

ASSESSMENT OF SHIP MANOEUVRING SAFETY IN WATERWAY SYSTEMS BY RELATIVE NAVIGATIONAL RISK

Stanisław GUCMA¹, Wojciech ŚLĄCZKA², Andrzej BĄK³

^{1, 2, 3} Maritime University of Szczecin, Szczecin, Poland

Abstract:

The safety of vessels navigating in the sea waterway system is ensured by fulfilling the acceptable restrictions called safe ship operation conditions in that system. The assessment of navigation safety is particularly important when the conditions for safe operation of ships in the waterway system are changed concerns increasing the maximum parameters of vessels, increasing the allowable hydrometeorological conditions or changing the minimum tug assistance. The article presents a method for assessing navigation safety when the conditions for the safe operation of vessels in the waterway system get changed. The method uses two indicators, which are difference in navigation risks and relative navigation risk. To determine the navigational risk, algorithms were developed for calculating the probability of accidents caused by the deterioration of navigation conditions and technical failure of ship equipment and tugs. Another algorithm was developed for calculating the consequences of the accidents that involve blocking a waterway by a ship anchoring in an emergency, grounding, impact of the ship against a port structure or moored ship and a collision with another ship in motion. The method developed for assessing navigation safety by means of relative navigation risk can be used in practice when changing the conditions for safe operation of vessels in the waterway system and when the system is modernized. Navigational safety management is a decision process that is implemented in the loop presented in the article. The acceptable risk is determined on the basis of vessel traffic intensity and ship parameters defined by safe operation conditions for a given waterway system. Relative navigational risk may be used in assessment and comparison of various conditions of safe ship operation. The probability of an accident caused by ship's moving outside the available navigable area due to technical failures of ship equipment or tugs is determined, depending on the type of port waterway and the manoeuvres performed.

Keywords: sea waterway system, navigational risk, navigation safety on sea waterways

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Contact:

1) s.gucma@am.szczecin.pl [<https://orcid.org/0000-0003-2286-8815>]; 2) w.slaczka@am.szczecin.pl [<https://orcid.org/0000-0003-3265-9726>]; 3) a.bak@am.szczecin.pl [<https://orcid.org/0000-0003-4977-6304>] – corresponding author

1. Introduction

The safety of ships manoeuvring in the sea waterway system is assured by satisfying allowable restrictions, called conditions of safe operation of ships in a specific waterway system. These conditions define basic parameters of 'maximum ships' that may safely manoeuvre under allowable hydro-meteorological conditions at the appropriate (safe) tug assistance, specific for each part of that waterway system. Such approach to the assessment of the ship's manoeuvring safety in the sea waterway system is conditional on the assumption that human errors, made by the navigator, are not taken into account, regarded as gross errors that generally result from the insufficient qualifications and physical and mental condition of the navigator.

To determine the navigational risk, algorithms were developed for calculating the probability of accidents caused by the deterioration of navigation conditions and technical failure of ship equipment and tugs. Another algorithm was developed for calculating the consequences of the accidents that involve blocking a waterway by a ship anchoring in an emergency, grounding, impact of the ship against a port structure or moored ship and a collision with another ship in motion.

The method developed for assessing navigation safety by means of relative navigation risk can be used in practice when changing the conditions for safe operation of vessels in the waterway system and when the system is modernized. Navigational safety management is a decision process that is implemented in the loop presented in the article. The acceptable risk is determined on the basis of vessel traffic intensity and ship parameters defined by safe operation conditions for a given waterway system. Relative navigational risk may be used in assessment and comparison of various conditions of safe ship operation. The probability of an accident caused by ship's moving outside the available navigable area due to technical failures of ship equipment or tugs is determined, depending on the type of port waterway and the manoeuvres performed.

