a block type model, consisting of blocks for the probability of collision and grounding estimation respectively as well as blocks for consequences of an accident modelling.

Probability of vessel colliding is assessed by means of a Minimum Distance To Collision (MDTC) based model. The model defines in a novel way the collision zone, using mathematical ship motion model and recognizes traffic flow as a non homogeneous process. The presented calculations address waterways crossing between Helsinki and Tallinn, where dense cross traffic during certain hours is observed.

For assessment of a grounding probability, a new approach is proposed, which utilizes a newly developed model, where spatial interactions between objects in different locations are recognized. A ship at a seaway and navigational obstructions may be perceived as interacting objects and their repulsion may be modelled by a sort of deterministic formulation. Risk due to tankers running aground addresses an approach fairway to an oil terminal in Sköldvik, near Helsinki.

The consequences of an accident are expressed in monetary terms, and concern costs

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of an oil spill, based on statistics of compensations claimed from the International Oil Pollution Compensation Funds (IOPC Funds) by parties involved.

Keywords: maritime risk, maritime transportation, collision, grounding, modelling, tankers, oil spill, the Gulf of Finland

1. Introduction

A process of a risk modelling of maritime traffic is complex in nature. It takes into account several aspects and integrates different scientific domains, usually being very remote one from another. Among engineers risk is defined as a product of the probability of the occurrence of an undesired event and the expected consequences in terms of human, economic and environmental loss. A maritime risk analysis consists of two steps: first the probability of a ship accident is determined (collision and/or grounding), and thereafter an estimation of the consequences following the accident is performed.

At present models for collision and grounding probability assessment are mostly rooted in approach suggested by Fujii et al. (1970) and MacDuff (1974). The equation introduced by these authors for estimation of a probability of an accident yields the combination of a geometrical probability and a causation factor. As these simplified models were robust, they still are commonly applied for marine traffic safety assessment. Pedersen (1995) proposed a method, similar to Fujii et al. (1970), to estimate the number of collision candidates, based on certain properties of the traffic flow over the waterways under consideration. Pedersen defines a static collision diameter as the critical distance in an encounter situation, dependent on the length and width of the vessels, the crossing angle and the respective speeds. The model was used to determine the safety of navigation in many European waters (Otto et al. 2002, Pedersen 1995, Søfartsstyrelsen 2008), hence in Europe it is mostly known as Pedersen model. Fowler et al. (2000) outlined a simple method in order to assess the frequency of collision, assuming uncorrelated traffic movements, a critical situation is assumed to occur when ships come to close quarters to a distance of 0.5 Nm of each other, which is constant for all meeting scenarios. Kristiansen (2005) described a method of assessing ship collision probability in a fairway using traffic flow characteristics in the probability analysis.

Another group of models is based on marine traffic simulation. Merrick et al. (2001, 2002, 2003) proposed a risk analysis methodology for ship traffic in coastal areas based on system simulation. Maritime traffic is simulated in the time domain based on routes obtained from expert opinion and vessel arrival records. An interaction counting model based on a static closest point of approach type arguments is devised, resulting in a number of opportunities for an incident. Accident probabilities given a certain interaction type were estimated using expert opinion through pairwise comparison surveys (van Dorp er al. 2001). Przywarty (2008) outlined a probabilistic model for the assessment of navigational accidents in an open sea area, based on concepts proposed by Gucma (2003). The method makes use of a simplified model of maritime traffic, which is simulated in the time domain. A recent model, introduced by Goerlandt et al. (2010) is based on an extensive time-domain simulation of maritime traffic in a given area. Vessel movements are modelled based on data obtained from a detailed study of route-dependent vessel statistics. The collision candidates are detected by a collision detection algorithm which assesses the spatio-temporal propagation of the simulated vessels in the studied area to a collision occurrence criterium equivalent to Pedersen's collision diameter.

The causation factor which quantifies the proportion of cases in which a collision candidate ends up as a collision is currently estimated in two ways: by a scenario approach or by a synthesis approach. The latter is based on available accident statistics, the former on application of Bayesian networks (Hänninen&Kujala 2009) or fault tree analysis (Martins&Maturana 2010, Pietrzykowski 2007) to error propagation in the vessel's action chain to avoid the collision.

A second part of the risk equation, concerns estimation of consequences of an accident, which can be of various types and can be estimated in many ways (Aven 2010, Duffey&Saull 2008, Klanac et al. 2010, Merrick et al. 2002, Montewka et al. 2010a, Soares&Teixeira 2001, Uluscu et al. 2009, Vinnem 2007).

The probabilistic methodology for oil outflow estimation was developed by IMO (1995, 2004). Smailys and Česnauskis (2006) worked out a method for calculation of an accidental oil outflow from specific types of tankers. The method is based on IMO probabilistic methodology, but requires less input data, and estimations can be performed in a short time span. Yamada (2009) proposed a practical and a straightforward way to estimate the cost of oil spills from ships within the framework of establishing environmental risk evaluation criteria in IMO. He carried out a regression analysis between the cost of oil spills and the weight of oil spilled, using historical oil spill data from tankers, reported by International Oil Pollution Compensation Funds (IOPCF).

The most significant shortcomings of existing geometrical models for ship collision frequency prediction are assumptions regarding marine traffic a stationary Poisson process. Another drawback concerns a definition of a collision zone, which in all existing geometrical models means or a physical contact or it is assumed some number, not giving any convincing explanation for it. Also the existing grounding models are too generic and simplified in Authors' opinion. They are usually lacking interactions among human, a ship and the environment, or these relations are based on some out-dated studies.

This paper focuses of chosen aspects of marine traffic risk modelling, taking as example marine traffic in the Gulf of Finland, and its non stationary nature. A novel method of modelling risk of a ship being collided and being aground is presented, with emphasis on tankers. A new geometrical model for collision frequency assessment, named the MDTC model, taking ship manoeuvrability into account, is used and a newly developed model for grounding probability calculation, accounting interactions between human-ship-environment, is utilized. Consequences presented in this paper are expressed in costs to incur caused by an oil spill, being a result of a tanker accident, obtained by means of modified IMO methodology and model provided by Yamada (2009).

A case study is carried out for two chosen areas of the Gulf of Finland. One is a junction of two busy waterways, between Helsinki and Tallinn, with RoPax ferries cross traffic and dense parallel tankers traffic. Another analyzed spot is an approach fairway to an oil terminal in Sköldvik east to Helsinki, experiencing dense tankers traffic.

2. Marine Traffic Modelling

Presented analysis concerns maritime traffic in the selected areas of the Gulf of Finland. Data regarding marine traffic concerns all ships above 300 tons gross, involved in international voyages that are required to be fitted with the transponder of Automatic Identification System (AIS). The analyzed data cover a period from 01.06.2006 to 31.06.2006.

