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Stochastic model of ship traffic congestion in waterways applied to determine the influence of Liquefied Petroleum Gas tanker introduction on ship traffic on the Świnoujście–Szczecin waterway

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Abstract

This paper presents the stages in stochastic ship traffic stream model creation, applied to determine the influence of liquefied petroleum gas (LPG) tanker introduction to Police Port on the Świnoujście–Szczecin waterway. The model is based on the Monte Carlo methodology, and is microscopic (which means that each ship's model is treated as a separate object possessing given attributes). The model is applied here in order to find the influence of ships with dangerous cargo (LPG tankers in the case study) on regular ship traffic, and hence to establish whether special traffic solutions are necessary.

Introduction and state-of-the-art

The increase of traffic in a port area demands new tools for traffic optimisation, assessment of different marine traffic engineering solutions and developing traffic control methods. This is needed especially within vessel traffic services (VTS). The analytical models traditionally used for capacity estimation are based on ship domain theory, are static and hence do not reflect the stochastic nature of the ship traffic process. To overcome this, stochastic models have been created (Groenveld & Hoek, 2000). Some models of capacity take into consideration alternative passing (Bačkalić & Škiljaica, 1998). Models for traffic optimisation with use of discrete optimisation have been developed for Kiel Canal by Mohring et al. (2005). Several models have been developed with use of 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 that a navigator intentionally keeps free from the other ships.

Usually two criteria are applied for assessing marine traffic systems in terms of traffic stream parameters:

1. Time of ship delay and its distribution.
2. Mean queue of ships waiting, with 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 are compared. In the presented research the area of the Świnoujście–Szczecin waterway (Figure 1) is analysed and two traffic situations are compared:

1. Alternative 1: normal traffic.
2. Alternative 2: normal traffic with introduction of LPG tankers to Police Port.

Microscopic stochastic model of ship traffic

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

1. Microscopic – that means that every ship is considered separately as an object.

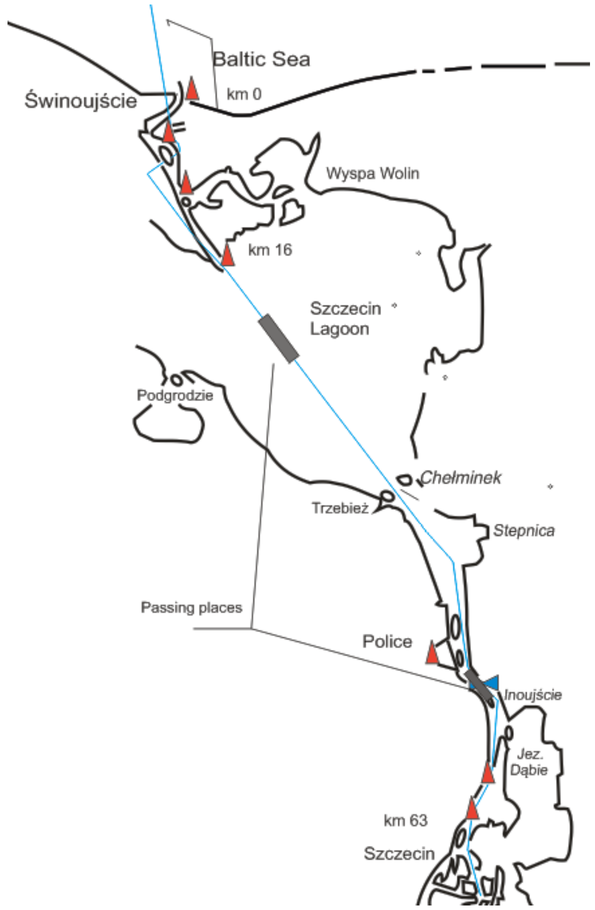

Figure 1. Layout of Świnoujście–Szczecin waterway with planned passing places for future layout

