Models of ship-ship collision. Qualitative assesment

Porównanie jakościowe wybranych modeli kolizji statków

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Key words: ships collision, ships traffic, stochastic model

Abstract

The paper presents the review and the comparison of the existing models of ships–ship collision. It also presents assumptions and preliminary results of collision model developed in Institute of Marine Traffic Engineering in Szczecin.

Słowa kluczowe: kolizje statków, ruch statków, model stochastyczny

Abstrakt

W artykule przedstawiono przegląd oraz porównanie istniejących modeli kolizyjnych typu statek–statek. Zaprezentowano założenia oraz wstępne wyniki modelu kolizyjnego opracowanego w Instytucie Inżynierii Ruchu Morskiego Akademii Morskiej w Szczecinie.

Introduction

Increasing intensity of sea traffic and accompanying this increasing risk of sea accidents caused a development of models of navigational safety assessment. The collisions between ships are the one of the most common types of accidents which have influence on navigational safety (fig. 1).
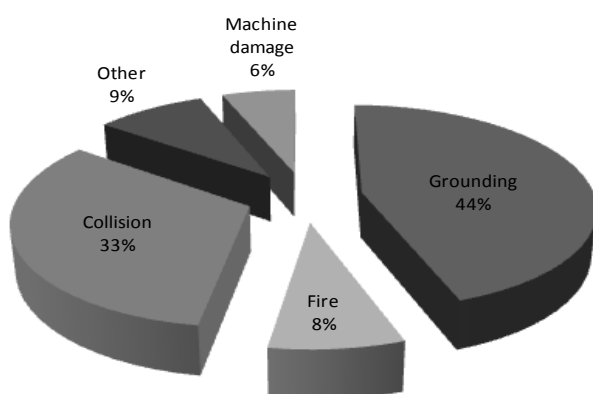

Fig. 1. Types of accidents in the Baltic Sea [1]
Rys. 1. Typy wypadków morskich na Morzu Bałtyckim [1]

The most popular approach to the assessment of marine accident probability is based on the models presented by Macduff [2] and Fujii at al. [3]. It defines the probability of accident as the product of geometrical probability depending on distribution of vessels traffic and the "causation probability" depending on such factor as visibility, failures, human errors, etc.

$$P = P_g \cdot P_c \qquad (1)$$

where: P – probability of accident, P_g – geometrical probability, probability of such situation that accident will occur if no manoeuvre be made, P_c – causation probability, probability of failing to avoid the accident.

In the further part of this paper the typical models which can be used to calculate the probability of ship-ship collision are presented. The probabilities calculated in this models are undoubtedly exclusive to the relative areas, but it is symptomatic that obtained results are comparable.

Macduff's model

The Macduff's model is a well known model using Molecular Collision theory. It assumes that if all ships are proceeding with the same speed and

one ship is proceeding on course making an angle with the main shipping lane then Mean Free Path of the single ship will be of length:

$$F = \frac{D^2}{L} \cdot \frac{1852}{2\sin\frac{\theta}{2}} \qquad (2)$$

where: F – Mean Free Path of single ship [Nm], D – average distance between ships [Nm], measure of traffic density, L – length of ship [m], θ – angle between track of the single ship and stream of ships.

The geometrical probability can be calculated by following formula:

$$P_g = \frac{X}{F} \qquad (3)$$

where: P_g – geometrical probability, X – actual length of path to be considered for a single ship [Nm].

Real collision probability can be calculated on the basis of statistical data.

$$P_{re} = \frac{n_c}{n_p} \qquad (4)$$

where: P_{re} – real collision probability, n_c – number of collisions in a given time, n_p – number of ships passing in a given time.

Knowing the real collision probability (4) and the geometrical probability (3) the causation probability can be calculated:

$$P_c = \frac{P_{re}}{P_g} \qquad (5)$$

The results presented in the paper by Macduff [2] was obtained for the Dover Strait and North Sea area. The calculations was carried out for the periods before and after establishing the Traffic Separation Scheme in given area. Achieved results are presented in table 1.