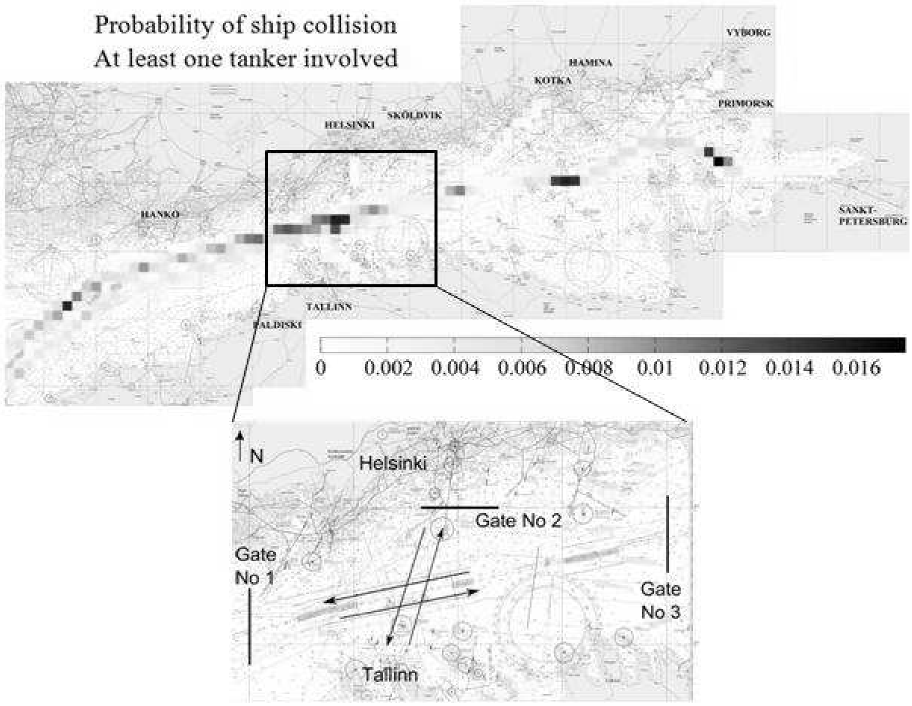

Fig. 1. Analyzed waterways junction, with counting gates and main traffic flows

The area to be analyzed is considered as one of the areas in the Gulf of Finland most prone to collision. Figure 1 presents calculations regarding a probability of a collision, in which at least one tanker is involved. These values show that it is the most probable to have a tanker collision in a narrow sea area between Helsinki and Tallinn. This data justified the choice of this particular area for further risk analysis.

To compute the traffic volume in the analyzed area three counting gates were established, as depicted in Figure 1. In gate number 3, E-W traffic entering the junction was recorded, whereas at gate 2, RoPax vessels cruising between Helsinki and Tallinn were counted. At gate 1 overall traffic, inbound as outbound, was recorded.

According to the analysis of marine traffic, the following main groups of vessels were considered: container carriers, tankers, general cargo vessels, ro-ro, cruise ships, and fast ferries. Marine traffic in the area under analysis was assumed to consist of four main flows: east, west, north, and south, while the north and south flows are assumed to contain passenger vessels only (Figure 1). Each flow was modelled with the following input parameters: an overall number of vessels, type of vessels, number of vessels of a given type, size of vessel of a given type, speed of vessels of a given type, course of vessel, and position of the vessel across the waterway. For modelling purposes most of these values were approximated by continuous distribution or by histograms. The distribution of the features being analysed was chosen according to the results of a chi-square test. Those which fitted the best (obtained the highest value of a chi-square test) were selected as inputs to the model. In some cases, if none of the available distributions fitted, then recorded discrete values were taken into the model, by random sampling (Montewka et al. 2010).

This paper pays special attention on tankers. Based on the recorded AIS data, tanker traffic in the Gulf of Finland consist of two major types of tankers: crude oil tankers (25%) and oil product tankers (70%), the remaining 5% includes chemical and gas tankers which were not considered in the analysis presented. Although tanker traffic is season dependent (Montewka, Krata, Kujala, 2010), this paper addresses only summer traffic. The main dimensions of tankers (their length, breadth and maximum design draught) were estimated with the use of triangular distributions, and the minimum, maximum and mean values adopted are presented in Figure 2. The triangular distributions were the ones that fitted best the observed discrete data.

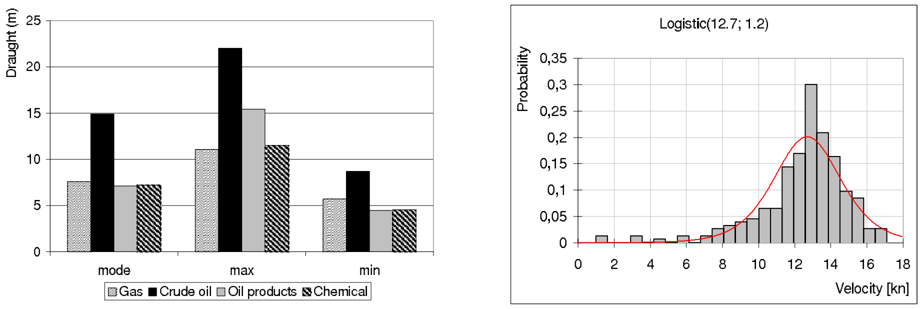

Fig. 2. Distributions of the main parameters of tankers navigating in the Gulf of Finland

Velocity of the tankers was modelled by a Logistic distribution, which fitted the best the recorded values (Figure 2), and follows the general formula (Palisade Corp, 2002):

$$v = f(x) = \frac{\operatorname{sech}^2\left(0.5\left(\frac{x-\alpha}{\beta}\right)\right)}{4\beta}, \tag{1}$$

where *sech* is a hyperbolic secant function, x is a random variable (velocity), α is a location parameter and equals 12.7, and β is a scale parameter which equals 1.2. The courses of the vessels were modelled by either distributions or a sampling method from the recorded AIS data. Another important factor, that was neglected in previous geometrical models used for collision probability assessment is the daily variation of marine traffic. As the marine traffic in the analyzed area is dominated by RoPax vessels, which follow their schedules, modelling this kind of traffic flow by means of a stationary Poisson process is questionable. Daily variations in north- and southbound RoPax traffic between Helsinki and Tallinn as well as in the east- and westbound traffic of cargo ships are depicted in Figures 3 and 4.

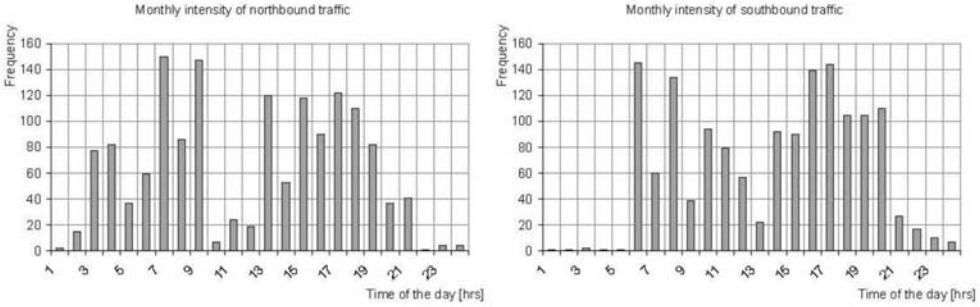

Fig. 3. The marine traffic intensity of N-S flow, recorded between Helsinki and Tallinn

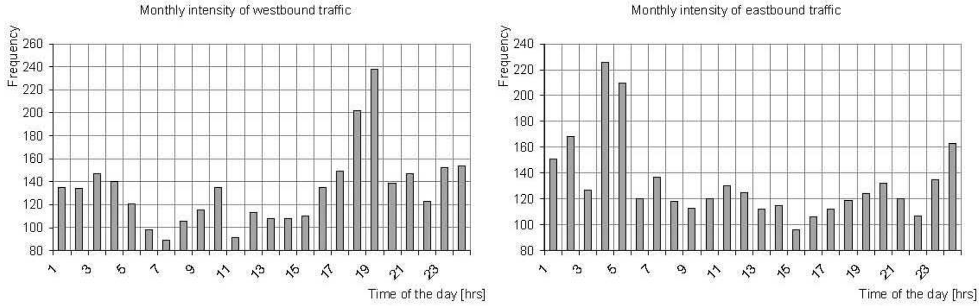

Fig. 4. The marine traffic intensity of E-W flow, recorded between Helsinki and Tallinn

From the presented data, certain peaks can be recognized, both for the N-S and the E-W flows. It may be noted that time of the day for peaks for N-S traffic generally differ from peaks for E-W traffic. Usually rush hours for N-S traffic do not correspond the rush hours for E-W flow. Thus modelling the marine traffic flow in the analyzed location as constant is highly questionable, and may lead to the underestimation of the results (a number of collision candidates and finally a risk of collision).