Safe passage through a given waterway system is usually possible for a number of types of 'maximum ships'. Each group of ship types (e.g. bulk ships, tankers, container ships, cruise ships) has different maximum parameters (L, B, T) allowing their safe manoeuvring in a given waterway system, with different kind of tug assistance for ships belonging to

such group. A 'maximum ship' is defined as the largest ship that under assumed navigational conditions may safely manoeuvre in the examined area. The concept of 'maximum ship' includes all ships whose only one of the three basic parameters (L, B, T) reaches the maximum value. The article presents the method of assessment of ship manoeuvring safety in the waterway system, using the concept of relative navigational risk.

2. Literature review

The safety of ship's manoeuvring in restricted areas is estimated by using navigational risk models. There are a number of methods of detailed risk estimation (Dhillon 2022; Huang J. C. et al., 2019; Kite-Powell H., Ozturk U. et al., 2019; Ozturk U. and Cicek K., 2019; Patrician N.M. 1998; PIANC 1997; Rausand M. 2011) and practical methods known as formal risk analysis (FSA) (Gucma S. and other 2017; Rausand M. 2011; Vinnem J. E. E. 2014). In maritime transport, the Formal Safety Assessment (FSA) developed by the International Maritime Organization (IMO) is used to assess safety (Gucma and Ślącza, 2018). The identification of navigational risks of accidents in fairways is a basic principle for the construction or modernization of waterways in restricted waters and when the conditions of safe operation change (Chen P., 2019; Gućma et al., 2020) and the traffic density is growing through the world (EC, 2019). These methods are used generally for the estimation of navigational risk on waterways of a specific type and do not relate to navigational risk of ships manoeuvring in sea waterway systems crossing restricted areas (Gucma and Gućma, 2019; Zhang W., 2020). The methodology, based on a systemic approach to the design and optimization of waterways, uses the method developed at the Marine Traffic Engineering Centre (MTEC), Maritime University of Szczecin and methods of computer simulation (Gucma S. 2016). The optimization criterion used is the minimization of the aggregated costs of construction and operation of the waterway and its navigation systems (Gucma and Zalewski, 2020, Bąk and Zalewski, 2021). Such methods are widely used inter alia for estimating the risk during normal operation of the vessel (Goerland F. and other 2010) especially in ferry transport (Herno Della et al., 2020), in the road transport (Szymanek A. 2010) and to optimise supply chains (Kulińska E. 2012), especially with the lack of safety procedures (Lau et al.,

2021). Another research concerned with fairway design taking into account the possibility of collision with infrastructure (Pedersen et al., 2020), which are parts of every inner sea road. As the basis of every analysis historical data must always be taken into account (Aalberg et al., 2022) as well as the actual data obtained by the continuous monitoring by any means e.g. AIS system (Liu et al., 2020).

Based on the above conditions, numerous navigation-related studies have been conducted. Recent study has found organizational factors, environmental circumstances, human errors in safety management, and other potential RFs for marine transportation. (Khan et al., 2018, Zhang et al., 2020). (Gucma et al., 2019a) presents a simulation method for determining the minimum safe pull of tugs assisting in port manoeuvres, which was tested in the LNG terminal in Świnoujście. (Gucma et al., 2019b) describes the methodology to design a universal berth for LNG discharge from tankers with a wide cargo capacity range of 500 m³ to 220,000 m³. Based on a waterway optimization simulation, the methodology has been used to determine parameters of the designed universal cargo handling berth located in the port of Świnoujście. (Szubrycht, 2020) characterizes Baltic shipping and analyzes the scale of threats generated by maritime accidents, as well as ways of responding and minimizing the probability of emergencies in the Baltic Sea. (Ung, 2021) related studies indicated that ship accidents caused by mechanical failure range from 10% to 51% of total accidents. His approach was utilize the Bayesian networks for risk estimation.

Another usage of safety criterion we will find in many navigational integrated system, widely used as ECDIS (Electronic Chart Display and Information System) and others. (Bray et al., 2020) describe dynamic positioning systems commonly used in the offshore industry as an excellent example of an integrated system. Such utilization of safety criterion is reflected in appropriate training programmes and training courses designed to prepare the future navigator to complete the sea voyage safely especially to focus on the problems of over-reliance on ECDIS and the broader issue of information exchange between man and machine (Car et al, 2021, 2019; Kristić et al., 2021). Moreover the aforementioned criteria play a key role in all kinds of decision support systems as they are written about in (Gil et al., 2020). (Rudyk et al., 2019) made the model that can be used

for the risk assessment of the different method of transport taking into account the aspects of safety, ecology and financial aspects.

