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Towards generalized ship's manoeuvre models based on real time simulation results in port approach areas

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ABSTRACT

This paper presents an attempts towards creation of generalized models of ships manoeuvring area determination and ship performance created on the base of real simulation results. Those models are needed for better understanding of the safe navigation process in ports areas and its approaches and for risk analysis when no full information about the ships behaviour is available. The data coming from real time ship simulations that are conducted by experienced pilots and captains are applied in the study. In the first step, general regression models are created to determine manoeuvring areas and major correlations between basic parameters affecting the safe area needed for ships to navigate in restricted areas of ports and its approaches. In the second step, the ship performance models are created to describe the behaviour of the ship including human factors. The ship performance for long-term prediction of the navigation risk regarding the possibility of ships exceeding the channel limits, assumed as grounding or collision with a fixed structure are created by the method which consists of two developed models: (1) an ARMAX (Auto Regressive and Moving Average eXogenous) model is adopted to identify the ship steering dynamic system. With the help of this model, the outputs of the system (course, position, etc.) can be estimated based on the system input conditions (rudder, engine, etc.); (2) the stochastic sequences of the inputs for the first model used are generated using a semi-Markov model. In the paper the implementation of the semi-Markov model for rudder actions has been described. The study used input/output measurements from a ship-handling simulator to estimate the model parameters, so the human factor has been included in the models. The method allows us to extend the results obtained from the simulator to predict future conditions of the system outputs. Since the predicted results and using probabilistic approach, possible ship manoeuvring area margins will be identified and long - term assessment of the navigation risk can be realized.

1. Introduction

Maritime simulation is a reliable and indispensable tool in the assessment of navigational safety of a ship in conjunction with harbours and fairways. The main application focuses essentially on channel design to indicate the ship manoeuvrability and possible accident occurrence in relation to the human behaviour and environmental conditions. This approach usually consists of a two-step process: application of a ship-handling simulator for generating the data of ship motions and assessment of waterway dimensions and navigation risk based on this data.

There are two approaches for long-term assessment of navigating risk on the waterway. One is the application of ship handling simulation, and the other is assessing the risk based on historical and available data of ship tracks. The first approach is focusing more on the accidental risk for transit concerning possible grounding on the shore or collision with the bank; while the second is more applicable to the risk assessment of the ship traffic in busy waterway areas.

The Bayesian network has often been found in the modelling of ship traffic and risk assessment of ship collision (Martins and Maturana, 2013; Akhtar and Utne, 2014). Further improvement of the Bayesian network mode by integrating with Technique for Retrospective and Predictive Analysis of Cognitive Errors (TRACER) studied by Sotiralis et al. (2016). More recently, it is of great interesting to utilize AIS data

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with simulation technique for verification and calibration of the risk assessment modes (Mou, J. M., et al., 2010; Fangliang et al., 2012; P. Chen et al., 2017, Rolf J.B. and Asbjørn Gilberg. 2018). Somewhat differs from the above is a more advanced model developed by Shahrzad et al. (2014) using a Markov modelling approach and Markov Chain Monte Carlo (MCMC). The limitation of the existing literature in this approach group is that historical data of ship tracks and accidents is not always available and furthermore impossible to apply to newly developed waterways.

Applying ship handling simulator to the risk assessment of the waterway is a merit tool belonging the first approach. Real time ship handling simulations should be executed for a wide range of environmental conditions (grouped into scenarios) and several repetitions for each condition in real time scale. So the time required would be comparable to the lifetime of the waterway. These requirements are expensive and seem impossible due to time consumption (Webster, 1992). From this arises the question of how to estimate the probability of ship accident during the lifetime of the channel project, the so-called "overall risk". The real time simulations are based only on a limited number of conditions and trials in each condition. So the risk calculated from the simulated data does not equal to the overall risk. Generalization of the real time simulation results of ship tracks for long-term period research turns out to address the disadvantage of the ship handling simulator method. Finding ways of extending the real time simulation experimental results and applying to lifetime channel risk analysis is still challenging to researchers.

To make fast time simulation results closer with those obtained from real time simulation is a promising approach. Early works developed a ship navigator cognitive model to be constructed for simple course-tracking task based on a cognitive task analysis of experimental navigation sessions using a maritime simulator (Itoh, K. et al., 2001; Willem A., et al., 2005). However, this model was programmed to control a ship only in a so-called simple single-ship situation. In recent years, some authors developed a fast time simulation - based models using either Fuzzy Logic controller (Guoqing Xia et al., 2016; Sheng-Long Kao et al., 2017) or Neural Network controller (Weilin Luo et al., 2016; Nam-Kyun Im et al., 2017). However, significant efforts should be made to consider more complex navigation tasks (multi-ship situation) to extend the model to more realistic ship navigation as met in the real world.

It have to be mentioned that many authors have undertaken researches focused on data generalization in the aspect of ship collisions, which is more difficult because it requires taking into account the behaviour of two objects and collision geometry consideration. An overview of currently used methods can be found in Chen et al. (2019). Weng et al. (2020) attempted to study the complex relationship among the traffic characteristics, environmental conditions, and ship collision frequency using AIS data. Gil et al. (2019) investigated feature based on an analysis of a process of merchant vessels' collision avoidance. Nguyen et al. (2018) examined the main elements of ship collision by mathematical model for the risk assessment, and simulated a collision assessment based on AIS information.

Despite the fact that the paper consist of some previously performed research by the authors on the generalization of data from ship traffic manoeuvring simulations, it contains a number of new unpublished yet researches. These are mainly new analyses concerning parameters of safe manoeuvring areas required by ships, including analyses based on linear multi-criteria regression. The new models of mean and standard deviation of ships manoeuvring area are presented together with the discussion of their applicability. These models are utilitarian and provide data for potential risk analyses. In addition, the paper introduces new analyses of the quality of ship's manoeuvring, including rudder movement and course analyses.

1.1. Ship handling simulators in waterway design

Many ship simulators exist worldwide for different applications with various levels of capacities. Essentially, a ship-handling simulator is a computer-generated system that simulates the actual operation parameters of the ship in various manoeuvring conditions in real time and displays the scenery from the navigation bridge visually and audibly on the screen. Simulators comprise wide range facilities and man-machine interfaces as depicted schematically in Fig. 1. An advanced ship simulator includes models of a ship, the simulated navigation channel, the environmental impacts, the visual scene, the radar image, tugs and thrusters, the ship bridge control, and typical bridge instruments.

The core of the ship dynamic model is the set of hydrodynamic equations of ship motion referred to a coordinate system commonly fixed in the ship. The equations should be complete and realistic with ship hull dynamics, engine thrust, bank and shallow water effects, currents, wind and wave impacts, and tug supporting forces.

The most important data and results derived from simulator experiments for the use of waterway design are:

- track plot, a two-dimensional plot which includes the proposed channel contour and the ship position at predetermined time intervals;
- time series tables of different variables (track distance, rudder angles, ship speed, turning rate, engine revolutions, etc.) throughout the simulation;
- swept path graphs and the channel border are presented in a two-dimension plot.

Reviews on the state-of-the-practice application of this technique to navigation risk assessment and waterway design have been well documented in the two guidelines (USACE, 2006).

1.2. The typical setup of full-mission bridge simulator

The example of the full-mission simulation is the Kongsberg Polaris navigational mock-up bridge, located in Maritime University of Szczecin (Fig. 2) where large part of this study was conducted. The facility consists of:

- one navigational bridge with the visualization of 270° angle and equipped with identical with real control and steering devices (DNV class A);
- two-part task simulators of 120° visualisations, partly equipped with control devices, with real like Voith-Schneider tug console (DNV class B);
- two simulators of the type PC type with the visualization of the projection-type and with simulated navigational devices.