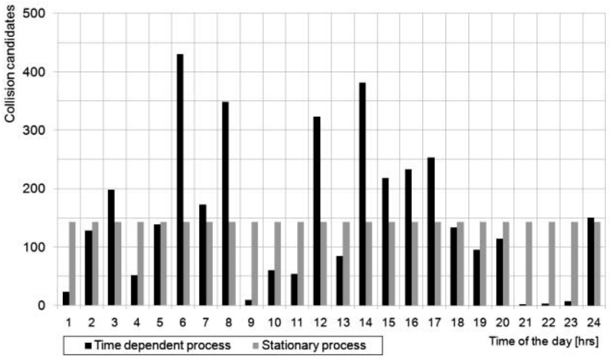

Fig. 5. A number of collision candidates obtained from the MDTC model for constant and time varying traffic flows

The comparison of results obtained from MDTC model, expressed as a number of collision candidates, is depicted in Figure 5. At first traffic intensity was assumed to be stationary, and the number of collision candidates was calculated, which is independent on the time of day. Then the traffic intensity was modelled according to the recorded AIS data, and the calculated number of collision candidates is found to depend significantly on the time of day.

In Figure 5 substantial differences can be recognized, especially during peak hours, where the number of collision candidates is almost three times higher in comparison with results obtained from the model with constant intensity. This of course translates directly into risk level.

3. Modelling the Accident Probability

The probability of ship collision and grounding is modelled by means of two original models. The probability of collision is estimated by means of the MDTC model which was described in detail in (Montewka et al. 2010) and (Montewka, Ståhlberg et al. 2010). The grounding model is based on concepts of one-way interactions between a ship and the obstacles surrounding her. An initial description of the model was given in (Krata 2007) and a case study with the use of this model was shown in (Montewka, Krata et al. 2010). The presented paper contains a brief introduction to both models, without going into detail, which is left for references.

3.1. A model for ship collision probability estimation

The collision probability prediction model presented in this paper is based on a molecular collision model and is supported by a model of ship dynamics. This paper presents a two-dimensional model, which was reduced from the original three-dimensional case for the purposes of marine navigation, thus only planar ship motion is considered. In this model, the vessel is represented as a particle surrounded by a disc of a given radius (Figure 6a), which constitutes a "no-go area" for other objects. Some researchers similarly define the vessel static domain (Fujii et al. 1984, Kao et al. 2007, Pietrzykowski&Uriasz 2009, Szłapczyński 2006). The main difference between ship domain, and the idea presented in this paper, is that the definition of the domain expresses it as the area around the vessel that the navigator wants to keep clear of other vessels or objects (Fujii et al. 1978, Goodwin 1975). Therefore a violation of the domain of a vessel is not tantamount to a collision, whereas in the presented model a violation of the outer boundary of the disc inevitable leads to a collision. A collision between two vessels (two discs) is described as an overlap of these two discs. The occurrence of such an overlap is equivalent to an event in which a point representing the centre of one vessel enters the disc of which the radius equals the sum of the radii of two original discs (Figure 6b).

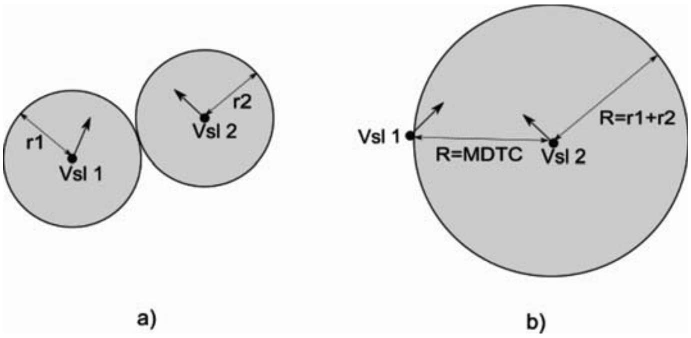

Fig. 6. Representation of vessels as discs and definition of collision situation (Montewka et al. 2010)

The diameter of the greater disc depicted in Figure 6b is not fixed, and is estimated for each type of vessel and encounter individually, thus it changes with the situation. The value of that disc diameter is considered the minimum distance to collision (MDTC). If the distance between these two vessels becomes less then MDTC, it means that a collision cannot be avoided by any manoeuvres, and the vessels will collide. In other words, as long as the disc of radius MDTC is not violated by another vessel no collision will take place. The main factors relevant to determine the MDTC value are: the vessels' manoeuvrability, the angle of intersection of ships' courses and the relative bearing from one vessel to the other. The value of MDTC is also dependent on a way that collision evasive manoeuvre is performed. Thus two patterns are recognized, the case of single vessel manoeuvre, when only one vessel is performing evasive action, and the case of manoeuvring of both vessels, when two vessels at the same time start to make collision avoidance.

To determine the value of MDTC and the factors that may affect it, an experiment using a hydrodynamic model of ship motion was conducted and several crossing-type meeting scenarios were simulated. Analysis was carried out for three types of vessel (container carrier, passenger vessel, and tanker), and 17 crossing angles varying from 10° (almost overtaking) to 170° (almost head-on), with 10 degrees increments. A detailed description of the experiment is given in (Montewka et al. 2010). The influence of hydro-meteorological conditions was omitted in this analysis.

Depending on the types of vessels engaged in the meeting, there are slight differences in the MDTC values. To prove whether these differences are statistically significant, an appropriate analysis was performed. A hypothesis was formulated that each MDTC curve was drawn from the same population, and therefore there is no influence of the vessel type on the value of MDTC. At first the Kolmogorov-Smirnov normality test was performed. This test compares the empirical cumulative distribution function of sample data with the distribution expected if the data were normal. The test hypotheses were H_0: the distribution of the random variable follows the Gaussian distribution, versus H_1: the distribution does not follow the Gaussian distribution. The p-values of this test were lower than the chosen α level ($p<0.05$) for 90% of the observations, and therefore it was concluded that the analysed random variable's distribution is non-normal.

In the next step a nonparametric Kruskal-Wallis test of the equality of medians for two or more populations was performed; it tests whether two or more independent samples come from identical populations. The test hypotheses were H_0: the population medians are all equal versus H_1: the medians are not all equal. The test does not require the data to be normal, but instead uses the rank of the data values rather than the actual data values for the analysis.

