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Stochastic model of ship traffic congestion in waterways for two different traffic solutions based on the Świnoujście–Szczecin case study

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Abstract

The paper presents stages of stochastic ship traffic stream model creation which was applied for the optimization of different solutions for the Świnoujście–Szczecin waterway design. The model is based on Monte Carlo methodology and is microscopic, which means that each ship's model is treated as a separate object possessing given attributes. The main output from the model is the sum of the delay time of waiting ships and the distribution of ships' queue. Two alternative waterway traffic solutions with different passing places for ships were analyzed in this study and compared with each other. The model was used for the first time for the optimization of the modernized Szczecin–Świnoujście waterway in respect of two different solutions of passing places for ships.

Introduction and state of the art

The increase of traffic in port areas demands new tools for traffic optimization assessment of different marine traffic engineering solutions and developing traffic control methods, especially within VTS. The analytical models used for capacity estimation are based on ship domain theory, are static and do not reflect the stochastic nature of the process of ship traffic. To overcome this, stochastic models are created (Groenveld & Hoek, 2000). Some models of capacity take into consideration alternative passing (Bačkalić & Škiljaica, 1998). Models for traffic optimization with the use of discrete optimization for the Kiel Canal have been developed by Mohring et al., (2005). Several models have been developed which use queue theory (Mou et al., 2005) and cellular automata (Feng, 2013). Usually domain models are applied (Zhou et al., 2013), where domain is defined as an area which the navigator intentionally keeps free from other ships.

Usually two criteria are used to assess marine traffic systems in the scope of traffic stream parameters:

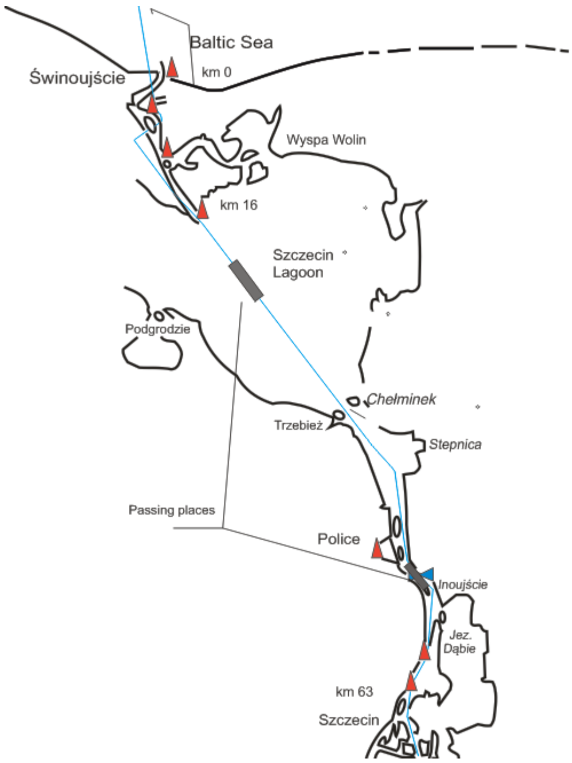

Figure 1. Layout of Świnoujście–Szczecin waterway with planned passing places for Alternative II and localizations of VTS radar stations

1) time of ships' delay and its distribution;
2) mean queue of ships waiting and its distribution.

It is much easier to draw conclusions from model research when the relative measures are applied, as in this study where two alternatives were compared. In the presented research the area of the Świnoujście–Szczecin waterway (Figure 1) is analyzed and two modernization alternatives are compared.

Microscopic stochastic model of ship traffic

The created simulation model of ship traffic on the waterway for the presented study has the following features:

1) microscopic – every ship is considered separately as an object;
2) domain based – the distances of following ships are based on ship domain theory;
3) stochastic – where some parameters like ship's output, ship length, draught, and speed are modeled as random variables generated from its distributions mostly by the Monte Carlo principle;
4) one dimensional – the movement of ships is modeled in one dimension only (along the waterway);
5) kinematic – the ships are modeled at line intervals (of length L) moving with uniform speed along the given section of waterway, speed changes (if any) are immediate.

