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SELECTED PROBLEMS OF MARITIME TRAFFIC RISK MODELLING

Abstract: The paper addresses selected problems of marine traffic risk modelling, in respect to collision and grounding probability modelling. Two original models are presented, and a case study regarding ships navigating in selected areas of Gulf of Finland in ice free conditions is putting forward. Probability of vessel colliding is assessed by means of 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 non homogeneous process, unlike other existing models. Calculations presented address waterways crossing between Helsinki and Tallinn, where dense cross traffic during certain hours is observed. Risk profile for a certain period of a day is presented.
For probability of grounding a new approach is proposed, which utilizes the gravity model, where 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 gravity formulation.
Keywords: maritime risk, transportation, navigation, collision, grounding, modelling

1. INTRODUCTION

Maritime traffic risk modelling is a complex process, which takes into account several aspects, integrating different scientific domains, usually being very remote one from another. Risk analysis consists of predicting ship accident probability, which means collisions and groundings. These depend on geographical location of analyzed area, traffic composition, weather conditions and time of the day. Statistics revealed that these two main types of accidents are caused mostly by human inappropriate actions, therefore knowledge about human behaviour during collision avoidance and grounding avoidance processes is essential here.

Knowing the probability of an accident, one should assess the consequences of these. Depending on a ship type involved in an accident, results may be different. In case of a tanker as a potential outcome of an accident, one may suspect an oil spill, resulting in environmental loss. In case of a passenger vessel facing an accident, the highest hazard considered is loss of human lives.

This paper focuses of chosen aspects of marine traffic risk modelling, taking as example marine traffic in the Gulf of Finland. Method of modelling risk of ship being collided and being aground is presented, with emphasis put on tankers and passenger ferries. A new geometrical model for collision frequency assessment, named the MDTC model is used and a gravity based model for grounding probability calculation is utilized. Consequences are expressed in costs to incur caused by an oil spill of given magnitude, being a result of a ship accident.

Existing geometrical models for ship collision frequency prediction simulate marine traffic as a stationary Poisson process, which not always holds truth. The analysis of AIS data over the Gulf of Finland revealed that traffic fluctuates, and peak hours may be defined, regarding both E-W (cargo ships, tankers) and N-S streams (RoPax ferries). These peak hours affect the probability of collision, which changes over a day.

This paper presents the results of risk analysis carried out for scheduled traffic, taking into account its non stationary nature. The results are then compared with results obtained from another version of the MDTC model, which assumes maritime traffic as a stationary process. The paper addresses only summer traffic, therefore influence of winter related parameters on risk are not taken into account. This paper does not contain the detailed description of models applied for risk analysis, as they are described in the literature cited.

Calculations were carried out for two chosen locations of the Gulf of Finland. One is a junction of two busy waterways, between Helsinki and Tallinn, with RoPax ferries cross traffic. Another spot is an approach to an oil terminal in Sköldvik, east to Helsinki.

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 tonnes gross, involved in international voyages that need to be fitted with the transponder of Automatic Identification (AIS), according to SOLAS Convention, Regulation 19 of Chapter V. The analyzed data cover period from 01.06.2006 to 31.06.2006. To compute the traffic volume in analyzed area two counting gates were established, as depicted in the Fig.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.

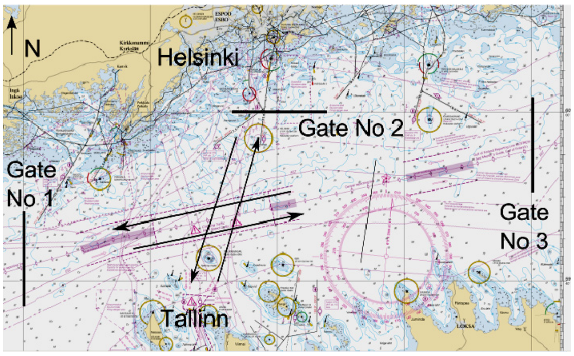


Fig.1. Analyzed waterways junction, with counting gates and main traffic flows [Montewka et al., 2010]

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 (Fig.1). Each flow was modelled with the following input parameters: 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 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.