For the experiment, where two involved ships were performing collision avoidance manoeuvres (MDTC_2), the test statistics had a p-value higher than adopted α-value ($p>0.05$), for all cases, indicating that the null hypothesis cannot be rejected. For an experiment where one vessel was manoeuvring in order to avoid collision (MDTC_1), less than 10% of all cases resulted in p-value lower than α-value. Although in some cases the threshold level was not reached, it was decided not to reject the null hypothesis.

As a result of experiments, it is concluded, that all MDTC_1 values as well as MDTC_2 values were drawn from two populations, irrespective of ship type.

As the survey sample was limited, further analysis was based on the bootstrap resampling method. Using bootstrap method both means and standard deviation values for a population were obtained, which allowed constructing the 95 percentile confidence levels for MDTC_1 and MDTC_2 data sets. The results obtained are depicted in Figure 7.

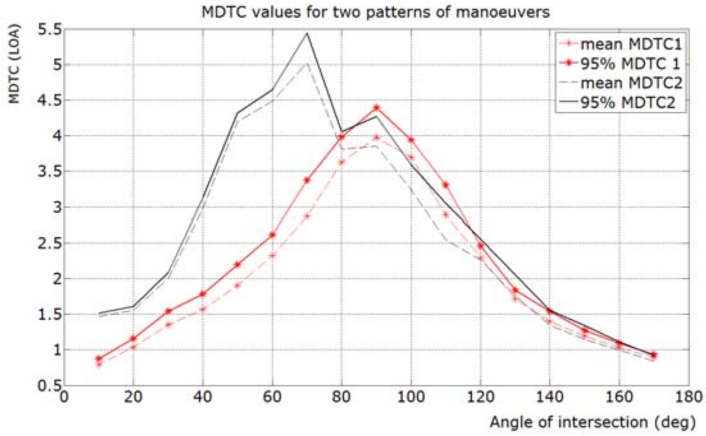

Fig. 7. MDTC curves (the mean values and the 95 percentiles) representing two analyzed manoeuvring patterns

3.1.1. A model formulae

The formulae used in the model are presented in this chapter. Model concerns three main types of vessel encounters: overtaking, head-on, and crossing. Overtaking means a situation in which two vessels are proceeding on the same route, along almost parallel courses, and the difference between their courses does not exceed 10 degrees. Head-on means a situation in which vessels are proceeding on almost reciprocal courses, and the courses difference falls in a range of 180 +/-10 degrees. Crossing means a situation in which difference between two vessels' courses fall in range of 10-170 degrees.

Overtaking and head-on situations

A situation where two vessels are navigating along the same route, on mutually parallel courses, with the difference between their courses not exceeding 10 degrees, but at different velocities, is considered an overtaking. The numbers of candidates for collision during overtaking is expressed as follows:

$$N_{overtaking} = T_O P_O, \tag{2}$$

where T_O is the overtaking rate and P_O is the probability that the vessels during overtaking will come to certain distance, which can be considered a collision. The overtaking rate is the number of vessels which will overtake another while on parallel courses, irrespective of the passing distance. The overtaking rate is not a collision frequency, unless the waterway width is zero. It is calculated with the following formula:

$$T_O = \frac{N^2}{2L} E'[V_{ij}], \tag{3}$$

where $N$is the expected number of vessels in the waterway on parallel courses, L is the length of waterway, and $E'[V_{ij}]$ denotes the expected relative velocity of all pairs of vessels of types i and j. The distribution of relative velocity (V_{ij}) between two ships of given types i and j were obtained by means of Monte-Carlo simulation, following the formula:

$$V_{ij,m} = \sqrt{(V_{i,m}^2 + V_{j,m}^2 - 2V_{i,m}V_{j,m}\cos\theta_m)}, \tag{4}$$

where $V_{i,m}$ is the velocity of a vessel of given group (i), picked up randomly from an appropriate distribution in the calculation step m, $V_{j,m}$ is the velocity of a vessel of given group (j), picked up randomly from an appropriate distribution in the calculation step m, Θ_m means the angle of intersection, which is defined as the difference between the courses of vessels in groups i and j in the calculation step m. The probability of the event that two vessels will pass each other at a distance that causes a collision is expressed as follows:

$$P_O = P\left(dist \leq \frac{B_i + B_j}{2}\right), \tag{5}$$

where *dist* is the distance between two ships while overtaking and B is the breadth of a vessel of a given class. This simplified approach neglects all hydrodynamic effects, which are present while two ships are navigating on parallel courses in very close proximity (Barras 2004, Clark 2005, Jiankang et al. 2001, Varyani et al. 1998). Therefore the distance, between two ships on parallel courses, that causes a collision may be greater than adopted value.

The number of collision candidates during head-on meetings is calculated using the formulae presented in Equations (2) to (5). It is assumed that the differences between the two vessel courses are to be within 180° +/-10° to consider such a situation as a head-on meeting.

A crossing situation

Collision rate at the intersections of waterways is calculated with assumption that the vessels are entering the waterway with a given velocity, which is modelled by a continuous distribution, and with a given hourly intensity, which changes over a day, but is assumed to be constant within a time period of one hour. The processes of the flow of vessels into waterways are independent. The number of collision candidates is determined on the basis of the following equation:

$$N_{\text{crossing}} = \sum\nolimits_{i,j} \frac{MDTC_{ij}E'[V_{ij}]\lambda_i\lambda_j}{V_iV_j\sin\alpha}, \tag{6}$$

where λ denotes the intensity of the vessels entering the waterway, V is the velocity of the vessels according to type, and α is the angle of intersection of the waterways.

The number of collision candidates depends on the vessels' velocities and dimensions, the traffic intensity, and the angle of intersection of the waterways. The rate does not depend on the lateral distribution of vessels across the waterway, whereas it is crucial in the case of overtaking and head-on situations.

3.1.2. Modelling of the collision probability

The MDTC model presented in this paper is a geometrical model and defines the probability of a collision as follows:

$$P = \sum_{k} N_{A,k} P_{C,k}, \tag{7}$$

where k denotes the number of scenarios considered, N_A is the number of collision candidates and P_C is the corresponding causation probability in a k^{th} scenario, also called the probability of failing to avoid a collision when on a collision course. A ship on a collision course is called a collision candidate, which may end up as a collision as a result of technical failure or human error. The causation probability quantifies the proportion of cases in which a collision candidate ends up as a collision. The value of the causation probability for this analysis is adopted from a state-of-the-art model based on a Bayesian Belief Network developed in earlier research (Det Norske Veritas 2003). The following values were adopted for collision cases: 1.3E-04 for vessels being on crossing courses and 4.9E-05 for head-on and overtake situations (Kujala et al. 2009). The number of analyzed scenarios depends on the complexity of traffic over the waterway in question. The area considered in this study is depicted in Figures 1 and 8, and four major traffic flows can be distinguished. Therefore four major crossing points (NE, SE, NW, SW) and four parallel routes (N, S, E, W) were defined as presented in Figure 8.