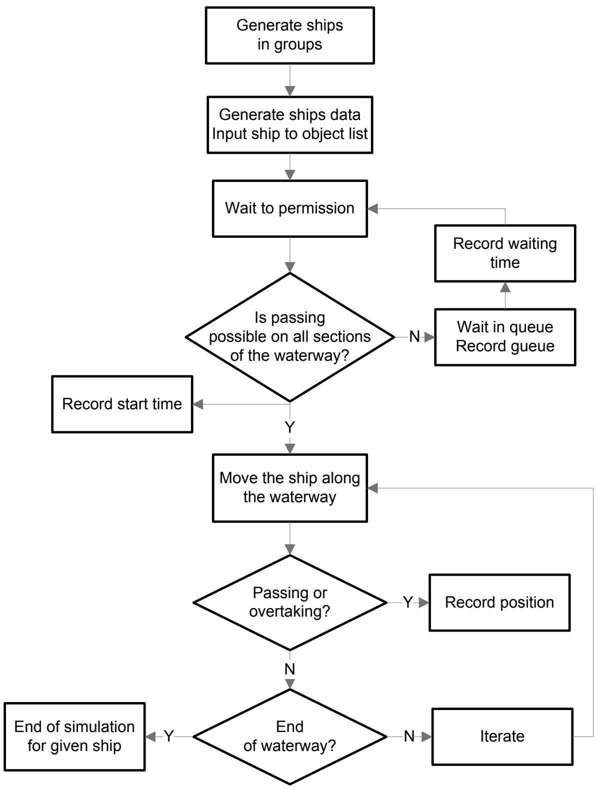

Figure 2. Stochastic microscopic simulation model of ship traffic in Świnoujście–Szczecin waterway

2. Domain based (the distances of following ships are based on ship domain theory).
3. Stochastic, where some parameters like ship's generators, ship length, draught, speed are modelled as random variables generated from distributions, mostly by the Monte Carlo principle.
4. One dimensional – the movement of ships is modelled in one dimension only (along the waterway).
5. Kinematic – the ships are modelled as a line interval (of length L) moving with uniform speed along the given section of waterway; speed changes (if any) are immediate.

The main algorithm of the model is presented in Figure 2. The model has several outputs, the main ones being:

1. Time of delay in respect to the ideal situation without delays.
2. Queue parameters in respect to ship categories and number of ships waiting.
3. Passing and overtaking points by ship categories.

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

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

Dynamic domain approach

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

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

where:

- L – ship 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 the width $D_B(x)$ of the ship domain:

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

where:

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

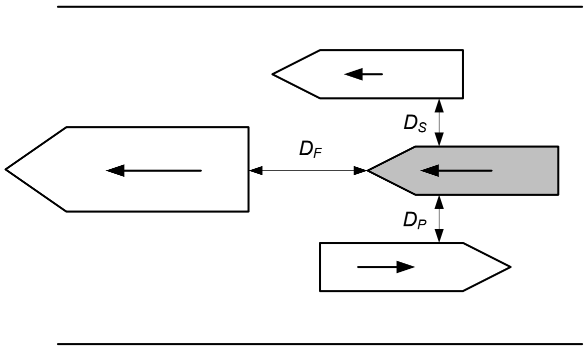

Figure 3. Ships domain parameters in narrow waterway

In this study, where a 1-dimensional model is applied, $D_B(x)$ could be defined as a two-state variable: $D_B(x) = \{o(x) = (1,0); p(x) = (0,1)\}$ where $o(x)$ and $p(x)$ are logical variables defining if 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 to the aft (D_A), and following ships adjust this domain size according to ship dimensions, port regulations and intentions, so it is set to zero. The dependence of the domain dimensions on x is the reason for variability of waterway sections and regulations inside the sections and ship speed variability in given sections. The domain variability (error) is changed according to navigators' behaviour. It is possible to model either risky, conservative behaviour or behaviour violating the regulations. This effect was neglected in this study.

The most important dimension of the domain in this study is D_F: the length before the ship, which the navigator intends to keep free. This 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 emergency stopping of their own ship. Emergency stopping in a narrow waterway is usually made by a so called step-manoeuvre, which depends on ship manoeuvring characteristics. The step-manoeuvre is usually performed in steps, changing engine settings in order to avoid grounding of the ship. Usually in the first phase of a step-manoeuvre, "Full Astern" is set on the engine; then when the ship starts to change her course significantly (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. Studies on step manoeuvres have been carried in Report (1980) for different ship size, and passing

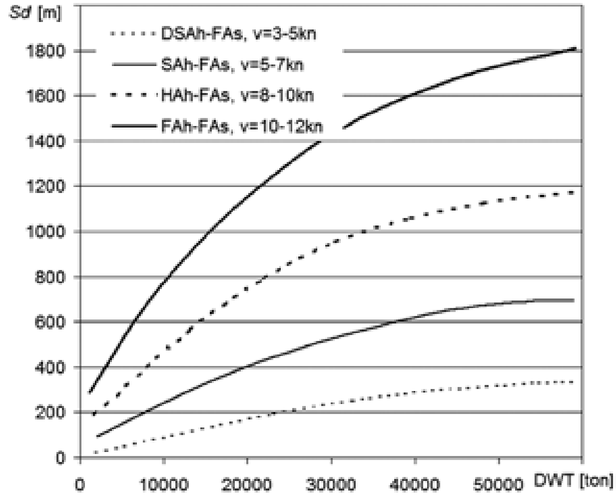

Figure 4. Stopping distance (*Sd*) in case of accident of followed-by ship in step-manoeuvre through narrow waterway for general cargo ships (Report, 1980)

through the waterway with different speeds and engine settings (Figure 4). In this study the dimension of the domain D_F has been set on the basis of stopping distance (Figure 3) as $D_F = Sd(Hah, \text{DWT})$.