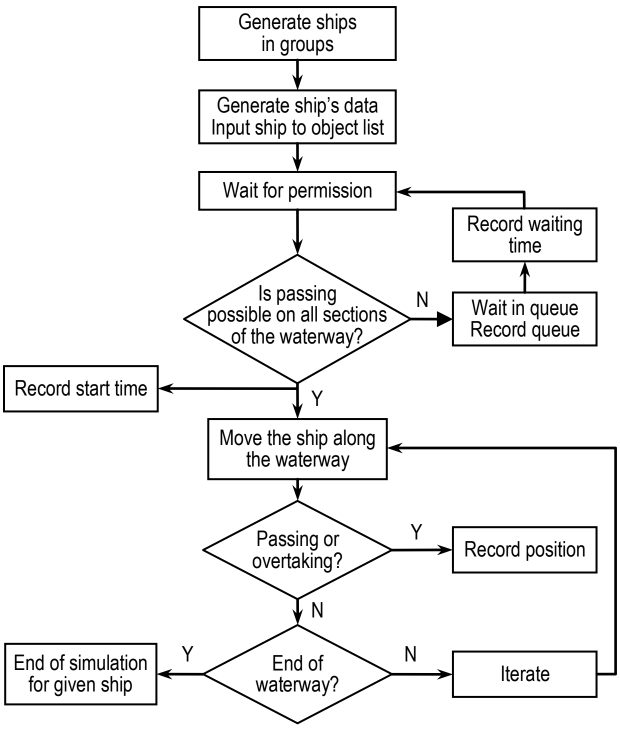

Figure 2. Stochastic microscopic simulation model of ship traffic in Świnoujście–Szczecin waterway

The main algorithm of the model is presented in Figure 2. The model has several outputs, of which the principal are as follows:

1) time of delay in respect to ideal situation without delays;
2) queue parameters in respect to ship categories and number of ships waiting;
3) passing and overtaking points with the ships categories.

The model is written in Object Pascal language and *Lazarus* compiler distributed by Open GPL license. The model has a very simplified graphical interface and the data are stored in text files.

The verification of internal consistency and accuracy of the model was done on the simplified chosen input data.

Dynamic domain approach

The ship domain dimensions on such very narrow waterways when the port regulations are playing a major role are dependent on the section of the waterway (x). The length of domain $D_L(x)$ could be defined as (Figure 3):

$$D_L(x) = L + D_F(x) + D_A(x) + \delta_L \tag{1}$$

where:

L – ship's length;
$D_F(x)$ – domain length forward (from zero to minimal following distance);
$D_A(x)$ – domain length aft (assumed as 0);
δ_L – domain variability.

A similar formula can be used for width $D_B(x)$ of ships domain:

$$D_B(x) = B + D_S(x) + D_P(x) + \delta_B \tag{2}$$

where:

B – ship's length;
$D_s(x)$ – domain width port;
$D_p(x)$ – domain width starboard;
δ_B – domain variability.

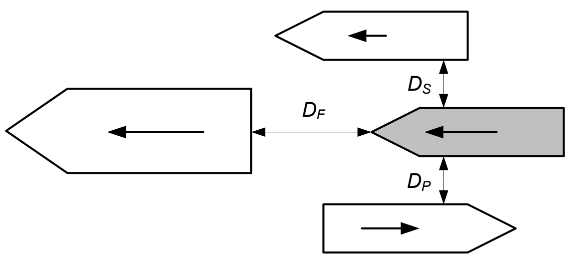

Figure 3. Ship's domain parameters in narrow waterway

In the presented study when the 1-dimensional model is applied, the $D_B(x)$ could be defined as two state variable: $D_B(x) = \{o(x) = (1,0);\ p(x) = (0,1)\}$ where $o(x)$ and $p(x)$ are logical variables defining whether the passing or overtaking of given ships is permitted on a given section of waterway (0 – passing / overtaking possible, 1 – passing / overtaking prohibited).

The navigator has very limited influence to adjust the length of the domain on the aft (D_A) and the following ship adjusts this domain size according to ship dimensions, port regulations and intentions, so it is set to zero. The dependence of domain dimensions of x is due to the variability of waterway sections and regulations inside the sections and ship speed variability in given sections. The domain variability (error) is changed according to the navigator's behavior. It is possible to model the risky, conservative behavior or violation of the regulations. This effect was neglected in this study.

