COLLISION RISK ESTIMATION FOR MOTORWAYS OF THE SEA

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ABSTRACT

The Motorways of the Sea is rather a new concept and, thus, is still in the process of development by the European Commission and in the Baltic Sea Region. The Baltic Sea Region is one of the most dynamic growth areas. Due to this fact the new ideas and technologies are needed to optimize the sea transport system. In the paper the simulation model for the system safety state evaluation is presented. The simulation program can constitute a base for decision-support tool, on the level of safety management, especially to optimally plan the safety transport system.

1 INTRODUCTION

The Motorways of the Sea is (MoS) still in the process of development by the European Commission in the Baltic Sea Region. Cargo transported in containers and trailers have increased rapidly, also oil tanker traffic has seen a noticeable increase in the Baltic. In the Motorways of the Sea the focus should be put on the safety of shipping. Sea motorways main elements can be point out as a part of the European transport corridors network, see Paulauskas & Bentzen (2007).

The safety of MoS routes and quality assurance of the main fairway system is the most important problem. Traditional risk analysis approach calculates the possibility of ship collision with historical data, mathematical models and opinions of experts, which evaluates the present risk level. However, there are not any historical data of MoS crossing that can be used for the analyses to describe the future of the studied area.

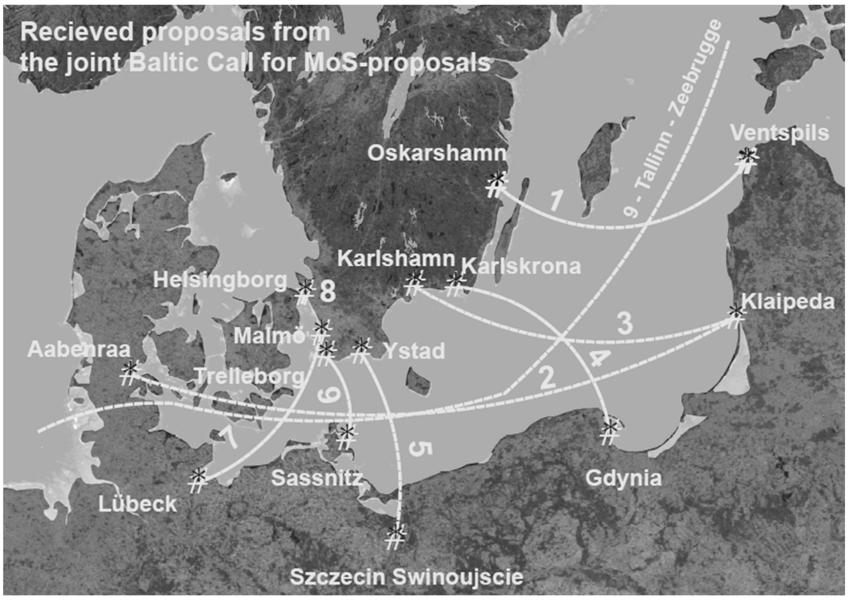

Figure 1. Proposals from the joint Baltic Call for MoS, www.pisil.pl

So it is necessary to do a risk analysis based on a mathematical model, with a combination of forecasting and simulating system, which should be verified by a concrete example.

2 STOCHASTIC MODEL

The model can be used to protect safety of navigation in the congested areas. This model presents an approach for modeling both spatial interactions and detailed succession dynamics in the MoS crossing by placing the semi-Markov processes within a class of stochastic process called piecewise deterministic Markov (PDM) processes.

A piecewise-deterministic Markov process is a stochastic process that evolves deterministically until a random time when the process jumps to a new (random) state. PDM processes were introduced by Davis (1984). These processes are readily amenable to computer simulations. PDM processes have been used in a variety of settings, including storage processes, capacity expansion problems, and financial investment models.

To define a PDM process we have to define four basic components such as:

–the state space,

–a description of the deterministic motion between jumps,

–the rate at which jumps occur,

–the distribution of the state after a jump has occurred.

Each of these components is described below within the context of ships dynamics. The deterministic motion of the PDM processes given here is only used to keep track of the times that ships have been in their current states. In fact, the processes used here are piece-wise linear. A MoS intersection is divided into several cells (Fig. 2). The area within a cell is assumed to be environmentally homogeneous – belongs to only one MoS or crossing place.