3. Research method

3.1. Assessment of navigational risk in waterway systems

Waterway systems consist of various types of fairways, anchorages, turning areas and port basins. Further considerations do not take into account the anchorage system, assuming the safety of anchoring is ensured when the anchorage capacity is not exceeded. With this assumption, the system was limited to the following types of waterways:

- fairway – straight:
 - one-way,
 - two-way,
- fairway bend,
- turning basin,
- port basin area - berth approach.

Taking into account the above limitations and existing literature data, (Gucma S., Ślącza W. 2019) the conditions of safe operation of the ship in the waterway system can be written as a set of factors as follows:

$$W = [S, h, H] \quad (1)$$

where

- W** – conditions of safe operation of ships in the waterway system;
- S** – conditions related to 'maximum ships' in the waterway system;
- h** – conditions related to tug assistance required by 'maximum ships';
- H** – hydrometeorological conditions allowable for manoeuvres of 'maximum ships' manoeuvres in the waterway system.

whereby:

$$S = [L_{ck}, B_k, T_k, V_{ik}] \quad (2)$$

$$h = [n_{hik}, U_{hik}, u_{hik}] \quad (3)$$

$$H = [s, V_w, V_{pi}, \Delta_{hi}] \quad (4)$$

where

- $L_{ck}; B_k; T_k$ – length overall, breadth and draft of 'maximum ship' of k -th type (group of types);
- V_{ik} – allowable speed of 'maximum ship' of k -th type' on i -th waterway;

- n_{hi} – number of tugs assisting in manoeuvres of k -th type of ship on i -th waterway;
- U_{hik} – minimum safe bollard pull of tugs assisting in manoeuvres of k -th type ship on i -th waterway;
- u_{hik} – minimum bollard pull of each tug assisting in manoeuvres of k -th type ship on i -th waterway;
- s – allowable visibility for manoeuvres in the waterway system;
- V_w – allowable wind speed for manoeuvres in the waterway system;
- V_{pi} – allowable current speed on i -th port waterway;
- Δ_{hi} – allowable water level drop on i -th waterway.

The analysis of risks on various types of waterways covered by a Vessel Traffic Service related to each type of manoeuvre brings the following classification of characteristic accidents:

- 1) Passage through a straight one-way fairway:
 - grounding (channel slope),
 - striking a port structure (vertical shore),
 - striking a ship moored by the fairway.
- 2) Passage through a straight two-way fairway:
 - grounding (channel slope),
 - striking a port structure (vertical shore),
 - striking a ship moored by the fairway,
 - collision with a ship on the opposite course.
- 3) Turn on a fairway bend:
 - grounding (channel slope),
 - striking a port structure (vertical shore).
- 4) Turning in the designated area:
 - grounding (channel slope),
 - striking a port structure (vertical shore),
 - striking a ship moored by the turning area.
- 5) Berthing in a port basin:
 - grounding (channel slope),
 - striking a port structure (vertical shore),
 - striking a ship moored at a quay.

The analysis of navigational risks in restricted areas (waterways) [Gucma S., Ślącza W. 2019] has demonstrated that:

- those accidents do not cause harm to humans (no fatalities or injuries),
- environmental safety risks should be limited only to the transport of hazardous materials,
- economic consequences, due to low speeds of the moving ships, should be limited to a maximum

loss of one small ship (LC<100 m - one hold) with the cargo (~25 million USD). This only refers to fairways located along the berths with the ships moored at them.

Taking into account the above conditions, consequences of accidents occurring during ship's transition through a given waterway system were limited to economic consequences. Therefore, navigational risk of the given type ship passage through the waterway system at a specific frequency can be defined as likely annual loss caused by accidents of such ships.