All equipment of simulator is standardized according to requirements of STCW'95 training (section A-I/12, section B-I/12, table A-II/1, table A-II/2 and table A-II/3) and is certified by DNV. The creation of new hydrodynamic models is possible and is based on the dedicated computer tool. There is also possibility of the creation of very exact ship models working in six degrees of freedom and the possibility of the modelling of ships with two engines and propellers of both fixed or controllable pitch, azimuth drives and the different type of steering devices.

1.3. Ship movement on the waterways as source of statistical data

The understanding of the type of information that simulation attempts to provide is fundamental to evaluate how simulation can contribute to the process of ships movement. Real time simulations are conducted by human pilots to navigate the simulated ship through the modelled waterway in real time scale. Interpretation of the simulated ship tracks provides insight into the various navigation factors (characteristics and dimensions of the waterway) and safety aspects (grounding or collision risks). Typically the analysis of the real time runs

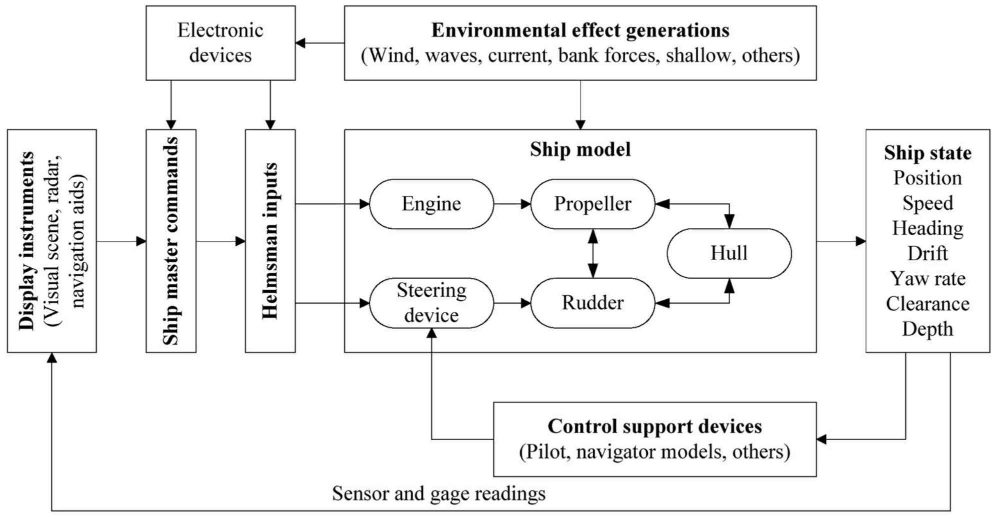

Fig. 1. A simplified ship-handling simulator.

Fig. 2. Main full mission bridge in Maritime University of Szczecin.

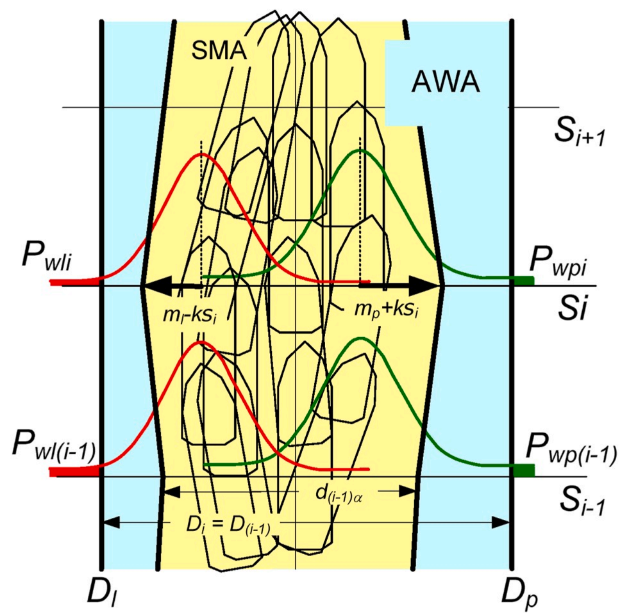

Fig. 3. Probabilistic method of defining the safe manoeuvre area (SMA) and the probability of ship outside the available water area (AWA).

aims at finding the ship response parameters (including human factors) based on:

- distribution of ship track distances (centre of gravity and extreme starboard and port points of ships) in respect to centre of the waterway;
- distribution of ships courses; and
- distribution of ships speed (horizontal, vertical and angular).

One of the most important measures for the risk assessment associated to waterway width design is the probability of ship accidents in each of the waterway sections. The probability of a ship exceeding from starboard i-th section waterway, P_{ex}, can be determined as follows:

$$P_{ex} = P_{wpi} = P(x > D_p | Env = i) = \int_{D_p}^{\infty} f(x)dx \quad (1)$$

where D_p is half of the waterway width; $f(x)$ is the density function of the ship positions for a given environmental scenario Env shown separately for port and starboard side and for all sections in Fig. 3.

The simulations are usually conducted in series, performed in different meteorological conditions, each consists of several trials. In principle, the environmental conditions of wind, waves, and currents are divided into several regions or categories to facilitate the probability assessment of the navigation results. These environmental categories, reflecting the frequency of occurrence and severity, are selected to define the different combinations of the environmental conditions that might be present when the ship is navigating the waterway. The different combinations of environmental conditions are divided into various classes (normally three or four), known here as "manoeuvring scenarios", by ordering degree of affecting the ship manoeuvrability. The probability of ship accident from the channel section borders during a given time, P_{life}, can be determined as:

$$P_{life} = N_{ship} \sum_{i=1}^{N_e} P_{ex} P_{oc}[Env = i] \quad (2)$$

where N_{ship} is the number of ships presents in the channel during a given time period; N_e is the number of the manoeuvring scenarios; $P_{oc}[Env = i]$ is the occurrence frequency of the manoeuvring scenario i. Estimation of occurrence frequencies of the manoeuvring scenarios is also an important topic. Two approaches could be found in the literature, which based on a linear programming technique (Briggs et al., 2003) or classifying external forces on the ship hull (Quy et al., 2007).

Fig. 4 shows the distributions of ship track distance respectively with three manoeuvring scenarios that are defined applying the above principle. The ship track samples can be well described by a normal Gaussian distribution. The figure has been created based on the data of the study case at the entrance channel of Ennore Port (Vrijling, 1995). Real time simulations were performed with the use of a 4.500 TEU container vessel. Eighteen scenarios of environmental conditions which are grouped into three scenarios (extreme, normal and gentle conditions) were carried out. For each scenario, several runs were executed.

It was found that the distribution of ship courses is strongly correlated with ship positions referred to the middle of the waterway. It can be straightforwardly explained that the more the ship is away from the centre of the waterway the more the navigator changes the course to come back to the desired track (Gucma, 2006). The 30 simulation passages by the model of tanker with parameters: $L = 196$ m and $B = 28$ m; manoeuvring on the bend of the waterway was applied in this study (Fig. 5).

This relation between distance from the centre of waterway (cross track error) and course can be seen on Fig. 6. To include this phenomenon for the later analysis of the navigation risk, it was proposed to use a linear regression model. The distance from the middle of the waterway could therefore be calculated by the distribution of courses using this regression model. The results presented in Fig. 6 are valid for single waterway section (as shown on Fig. 5) and to consider waterway as a whole more advanced models such as the one presented in part 3 of this paper are needed.