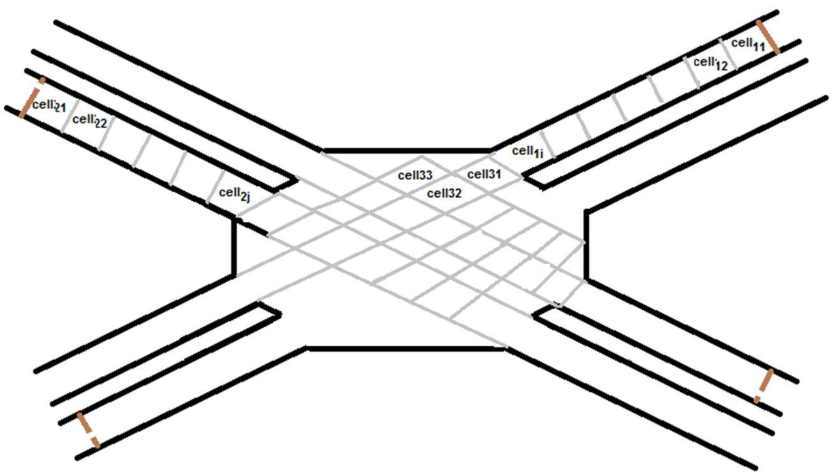

Figure 2. An example of a MoS intersections' grid of three types of cells

The state of a MoS intersection is determined by the distribution of ships within it and the respective functional roles of those ships. This paper focuses on modeling the dynamics of cells. Assume that a cell may be in any of 5 states and denote the set of possible states by *S*. The Table 1 specifies five status types or states defined by a ship appearance.

Table 1. Status types and state numbers

State Number	Status Type
1	Gap
2	A ship entering a cell
3	A ship in a cell
4	A ship living a cell
5	Collision alert

The state space of the MoS crossing is defined to be, (Monticino et al. 2002)

$$E = (S \times [0,\infty))^N . \tag{1}$$

The state of the MoS crossing at time t is

$$X_t = ((s_1(t), \tau_1(t)), \ldots, (s_N(t), \tau_N(t)))$$

where N = number of cells; $s_i(t)$ = is the state of cell i at time t; $\tau_i(t)$ = is the time that the plot has been in state $s_i(t)$ since the last time it changed states.

The deterministic portion of the PDM processes is used here only to keep track of how long cells have been in their current states. Thus, between jump times, the state of the each cell remains constant, while the time in that state evolves at unit rate.

3 COLLISION FREQUENCY MODELS

There is one major difference between two collision types (Fig. 3). At X-shaped intersection the traces of two ships always intersect, whereas they on average only intersect in one out of two cases at Y-shaped intersection. This means that the geometrical collision probability needs to be corrected by a factor of 0.5 in case of a Y-shaped intersection.

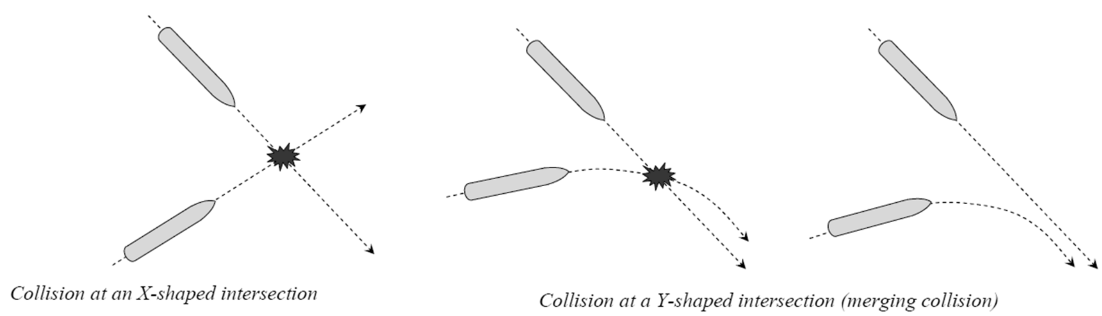

Figure 3. The two collision type, www.sofartsstyrelsen.dk/SiteCollectionDocuments/CMR/Sejladssikkerhed,%20GMDSS%20og%20SAR/Bassy/BASSY%20Evaluation.pdf

The Pedersen's model considers the crossing of two waterways, (Pedersen 1995). Ships are grouped by their type and length in order to utilize the different characteristics of vessel groups like the average speed or manoeuvrability which varies significantly from one ship group to another.