Table 1. Causation probabilities – Macduff's model [2]
Tabela 1. Prawdopodobieństwa przyczyn – model Macduff'a [2]

Type of encounter situation	Causation probability	Remarks
Head on	0.000518	without TSS
	0.000315	with TSS
Crossing	0.000111	without TSS
	0.000095	with TSS

Model of Fowler & Sørgård – MARCS

Model presented in paper of Fowler & Sørgård [4] assumes that marine traffic may be modelled by shipping lanes that have characteristic lane width, traffic frequency and lateral distribution. The model assumes that traffic is uncorrelated. The critical situation is defined as when two ships come to close quarters-crossing within half a nautical mile of each other (encounter situation). The area of interest is divided into large number of calculation locations. Encounter frequencies at each calculation location are evaluated using a pair – wise summation across all shipping lanes. This enables the calculation of either total collision rates, or collision rates involving specific types of vessels. It then applies a probability of a collision for each encounter, to give the collision frequency The collision frequency at a location is given by:

$$f_c = n_e\left(P_{gv}p_{c,gv} + P_{rv}p_{c,rv}\right) \qquad (6)$$

where: f_c – collision frequency at a calculation location, n_e – encounter frequency, P_{gv} – probability of good visibility, P_{rv} – probability of reduced visibility, $p_{c,gv}$ – probability of collision in good visibility, $p_{c,rv}$ – probability of collision in reduced visibility.

The probabilities of collision are derived by fault trees analysis and depends on the visibility conditions and degree of internal and external vigilance. Example of fault tree used to evaluation of probability of collision is presented in figure 3.
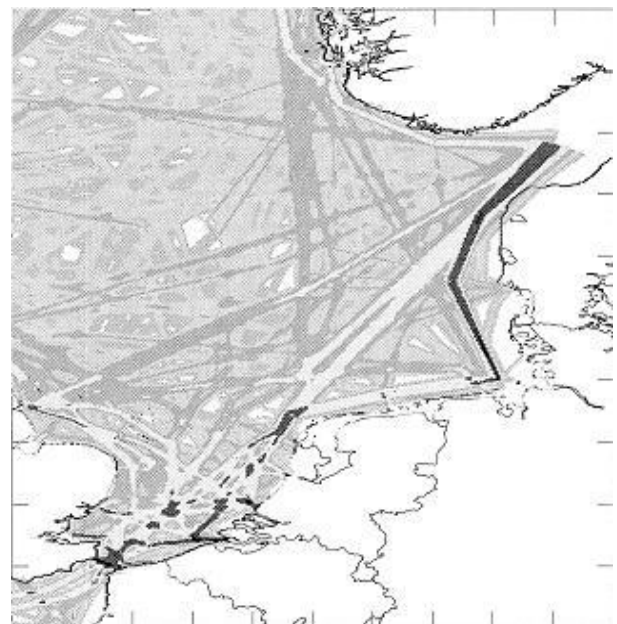