The most important dimension of domain in this study is D_F. The length before the ship which the navigator intends to keep free is important when one ship follows the other due to overtaking prohibition. This distance is set by regulations or by the navigator himself, taking into account the possibility of the accidental stopping of his own ship. Accidental stopping in narrow waterways is usually caused by a so called step-maneuver which depends on the ship's maneuvering characteristics. The step-maneuver is usually performed in steps, changing engine settings in order to avoid the grounding of the ship. Usually in the first phase of the step-maneuver "Full Astern" is set on the engine, then when the ship starts to considerably change her course (usually to starboard) the speed telegraph is set to "Stop" and the rudder is set to "Hard To Port" (or starboard depending on the ship's reverse turning ability). Then the procedure is repeated. In the last step the anchor is usually dropped when possible. A study into step maneuvers has been carried out by Report (1980) for different ship sizes, passing the waterway at different speeds and engine settings (Figure 4). In the presented study the dimension of domain D_F has been set on the basis of stopping distance (Figure 3) as $D_F = Sd(Hah, DWT)$.

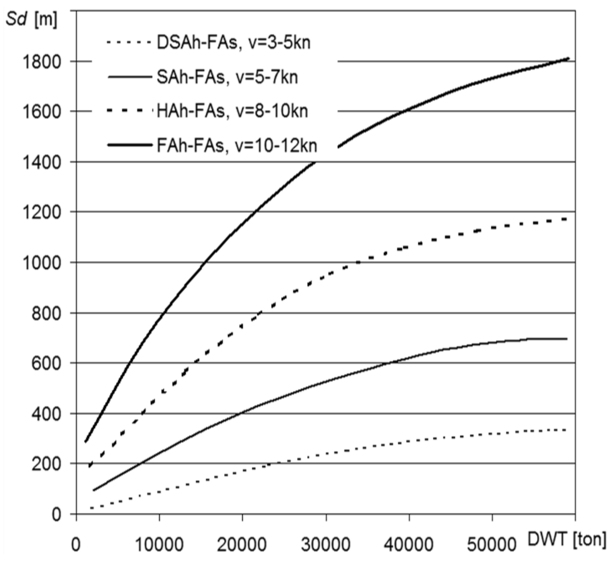

Figure 4. Stopping distance (*Sd*) in case of accident of followed-by ship in step-maneuver through narrow waterway for general cargo ships [based on results of Report (1980)]

Due to the model's level of abstraction some approximations and conditions have been applied to the model divided into the following groups:

A. Ship generators

The model used ships generated by the Poisson distribution in 9 groups with given intensities. The Poisson model is adequate and has good statistical consistency for under-critical intensities such as exist in the analyzed waterway (Kasyk, 2014; Gucma & Schefs, 2007). The computer Poisson generator used in this study was created on the basis of Zieliński and Wieczorkowski (1997). The length of ships in groups was generated by uniform distribution with parameters: [L_{max}, L_{min}]. The speed of ships was generated by normal right side cut distribution, where cutting distance was set as maximum regulation speed in the given section. Extended studies over the speed distribution in this area were completed by the author Gucma and Schefs (2007). The same intensities have been set for inbound and outbound ships (the choice of direction by the ships was modeled by Bernoulli distribution). The main elements of the algorithm of the model are 3 loops realized by the computer program in different time intervals:

1) The loop of ships' generation and the recording of their main parameters (time interval = 1 h).

2) The loop of the updating of the position of ships and the record of their passage (time interval = 1 min).

3) Decision loop of the check of the possibility of letting in ships on the waterway or to the queue (time interval = 10 min).

B. Waterway characteristics

Described by n sections, defined by (X_i, X_{i+1}), each contain width of waterway, admissible speed, and a matrix of passing/overtaking possibility as a Boolean matrix of dimension 5×5 (i.e. number of ships in the classes).

C. Traffic control measures

Traffic control is mostly neglected in this study except keeping the ships in a queue in case the waterway is busy. In a practical situation sometimes speed reduction is applied as a traffic control measure by VTS operators.