Special attention was paid on tankers. Based on the recorded data, tanker traffic in the Gulf of Finland was assumed to 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 triangle distributions, and the minimum, maximum and mean values adopted are presented in Figure 2. The triangle distributions were the ones that fitted best the observed discrete data.

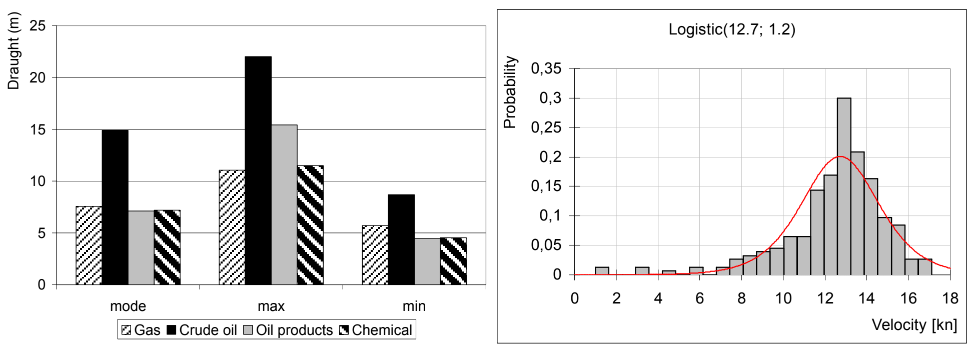


Fig.2. Distributions of the main parameters of tankers navigating in the Gulf of Finland

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

$$v = f(x) = \frac{\sec h^2\left(0.5\left(\frac{x-\alpha}{\beta}\right)\right)}{4\beta}\ , \qquad (1)$$

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 was daily variations 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 may be 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.

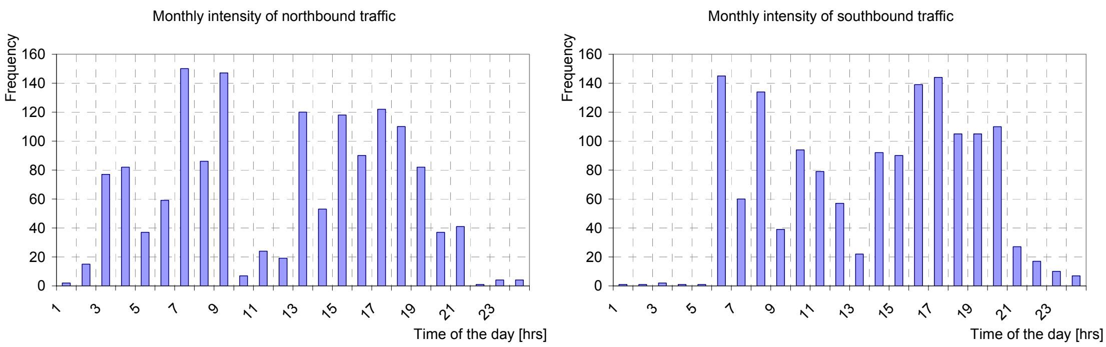


Fig.3. The marine traffic intensity of N-S flow, recorded between Helsinki and Tallinn