It should be noted that Eqs. (1) and (2) can only give the probable results of ship position in given section of the waterway; they are no indications for the waterway as whole. Two approaches of integrated risk for entire channel have been presented in the literature (Burgers and Kok, 1989; Quy et al., 2007).

1.4. Generalized models of ship movement and performance

The existing systems, due to their complexity, require constructions of suitably specialized models with several parameters, such as: ships traffic, hydrometeorological conditions, parameters of the water area and other. Most of these parameters are random and simple analytical methods are not suitable, especially when these models are supposed to include also a human factor (the probability of navigator error). The modelling of such systems can be carried out by means of simulation methods, and particularly Monte Carlo based methods. Fig. 7 presents several stages necessary for such models creation with previous generalization of various data comes from both simulations and real (like AIS-based) experiments or observations.

In general the present models can be divided into three following classes (Fig. 8):

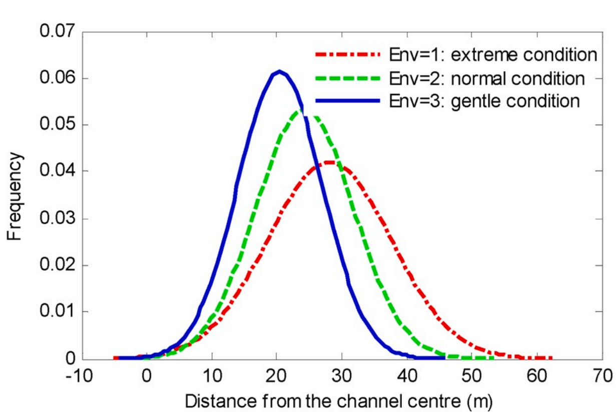

Fig. 4. Density function of distance from the centre of the channel fitted with normal distribution (in starboard side).

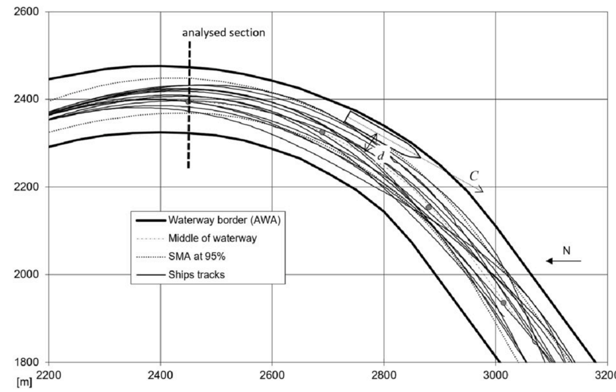

Fig. 5. Waterway area and 15 example ships tracks used for determining the relation between distance from the waterway centre (d) and ships course (C).

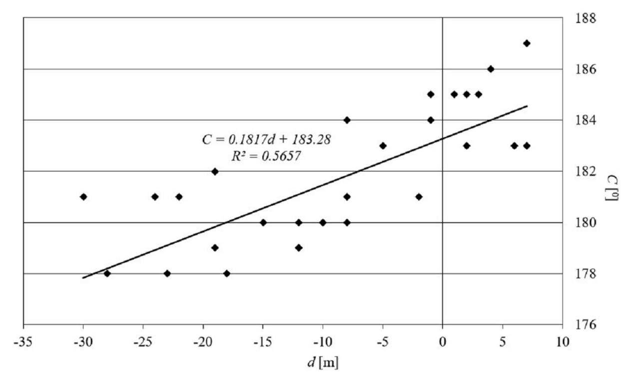

Fig. 6. Linear correlation between distance from the waterway centre (d) and ships course (C) for one investigated simulation waterway section presented on Fig. 6.

1. General probabilistic models of ship manoeuvring area parameters;
2. Causation models;
3. Ship performance models.

The first and last were presented in this study in point 2 and 3 respectively. The second kind of the models try to find the relation between ships consecutive positions of ship manoeuvring on the waterway. Some of them are presented in (Semerdjiev and Mihaylova, 2000; Gucma, 2007). The previously mentioned MCMC or Hidden Markov Chains or other based on stochastic processes finding the dependence between consecutive ships position could be applied there. Such a model was presented by Gucma (2007). It differs from the above in several ways. It assumes that the next ship position can be generated from the past consecutive position using two types of probability distributions. The first type describes the probability distribution of maximum and minimum points of ship track on starboard and port sides respectively. The second is the conditional distributions between the ship course and the generated track distance. The probabilistic model parameters were also obtained from statistical analysis results of the real time simulations.

2. Generalized models for determination of ship manoeuvring area

Authors carried out some researches concerned with generalization of ship data possessed in simulation experiments. They were led in two directions:

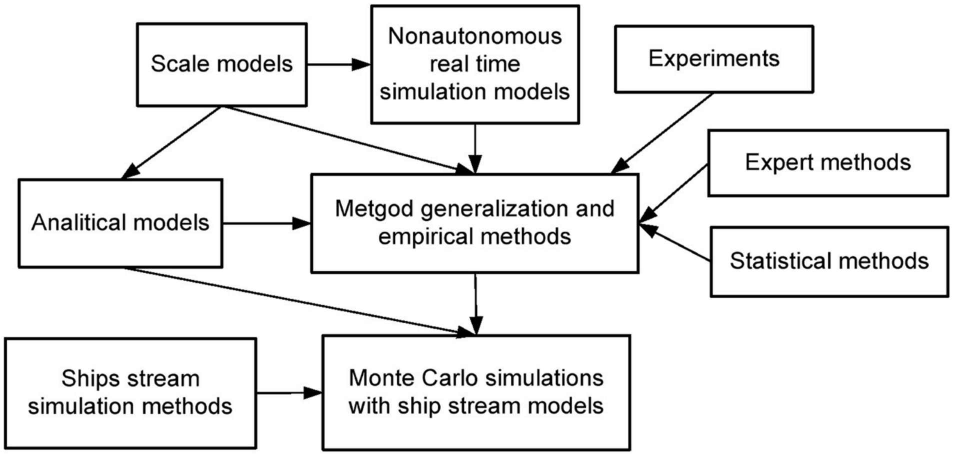

Fig. 7. Towards construction of generalized simulation methods (Gucma, 2000).

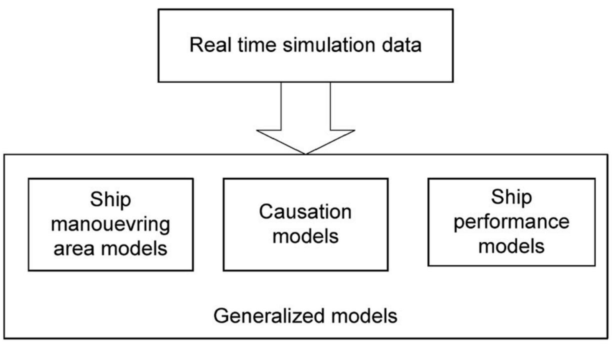

Fig. 8. The division of general models based on ship simulation data.

– to find the shape of distributions describing the position of the ship on waterways;
– to estimate parameters of those distributions and model dependences between most important variables (Gucma, 2012).

It was proven in many studies that the normal distribution is well fitted for the description of the variability of the position of ships on waterways in the horizontal plane (Gucma, 2012). In many researches (Iribarren, 1999) the asymmetrical distributions, e.g. extreme values were also successfully fitted. To model the movement of ships on coastal areas, the mixture of normal and uniform distribution in relation 99%–1% is usually used (Karlsson et al., 1998). Such a mixture is useful when traffic consists of typical merchant ships (normal distribution) and pleasure crafts (uniform distribution).