Practical application of created traffic model for assessing two alternatives of the Świnoujście–Szczecin waterway modernization

The planned modernization from 16 km to 63 km (so called project "12.5 m") of the waterway from Świnoujście to Szczecin will cover:

1) deepening the depth from 10.5 to 12.5 (max ship draught from 9.15 m to 10.5 m);
2) widening the waterway depending of the area for two different Alternatives I and II (Figure 5).

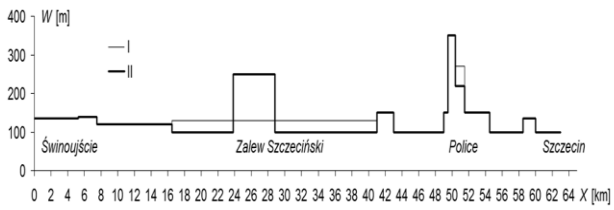

Figure 5. Width of the waterway (*W*) in function of its length (*X*) for two analyzed Alternatives I and II

For the traffic modeling purpose the ships were divided into 9 types and 5 classes (Table 1). The possibility of ships passing and overtaking is dependent on the width of the waterway and was different for given sections in Alternative I (14 sections) and Alternative II (16 sections).

Table 1. Applied division of ships in Świnoujście–Szczecin waterway

Class/ Type	Name	L [m]	B [m]	T [m]
I Very large ships				
1	Cruiser	200–260	28.0–33.0	7.0–9.0
2	Container	180–240	28.0–32.3	9.0–11.0
3	Bulk	180–220	26.0–32.3	9. 0–11.0
II Large ships				
4	Cruiser	140–200	20.0–28.0	6.0–8.0
5	Container	140–180	20.0–28.0	6.0–9.0
6	Bulk/General	140–180	20.0–26.0	6.0–9.0
III Medium ships				
7	All kinds	120 –140	< 20.0	< 8.0
IV Small ships				
8	All kinds	< 120 (100–120)	< 18.0	< 7.0 m
V Very small ships				
9	All kinds	< 120 (70–100)	< 18.0	< 5.0 m

Alternative I assumes widening the waterway in Szczecin Lagoon to 130 m in the section from 16.5 km to 41.0 km and allowing for passing of the following classes of ships: (3, 4, 5) with (3, 4, 5). Alternative II assumes a narrower waterway in this area (100 m) but creates a long passing place of 250 m width on Szczecin Lagoon from 23.8 km to 28.8 km which will allow the passing of ships in the following classes: (2, 3, 4, 5) with (1, 2, 3, 4, 5) i.e. only maximal (class 1) with maximal cannot pass each other.

Example matrices used in the simulation program of the possibility of ships' passing (1 means the passing is possible in given class, 0 means that passing is forbidden in given classes) for the section from 23.8 km to 28.8 km (Alternative II) and from 16.5 km to 41.0 km (Alternative 1) are presented in Figure 6.

```
4 16500 41000 130 10        5 23800 28800 250 10
0 0 0 0 0               0 1 1 1 1
0 0 0 0 0               1 1 1 1 1
0 0 0 0 0               1 1 1 1 1
0 0 0 1 1               1 1 1 1 1
0 0 0 1 1               1 1 1 1 1
```

Figure 6. Passing ships' possibility matrices for major passing places in Szczeciński Lagoon for two analyzed Alternatives I (left) and II (right)

Determining the future ship traffic intensities in the Świnoujście–Szczecin waterway

The Port of Szczecin does not show significant dynamics of change in ship traffic, which is below 3000 ships entering per year. This is recorded in data from the Polish Statistical Office (GUS, 2013) presented in Table 2.

Table 2. Ship traffic in Szczecin and Police ports

Year	Szczecin	Police	Sum
2009	2775	173	2948
2010	3185	349	3534
2011	3084	306	3390
2012	2822	276	3098

Analysis and forecast of ship traffic was done for the so called project "12.5 m" based on previous studies by Report (2008) and previous works such as Gucma and Sokołowska (2012). In 2011, 2680 ships above 50 m entered Szczecin. The cumulative distribution (Figure 7) of their length shows a very high concentration of ships of 80 m to 10 m (small ships).