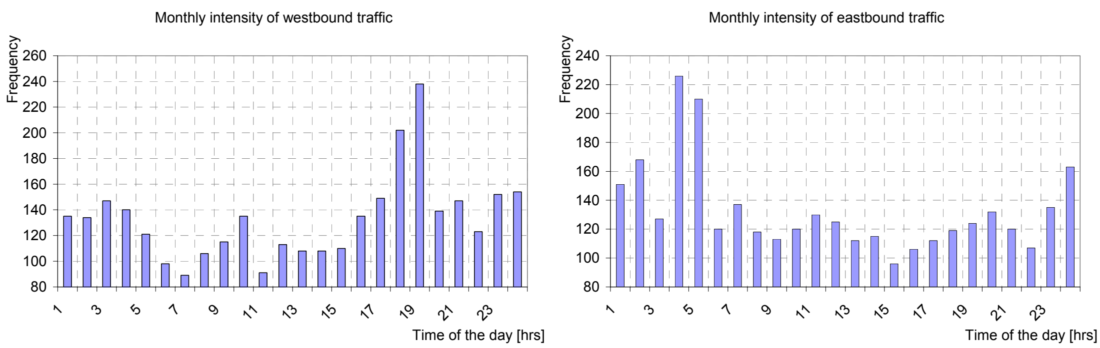


Fig.4. The marine traffic intensity of E-W flow, recorded between Helsinki and Tallinn

From the data presented, 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. And usually rush hours for N-S traffic do not correspond the rush hours for E-W flow. Thus modelling the marine traffic flow in analyzed location as a constant number is burden with high uncertainty, and may lead to the underestimation of the results (a number of collision candidates and risk of collision).

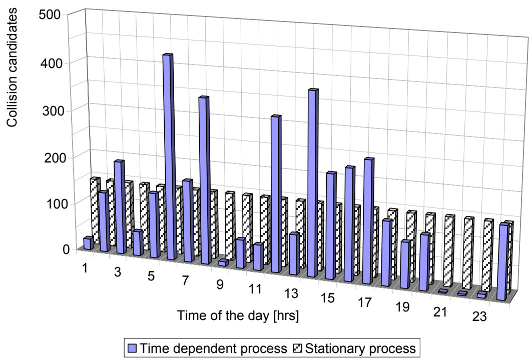


Fig.5. A number of collision candidates obtained from the MDTC model for constant and time varying traffic flows

The comparison of results obtained from MDTC model, expressed as a number of collision candidates, is depicted in Fig. 5. During experiment, at first traffic intensity was assumed to be stationary, and number of collision a candidate was calculated, which was not depending on time of the day. Secondly traffic intensity was modelled according to the AIS data recorded, and number of collision candidates calculated depended significantly on time of the day.

In Fig.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 obviously translates directly into risk level.

3. PROBABILITY OF ACCIDENT MODELLING

Probability of ship colliding and grounding was modelled by means of two original models, which have been developed by the authors. A model which assesses the probability of collision is called the MDTC model and was described in detail in (Montewka et al., 2010) and after improvements in (Montewka J, Ståhlberg K et al., 2010). A grounding model is a gravity model, which considers a ship and surrounding her obstacles the imaginary masses which affect each other, an initial description of the model was given in (Krata, 2007).

Due to the existing detailed description of the MDTC model in the references, only the main idea is presented in this paper. However the description of the gravity model presented here is lacking in the literature, therefore more space will be devoted to it.

3.1. MDTC model for ship collision probability estimation

In the presented MDTC model it is assumed that a collision between two vessels becomes reality when the distance between these two vessels is not enough to perform efficient anti-collision manoeuvres. The space and time required for a given vessel to perform a given manoeuvre depends mostly on her hydrodynamics and manoeuvrability features. This distance is called minimum distance to collision (MDTC) and has been defined for different meeting scenarios and different ship types, based of series of experiments using a ship motion model (Montewka et al., 2010). Based on the findings from the experiment the significant variable, that impact the MDTC value the most, was defined as an angle of intersection of two ships courses. The MDTC model is a geometrical model and defines the probability of a collision as follows:

$$P = N_A P_C \,, \tag{2}$$

where N_A is the geometrical probability of a collision course and P_C is the causation probability, 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).

3.2. Gravity model for ship grounding probability estimation

A probability of ship grounding is considered a probability of a situation occurrence where vessel breaches a "safety contour", which should be defined beforehand. In some cases it may be just a depth curve, but presented paper introduces the method of estimation the "safety contour", by means of the gravity model, which takes into account a number of factors that affect ship behaviour in restricted waterways.