The navigational risk of given type ship passage through the waterway system in a year is the sum of risks of specific accidents during manoeuvres on all waterways passed by those ships.

$$R = \sum_{i=1}^m \sum_{q=1}^p IP_{iq} S_{iq} = I \sum_{i=1}^m \sum_{q=1}^p P_{iq} S_{iq} \quad (5)$$

where

R – navigational risk of passage by a specific ship through a waterway system [USD/year];

I – yearly frequency of passage through the waterway system by specific type and size ships [year⁻¹];

P_{iq} – probability of the occurrence of q -th accident on i -th waterway;

S_{iq} – consequences of q -th accident on i -th waterway (economic indicator of consequences - losses) [USD].

3.2. Assessment of navigational safety in waterway systems

One of the major problems in maritime traffic engineering is the assessment of navigational safety when conditions of safe operation for ships are changed in a given waterway system by:

- increase in parameters of 'maximum ship' of the given type (L_c, B, T),
- raising allowable hydrometeorological conditions ($s, V_w, V_p, \Delta h$)
- changing the minimum required tug assistance (n_h, U_h, u_n).

The relative navigational risk is used for the assessment of navigational safety of ships in waterway systems.

Navigational safety assessment done when the conditions of safe operation of ships change in a given

waterway system is conducted using two indicators: relative navigational risk and the difference of navigational risks.

The difference of navigational risks is determined between the risk of passing through a given waterway system in test (planned) and existing conditions of safe operation of ships:

$$\Delta R_{yx} = R_y - R_x \text{ [USD/year]} \quad (6)$$

where

ΔR_{yx} – difference of navigational risks for test (planned) and existing conditions of safe operation of ships in the waterway system [USD/year];

R_y – navigational risk of the waterway passage in test (planned) conditions of safe ship operation (USD/year);

R_x – navigational risk of the passage of the waterway system in existing safe ship operation conditions [USD/year].

After substitution and transformation, the differences in navigational risks can be written as:

$$\Delta R_{yx} = I \sum_{i=1}^m \sum_{q=1}^p P_{yiq} S_{yiq} - P_{xiq} S_{xiq} \quad (7)$$

where

P_{yiq} ; P_{xiq} – probability of the occurrence of q -th accident on i -th waterway in test (y) and existing (x) conditions of safe ship operation;

S_{yiq} ; S_{xiq} – consequences of q -th accident on i -th waterway in test (y) and existing (x) safe ship operation conditions [USD].

Relative navigational risk is the ratio of navigational risks of the passage through a given waterway system under various conditions of its safe operation (test to existing conditions).

$$R_{yx} = \frac{R_y}{R_x} 100 [\%] \quad (8)$$

After substitution and transformation the relative navigational risk in various safe ship operation conditions can be written as:

$$R_{yx} = \sum_{i=1}^m \sum_{q=1}^p \frac{P_{yiq} S_{yiq}}{P_{xiq} S_{xiq}} \quad (9)$$

Differences of navigational risks can be used for the assessment of the navigational safety of the waterway system when the safe ship operation conditions are changed, by comparison with the acceptable risk:

$$\Delta R_{yx} \leq R_{akc} \quad (10)$$

where

R_{akc} – acceptable risk of changing the conditions of safe operation of ships in the waterway system.

The acceptable risk is determined on the basis of vessel traffic intensity and ship parameters defined by safe operation conditions for a given waterway system. This risk is related to the waterway system through the scale of consequences of navigational accidents. Relative navigational risk may be used in assessment and comparison of various conditions of safe ship operation on a given waterway.