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

A. Ships generators

The model uses ships generated by a Poisson distribution in groups with given intensities. The Poisson model is adequate and has good statistical validity for sub-critical intensities such as exist in the analysed waterway (Gucma & Schefs, 2007; Kasyk, 2014). The computer Poisson generator used in this study was created on the basis of Zieliński & Wieczorkowski (1997). Lengths of ships in groups were generated by a Uniform distribution with parameters: $[L_{max}, L_{min}]$. Speed of ships was generated by a Normal right side cut distribution where cutting distance was set as maximum regulation speed in a given section. Extended studies over the speed distribution in this area have been done by the author (Gucma & Schefs, 2007). The same intensities have been set for inbound and outbound ships (the choice of direction by ship was modelled by a Bernoulli distribution). Main elements of the algorithm of the model are three loops with different time intervals realised by a computer program:

1. The loop of ship generation and the recording of their main parameters (time interval = 1 h).
2. The loop of updating the position of ships and recording their passage (time interval = 1 min).

3. The decision loop of checking the possibility of letting ships into the waterway or 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 matrix of passing/overtaking possibilities as a Boolean matrix of dimension 5×5 (i.e. number of ships in classes).

C. Traffic control measures

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

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

In this section the case study is presented whose aim is to show the influence on traffic of the introduction to operation of LPG tankers in Police Port. Thus two alternatives are examined:

1. Alternative 1: current ship traffic.
2. Alternative 2: current ship traffic with LPG introduction (120 ships/year).

For traffic modelling purposes and due to port regulation, the ships were divided into four classes related to ship draught (T) (Przepisy Portowe, 2013):

1. All ships of draught between 7.4 m < T < 9.1 m.
2. All ships of draught between 6.1 m < T < 7.4 m.
3. All ships of draught between T < 6.1 m.
4. LPG carriers (draught between 7.4 m < T < 9.1 m) as ships with dangerous cargo.

The details of the four ship groups are presented in Table 1. Table 2 presents the possibilities of ships passing according to port regulation in different waterway sections.

Table 1. Applied division of ships into groups

Class of ship due to passing possibility regulations	Type	Name	Remarks: It was assumed that
1	T < 6.1 m	Small	L < 100 m
2	6.1 m < T < 7.4 m	Mean	100 m < L < 130 m
3	7.4 m < T < 9.1 m	Large	L > 130 m
4	LPG	LPG	7.4 m < T < 9.1 m

Determining future ship traffic intensities in the Świnoujście–Szczecin waterway

The port of Szczecin does not show significant dynamics of changes of ship traffic, which is around 3000 and 300 ships entering per year respectively to Szczecin and to Police. The basic traffic data presented in Table 3 comes from the Polish Statistical Office (GUS, 2014) and covers the period 2009 to 2014.

Table 3. Ship traffic in Szczecin and Police (GUS, 2014)

Year	Szczecin	Police
2009	2775	173
2010	3185	349
2011	3084	306
2012	2822	276
2013	2872	220
2014	2638	265
Mean	2896	265
Total	3161	

Table 2. Basic regulation rules according to ship passing possibilities in groups and sections of the waterway

No.	Name of section “from”	Name of section “to”	Waterway km “from” [km]	Waterway km “to” [km]	Speed [kn]	Possibility of passing in classes	Passing forbidden in classes
1	Breakwater Świnoujście	Karsibór crossing	0	9.5	8	1 and 1, 2, 3 2 and 1, 2 3 and 1	between 3 and 2, 3, 4 between 4 and 1, 2, 3, 4
2	Karsibór crossing	Karsibór bend	9.5	10.5	8	1 and 1, 2, 3 2 and 1, 2 3 and 1	between 3 and 2, 3, 4 between 4 and 1, 2, 3, 4
3	Karsibór bend	Chełminek Island	10.5	35	8/12	1 and 1, 2 2 and 1, 2 3 and 1, 2 4 and 1, 2	between 3 and 3, 4 between 4 and 3, 4
4	Chełminek Island	Police Port	35	50	8/12	1 and 1, 2, 3 2 and 1, 2 3 and 1 4 and 1	between 4 and 2, 3, 4 between 3 and 2, 3, 4

In a further step, three years (2012–2014) of ship traffic data from VTS Szczecin data have been analysed by ship size (length and draught). The intensities of ships in given groups resulting from this analysis are presented in Table 4.