The group of gravity models is one of the most convenient formulations of spatial interactions. 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 gravity 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, a coefficient of manoeuvrability of ship m. Thus, the field of characteristics of ships location is described by the formula:

$$S = S(T_{(j,i)}, R, d_{(R,e.m)}) \,, \tag{3}$$

where S denotes a field of characteristics of ships, T, R, d are the fields which describe the ships, and (j, i) denotes coordinates of ships. It is assumed that features of obstructions describing fair enough the source of their threat 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 obstructions' features is given by the formula:

$$P = P(H_{(j',i')}, b_{(j',i')}, s_{(j',i')}, c_{(j',i')}), \quad (4)$$

where P means a field of obstructions characteristics, H, b, s, c denote fields describing obstructions, and (j', i') 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 at, 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 P 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:

$$F = F\left[S(T_{(j,i)}, R, d_{(R,e,m)}), P(H_{(j',i')}, b_{(j',i')}, s_{(j',i')}, c_{(j',i')}), r_{(j,i)}\right] = M \cdot \frac{T}{H \cdot r}, \quad (5)$$

where the coefficient M is defined as follows:

$$M = \frac{R \cdot b}{d \cdot s \cdot c}, \quad (6)$$

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 (5). It is transformed into the grounding threat intensity field given by the formula:

$$E = \lim_{T \to 0} \frac{F}{T}, \quad (7)$$

For the purpose of the model presentation the exemplary sea area is depicted in Fig.6 It comprises some shallows of different characteristics.

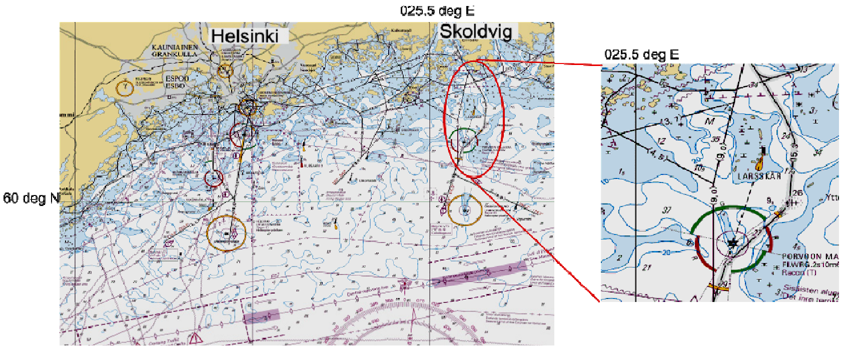


Fig.6. A fragment of a sea chart presenting the considered fairway to Sköldvik harbour [Montewka, Krata&Kujala, 2010].

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 Fig.7.

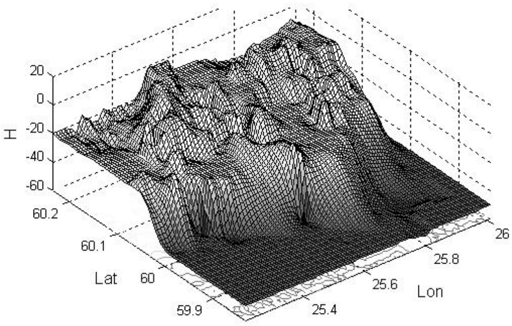


Fig.7. A profile of a bottom of the analyzed area

The distribution of the grounding threat intensity *E* in the modelled exemplary area is determined with regard to the formulas mentioned above. For the sake of a realistic modelling of navigator's behaviour, the area of interactions taken into account was restricted to 2 nautical miles. The resultant spatial distribution of the values of the grounding threat intensity (applied utility function) is shown in Fig.8.