2.1. Models based on linear regression

To find the general models of ships manoeuvring area parameters (mean – m and standard deviation – s) the database of real time ship simulation experiments was used. The database includes 25 different ships manoeuvring in 121 conditions (Table 1). This experiment was not designed intentionally but done within the routine port design works made by simulation research team of Maritime University of Szczecin.

To find relation between the mean safe manoeuvring area (denoted as m_p i m_z for straight part legs of waterway and bends accordingly) and ships breadth *(B)* the simple linear regression model was chosen. Breadth of ship was chosen because it's the most significant factor influencing the width of waterway. Other factors like: available width of manoeuvring water area, length of ship, ship's manoeuvrability, wind or current influence are less important. Fig. 9 demonstrates two models of linear relations of those parameters for straight and bend legs of waterway. The parameters of regression for straight leg (m_p) are as follows: coefficient of determination $R^2 = 0.76$, overall regression error $s_e = 9.5$ m and F-statistics F = 440.

Table 1
The sample of ships simulation models and number of trials used for regression.

Type of ship	L [m]	B [m]	No of environmental conditions
Bulk carrier	250	40.0	9
General cargo	100	15.0	11
General cargo	50	16.0	10
Inland ship	50	9.0	10
Passenger	26	7.2	13
General cargo	92	11.3	4
Inland ship	110	9.0	2
Inland ship	95	9.5	2
Bulk carrier	255	29.2	3
Bulk carrier	240	36.8	3
Bulk carrier	250	38.5	3
Bulk carrier	260	40.0	3
General cargo	65	16.3	3
Ro-Pax	150	22.4	8
Ro-Pax	175	25.0	2
Ro-Pax	185	26.5	2
Ro-Pax	195	28.0	2
Bulk carrier	245	34.5	4
Bulk carrier	270	41.5	3
Bulk carrier	280	45.0	8
Bulk carrier	285	43.4	2
Container	300	50.0	3
Ro-Pax	174	24.0	7
Ro-Pax	189	23.1	2
Bulk carrier	270	49.5	2

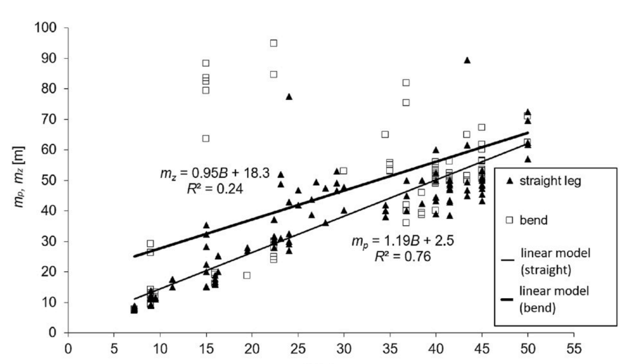

Fig. 9. Linear relation of mean width of manoeuvre area for straight waterways (m_p) and bends (m_z) to the ship's breadth (B).

Similar model was built to find the relation of standard deviation of the width of available waterway area (AWA). Fig. 10 shows this relation by linear regression model with use of simulations presented on Table 1. The parameters of regression for straight (s_p) were as follows: coefficient of determination $R^2 = 0.41$, overall regression error $s_e = 5.8$ m and F-statistics F = 100. The linear model of standard deviation on straight waterway (s_p) dependence of the available waterway's width *(D)* could be presented in the following form:

$$s_p = 0.05D + 3.4 \tag{3}$$

2.2. Models based on linear multiple regression

In this point the method of multiple regression was applied to determine the mean and the standard deviation of maximum ship distance from the middle of waterway. The model based on multiple regression describes the relationship between the dependent variable y and n independent variables x in the form of:

$$y = b_0 + b_1x_1 + \ldots + b_nx_n \tag{4}$$

where:

b_i – multiple regression model coefficients.

Two types of characteristic water areas were chosen, which results were taken from simulation tests:

- straight leg of the waterway;
- bend of the waterway.

As the dependable variables average width of safe waterway area, the standard deviation of maximum distance from the middle of the waterway is selected. Average width of the safe manoeuvring area is therefore defined as:

$$d_m = m_{dp} - m_{dl} \tag{5}$$

where:

m_{dp}, m_{dl} – average maximum distance of the ship points to the port and starboard from the middle of the waterway.

It was assumed, that the middle of the waterway is symmetrically located in relations to the average (mean) width of safe manoeuvring area. In most of simulation tests, there is no specified centre and it is necessary to establish the hypothetical middle of the waterway (Fig. 11).

Standard deviation of the maximum distance to the waterline to right and left from the middle of the waterway is devoted as s_{dl} and s_{dp}.

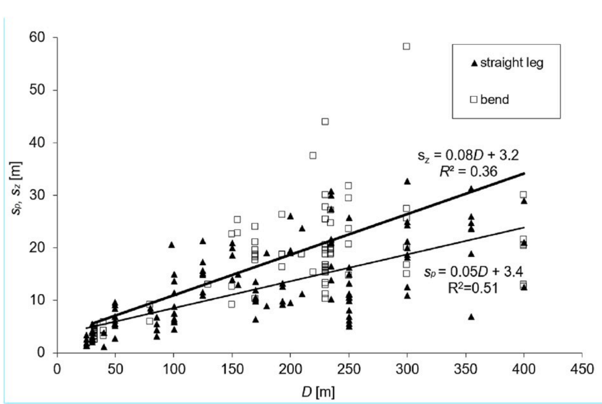

Fig. 10. Standard deviations on straight legs (s_p) and bends (s_z) dependence of available waterway width (D).

Considering small differences between the standard deviations to the port and starboard side, it was decided to analyse the mean of standard deviation as $s_d = (s_{dl} + s_{dp})/2$. Following independent variables in the model of regression were used as the most influencing ships manoeuvring area:

1. Breadth of ship B [m];
2. Available width of manoeuvring water area D [m];
3. Length of ship L [m];
4. Factor of ship's manoeuvrability *Ms* [dimensionless];
5. Cross wind intensity s*W* [m/s];
6. Water current factor *Pr* [dimensionless].

Because of difficulty to define relations between variables within the model, the wind direction was not taken into consideration during the research. Current factor is assumed as:

- 0, for opposite and the lack of current;
- 1, when a ship is moving downstream being consistent with its movement, what is considered to be the most impeding the ship's manoeuvre.

To introduce different manoeuvring abilities of ships, it is suggested to define manoeuvre factor as the number from 0 to 3:

- 0 for small ships with the perfect manoeuvre ability which perform manoeuvres all on their own;
- 1 for big ships with good manoeuvre ability equipped in bow thruster and twin-propeller;
- 2 for ships with poor manoeuvre ability and in ballast;
- 3 for ships with very bad manoeuvrability and loaded.

Basic problem during construction of multiple regression models is the internal correlation between independent variables. In the proposed model, the internal correlation is obvious and appears between ship's length and breadth, ship's width and manoeuvre factor, and available water area's width and ships' breadth. The first pair characterizes the biggest correlation. However, there was no decision made to remove independent variable, which describes ship's length, because in theory, it has influence on the lane's width, especially, when the ship moves at a big rate of drift, what occurs when moving through the bends. In the model, the width of available water area is the independent variable of great importance. The smaller available width, the manoeuvre width has to be done with higher confidence and precision and with smaller errors tolerance when the probability of collision rises. It also decreases freedom of manoeuvre and only some manoeuvring methods are effective and safe. The data for researches were gathered with use of simulation tests as presented in Table 1.