On the basis of detailed size group analysis in 2011 and economic forecasts for container and cruise ships, the intensities and yearly dynamic of ships in groups were determined and final forecast intensities for 2021 were applied as input data for the traffic model.

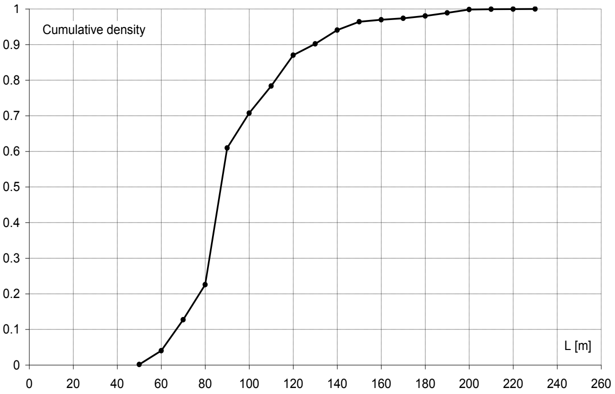

Figure 7. Cumulative distribution of length of ships entering to Szczecin in 2011

Results of traffic simulations for two analyzed alternatives

The simulation research was carried out in 4 scenarios (2 waterway alternatives in 2 traffic conditions):

- Alternative I – traffic forecasted for 2021 (Table 3).
- Alternative II – traffic forecasted for 2021.
- Alternative Ix2 – traffic for 2021 with doubly increased traffic in groups 1 and 2 (sensitivity analysis for biggest ships due to expected passing problems).
- Alternative IIx2 – traffic for 2021 with doubly increased traffic in groups 1 and 2 (as above).

Duration time of simulations was 365 days (1 year). Single scenario consumes approximately 1 minute of simulation time for standard PC computer.

The recorded output data from the simulation were analyzed under several parameters of traffic streams such as:

- Distribution of ingoing ships' queue in classes.
- Distribution of outgoing ships' queue in classes.
- Time of passage without delays (ideal).
- Sum of delay time in classes and types.
- Number of ships generated in classes and types.
- Mean delay time in classes and ships types.

Table 4 presents the results of the annual simulation for forecasted data for the year 2021 for

Table 3. Forecast of ship traffic in 2021 and intensities for given types of ships in Szczecin and Police

Type	Class for waterway	Kind	No. of ships in 2011	Yearly dynamic of traffic increase for "12.5m" [%]	Forecast of ships entrance in year 2021	Intensity of ships applied in the study [ship/h]	Double intensity of biggest ships [ships/h]
1	1	Cruise	2	100	20	0.005	0.009
2	1	Cont.	10	25	25	0.006	0.011
3	1	Bulk	60	15	90	0.021	0.041
4	2	Cruise	5	100	50	0.011	0.023
5	2	Cont.	20	30	60	0.014	0.027
6	2	Bulk	181	15	272	0.062	0.124
7	3	General	421	15	632	0.144	0.144
8	4	General	466	15	699	0.160	0.160
9	5	General	1634	15	2451	0.560	0.560
Sum			2799		4298	0.981	1.099

Table 4. Results of yearly simulations for Alternative I and II for traffic intensity in the year 2021

Type	1	2	3	4	5	6	7	8	9	Sum
Class	1	1	1	2	2	2	3	4	5	
Alternative 1										
Time without delay [h]	159	176	704	317	452	1808	3902	4523	13124	
Time with delay [h]	255	349	1310	608	768	3252	6570	5565	15892	
Total ships generated	46	51	204	92	131	525	1132	1313	3806	7300
Sum of delays [h]	97	174	606	291	316	1444	2669	1042	2768	9407
Delay per 1 ship [h]	2.1	3.4	3.0	3.2	2.4	2.8	2.4	0.8	0.7	1.3
Alternative 2										
Time without delay [h]	155	155	604	283	424	1756	4030	4454	13317	
Time with delay [h]	275	263	967	453	664	2749	6130	5416	16104	
Total ships generated	45	45	175	82	123	509	1168	1292	3862	7301
Sum of delays [h]	120	107	364	171	239	993	2100	962	2787	7843
Delay per 1 ship [h]	2.7	2.4	2.1	2.1	1.9	2.0	1.8	0.7	0.7	1.1