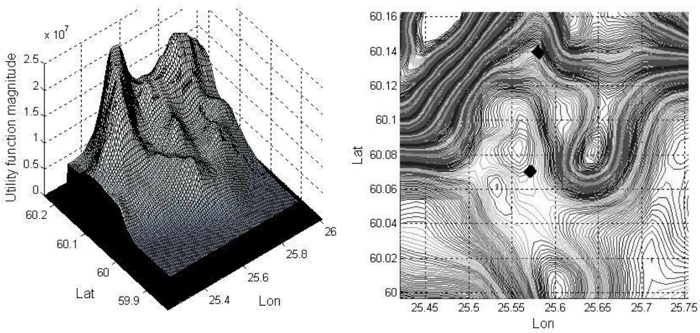


Fig.8. Spatial distributions of the values of the utility function vector field

The approach presented in Fig. 8 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 safe enough track is not obtainable. The 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):

$$UKC = \sum R_S + \sum R_D \text{ ,} \tag{8}$$

where: $\sum R_S$ is a sum of static corrections and $\sum R_D$ is a sum of dynamic corrections. The static corrections include 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 equation [Millward, 1990]:

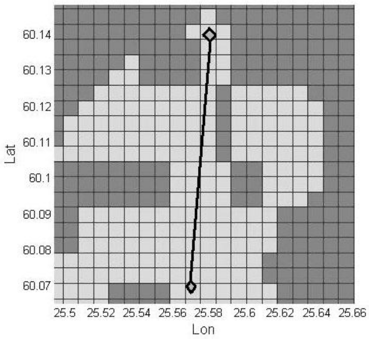
$$\delta_{MAX} = \frac{C_B S^{0.81} V^{2.08}}{20} \text{ [m],} \tag{9}$$

where C_B is a block coefficient, *S* blockage factor, an *V* ship speed in knots. The assumed computed value of the required *UKC* was set to 3.9m while the draft of considered ships equals 10m. 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 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 estimation of the safety contour obtained by means of the proposed model is presented in Fig. 9.

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

$$P_{G\_i} = \int_{d\_\max}^{+\infty} f(y)dy \text{ ,} \tag{10}$$

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.



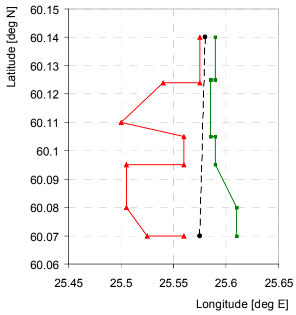


Fig.9. The safety contour obtained me means of gravity model (to left) and its generalization used for grounding probability calculation (right).

A number of cross sections for analyzed waterways depended on the level of discrimination, waterway composition and speed of an approaching vessel. In the analysis presented, the length of a straight leg of the waterway was 4 Nm and a number of cross sections (n) was equal 8. The probability of grounding for the whole length of the waterway was expressed as the one-dimensional probability matrix:

$$(P_G)^T = [P_{G\_1}, \quad P_{G\_2}, \quad \dots \quad P_{G\_n}], \tag{11}$$

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:

$$P_G = \max(P_G)\,, \tag{12}$$

The waterway centre line and safety contours for the analyzed leg of the approach channel to Sköldvik are presented in Fig. 9. 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 Fig. 10, and as such were used for modelling.

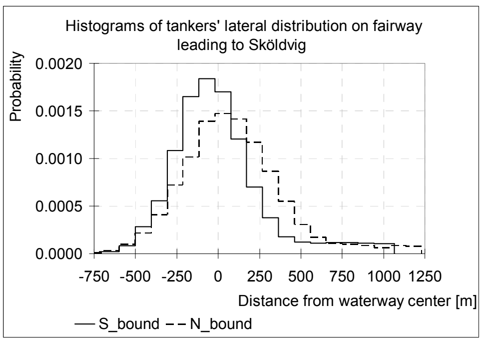


Fig.10. The overlaid two histograms of lateral distribution of tankers on the fairway to Sköldvig, a black dotted line represents north bound traffic whereas a solid black line is south bound traffic [Montewka, Krata&Kujala, 2010]