Models of two dependent variables: average width of the lane, standard deviation of the distance in the defined level of significance can be described as:

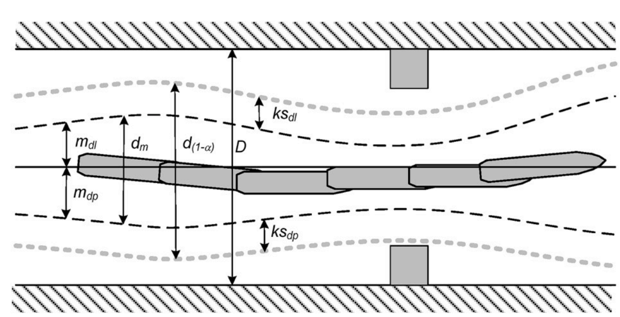

Fig. 11. Definitions of variables assumed within the model.

$$d_m = b_0 + b_B B + b_D D + b_L L + b_{Ms} Ms + b_{sW} sW + b_{Pr} \mathrm{Pr} \quad (6)$$

$$s_d = b_0 + b_B B + b_D D + b_L L + b_{Ms} Ms + b_{sW} sW + b_{Pr} \mathrm{Pr} \quad (7)$$

Parameters and verification of the models were described in (Gucma, 2012). It is important to remember, that application of models is often restricted by environmental conditions *Env* prevailing during simulation tests. Table 2 presents the multiple regression coefficients of the models obtained by the least squares method, in which all independent variables were included. Additionally, the coefficient of determination R^2 is given, which determines what percentage of dependent variable variation is explained by the model and standard error of estimation (s) which can be interpreted as the average deviation of the dependent variable in the sample from the theoretical value. Additionally the F statistics coefficient is presented. Some independent variables that are not bolded in Table 2 weren't significate to overall model of regression which lead to need of further analysis considering the excluding variables. It should be noted that the model is sensitive on regression parameters and some independent variables have unimportant influence on presented model, mostly due to complexity of ships behaviour and too small sample size. Such model could be used for probability of a ship collision with technical structures or embankments assessment.

3. Ship performance model

In the following part, the use of ARMAX model and semi-Markov process to extend real time simulation results for long term-prediction of the navigation risk will be presented.

This study is an ongoing effort to the generalization of real time simulation used for the risk assessment of navigable limits. Two models have been developed: the first model uses ARMAX technique to estimate the system outputs (course, position, etc.) from the inputs (rudder, engine, etc.) of the ship steering dynamics. The stochastic sequences of the inputs for the first model used are generated using a semi – Markov model. One implementation of the semi - Markov model for rudder actions has been studied. The study used input/output measurements from a ship-handling simulator to estimate the model parameters. The human factor has therefore been included in the models. The method allows the results obtained from the simulator to be extended to predict the future conditions of system outputs. Based on the predicted results and using probabilistic approach, possible margins of ship manoeuvring area will be identified and long - term assessment of the navigational risk can be implemented involving a straightforward use of the optimal design of the waterway widths. Satisfactory results were obtained even there were limited ship handling results available. However, the study is constrained to one failure mechanism, which is the even of ships exceeding the waterway limits and being viewed as grounding or colliding with surrounding structures. The general procedure for the study is presented in Fig. 12.

3.1. Model of ship steering dynamic

A ship operating in seawater is assumed as an dynamic system with inputs $u(t)$, outputs $y(t)$ and white noises $e(t)$ as shown in Fig. 13. The inputs can be rudder angle, propellers, and thrusters and etc. The outputs are ship heading (yaw), sway, surge, roll, yaw rate, sway velocity, surge velocity, roll rate and etc. There are several ways to represent the relationship between the outputs and inputs, for example, by means of a continuous time model (classical way or differential equation), a model in transfer function form, a model in time or frequency domain, and a discrete time model (digital technique or difference equation) (Fossen, 1994). In this paper, discrete-time Auto-Regressive Moving Average eXogenous (ARMAX) model was adopted.

The ARMAX model applied to the above-described dynamic system can be assumed as a discrete-time model, a multiple - input and single-output (MISO) system in a transfer function form as follows (Ninness and Wills, 2005):

$$y\ (t) = G(q)\ u\ (t) + H\ (q)\ e\ (t) \quad (8)$$

In above $u(t)$ and $y(t)$ are sequences of the multiple - input ($u(t)\ \varepsilon\ R^m$) and single-output ($y(t)\ \varepsilon\ R_1$) system with the same length; $G(q)$ is $1 \times m$ rational transfer function of the system; and $H(q)$ is rational transfer function of the filter which are defined as:

$$G_i(q) = q^{-nk_i} \frac{B_i(q)}{A_i(q)};\ H_i(q) = \frac{C(q)}{A_i(q)} \quad (9)$$

where n_{ki} is the number of delays from input to output of the ith input, q is the delay operator, $A(q);B(q)$ and $C(q)$ are polynomials of q - 1 defined as:

$$A_i(q) = 1 + a_1 q^{-1} + a_2 q^{-2} + \cdots a_{na} q^{-na_i} \quad (10)$$

$$B_i(q) = b_o + b_1 q^{-1} + b_2 q^{-2} + \cdots b_{nb} q^{-nb_i} \quad (11)$$

$$C(q) = 1 + c_1 q^{-1} + c_2 q^{-2} + \cdots c_{nc} q^{-nc} \quad (12)$$

where n_{ai}, n_{bi} and n_c are orders of polynomials A_i, B_i and C, respectively. Having observed the input-output data (u, y), the most appropriate orders and the parameters of the polynomials can be determined using prediction error, $e(t)$, method (Ninness and Wills, 2005), which is available in the Matlab Identification System Toolbox (Matlab, 2005).

The model described in Eq. (4) with known A, B and C can then be applied to generate a random sequence ship course from the inputs $u(t)$. The following section will present how to apply a semi-Markov model to describe rudder motions based on measured rudder angles achieved from the real time simulation.

3.2. A semi-Markov model of rudder motions

Markov chains and semi - Markov models are powerful and commonly used technique for studying the reliability and characteristic of complex systems. These models use a set of data observed in present to predict system behaviour in future by generating a random sequence that contains patterns of data characteristics. Details about this class of processes can be found in (Janssen and Manca, 2006).

Consider a finite set of rudder angles $R = [r_1, r_2, \ldots, r_k]$ (degree) and respectively numbered and represented by rudder states $S = [1, 2, \ldots k]$ that occur at random times during all the simulation trials, and denote $p(i,j)$ as the transition probability that the helmsman moves the rudder randomly from state i (at rudder angle r_i) at time t_i to state j (at rudder angle r_j) at time t_j. A Markov chain is a discrete-time stochastic process, where the conditional probability of any future event depends on only the present state; the transition probability $p(i,j)$ is expressed by this law as:

Table 2
Multiple regression coefficient for general model of chosen variables for straight part of waterway and bend.