Model of Fowler and Sørgård suggest that the frequency of critical situations is calculated assuming that traffic movements are uncorrelated, (Jutta 2010). A critical situation denotes that two ships are crossing within half a nautical mile from each other. Encounter frequency is estimated by a pair-wise summation across all shipping lanes at the considered location. They do not present a practical procedure to calculate the number of critical situations.

Macduff's Model is build on molecular collision theory, (MacDuff 1974). Ships on a shipping lane are regarded as a homogenous group: they are navigating at the same speed and they have similar dimensions.

Cowi Crossing Collision Model defines crossing collision as a collision that includes ships sailing along different waterways. Two ships can theoretically collide if their traces intersect. The possibility of a collision between two ships navigating at intersecting routes can be expressed by critical time interval.

4 SIMULATION APPROACH

The necessary time to make a decision by navigator usually amounts 3 to 6 min and this decision time can be also considered in the collision checking range (Xue et al. 2009). However as we consider only the crossing situation, in which may be involved more than two ships in close proximity, the average checking range on the waterway should be smaller. For example, nowadays, for security reasons it is recommended that Automatic Identification System AIS, thereby controlling system, allows for transmitting minimum 2000 messages per minute.

First we have to find the cell size, as we will determine the simulation time step with the use of it. We assume, similarly as in the Nagel-Schreckenberg model presented in (Nagel & Schreckenberg 1992, Wahle et al. 2001), that the waterway is divided into cells with a length of $CS = \rho_{cross}^{-1}$. We determine the total crossing density ρ_{cross} according to the following formula:

$$\rho_{cross} = \max\{\rho_{12}, \rho_{13}\}, \text{ where } \rho_{12} = \sqrt{\rho_1{}^2 + \rho_2{}^2}, \ \rho_{13} = \sqrt{\rho_1{}^2 + \rho_3{}^2} \quad (2)$$

$$\text{and } \rho_1 = \frac{LOA_1}{T_1 \cdot V_1 + LOA_1}, \ \rho_2 = \frac{LOA_2}{T_2 \cdot V_2 + LOA_2}, \ \rho_3 = \frac{LOA_3}{T_3 \cdot V_3 + LOA_3},$$

LOA_1 = a length of a ship on the main waterway; LOA_2, LOA_3 = a length of ships on the lateral waterways 2 and 3; T_1, T_2, T_3 = mean times between ships' starting for waterways no 1, 2 and 3.

The article deals with different levels of risk depending on the mutual distance of vessels that are on collision courses. Distance is measured in taxicab metric, according to the sequence of grid cells. We denote a size of a cell by *CS*. To determine the threshold values of safety distances defining the states of collision risk we have to consider following results. A ship domain is the area around the vessel that should be avoided by other vessels and an overlap of two vessels' domains is concerned with a very high risk of collision. A length of a ship domain is assumed to be equal 4*LOA* (Fujii & Tanaka 1971) and we consider this values as a critical distance of high risk of collision to define the first risk level. To define the second risk level we assume from references a distance of passing clear *CPA* (*Closest Point of Approach*) equal to 1 *nm* (1852*m*). This distance of passing clear will be considered in the simulation as a critical value between high and low risk of collision. Further we take a distance of 2 *nm* as a safety distance corresponding to the low risk of collision.