Fig. 2. Example chart of geographical distribution of accident frequencies in the North Sea
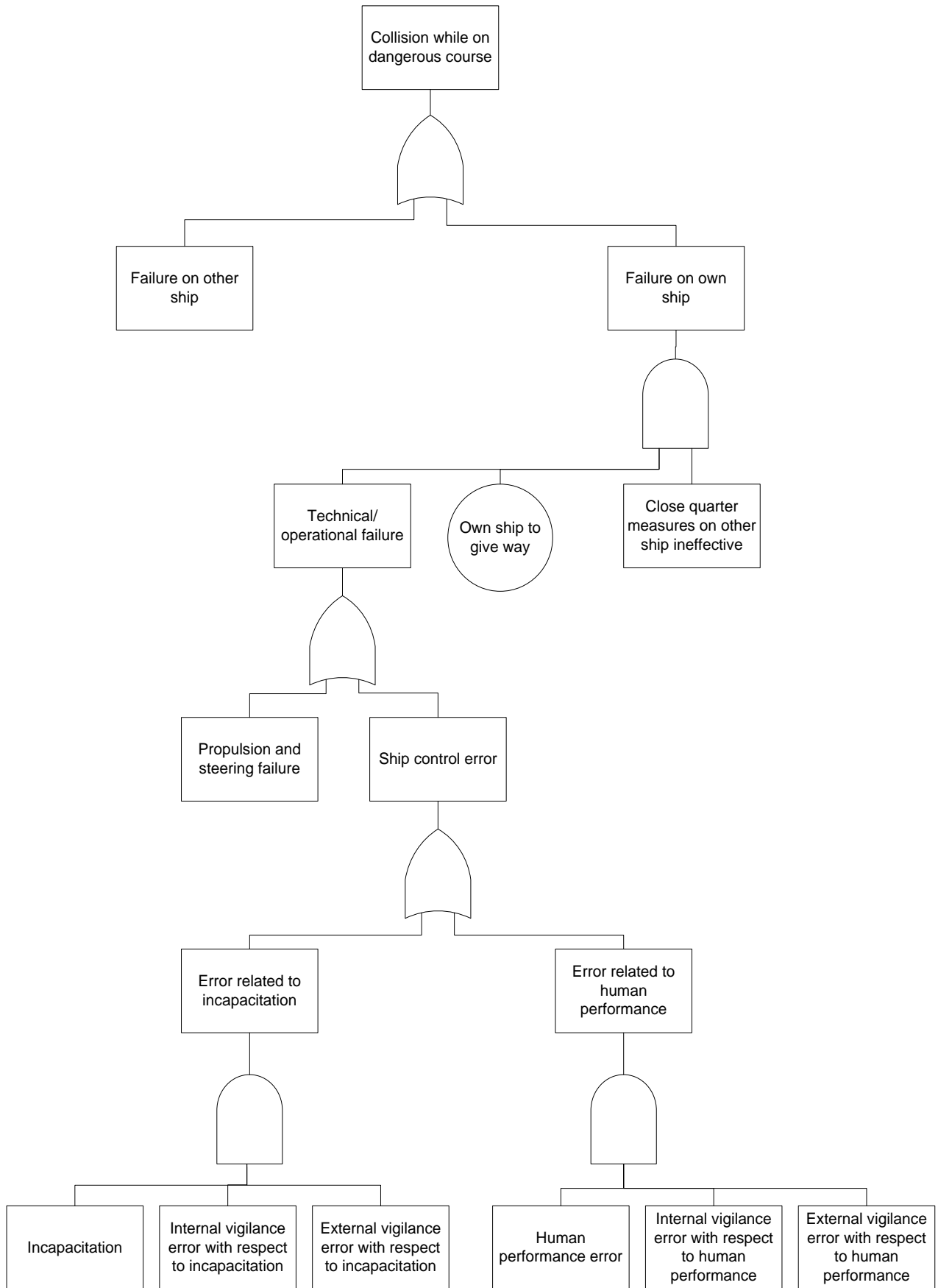Rys. 2. Częstotliwości wypadków na Morzu Północnym

Fig. 3. Collision in good visibility fault tree [4]
Rys. 3. Drzewo uszkodzeń dla kolizji w warunkach dobrej widzialności [4]

The research area corresponds to the North Sea area (including the Dover Straits). The area is defined to be within latitudes 50°N and 60°N and within longitudes 0°E and 10°E. The geographical distribution of collision frequencies is calculated on grid-net with a resolution of 1 minute north-south by 2 minutes east-west (approximately 1 Nm by 1 Nm). The results are presented in table 2.

Table 2. Causation probabilities, Fowler & Sørgård model [4]
Tabela 2. Prawdopodobieństwa przyczyn, model Fowlera i Sorgarda [4]

Causation probability	Remarks
0.0000848	good visibility
0.0000683	good visibility, within VTS zone
0.00058	poor visibility
0.000464	poor visibility, within VTS zone

Model of Otto et al.

Model of collision published by S. Otto et al. [5] can by an example of the models based on Bayesian method. This model assumes that factor related to machinery and steering failure is negligible and the collisions are attributed to human failure. Therefore, an analysis of collision rates must be based on a study of a role of human resolving an encounter situation. The authors selected a Bayesian Network to describe the task of the OOW. The network is a graphical representation of influence factors (nodes) and explicitly reveals their probabilistic dependence and the flow of information between the nodes.

The traffic in presented model is simulated by traffic streams. Each traffic stream is characterized by a number, type and size of the ships. The variability of traffic is modelled by Gaussian distribution. Three collision scenarios were taken into account:

– crossing waterways,
– intersecting waterways,
– parallel waterways.