Model	Dep. variables	b_0	b_B	b_D	b_L	b_{Ms}	bs_W	b_{Pr}	R^2	s [m]	Regression significance
Straight	d_m	0,7	0,43	0,02	0,11	−1,4	0,1	0,7	0,91	4,6	yes (F = 149)
Leg	s_d	4,0	−0,12	0,01	−0,02	0,2	0,1	−0,3	0,64	4,0	yes (F = 52)
Bend	d_m	1,5	3,73	0,02	−0,96	49,3	1,0	−14,8	0,54	22,0	yes (F = 12)
	s_d	3,2	0,61	0,04	−0,17	8,8	0,1	−0,8	0,48	8,3	yes (F = 19)

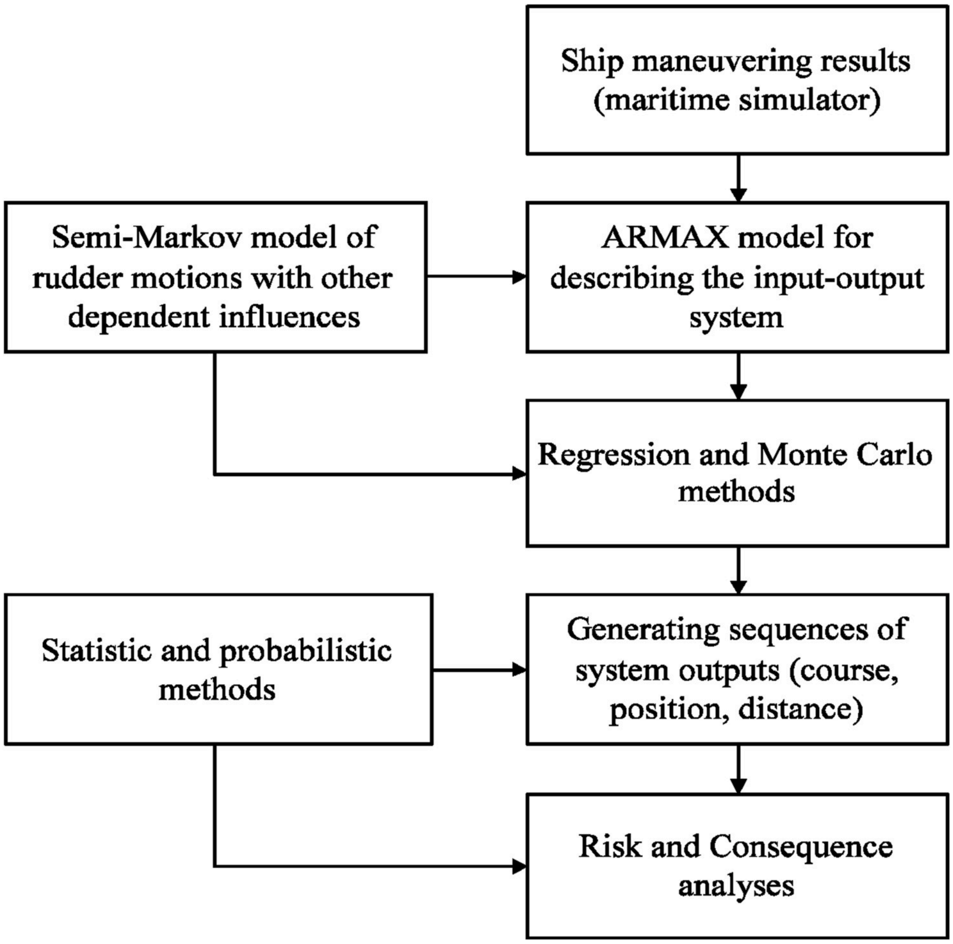

Fig. 12. General procedure for created ships performance model.

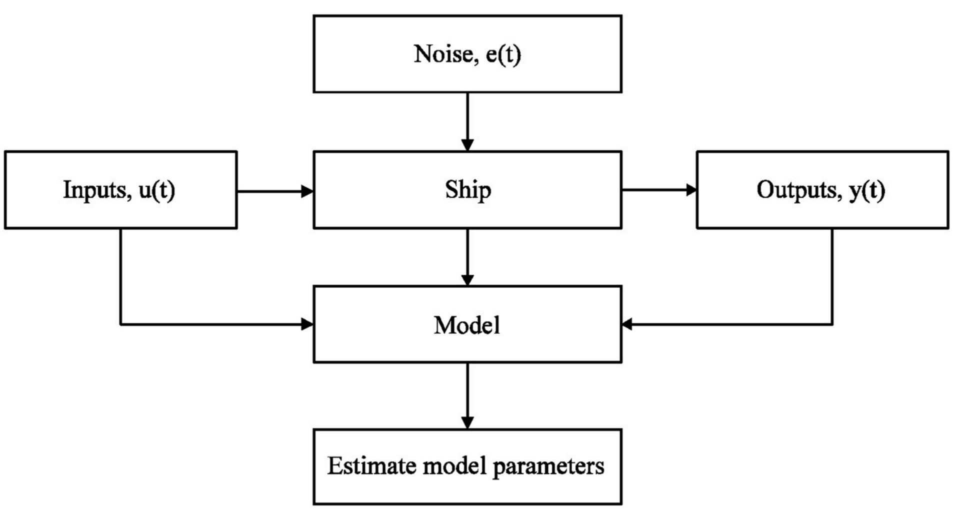

Fig. 13. Simplified model of ship dynamic.

$$P\left(S_{t_j}=j\middle|S_{t_i}=i\right)=p(i,j);\ t_j>t_i \tag{13}$$

In practice, the transition probabilities $p(i,j)$ can be determined from the measured data as:

$$P(i,j)=\frac{n(i,j)}{m(i)};\ m(i)=\sum_{j=1}^{k}n(i,j) \tag{14}$$

where $n(i,j)$ is the number of times that the rudder is moved from state i to state j. The quantity $p(i,j)$ is an element of square matrix, called the transition probability matrix (or transition matrix) in which the size (k x k) equals to the number of the states. All the transition probabilities of the Markov process can be estimated based on the data recorded in the simulator trials. Now, the Markov chain can be extended to the semi-Markov model by considering the times that the helmsman used to move the rudder from state i to state j and retain it in each state.

The rudder motion records during a series of the simulator trials were obtained as shown in Fig. 14. The real time simulations were carried out at the Piastowski Canal leading from Szczecin to the Baltic Sea (Fig. 15). A total of 45 trials with various environmental conditions were performed at Paprotno Mielin bend part with the use of a 4.500 TEU container vessel. The rudder of the ship can be adjusted from 35° port to 35° starboard with a unit angle $\Delta r = 1^\circ$.

It was observed that in all trials the helmsman tried to move the rudder with the same rudder rate, V_r. The time that the helmsman spent moving the rudder from state i to state j can therefore be determined as:

$$t(i,j) = t_j - t_i = \frac{|r_j - r_i|}{V_r} = \frac{|j - i|\Delta r}{V_r} \quad (15)$$

In this case the time spent on the transitions (or moving rudder) is a deterministic quantity. The model thus has a transition time matrix analogous to transition probability matrix. Now, the only thing left is to estimate the time (called sojourn time) that the helmsman maintains the rudder angle in every rudder state. The sojourn times $t(i,i)$ are, of course, random and depending on many factors where the helmsman's competence, ship characteristics and navigational conditions are the main factors. Usually a certain distribution can be found to fit the sojourn times obtained from simulator trials. Fig. 16 shows, for example, distribution of the sojourn times in the state with the 5° rudder angle fitted lognormal distribution. It should be clear that the sequence of rudder angles from the simulation is commonly recorded for every 1 s, the sojourn time in a state therefore exactly equals to the number of times, $n(i,i)$, that the same rudder angle values have continuously been recorded. It means that the length of the sojourn times increases proportionally to the transition probabilities $p(i,i)$. This makes it easier to generate the sojourn times in each state.

$$\begin{aligned} A(q) &= 1 - 1.878q^{-1} - 0.1112q^{-2} + 2.456q^{-3} - 1.423q^{-4} - 0.5896q^{-5} + 0.5371q^{-6} \\ B(q) &= 0.05611q^{-4} - 0.1714q^{-5} + 0.1408q^{-6} + 0.0858q^{-7} - 0.1982q^{-8} + 0.08981q^{-9} \\ C(q) &= 1 - 1.108q^{-1} - 0.8104q^{-2} + 1.744q^{-3} - 0.2931q^{-4} - 0.5921q^{-5} + 0.1367q^{-6} \end{aligned} \quad (16)$$

3.3. Results of part 3

Fig. 17 presents sequences of rudder angles generated randomly from the semi -Markov model developed in the above section. The results seem like those measured from the simulator trials in time series. But some differences can be found in the shape of their probability distributions and power spectra as shown in Fig. 18 and Fig. 19.