Then we define following risk levels:

high risk of collision – both ships are entering a cell and number blank cells between two ships is equal at least d_1-2, one ship is entering a cell and second ship is in a cell or leaving a cell and number blank cells between two ships is equal at least d_1-1, both ships are in a cell or leaving a cell and number blank cells between two ships is equal at least d_1; if none of these conditions if fulfilled we define this situation as a collision alert; the distance d_1 is determined from the equation:

$$d_1 = \left\lceil \frac{4LOA_1 + 4LOA_{\max}}{CS} \right\rceil; \tag{3}$$

where $\lceil d \rceil$ denotes the integer part of number d plus 1; LOA_1 = a length of a ship on the main waterway; LOA_2, LOA_3 = a length of ships on the lateral waterways 2 and 3; $LOA_{\max} = \max\{LOA_2, LOA_3\}$; CS = size of a cell;

low risk of collision – both ships are entering a cell and number blank cells between two ships is equal at least d_2-2, one ship is entering a cell and second ship is in a cell or leaving a cell and number blank cells between two ships is equal at least d_2-1, both ships are in a cell or leaving a cell and number blank cells between two ships is equal at least d_2, were distance d_2 is determined from the equation:

$$d_2 = \left\lceil \frac{1852}{CS} \right\rceil; \tag{4}$$

negligible risk of collision – both ships are entering a cell and number blank cells between two ships is equal at least d_3-2, one ship is entering a cell and second ship is in a cell or leaving a cell and number blank cells between two ships is equal at least d_3-1, both ships are in a cell or leaving a cell and number blank cells between two ships is equal at least d_3, were distance d_3 is determined from the equation:

$$d_3 = \left\lceil \frac{2 \cdot 1852}{CS} \right\rceil. \tag{5}$$

We assume that the simulation time step corresponds to time of vessel moving with the largest velocity from one cell to the next. Thus the simulation step time, denoted by Δt, is determined from the formula:

$$\Delta t = \frac{CS}{V_{\max}}, \text{ where } V_{\max} = \max\{V_1, V_2, V_3\} \tag{6}$$

and size of a cell CS was described with use of crossing density given in (2). Velocities of vessels on each waterway V_1, V_2, V_3 in knots in the program corresponds to the speed measured in cells per time step.

4.1 Simulation language and environment

The computer program is written in Java language using SSJ V2.1.3 library with support of stochastic simulations. The documentation of SSJ can be found in Simard (2012). The Java platform is the object-oriented programming language that provide several standard packages. To perform the simulation we use a javaSimulation package that is devoted to process-based discrete event simulation. The package is a Java implementation of the simulation facilities provided by the programming language SIMULA. The javaSimulation package provides three different approaches to discrete event simulation: event-based, activity-based and process-based. The description in details along with appendices containing Java source code and documentation are given in the report (McNab 1996).

Java-based simulation tools are very popular because it is the only object-oriented programming environment that effectively supports standardized components (Kilgore et al. 1998). For example the book (Garrido 2001) concentrates on object-oriented modeling of simulation using Java and practical simulation techniques.

4.2 Simulation model

Discrete-event system is a system completely determined by random event times and by the changes in state taking place at these moments. Basic approaches for constructing a discrete-event simulation model are event scheduling, activity scanning and process interaction approach. The event scheduling approach focuses on event, i.e. the moment in time when state changes occur, while process interaction focuses on processes, i.e. the flow of each entity through the system. In the activity scanning approach in each cycle of simulation there are independently checked conditions of all events occurring. For a comprehensive description of basic methods and techniques related to computer simulation of discrete event systems, a reader is referred to Tyszner (1990). In the paper we will concentrate on simulation of discrete-event systems by event scheduling approach.

The event oriented simulation concentrates on handling and sending events. The activity following each event is implemented as an event routine and the event routine may schedule new events and re-schedule existing event. In this approach we have to define states, events, rules telling what will happen when an event occurs and some parameters.

In the simulation model there are considered three sea motorways with four points of collision marked at the scheme (Fig. 4). Collision points number 1 and 3 are X-shaped intersection while collision points number 2 and 4 are the type of Y-shaped intersection. These two types of collision are described in Section 3. The main flow is on the sea motorway 1. The collision problem includes the characteristics of the ships and their motion before, during and after collision.