The used network allows to compute the value of causation factor for each type of encounter situation. Causation factor is the probability that actions to prevent the collision are not sufficient or not taken.

On the basis of statistical data the number of collision candidates was estimated separately for each segment of route and for each type and size of vessel. Knowing the number of collision candidates and causation factor (estimated by Bayesian Network) it is possible to calculate number of collisions in given time.

Exemplary calculations were carried out for Ro-Ro passenger ferry. The main dimensions of the reference ship are:

– Length between perpendiculars $Lpp = 173$ m,
– Breadth $B = 26$ m,
– Service speed = 27 kn.

As an example route the existing route between Cadiz and the Canary Island is used. The route length is 700 nm and the voyage time is assumed 25 h per trip, the number of voyages is assumed 240 per year. The following results were achieved:

Table 3. Causation probabilities – Otto et al. model [5]
Tabela 3. Prawdopodobieństwa przyczyn – model Otto [5]

Type of encounter situation	Causation probability
Head on	0.000049
Intersection	0.00013
Crossing	0.00013

Model of Otay and Tan

Model presented by Otay and Tan [6] is a example of model determining the probability of collision resulting from course changes due to hydrodynamics forces acting on the vessel. The computation of vessel positions and the drift probabilities are based on probabilistic considerations of physical quantities that affect navigation including vessel characteristics, randomness of hydrodynamic forces and vessel arrival times.

Hydrodynamic forces, specifically the distribution of magnitude and direction of currents at a given location are used to update the original course of the vessel resulting in drift probabilities. These probabilities and random arrival of vessels are then incorporated into a Markov chain model. By analyzing the time-dependent probabilities of the Markov process, performance measures are obtained including the probability of casualty and the expected number of casualties.

The model output includes risk charts indicating casualty probabilities across the geometry of the waterway at a given time and vessel intensity. Furthermore the model can be used to investigate the relationship between the vessel traffic intensity and global measures of casualty risk such as the expected number of casualties per vessel or per time.

The model operates in three building blocks (fig. 4). The first building block is the hydrodynamic model. The most important forcing mechanism that affects vessels travelling in a waterway is the surface current. This model determines the current velocity at a given location of the waterway depending on wind, channel geometry, bottom topography, and boundary conditions. In order to ensure numerical tractability, a waterway repre-

sented as a grid consisted of a finite number of elements. The first building block yields the current velocity in each of these elements.
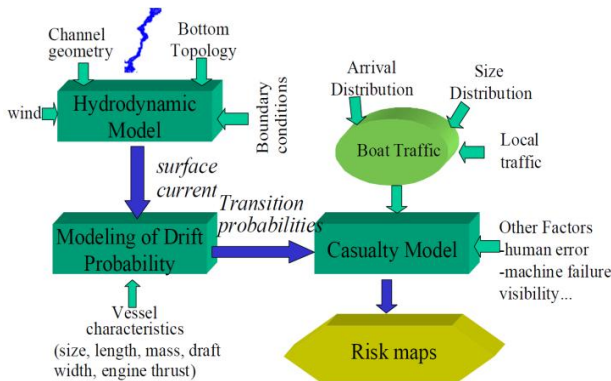

Fig. 4. Components of the General Model [6]
Rys. 4. Komponenty modelu ogólnego [6]

The second building block gives the drift probabilities for a vessel travelling at a given location of a waterway. Due to the surface current, the vessel may drift from its original route. This drift is one of the most important factors for vessel casualties along a waterway. Important parameters effecting the course drift are the hydrodynamic conditions and the vessel characteristics including size, length, draft, mass, engine thrust, etc. This building block first determines the distribution of drift from a vessel's original route and then discretize this distribution to three drift probabilities: (1) maintain the original course (2) drift to the right (3) drift to the left. For example, for a north bound vessel located at a certain grid, this model estimates the probabilities that there will be no drift, or a drift to the north-westerly or north-easterly grids during the next time step depending on the vessel and current characteristics in this grid.

The third building block is a state-space model of vessels travelling along a waterway. This model incorporates the drift probabilities obtained from the second building block, arrival distribution of the vessels, and other effect into a Markov chain model. By analyzing the probability distribution of vessel positions in the waterway at a given time, the probabilities that an inter-vessel collision occurs place at a given location at a given time are derived. Finally, steady-state probability distributions and expected number of inter-vessel collisions, and total casualties are obtained. These results allow to construct various risk charts.