It is more interesting to observe the results in the frequency domain. In both cases, the power spectra of the motions shows significant peaks around zero frequency, but the higher peak is obtained in the generated rudders than in the simulator. However, the amount of the rudder motion in the simulator is larger by comparison in the frequency range from 0.2 to 0.7 (rad/s) and then both approximately drop to zero.

Here remained only the problem of estimating parameters of the ARMAX model. For the measured data of rudders and courses as shown in Fig. 20, the resulting model has been found as follows:

It can be seen from Fig. 13 that the simulated courses from the above ARMAX model compare well with those from the measurement for the same generated rudder. However, there is still slightly different in aspect of a higher resolution in the simulated course. This requires more effort on finding the parameters of ARMAX model.

Having determined the semi-Markov model of rudder motions and the ARMAX model of the system, sequences of the course fluctuation can be achieved, which may represent "true" behaviour of the ship - human performance. The ship positions can then be calculated from the regression formula as investigated in Fig. 4. One of the most important aspects provided by the models presented might well be the validation

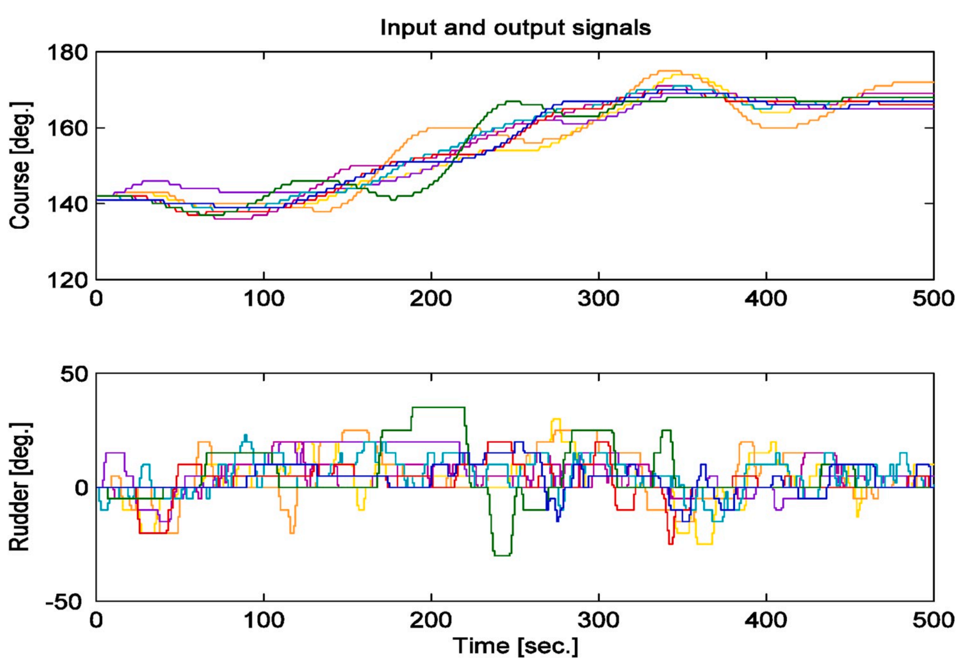

Fig. 14. Measured rudder angles in calm environmental condition for total 15 real time simulation trials.

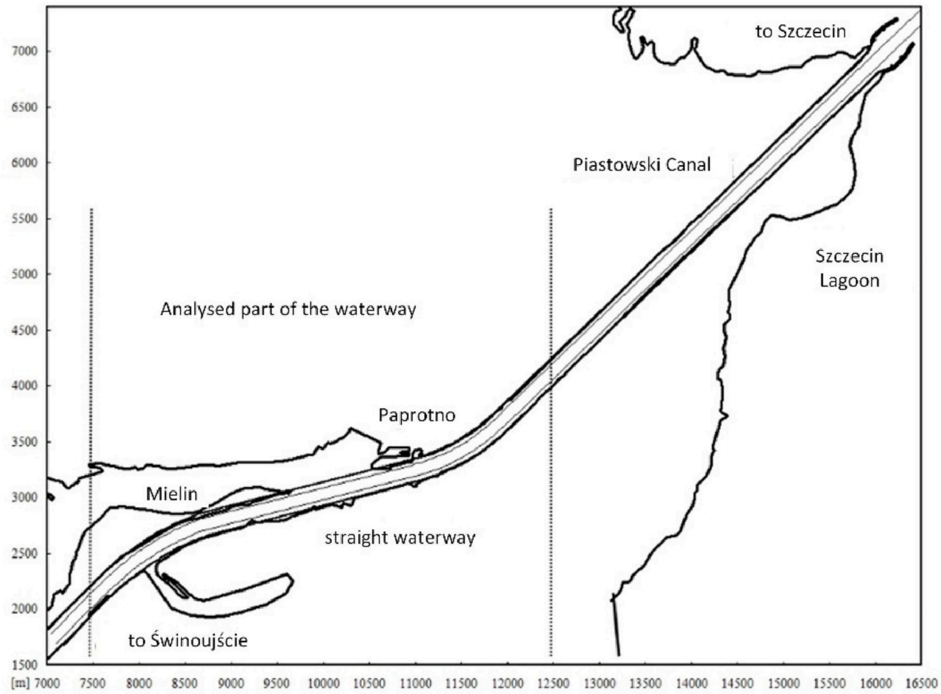

Fig. 15. The area of investigation.

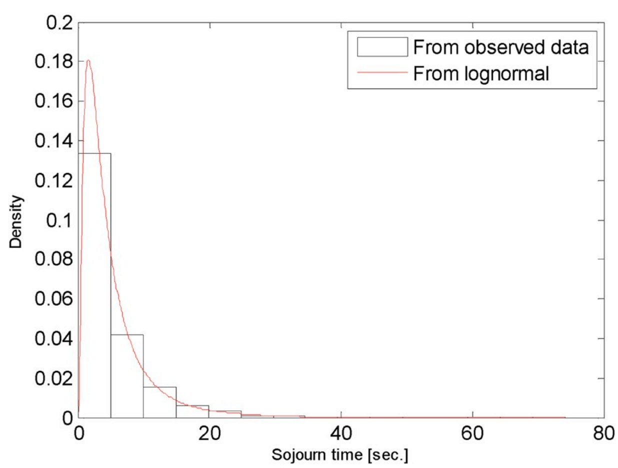

Fig. 16. An example of distribution of the sojourn time fitted with lognormal distribution.

with the use of extreme value distributions. The probability of the ship exceeding any margin of the designed waterway widths during a given period can be estimated using Eqs. (1) and (2).