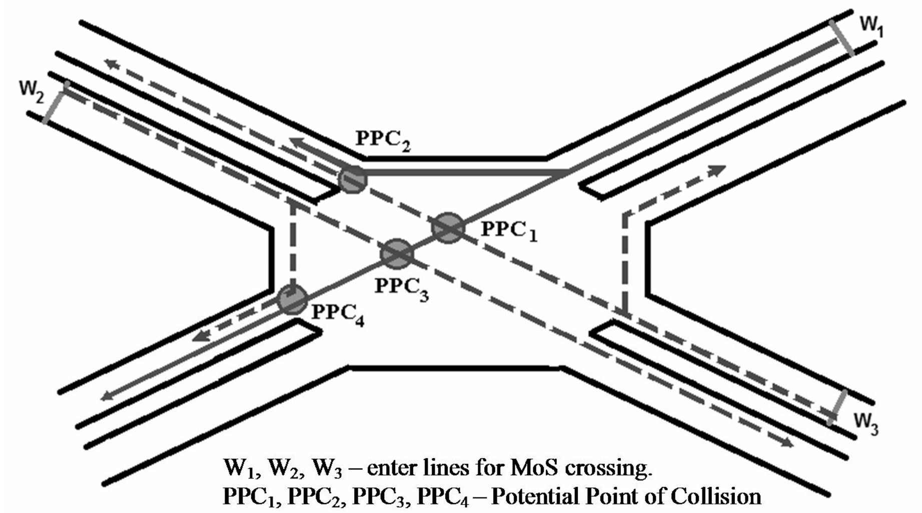

Figure 4. The scheme of the collision problem

4.3 Computer program

We consider following major ship types: a tanker, a container carrier, a passenger ship, a RoPax, a general cargo ship and fast ferry. The mean velocity and length for different types of vessels at each waterway is given by default from empirical data for maritime traffic in Gulf of Finland presented in (Montewka et a. 2010). The user can change manually, given by default while computer starting, values of the vessels' velocity and length (Fig. 5).

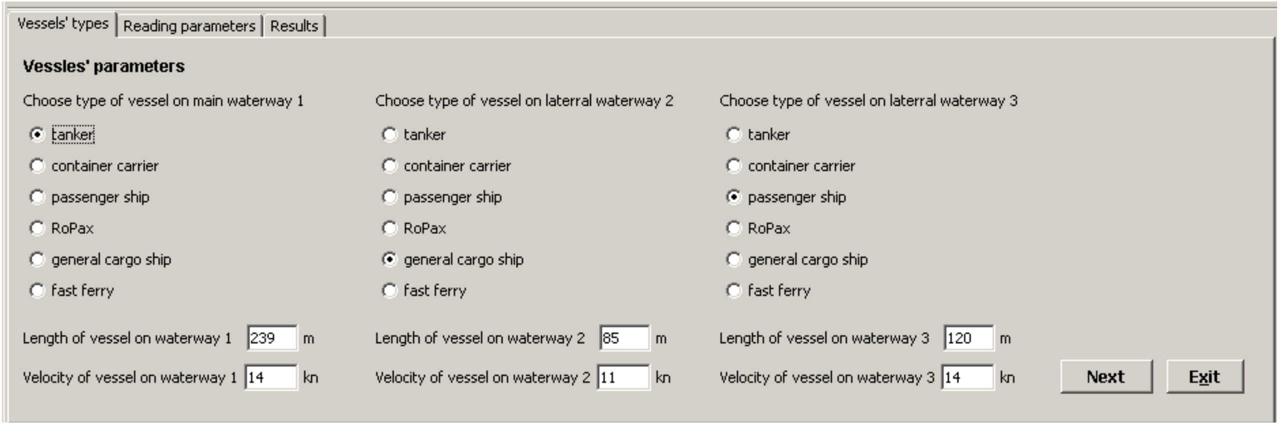

Figure 5. The starting window of the simulation program

In the simulation the ships' starting times can follow different distribution. We can choose these distribution on the main and lateral waterways from the following list: deterministic, uniform, exponential, Erlang, normal, log-normal, Beta, gamma and triangular. Thus using the program there is possible to simulate also non Poisson streams. In Fig. 6 there is presented a program window that is showing the moment of reading data and choosing the distributions of ships' starting times. The mean waiting time between ships' departing for each sea motorway is given by the user. Given by default the percentage of the starboard ships at each waterway can be modified by the user. In the simulation the user can also change the distances to collision points. In the case the flow of vessels into waterway is uniform there is also necessary the minimal accepted distance between vessels, that is given by default in the computer program depending on the vessels length. It is assumed by default that the intervals times between successive notifications at the sea motorways 2 and 3 have exponential distribution and at the sea motorway 1 an uniform distribution.