Model developed in Institute of Marine Traffic Engineering

Collisions and oil spills are modelled with use of complex stochastic safety model and real statistical

data. Fully developed model presented in figure 5 can assess the navigational risk on large complex system with consideration of navigators behaviour, ship dynamics, real traffic streams parameters and external conditions like wind current visibility etc. It can be used for assessing risk of the most common navigational accidents. The model works in fast time and can simulate large number of scenarios. The output of the model is number of accidents, positions, types of vessels and size of oil spills.
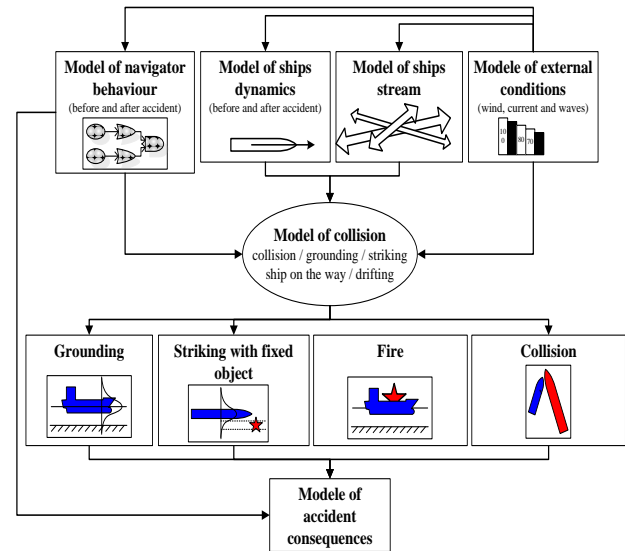

Fig. 5. Fully developed stochastic model of navigation safety assessment
Rys. 5. Opracowany model stochastyczny szacowania bezpieczeństwa nawigacyjnego

Traffic data

There are several sources of data necessary for the developing of simulation model. The data of traffic was obtained on the basis of AIS records (fig. 6) [1, 7, 8], Polish national AIS network studies and statistics of ships calls to given ports. Navigational data was obtained from sea charts, guides and own seamanship experience.

Simulated routes are presented in figure 7. External conditions model was developed on the basis of data from Polish meteorological stations and extrapolated to achieve open sea conditions.

The variability of ships routes is modelled by two-dimensional normal distribution (fig. 8) which parameters were estimated by real data from AIS and expert-navigators opinion.

The traffic of ships is modelled by Poisson process where actual intensity of traffic is evaluated on the basis of real AIS data from the Helcom network which is operated since mid 2005. The collected AIS data is also used for determination of type, speed, length and draught distributions.
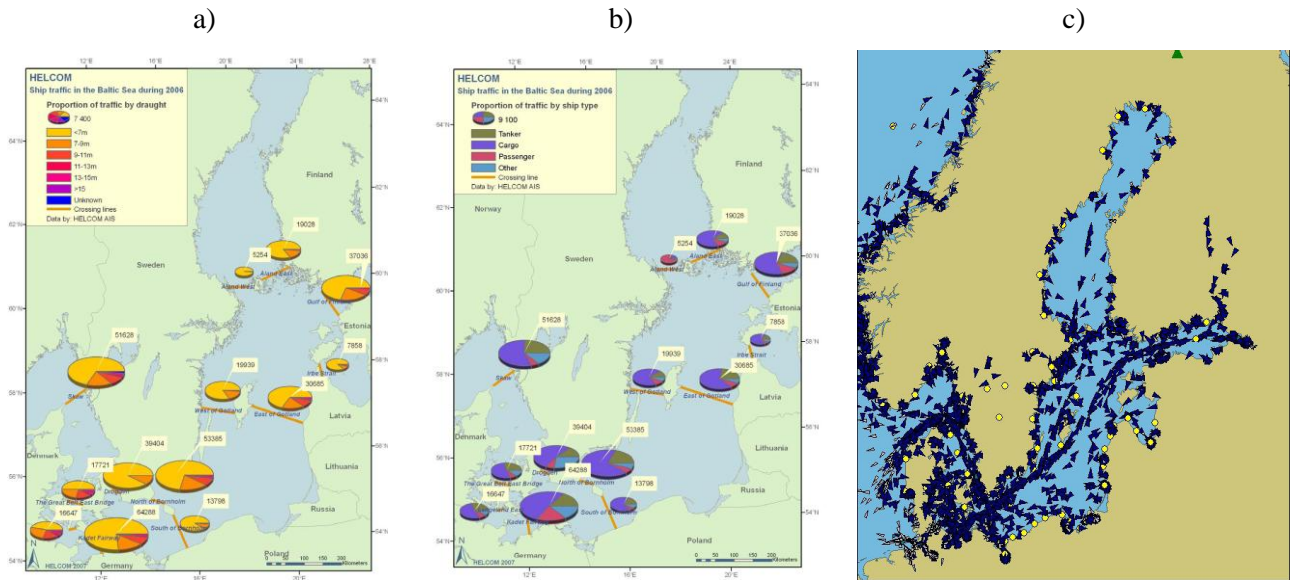
a)   b)   c)