4. Conclusions and future study

This paper presents the procedures of the analysis of real time ship manoeuvring simulation results and review of the existing approaches to

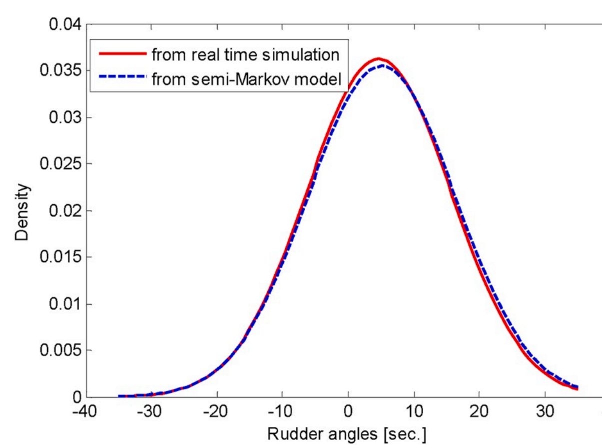

Fig. 18. Comparison of rudder distribution between the real time simulation and new model.

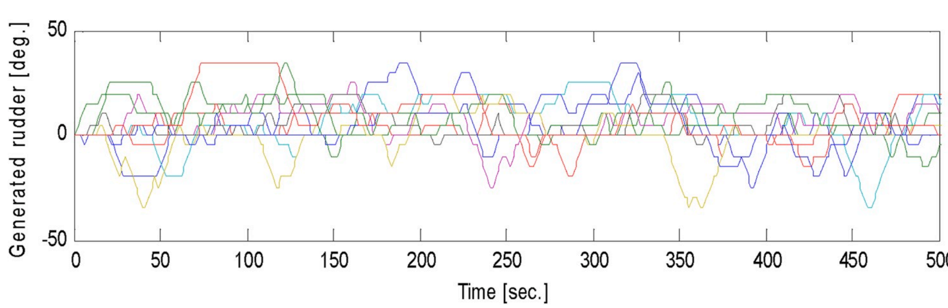

Fig. 17. An example of sequences of generated rudder angles from the semi – Markov model.

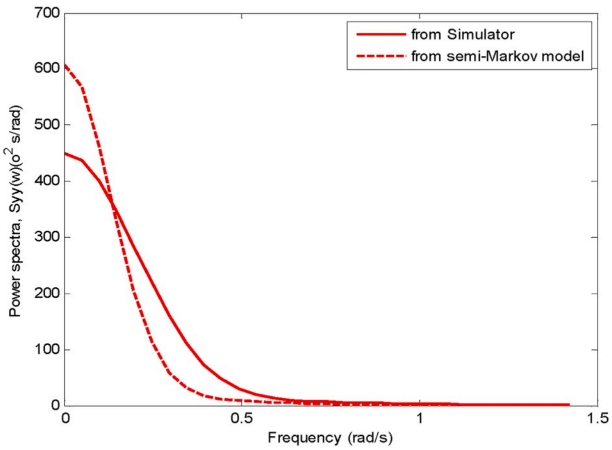

Fig. 19. Comparison of rudder power spectra between two models.

extend the simulation results for determination of manoeuvring area and ship performance for long-term risk assessment. Improving a fast time simulation for generated ship tracks is a promising approach. However, such procedure requires reliable description of human behaviour, which is still beyond today's possibilities in marine industry. The other approaches focus on generation of ship passages and track distances using the probabilistic-based model and the Monte Carlo method. However, they generally fail to achieve satisfactory model parameters.

In the presented study, several generalized models for determination the parameters of ships manoeuvring area in restricted waterways have been presented. Such generalisations lead to better understanding of process and have utilitarian value for marine traffic engineers as fast tools to predesign the waterways and their parts. The models based on multiple regression revealed that further analysis with more simulation data are necessary.

The emphasis has been placed on the development of a new method with the application of ARMAX and semi-Markov models that can be used for long - term prediction of navigation risk in restricted waterways. Information that is lacking in the real time simulation due to a limited number of trials can be realized in the proposed models that will thus provide more accurate readings of the system behaviour. The parameters of the system outputs achieved from these models can satisfy several aspects of the risk and consequence analysis in long-term studies. However, the method is restricted to the problem when the trajectories of ship passage are "stationary" random processes.

Following this approach, the definition whether the ship trajectories are "stationary" or "non-stationary" random processes is an important task, as has been presented in (Quy et al., 2006). This restriction produces issues that the model will be improved more comprehensive in the future. First, the transition matrix should be time - dependence conditional probabilities. It means that the next state of the rudder is not only depending on the present state but is also subjected to the space (position) given that state. The procedure calculation is the same as that presented in this paper, although of greater complexity because of more than one transition matrix being estimated. Secondly, more efforts should also be made on the analysis of dependence between ship speed and rudder states.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

N.M. Quy: Conceptualization, Software, Methodology, Investigation, Writing - original draft. **Kinga Łazuga:** Writing - review & editing, Visualization, Formal analysis, Investigation. **Lucjan Gucma:** Conceptualization, Software, Methodology, Investigation, Resources, Project administration, Data curation. **J.K. Vrijling:** Validation, Supervision. **P. H.A.J.M. van Gelder:** Validation, Supervision.

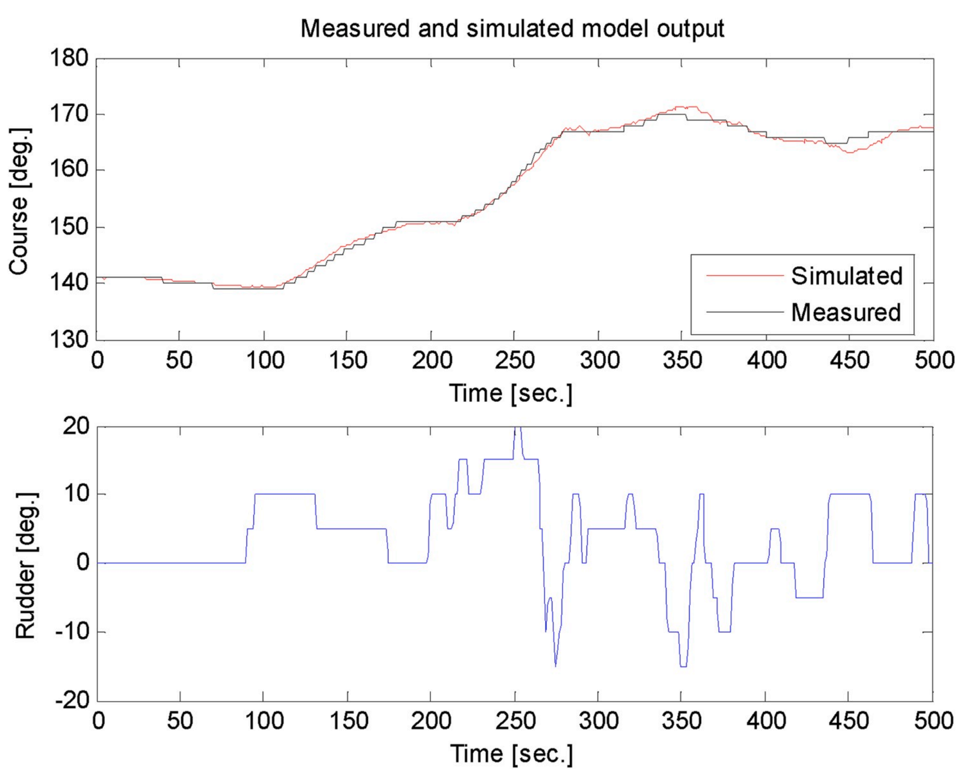

Fig. 20. Comparison between simulated and measured courses.

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