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:

$$R = P_A \cdot P_{OS|A} \cdot P_{OS} \cdot C \ , \qquad (10)$$

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, which refers to an oil spill clean up costs, and model was derived from literature (Yasuhira, 2009). Probability density function of an oil spill volume, for the Gulf of Finland is expressed as follows (Montewka, Krata, Kujala, 2010):

$$P_{OS} = f(x) = \frac{qb^q}{(x+b)^{q+1}} \ , \qquad (11)$$

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 generic diagram of the risk assessment process implemented in this study is shown in the Fig. 11.

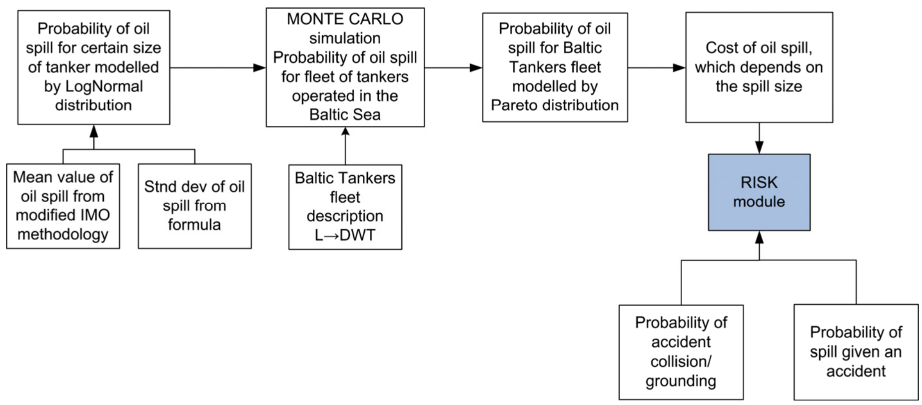


Fig.11. Block diagram of risk assessment process applied in presented study [Montewka, Krata, Kujala, 2010]

The results obtained using the method depicted in Fig.11 are presented in the consecutive figures 12 and 13. 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.

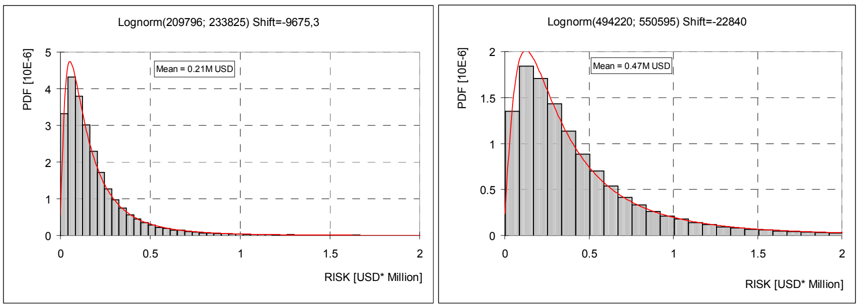


Fig.12. Distributions of random variable "RISK" in case of collision between a tanker and RoPax, for constant traffic intensity (left) and traffic intensity according to recorded data (right), summer traffic

Distribution of random variable „risk" in case of tankers grounding on approach to Sköldvik harbour is depicted in Fig.13. In this case as an input value for Monte Carlo simulations the maximum value of risk calculated that tankers pose while navigating in the approach

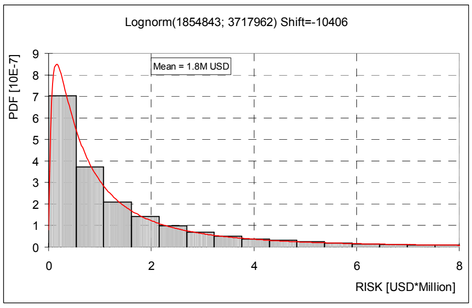


Fig.13. Distribution of random variable "RISK" in case of tankers grounding, summer traffic

5. DISCUSSION

Two novel models for marine accident probability modelling were introduced in the paper. Risk analysis for chosen locations and chose ship types were carried out with use of the models. The risk was expressed 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.