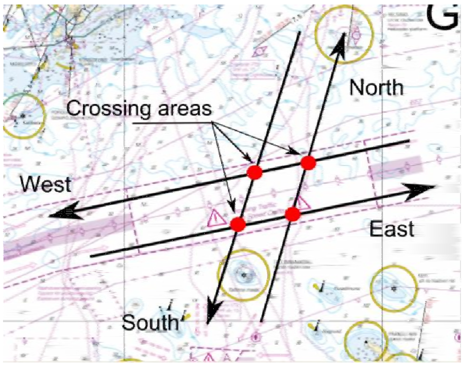

Fig. 8. A crossing between Helsinki and Tallinn, with major crossing points and parallel routes marked (Montewka et al. 2010)

Thus the probability of a collision between two ships (P) over the whole analyzed area yields:

$$P = \sum_{k=1}^{k=4} P_{\text{crossing}} + \sum_{k=1}^{k=4} P_{\text{overtaking}} + \sum_{k=1}^{k=2} P_{\text{head-on}} \tag{8}$$

The value of k for each element of the above equation represents the number of traffic scenarios defined: four crossing scenarios (NE, SE, NW, SW), four overtaking (E, W, N, S) and two head-on (N-S, E-W).

3.2. A model for ship grounding probability estimation

The probability of ship grounding is considered a probability of the occurrence of a situation where a vessel breaches a certain "safety contour". The presented paper introduces a method for estimating this "safety contour", by means of a modern model, which takes into account a number of factors that affect ship behaviour in restricted waterways.

Models based on similar equations as in case of physical phenomena (i.e. gravitation, electrostatics), are convenient formulation of spatial interactions problems. Spatial interactions between objects in different locations are proportional to their respective importance divided by their distance. A ship at a seaway and navigational obstructions may be perceived as interacting objects and their repulsion may be modelled by a sort of deterministic formulation. The main features describing essential ships' characteristics are: maximum draught T, turning circle radius R, coefficient of the effective distance of obstruction detecting d, a coefficient describing a technical equipment of a ship e. All the mentioned variables recounting ships' characteristics are distributed over a considered space therefore the use of field notion is convenient. Such a field is a construction which assigns a variable or a set of variables to each point in a space. In the discussed case the variables are just selected features of ships at seaway. Thus, the field of characteristics of ships location is described by the formula:

$$S = S(T_{(\varphi,\lambda)}, R, d_{(e)}), \tag{9}$$

where S denotes a field of characteristics of ships, T, R and d are the fields which describe ships, and (ϕ, λ) denotes coordinates of ships. It is assumed that features of obstructions in the investigated area are: the water depth H, a coefficient of soundings accuracy s, a coefficient of destruction of ship's hull when contacted with the seabed b, a coefficient of soundings position accuracy c. The function describing the field of features of obstructions is given by the formula:

$$O = O\left(H_{(\varphi',\lambda')}, b_{(\varphi',\lambda')}, s_{(\varphi',\lambda')}, c_{(\varphi',\lambda')}\right), \tag{10}$$

where O means a field of characteristics of obstructions, H, b, s, c denote fields describing obstructions, and (ϕ', λ') the coordinates of obstructions. The comprehensive description of an influence of the distance on the relation ship-obstruction may be given by the distance decay curve (Rodrigue et al. 2009). The applied one in the model presents the decay of a threat impact of any obstruction in terms of distance as r^{-1} where r is the considered distance. Considering the fields S and O effecting ships tracks and taking into account the distance decay function r^{-1} the function of a grounding threat F is constructed in a form given by the formula:

$$F = F\left[S(T_{(\varphi,\lambda)}, R, d_{(R,e,m)}), O(H_{(\varphi',\lambda')}, b_{(\varphi',\lambda')}, s_{(\varphi',\lambda')}, c_{(\varphi',\lambda')}), r_{(\varphi,\lambda)}\right] = M \cdot \frac{T}{H \cdot r}, \quad (11)$$

where the coefficient M is defined as follows:

$$M = \frac{R \cdot b}{d \cdot s \cdot c}, \quad (12)$$

The interaction described by the grounding threat function aims at deterring a ship to near excessively to a shallow. It is one-way relation with no feedback. The utility function applied in the model is based on the grounding threat field described by the function (11). It is transformed into the grounding threat intensity field given by the formula:

$$E = \frac{F}{T}, \quad (13)$$

For the purpose of the model presentation the exemplary sea area is depicted in Figure 9. It comprises some shallows of different characteristics.

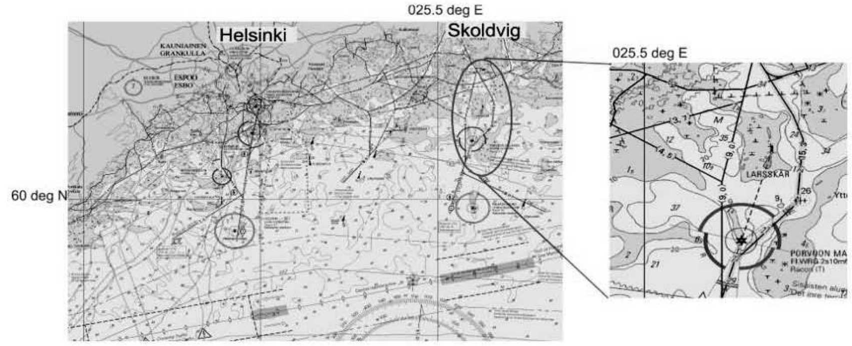

Fig. 9. A fragment of a sea chart presenting the considered fairway to Sköldvik harbour (Montewka, Krata&Kujala 2010)

For the modelling purposes the bottom profile of the area in question was needed. Therefore the sea chart has been digitalized and the bathymetry data were derived and converted into a grid, which is presented in Figure 10.

The distribution of the grounding threat intensity E in the modelled exemplary area is determined with regard to the formulae mentioned above. For the sake of a realistic modelling of navigator's behaviour, the area of interactions taken into

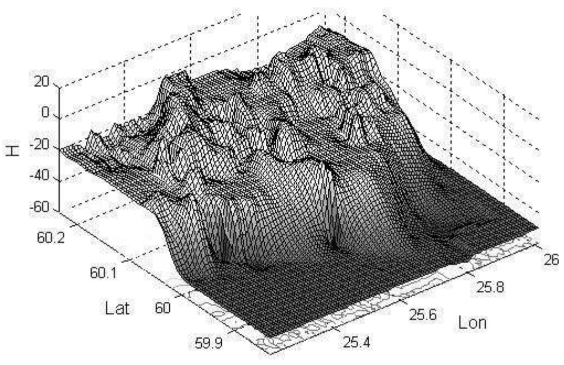

Fig. 10. A bottom profile of the analyzed area

account was restricted to 2 nautical miles. The resultant spatial distribution of the values of the grounding threat intensity (applied in the model utility function) is shown in Figure 11.