Fig. 6. AIS data, a) proportion of traffic by draught, b) proportion of traffic by ship type, c) ships routes [1]
Rys. 6. Dane z systemu AIS a) odsetek statków według zanurzenia, b) odsetek statków według typu, c) trasy statków [1]
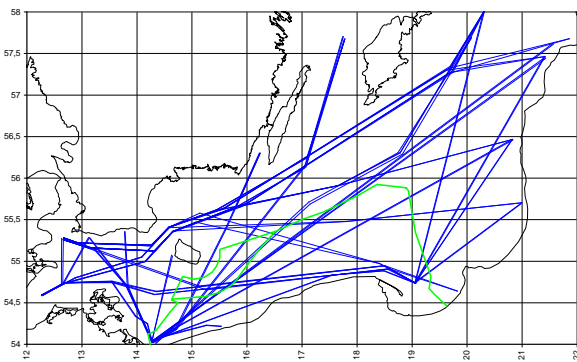

Fig. 7. Research area and simulated routes
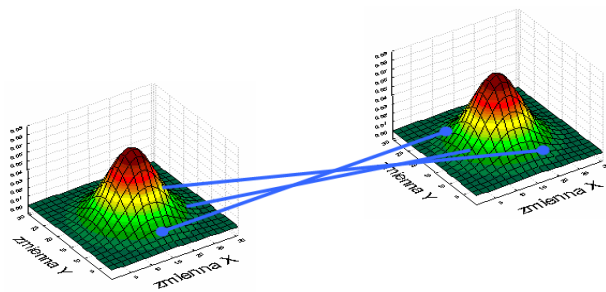Rys. 7. Obszar badań oraz symulowane trasy statków

Fig. 8. Distributions of waypoints coordinates
Rys. 8. Rozkład współrzędnych punktów drogi

Collision accident model

To model the collisions simplified statistical model is used. The model neglects several dependencies but because it is based on real statistical data the achieved results are very close to reality. The most unknown parameter necessary for collision probability assessment on large sea areas is number of ships encounter situations. In complex systems with several traffic routes this number could be evaluated only by traffic streams simulation models such as the one presented in this study.

After collecting necessary input data the simulation experiment was carried out and the expected number of encounter situation was calculated. The critical distance where navigators perform anti-collision manoeuvre was assumed separate for head on, crossing and overtaking situations. These distances (table 4) called minimal distances of navigator's reaction were estimated by simulation studies and are valid under the open sea conditions.

Table 4. Distances of reaction
Tabela 4. Odległości potrzebne do wykonania manewru

Type of encounter situation	Distance of reaction	
	Good visibility	Restricted visibility
Head on – port/port-side	$2.5L_{max}$	$5L_{max}$
Head on – strb/strb-side	$5L_{max}$	$10L_{max}$
Overtaking	$2.5L_{max}$	$5L_{max}$
Crossing	$5L_{max}$	$10L_{max}$

The overall number of encounter situations estimated by simulation model is around 3 800 000 per year where 40% of them are head on situations, 20% of crossing and 40% of overtaking.