Table 4. Yearly intensities of ships in investigated groups

Group	*T* [m]	Intensity in Szczecin and Police (mean from 3 years)
1	up to 6.1 m	75.6%
2	6.1 m to 7.4 m	15.9%
3	7.4 m to 9.1 m	8.5%
4	7.4 m to 9.1 m	0%

Analysis and forecasts of ship traffic data together with economic forecasts are based on previous studies (Report, 2008), the authors' previous works (Gucma & Sokołowska, 2012) and from the VTS data from 2013–2014. The assumed traffic forecast for 2021, used as input data to the model, is presented in Table 5.

Table 5. Forecast of ship traffic in 2021 and hour density of traffic for given ship groups

Class	Draught (class) *T* [m]	Yearly intensity Szczecin and Police	Yearly increased in Szczecin [%]	Forecast Szczecin and Police at 2021 [ship/year]	Hour intensity for 2021 (entrance/departure) [ship/h]
1	to 6.1	2390	5	3226	0.737
2	6.1 to 7.4	503	10	854	0.195
3	7.4 to 9.1	269	10	457	0.104
4	LPG	0	0	120	0.027
Total		3161	0	4657	1.063

Results of traffic simulations for two analysed alternatives

The research has been carried out for two different alternatives and scenarios:
1. Alternative 1 – traffic for 2021, no LPG.
2. Alternative 2 – traffic for 2021, LPG traffic with intensity 120 [1/year].

Duration of simulation was equal to 365 days (1 year). Elapsed time for a single simulation on an average PC computer was around 1 minute.

Data achieved in simulations were recorded and analysed by the following parameters:
1. Distribution of ship queue in classes on entrance.
2. Distribution of ship queue in classes on departure.
3. Time of waterway passage without delays (ideal).
4. Time of waterway passage with delays in classes.
5. Sum of generated ships.
6. Mean delay per ship in classes.

Table 6 presents results of a yearly simulation for forecasted traffic in 2021 for the two analysed alternatives. Detailed analysis does not show any significant differences in delays of ships because the blockage factor is due to large ships, however their intensities are not too high. The LPG carriers suffer considerably in respect of delay time due to restrictions of dangerous cargo and they need to wait nearly 0.8 hours per ship until the waterway is cleared. In practical situations such delays will be reduced due to human traffic control influence.

Table 6. Results of one year of traffic simulations for Alternatives 1 and 2 for traffic intensity of the year 2021

Ships class	1	2	3	4	Sum/ Mean
Class name	Small	Mean	Large	LPG	
Alternative 1 (no LPG)					
Time of ships on the waterway without delay [days]	381	131	71	0	584
Time of ships on the waterway with delay [days]	456	155	89	0	700
Total ships generated (entr./dep.) 4523		1554	847	0	6924
Sum of delays per year [days]	74	24	18	0	116
Mean delay per 1 ship [h]	**0.39**	**0.37**	**0.50**	**0.00**	**0.40**
Alternative 2 (introduction of LPG)					
Time of ships on the waterway without delay [days]	385	137	74	19	614
Time of ships on the waterway with delay [days]	461	160	92	26	739
Total ships generated (entr./dep.)	4559	1620	876	225	7280
Sum of delays per year [days]	76	24	18	7	125
Mean delay per 1 ship [h]	**0.40**	**0.35**	**0.49**	**0.80**	**0.41**

Conclusions

The stochastic model of ship traffic flow that has been created is stable and its parameters such as queue length and number of ships stabilise in time for different input data. The model neglects several aspects of ship traffic behaviour, especially human influence, but since relative results are used, the achieved results could be representative of the class of problem solved.

The detailed conclusions to the case study are as follows:
1. Queues of more than one ship are rare and usually exist in group 1; maximal length of queue is two

ships. In classes 2 and 3 the queues practically never exist due to small intensities.
2. It should be noted that LPG carriers' waiting time for clearance of waterway is considerable and equals about 0.8 h per ship. The traffic control neglected in the model could significantly decrease this in real life.
3. Alternative 1 (without LPG carriers) has no significant differences to Alternative 2 (with LPG) in respect to mean time of waiting for waterway clearance. This implies that introduction of LPG to Police Port does not restrict traffic on the waterway. Mean waiting times are less than one minute longer in comparison to Alternative 1.
4. Mean delays for ships are around 0.4 h per ship.

Intelligent traffic control should be used to minimise delays to ships and to optimise the traffic. A planned passing place in Szczecin Lagoon will significantly smooth the traffic parameters.

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