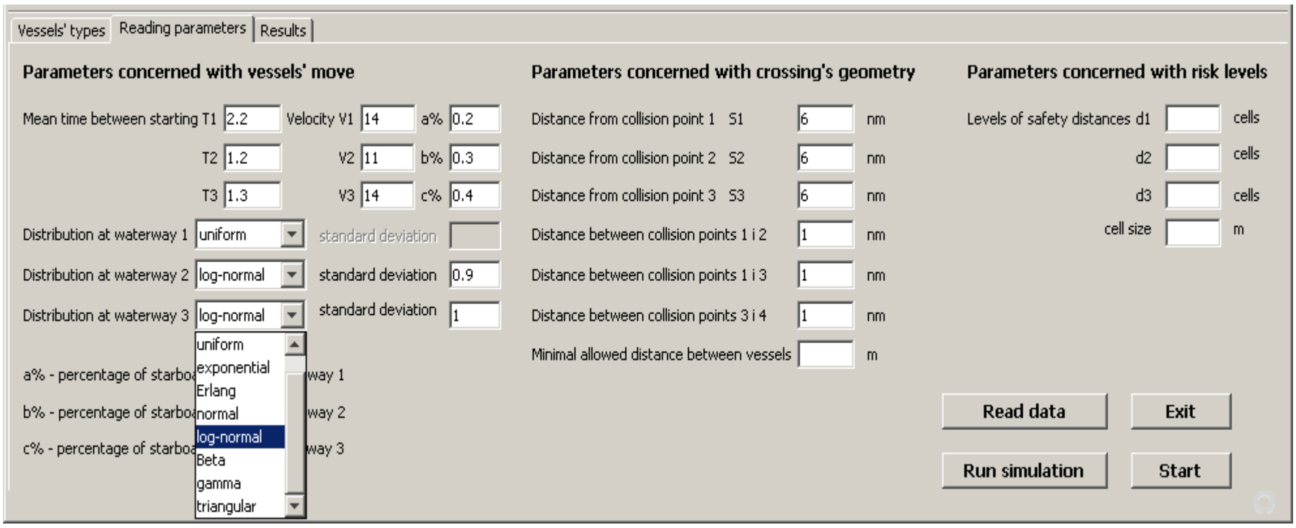

Figure 6. The program window for reading parameters concerned with vessels' move

The scheme of the computer program used for simulation is presented in Fig. 7 and the rules applied in the computer simulation can be described as follows:

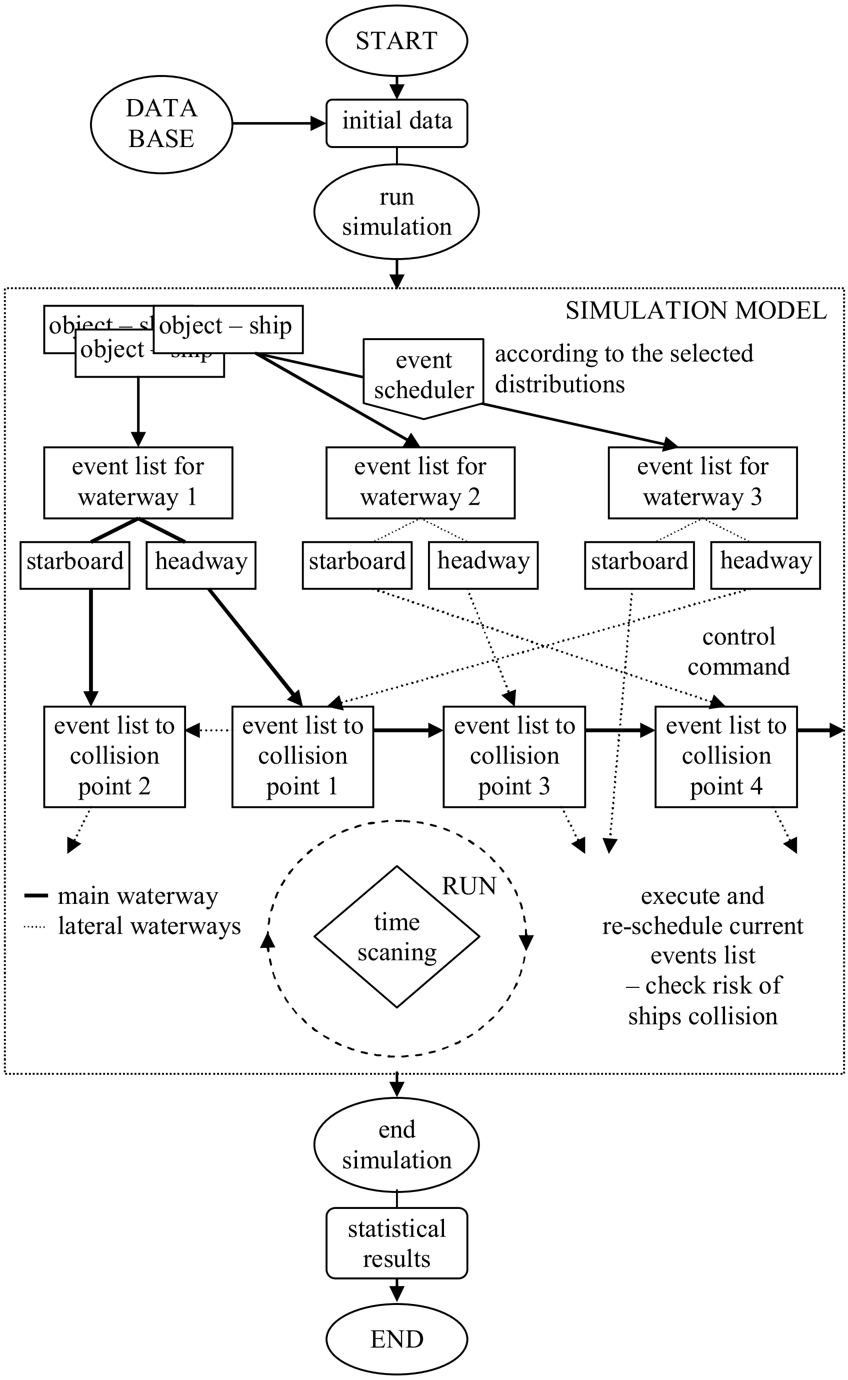

Figure 7. The scheme of the simulation program

–the system saves data and gives results from the point of view vessels being on the main waterway 1; we assume that vessels on the main waterway 1 are stand-on vessels, while vessels on the waterways 2 and 3 are give-way vessels,

–at each time step the system examines the ship closest to the crossing on each waterway and if the safety state of a ship on the waterway 1 has changed the system saves this transition and the time during which the ship was in the previous safety state,

–if the ship on the main waterway 1 is not fully safe the system also examines the next ships on this waterway,

–in the considered crossing situation the starboard ships on the waterway 3 are safe as they do not cross any other waterway,

–in the vessel on the waterway 3 follows headway this waterway then the system checks situation at the collision point 1 and 2 and the safety state of the vessel, if there is on the main waterway 1; after passing the collision point 1 if there is a ship on the waterway 1 going starboard the system checks the situation at the collision point 2, if there is no starboard ship on the waterway 1 the vessel on the waterway 3 is safe and it is not controlled by the system,

–the starboard ships on waterway 1 are examined at the collision point 2, while the headway ships are first checking at the collision point 1, next at the collision point 3 and 4; after passing the collision point 4, there is assumed the negligible risk of collision,

–the starboard ships on the waterway 2 are examined at the collision point 4, while the headway ships are examined at the collision point 3,

–the process is repeated throughout the entire simulation time.

In the computer program, according to the accepted before risk levels and their critical distances defined by (3)-(5), there are assumed following states:

state 0 – collision alert;
state 1 – high risk of collision;
state 2 – low risk of collision;
state 3 – negligible risk of collision.

We denote by $p(i)$, i = 0,1,2,3, probability of system being in the safety state i.

4.4 Results of the program

As a result of the program we obtain following data: the matrix of the system transitions' number between the states and the realizations of the conditional sojourn times at the state until the transition to the other state. From these results there are also determined the matrix of probabilities of the system's transitions between the states and the vector of probabilities of the system's being in the particular states during the simulation time. The obtained from the simulation results can be used for further identification and safety analysis of the system (Blokus-Roszkowska et al. 2011).