In the next step, statistical data from Southern Baltic Sea accidents were used for evaluation of mean intensity of ship collision accidents in the Southern Baltic. Only the accidents at the open sea area were considered. Figure 9 presents number of accidents per year on the investigated area.

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The mean intensity of collision accidents equals 1.8 per year. Observation of tendency of accidents shows high correlation of collision accidents of traffic intensity.
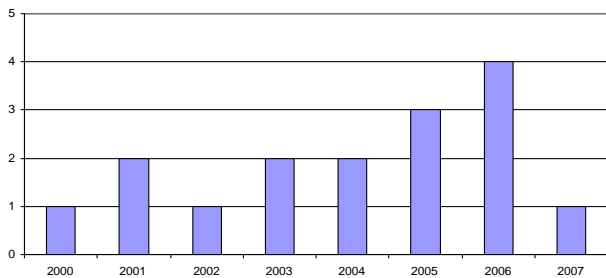

Fig. 9. Number of collision accidents per year located at the open sea of the Southern Baltic
Rys. 9. Liczba kolizji zarejestrowanych na pełnym morzu na akwenie Morza Bałtyckiego

Data presented in figure 9 and the number of ships encounter situations have been used for estimating the probability of collisions in single encounter situation. This probability can by estimated by following formula:

$$P_c = \frac{n_c}{n_e} \qquad (7)$$

where: P_c – probability of collision in single encounter situation, n_c – number of collisions (real data), n_e – number of encounter situations.
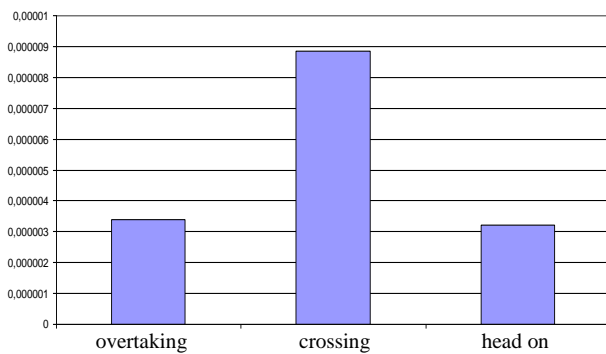

Fig. 10. Probability of collision accident in different encounter situations
Rys. 10. Prawdopodobieństwo kolizji dla różnych sytuacji spotkaniowych

The mean calculated probability of collision in single encounter situation (fig. 10) equals about $5 \cdot 10^{-6}$ which less than the typical value of probability used in safety of collision assessment.

Oil spill model

The collision can be followed by the oil spills. The conditional probability is used and finally the probability of oil spill accident (P_S) is calculated as follows:

$$P_S = P_A P_{A/OS} \qquad (8)$$

where: P_A – probability of accident, $P_{A/OS}$ – conditional probability of oil spill if accident occur.

Several databases [MEHRA 1999, ITOPF 1998, MAIB 2005, LMIS 2004, HECSALV 1996, and IMO 2001] were used to find the conditional probability of oil spills if given accident occurs.

Figure 11 shows conditional probability of oil spill. Oil spills due to collision is estimated with the double bottom tankers with relation to ships size expressed in DWT.
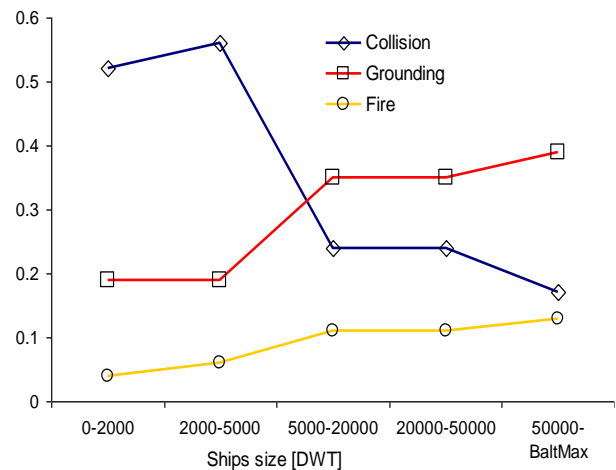

Fig. 11. Conditional probability of oil spill if given kind of accident occurs
Rys. 11. Prawdopodobieństwo warunkowe rozlewu olejowego dla danego typu wypadku