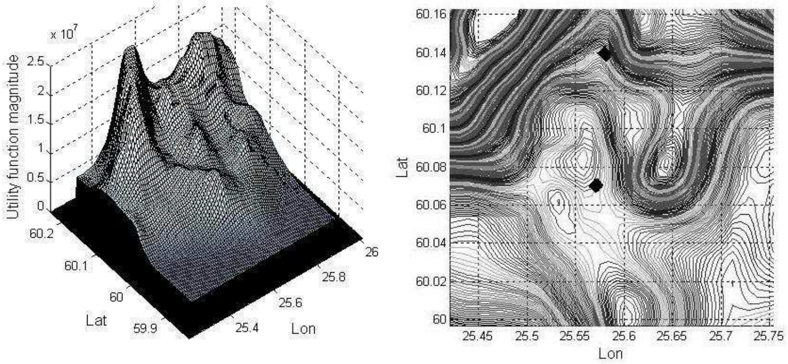

Fig. 11. Spatial distributions of the values of the utility function field

The approach presented in Figure 11 is convenient for the purpose of ship's track optimization from the grounding avoidance point of view. The safest track can be obtained although the non-optimal but still a 'safe enough track' is not obtainable. An additional objective is required to attain the safety contour and such an objective may be the minimum required value of under keel clearance (*UKC*). The minimum allowed value of *UKC* was obtained according to formula (Jurdzinski 1998):

$$UKC = \sum R_S + \sum R_D, \tag{14}$$

where $\sum R_S$ is a sum of static corrections and $\sum R_D$ is a sum of dynamic corrections. The static corrections include an accuracy of bathymetric data, an uncertainty of actual sea level, and an error of draught readings. The dynamic corrections comprise a squat and changes in ship's draught due to heave and pitch motions. The maximum squat (δ_{MAX}) for analyzed area and for tanker types considered was calculated according to the simplified formula (Millward 1990):

$$\delta_{MAX} = \frac{C_B S^{0.81} V^{2.08}}{20} (m), \tag{15}$$

where C_B is a block coefficient, S blockage factor, and V ship speed in knots. The assumed computed value of the required UKC was set to 10% of draft while the draft of considered ships equals 10 m. The shape of a safety contour depends on the assumption regarding the acceptable distance to the specific value of the UKC-modified grounding threat intensity function at the closest point of a shallow approach. The model calibration which means the critical value adjustment was performed on the basis of a minimum distance to the critical value of UKC-modified grounding threat intensity function, which was assumed to be one ship's length. The average value of a tanker length in the considered area is 145 meters according to the AIS data collected. The resultant estimate of the safety contour obtained by means of the proposed model is presented in Figure 12.

Probability of grounding (P_G) in a specific cross section of the waterway (i) was obtained from the formula:

$$P_{G\_i} = \int_{d\_\max}^{+\infty} f(y)dy, \tag{16}$$

where d_max is a distance from a waterway centre to the safety contour and $f(y)$ is a probability density function of ship lateral distribution across a waterway.

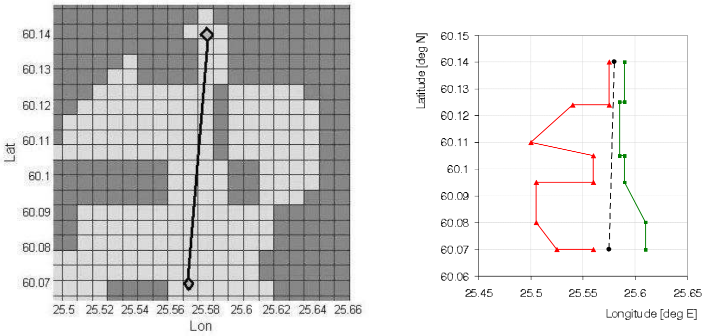

Fig. 12. The safety contour obtained me means of grounding model (to left) and its generalization used for grounding probability calculation (right)

A number of cross sections of analyzed waterways depends on the level of discrimination, waterway composition and speed of an approaching vessel. In presented the analysis, the length of a straight leg of the waterway was four nautical miles and a number of cross sections (n) was eight. The probability of grounding for the whole length of the waterway was expressed as the one-dimensional probability matrix:

$$(P_G)^T = [P_{G\_1}, \quad P_{G\_2}, \quad ... \quad P_{G\_n}] \ . \tag{17}$$

After the probability matrix was calculated, the appropriate element of maximal probability value was selected and assigned as a probability of grounding for an analyzed waterway, and thus considered an input value for further risk analysis:

$$P_G = \max(P_G). \tag{18}$$

The waterway centre line and safety contours for the analyzed leg of the approach channel to Sköldvik are presented in Figure 12. The lateral distribution of tankers across the leg of a waterway was described by the normal and uniform distributions mixture, but the parameters of distributions varied for S- and N-bound traffic, therefore these two mixture distributions were overlaid as depicted in Figure 13, and were used as such for modelling.

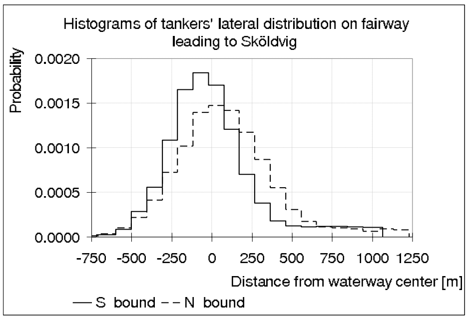

Fig. 13. The overlap of two histograms of lateral distribution of tankers on the fairway to Sköldvig, the black dotted line represents north bound traffic whereas the solid black line is south bound traffic (Montewka, Krata&Kujala 2010)

4. Marine Traffic Risk Analysis

Risk may be expressed in several ways, by distribution, expected values, or single probabilities of specific consequences, but probably the most commonly used is the expected values (Vinnem 2007). An approach presented in this paper uses the latter that describes the risk, which was considered a random variable. Expressing the random variable risk as a distribution is very useful, it takes into account uncertainties of input values, and seems mode accurate than single value. The risk that tankers colliding or grounding posed to the environment was calculated using the general formula, separately for collision and grounding:

$$R = P_A \cdot P_{OS|A} \cdot P_{OS} \cdot C, \tag{19}$$

where P_A means a probability of an accident (collision or grounding), $P_{OS|A}$ means a probability of an oil spill given an accident, P_{OS} denotes a probability density function of an oil spill volume in the Gulf of Finland, C stands for consequences of an accident, and it refers to an oil spill clean up costs, which model was derived from literature (Yamada 2009). Probability density function of an oil spill volume, for the Gulf of Finland is expressed as follows (Montewka, Krata&Kujala 2010):

$$P_{OS} = f(x) = \frac{qb^q}{(x+b)^{q+1}}, \tag{20}$$

where q in case of collision is 1.9 and in case of grounding 1.5, b in case of collision is 9009.1 and 3847.6 in case of grounding, x is a volume of spill size in tons. The conditional probability of spill given an accident ($P_{OS|A}$) is expressed as follows:

$$P_{OS|A} = 1 - P_{NO\_SPILL}, \tag{21}$$

where P_{NO_SPILL} means probability of having no oil spill given an accident and refers to the likelihood of no spill in all potential collision and grounding scenarios. The following values were adopted (Marine Board & Transport Research Board 2001):

- for collision: 0.86 irrespective of tanker's size,
- for grounding:
  - 0.94 for tankers of 40000 DWT,
  - 0.73 for tankers of 150000 DWT.

The generic diagram of the risk assessment process implemented in this study is shown in the Figure 14.