The proposed simulation model is sensitive to its changing parameters, that is depicted at the graph (Fig. 8). For this reason the input data of the program must be properly selected. The obtain from the simulation results show the dependency of probabilities of system being in the safety states during the simulation time on the mean time between vessels' departure i.e. on the intensity, at the sea motorway 1. In the presented example we assume that the departure time of a ship on the main waterway follows an uniform distribution and the interval times between ships' departure on the crossing waterways are log-normal. We assume that the mean time between ships' departure on the sea motorway 2 equals 1.2 h with standard deviation 0.9 h and on the sea motorway 3 equals 1.3 h with standard deviation 1 h, equivalently.

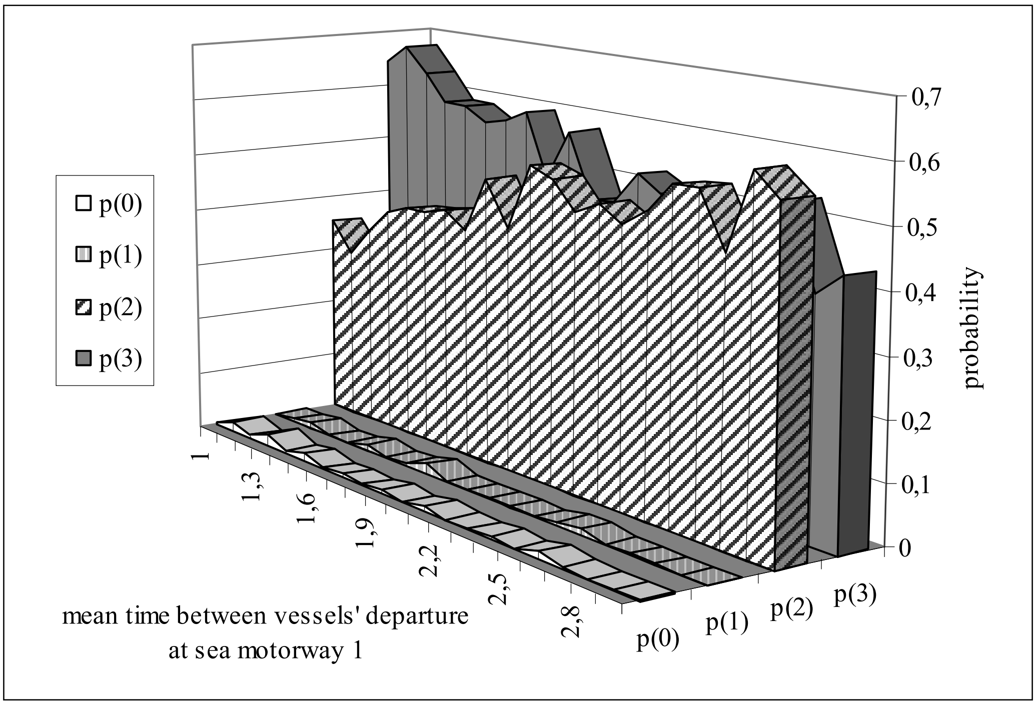

Figure 8. Probability of being in the safety states depending on the mean time between vessels' departure at the sea motorway 1

5 CONCLUSIONS

Java can expose the benefit of computer simulation to a larger audience of problem-solvers, decision-makers and trainers. Java-based simulation components could be easily distributed, executed and modified throughout the word over the internet. The main advantage of Java is cross-platform compatibility that can eliminate the need to maintain different versions of the software. Considering this Java-based programs can provide solutions or assistance in safety transportation system planning and support cooperation or exchange of information between ships, ports and terminals. The presented program can serve a base to create a new service that supports the development of the concept of sea motorways. The simulation programs can optimize the logistical transportation system with integration of sea motorways.

The idea of the paper was to develop the simulation environment to test the features of computer-controlled sea motorways. The proposed simulation model for safety state evaluation can be helpful on the level of safety management. The model allows to predict safety state depending on changing traffic strength at sea motorways. With the concept of safety management such simulation models could face the problem of sea transportation development and provide new solutions for operational optimization and safety transportation system planning.

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