The simplified statistical model is used to evaluate the size of oil spill after collision. The model assumes that the size of oil spill depends on ships size expressed in DWT in tons and type of accident. The results are presented in figure 12.
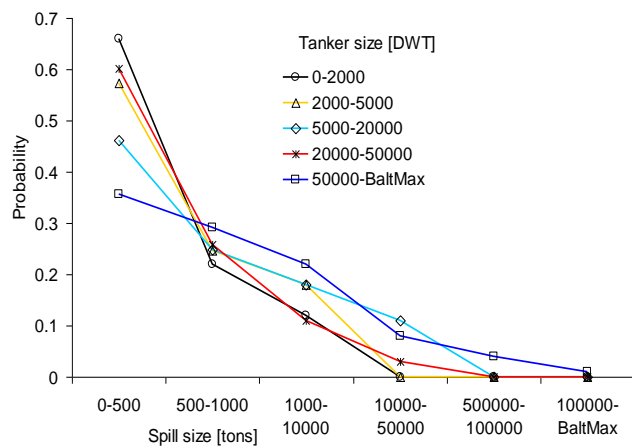

Fig. 12. Distribution of oil spill size caused by collision
Rys. 12. Rozkład wielkości rozlewu olejowego będącego wynikiem kolizji

Preliminary results

Presented model allows the user to establish the places of accidents and places of oil spills. Simulation is carried out in series, each of 5 years period. This short period makes prediction of traffic parameters relatively accurate. The results of simulation are presented in figures 13–14.
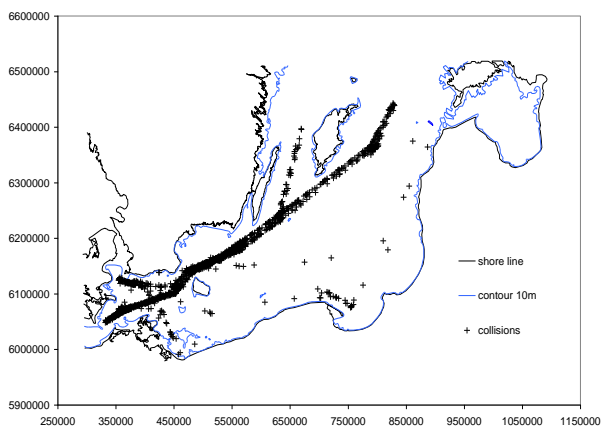

Fig. 13. Places of simulated collisions (140 × 5 years period)
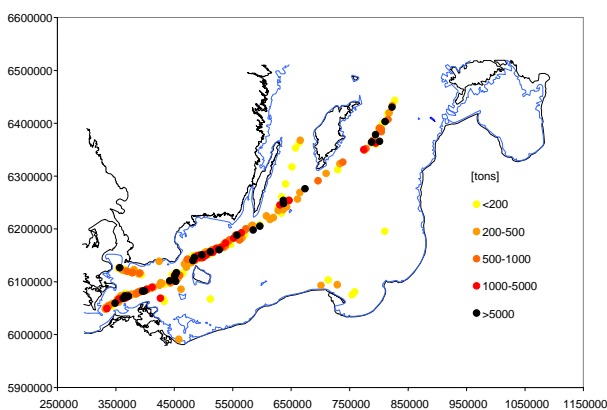Rys. 13. Miejsca symulowanych kolizji (140 symulacji po 5 lat obliczeniowych każda)

Fig. 14. Places of simulated oil spills caused by collisions (140 × 5 years period)
Rys. 14. Miejsca symulowanych rozlewów olejowych spowodowanych kolizjami (140 symulacji po 5 lat obliczeniowych każda)

Summary

The paper presents models of ship-ship collision. All of presented models are, in a manner, based on formula (1). The main difference between them is the way of establishing of "causation probability". Models based on the fault trees are the most detailed. But therefore they are the most complicated and they need large number of data. Model of Otto et al. consider only collisions caused by human failures. Model of Otay and Tan was developed for concrete sea area and it can be difficult to use it in other. Model developed in Szczecin used in the simulation allows to determine areas where the probability of collision is highest. In the next step it is possible to develop the models of oil spills. The output of the model as the collision places, ships involved, size of spill and navigational conditions could be useful for risk assessment of large sea areas.

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