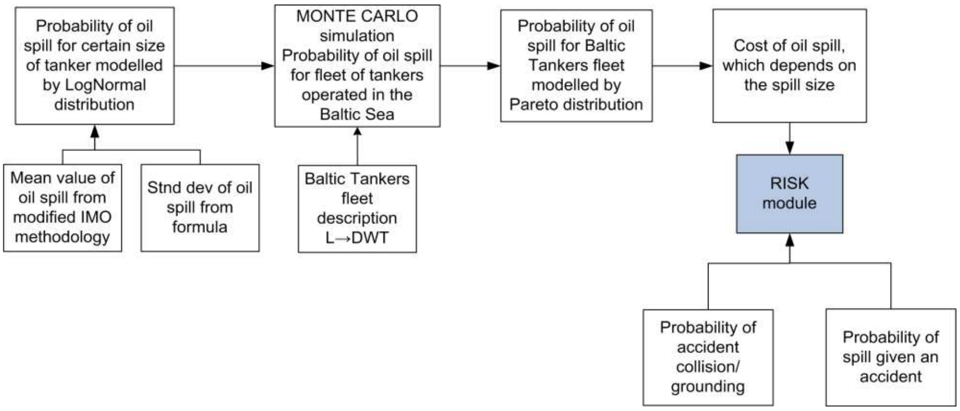

Fig. 14. Block diagram of risk assessment process applied in presented study (Montewka, Krata&Kujala 2010)

The results obtained using the method depicted in Figure11 are presented in the consecutive Figures 15 and 16. The continuous distributions were obtained by means of Monte Carlo simulation, which were run with 10000 iterations. To calculate the risk due to tankers colliding with RoPax in the crossing between Helsinki and Tallinn two experiments were run. First experiment assumed constant traffic intensity while another assumed variable traffic intensity, thus appropriate numbers of collision candidates were obtained. In the latter case, the risk was calculated assuming the maximum obtained number of collision candidates over the whole day, which was considered the worst case scenario. Substantial differences between two distributions obtained can be recognized, as a mean value of random variable "risk" in case of non stationary traffic flow is more than two times higher then in case of constant traffic flow.

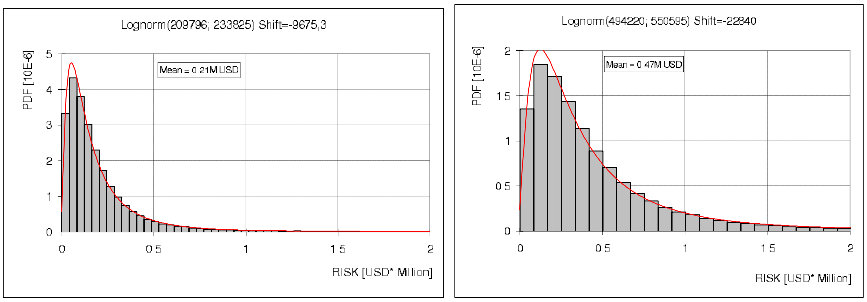

Fig. 15. Annual distributions of random variable "RISK" in case of collision between a tanker and RoPax, for assumed constant traffic intensity (left) and hour-dependent traffic intensity according to recorded data (right), summer traffic

Distribution of random variable "risk" in case of tankers grounding on approach to Sköldvik harbour is depicted in Figure 16.

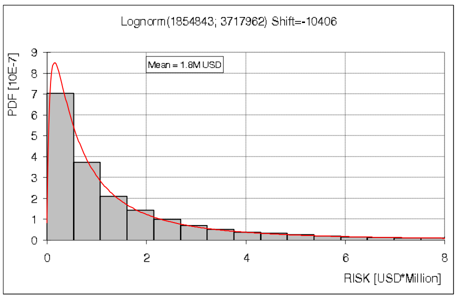

Fig. 16. An annual distribution of random variable "RISK" in case of tankers grounding, summer traffic

5. Discussion

In this paper two novel models for marine accident probability modelling were introduced, and utilized in order to perform a risk analysis for chosen locations and chosen ship types. The risk is expressed here as a product of probability of an accident (collision or grounding of a tanker) and its consequences (costs of an oil spill given the accident). The costs of an oil spill are estimated with use of the state-of-the-art, statistic based model.

A stochastic model for collision probability assessment used recorded AIS data and took into consideration ship manoeuvrability and the non homogenous nature of flow of marine traffic in the analyzed area. Therefore an intensity of marine traffic was modelled for each hour over day separately, instead of taking a daily average value. Substantial differences in results obtained following the approach adopted in the presented model and commonly used approach adopted in previous geometrical models are shown. For modelling purposes of risk of tankers colliding, the highest number of collision candidates over the whole day was selected, regarding a worst case scenario. This number was almost three times higher than the average value. These differences in risk profiles as a result of assumption of non stationary nature of marine traffic are significant, and can not be neglected in further analysis. It must be stressed that considering marine traffic a stationary process should be avoided in enclosed areas as the Gulf of Finland and areas experiencing scheduled traffic, as it leads to large uncertainties and is highly questionable.

An important factor, affecting the level of an accident probability, is the causation factor (P_C). The value of the causation factor seems to be location dependent, as the original studies regarding this parameters have been conducted in the specific locations (eg. straits in Japan, the Dover Strait) it is difficult to assess how the results obtained there can be transferable to other sea areas. The causation factor is also highly dependent on a geometrical model used for the probability of ship accident estimation, thus transferring the same value between two different models may not be justified from the scientific point of view. However, the results presented in the paper, can be utilized for the comparative purposes, and the numbers obtained, at this stage of research, should be considered rather an indication that the absolute. The further studies towards the causation factor estimation for MDTC model are being carried out.

The model for grounding probability assessment was examined on one of two legs of the outer fairway to Sköldvik oil terminal. The main factor that influenced the probability of grounding was “the safety contour”. This value determined the allowed navigable width of a waterway for a certain type of vessel and area and was obtained by means of the applied model of grounding. The model in the form presented in this study is still under developed. Therefore it is to some extent subjective in terms of the determination of safety contour; therefore further improvement work is being carried out.

The risk analysis presented concerns summer traffic only. The obtained results show significant differences between the mean values of random variable 'risk' for grounding and collision in annual perspective. The risk is considerably higher in case of grounding.

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References

1. Aven T.: On how to define, understand and describe risk. Reliability Engineering & System Safety 95(06), pp. 623-631, 2010.
2. Barrass C.B.: Ship design and performance for masters and mates. Butterworth-Heinemann, 2004.
3. Clark I.: Ship dynamics for mariners. London, The Nautical Institute, 2005.
4. Det Norske Veritas. Formal Safety Assessment – Large Passenger Ships, ANNEX II: Risk Assessment – Large Passenger Ships – Navigation, 2003.
5. Duffey R.B, Saull J.W.: Managing Risk. Chichester, UK, John Wiley & Sons, Ltd, 2008.
6. Fowler T.G, Sørgård E.: Modeling ship transportation risk. Risk Analysis 20(2), pp. 225-244, 2000.
7. Fujii Y., Shiobara R.: The analysis of traffic accidents. The Journal of Navigation 24(4), pp. 534-543, 1971.
8. Fujii Y., Yamanouchi H., Matui T.: Survey on vessel traffic management systems and brief introduction to marine traffic studies. Electronic Navigation Research Institute Papers 45, pp. 1-48, 1984.
9. Fujii Y., Yamanouchi H., Tanaka K., Yamada K., Okuyama Y., Hirano S.: The behaviour of ships in limited waters. Electronic Navigation Research Institute Papers 19, pp. 1-14, 1978.
10. Fujii Y., Yamanouchi H., and Mizuki N.: On the fundamentals of marine traffic control. Part 1 probabilities of collision and evasive actions. Electronic Navigation Research Institute Papers 2, pp. 1-16, 1970.
11. Goerlandt F., Kujala P.: Modeling of Ship Collision Probability using Dynamic Traffic Simulation. In proceedings of ESREL'10 conference, Rhodes, 2010.
12. Goodwin E.: A statistical study of ship domain. The Journal of Navigation 28, pp. 328-344, 1975.
13. Gucma L.: Models of ship's traffic flow for the safety of marine engineering structures evaluation. In: Beford, van Gelder, editors. Proceedings of ESREL 2003, Lisse: Swets & Zeitlinger, pp. 713-718, 2003.
14. Hänninen M., Kujala P.: The effects of causation probability on the ship collision statistics in the Gulf of Finland. In: Weintrit A, editor. Marine Navigation and Safety of Sea Transportation, London: Taylor and Francis, pp. 267-272, 2009.
15. IMO, Amendments to the Annex of the Protocol of 1978 relating to the International Convention for the Prevention of Pollution from Ships, 1973 (Revised Annex I of MARPOL 73/78), resolution MEPC.117(52), 2004.