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 were shown. For modelling purposes of risk of tankers colliding, the highest number of collision candidates over the whole day was selected; 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. Therefore modelling the marine traffic flow as a constant process is highly questionable, at least in the analyzed location or in the areas where scheduled traffic may be observed.

Model for grounding probability assessment was examined on one of two legs of the outer fairway to Sköldvik oil terminal, which was able to accommodate ships of maximum draft of 9 meters. 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 gravity model of grounding. The gravity model in the form presented in this study is still under developed. Therefore it is to some extent subjective in terms of the safety contour determination, therefore further improvement works are carried out, to make the model as much as possible objective.

The risk analysis presented concerns summer traffic only.

5.1. Acknowledgments

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References

1. Det Norske Veritas. Formal Safety Assessment - Large Passanger Ships, ANNEX II: Risk Assesment - Large Passenger Ships – Navigation, 2003.
2. Jurdzinski, M. Navigational planning in restricted waterways. Maritime University of Gdynia, Publishing House of Maritime University of Gdynia, 1998 (in Polish).
3. Krata P. A model of chosen interactions during SAR action. In: Marine Traffic Engineering 2007. Świnoujście, Maritime University of Szczecin, 2007 (in Polish).
4. 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.
5. Millward, A. A preliminary design method for the prediction of squat in shallow water. Marine Technology, 27 (1), pp.10-19, 1990
6. Montewka J, Hinz T, Kujala P, and Matusiak J. Probability modelling of vessel collisions. Reliability Engineering & System Safety 95 (5), pp. 573-589, 2010.
7. 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. 5th International Conference on Collision and Grounding of Ships, Helsinki, 2010 (paper accepted, to be published).
8. Montewka J, Ståhlberg K, Seppala T, Kujala P. Elements of risk analysis for collision of oil tankers. In proceedings of ESREL 2010 (to be published).

9. Rodrigue J.P, Comtois, C. & Slack, B. The geography of transport system. 2nd ed. New York, Routledge, 2009.
10. Vinnem J. Offshore Risk Assessment. 2nd ed. Springer London, 2007.
11. Yasuhira Y. The Cost of Oil Spills from Tankers in Relation to Weight of Spilled Oil. Marine Technology, 46, pp.219-228, 2009.

WYBRANE PROBLEMY MODELOWANIA RYZYKA RUCHU MORSKIEGO

Streszczenie: w artykule przedstawiono wybrane problemy z zakresu modelowania ryzyka w transporcie morskim, w aspekcie kolizji statków oraz wejść na mieliznę.
W pracy przedstawiono dwa nowatorskie podejścia do modelowania prawdopodobieństwa wystapienia powyższych wypadków. Model do oceny prawdopodobieństwa kolizji statków definiuje w nowy sposób strefę kolizji, w oparciu o właściwości manewrowe statku oraz jego hydrodynamikę. Intensywność ruchu morskiego na analizowanym akwenie modelowana jest w oparciu o proces niestacjonarny, w przeciwieństwie do istniejących modeli.
Model oceny prawdopodobieństwa wejścia na mieliznę wykorzystuje model grawitacyjny, gdzie statek i otaczające go płycizny traktowane są jako masy, wzajemnie na siebie oddziaływujące. Model określa bezpieczny obszar manewrowy dla danego statku i danego akwenu.
Analiza ryzyka przeprowadzona została dla dwóch wybranych akwenów w Zatoce Fińskiej. Jako konsekwencje wypadku przyjęto model kosztów, skonstruowany w oparciu o dane statystyczne z międzynarodowego fundusz IOPCF, który pokrywa koszty w związku z rozlewem olejowym na morzu.
Słowa kluczowe: ryzyko, nawigacja, transport morski, kolizja, modelowanie, statki