Table 5. Results of yearly simulations for Alternative I and II for traffic intensity for the year 2021 and double traffic in ship class 1 and 2

Type	1	2	3	4	5	6	7	8	9	Sum
Class	1	1	1	2	2	2	3	4	5	
Alternative 1x2										
Time without delay [h]	311	335	1180	735	835	3443	4005	4337	13283	
Time with delay [h]	566	616	2416	1402	1403	6292	7037	5603	16943	
Total ships generated	90	97	342	213	242	999	1162	1257	3851	8253
Sum of delays [h]	256	281	1236	667	568	2849	3031	1266	3660	13814
Delay per 1 ship [h]	2.8	2.9	3.6	3.1	2.3	2.9	2.6	1.0	1.0	1.7
Alternative 2x2										
Time without delay [h]	221	293	1194	725	883	3519	3978	4495	13245	
Time with delay [h]	378	505	1965	1206	1453	5880	6231	5603	16668	
Total ships generated	64	85	346	210	256	1022	1154	1304	3839	8280
Sum of delays [h]	158	211	772	481	570	2361	2254	1108	3423	11337
Delay per 1 ship [h]	2.5	2.5	2.2	2.3	2.2	2.3	2.0	0.8	0.9	1.4

Alternatives I and II. There are visible differences between the length of delay of large ships, which is equal to approximately 1 hour more per ship of class 1 and 0.5 hour per ship of class 2.

In Table 5 the sensitivity analysis is presented where the sensitivity factor was the influence of the largest ship intensity increase (applied double traffic increase). The reason for such an approach was the fact that the largest ships are the main waterway blocking factor. The significant influence of large ships for the waterway could be observed particularly in Alternative I. In comparison to the previous results, Alternative II is more robust on increasing large ship intensity in classes 1 and 2 because the differences are much smaller than in the primary simulation without traffic increase.

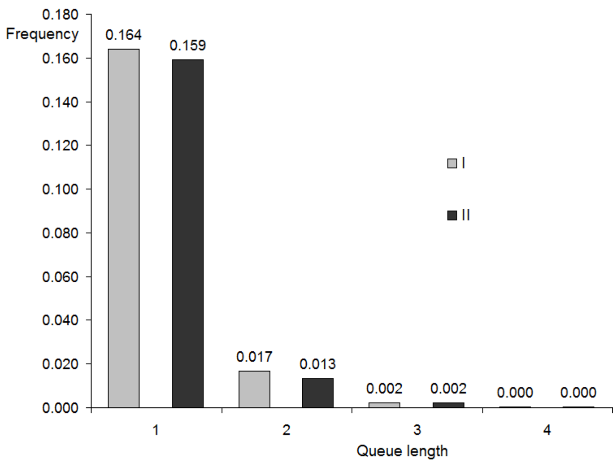

Figure 8. Probability of queue in ships classes 3, 4 and 5 for Alternatives I and II

Histograms of ships' queue length and probability of queue on entrance (at the Świnoujście approach) and departure (in Szczecin Port) are presented in Figure 8 (for Alternatives I and II) for classes 3, 4 and 5 (ships with the highest intensity). In ships of classes 1 and 2 the queues are minimal due to small intensity.

Conclusions

The following conclusions could be drawn from the studies presented:

- The need for this study into stochastic modeling of ship traffic flow is stable and its parameters such as queue length and number of ships are stabilizing over time for different input data.
- The better solution in respect of total ships' delay is Alternative II. This alternative saves about 65 waiting days per year in comparison to Alternative I. Most advantages appear in delays for ships in class 2 and 3, where the cost of the ship's delay is highest.
- The sensitivity analysis showed that Alternative II is less sensitive to traffic increase in the biggest ship's group, which are the major cause of waterway blockage.
- The queue of ships stabilizes in time and probability of queue for class 3, 4 and 5 and is about 16%. The probability of a queue is slightly less in Alternative II. The length of the queue is less than 5 ships for both alternatives.
- The application of intelligent traffic control should optimize the ships traffic parameters in these areas.

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