16. IMO, Interim Guidelines for approval of Alternative Methods of Design and Construction of Oil Tankers under Regulation 13F(5) of Annex I of MARPOL 73/78, Resolution MEPC.66(37), 1995.
17. Jiankang W., Lee T.S., Shu C.: Numerical study of wave interaction generated by two ships moving parallely in shallow water. Computer Methods in Applied Mechanics and Engineering, 190(15-17), pp. 2099-2110, 2001.
18. Jurdzinski M.: Navigational planning in restricted waterways. Maritime University of Gdynia, Publishing House of Maritime University of Gdynia, 1998 (in Polish).
19. Kao S., Lee K., Chang K., Ko M.: A fuzzy logic method for collision avoidance in Vessel Traffic Service. The Journal of Navigation 60, 01, pp. 17-31, 2007.
20. Klanac A., Duletic T., Ehlers S., Goerlandt F., Frank D.: Environmental risk of collision for enclosed seas: the Gulf of Finalnd, the Adriatic, and implications for tanker design. In proceedings of the 5th International Conference on Collision and Grounding of Ships, Espoo, 2010.
21. Krata P.: A model of chosen interactions during SAR action. In: Marine Traffic Engineering 2007. Świnoujście, Maritime University of Szczecin, 2007 (in Polish).
22. Kristiansen S.: Maritime transportation: safety management and risk analysis. Oxford: Butterworth-Heinemann; 2005.
23. Kujala P., Hänninen M., Arola T. & Ylitalo J.: Analysis of the marine traffic safety in the Gulf of Finland. Reliability Engineering & System Safety, 94 (8), pp. 1349-1357, 2009.
24. MacDuff T.: The probability of vessel collisions. Ocean Industry pp. 144-148, 1974.
25. Marine Board & Transport Research Board. Environmental Performance of Tanker Designs in Collision and Grounding: Method for Comparison -Special Report 259. Washington D.C., National Academy Press, 2001.
26. Martins M.R., Maturana M.C.: Human error contribution in collision and grounding of oil tankers. Risk Analysis, Vol. 30, No. 4, 2010.
27. Merrick J.R.W., van Dorp J.R., Mazzuchi T., Harrald J.R., Spahn J.E., Grabowski M.: The Prince William Sound Risk Assessment. INTERFACES, 32 (11), pp. 25-40, 2002.
28. Merrick J.R.W., van Dorp J.R., Blackford J.P., Shaw G.L., Harrald J., Mazzuchi A.: A traffic density analysis of proposed ferry service expansion in San Francisco Bay using a maritime simulation model. Reliability Engineering and System Safety 81(2), pp. 119-132, 2003.
29. Merrick J.R.W., van Dorp J.R.: Modeling risk in the dynamic environment of maritime transportation. Proceedings of the Winter Simulation Conference, pp. 1090-1098, 2001.
30. Millward A.: A preliminary design method for the prediction of squat in shallow water. Marine Technology, 27 (1), pp.10-19, 1990.
31. Montewka J., Hinz T., Kujala P., and Matusiak J.: Probability modelling of vessel collisions. Reliability Engineering & System Safety 95 (5), pp. 573-589, 2010.
32. Montewka J., Krata P., Kujala P.: Elements of risk analysis for collision and grounding of oil tankers in the selected areas of the Gulf of Finland. In proceedings of the 5th International Conference on Collision and Grounding of Ships, Espoo, 2010.
33. Montewka J., Krata P., Kujala P.: Selected problems of marine traffic risk modelling. In proceedings of Transport of 21st century, Technical University of Warsaw, 2010a.
34. Otto S., Pedersen P.T., Samuelides M., Sames P.C.: Elements of risk analysis for collision and grounding of a RoRo passenger ferry. Marine Structures 15, 4-5, pp. 461-474, 2002.
35. Palisade Corporation. A Concise Summary of @RISK Probability Distribution Functions. Palisade Corp., NY, USA, 2002.
36. Pedersen P.T.: Collision and grounding mechanics. The Danish Society of Naval Architects and Marine Engineers pp. 125-157, 1995.
37. Pietrzykowski Z., Uriasz J.: The Ship Domain – A criterion of navigational safety assessment in an open sea area. The Journal of Navigation 62, 01, pp. 93-108, 2009.

38. Pietrzykowski Z.: Assessment of navigational safety in vessel traffic in an open area. In: Weintrit A, editor. Marine Navigation and Safety of Sea Transportation, London: Taylor and Francis, pp. 413-416, 2007.
39. Przywarty M.: Probabilistic model of ships navigational safety assessment on large sea areas. In: Proceedings of the 16th International Symposium on Electronics in Transport, Ljubljana, Slovenia, 9-10 October 2008.
40. Rodrigue J.P., Comtois C. & Slack B.: The geography of transport system. 2nd ed. New York, Routledge, 2009.
41. Smailys V, Česnauskis M.: Estimation of expected cargo oil outflow from tanker involved in casualty. Transport Vilnius, 21 (4), pp. 293-300, 2006.
42. Soares C.G, Teixeira A.P.: Risk assessment in maritime transportation. Reliability Engineering & System Safety, 74(12), pp. 299-309, 2001.
43. Søfartsstyrelsen. Risk analysis for sea traffic in the area around Bornholm. COWI, Konges Lyngby, 2008.
44. Szłapczyński R.: A unified measure of collision risk derived from the concept of a ship domain. The Journal of Navigation 59, 03, pp. 477-490, 2006.
45. Uluscu Ö.S, Özbas B., Alt|ok T., Or Ö.: Risk Analysis of the Vessel Traffic in the Strait of Istanbul. Risk Analysis, 29, pp. 1454-1472, 2009.
46. Van Dorp J.R., Merrick J.R.W., Harrald J., Mazzuchi T., Grabowski M.: A risk management procedure for the Washington State Ferries. Risk Analysis, 21(1), pp. 124-142, 2001.
47. Varyani K.S., McGregor R., Wold P.: Interactive forces and moments between several ships meeting in confined waters. Control Engineering Practice, 6(5), pp. 635-642, 1998.
48. Vinnem J.: Offshore Risk Assessment. 2nd ed. Springer London, 2007.
49. Yamada Y.: The Cost of Oil Spills from Tankers in Relation to Weight of Spilled Oil. Marine Technology, 46, pp. 219-228, 2009.