A model of navigation safety management was built on the basis of above algorithms of relative risk and risk difference calculation. In the model, navigational safety management is a decision process that is implemented in the loop (Fig. 1) and consists of:

- 1) determination of current acceptable and criteria values of navigational risk in restricted areas;
- 2) estimation of existing navigational risk based on ship parameters, required tug assistance and current hydrometeorological conditions;
- 3) estimation of planned navigational risk based on ship parameters, required tug assistance and forecast hydrometeorological conditions;
- 4) comparison of risk differences (existing and planned) with the acceptable risk in order to assess navigational safety in the waterway system;
- 5) use the quotient of the existing and planned risks for the assessment and comparison of the conditions of safe safe operation on the given waterway and the assessment of the increase of the planned risk based on probable annual losses determined by a statistical method; the increase of the planned risk is determined by the statistical method as the product of relative risk and annual losses caused by a given type of accidents, calculated from a database of marine accidents;
- 6) making changes in the system, when the risk larger than the assumed one is unacceptable;
- 7) verification of the effects of these changes by calculating the expected navigational risk (lower than the acceptable risk).

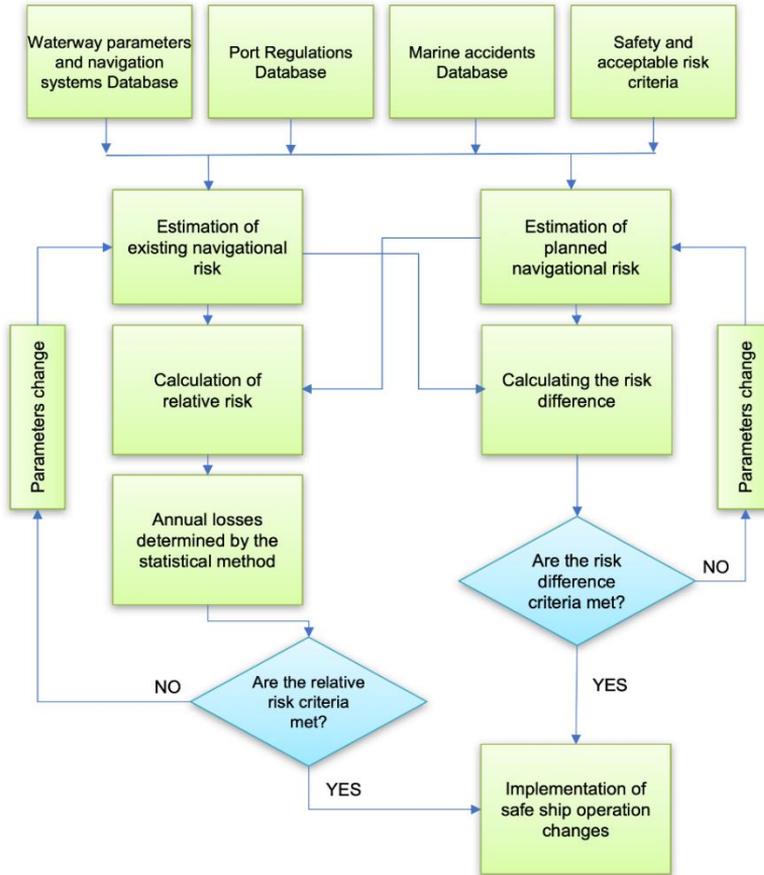


Fig. 1. The schematic diagram of the navigational safety management model

4. Results and methods of the determination of navigational risk on waterways

4.1. Probability of accidents on waterways

An analysis of accident risks and accident types indicated two general causes of accidents that may occur when a ship manoeuvres within a waterway system:

- 1) moving out of the available navigable area due to deteriorated navigational conditions,
- 2) technical failures of shipboard equipment: rudder, main engine, generator sets or technical failure of tugs assisting in the manoeuvres.

Moving out of the available navigable area by a ship caused by worsened navigational conditions creates

a risk of an accident, depending on the restrictions in the area. An accident may involve grounding (channel slope), hitting a marine structure or moored ship. The probability of such accident can be determined when the safe manoeuvring area is known for a tested ship in the waterway under allowable hydrometeorological conditions.

The probability of performing a smooth collision free manoeuvre by a given type and size ship, in specific navigational and hydrometeorological conditions, steered by a navigator with specific qualifications, is as follows:

$$P_{nj} = P(X_j \leq d_j) \tag{11}$$

and expressed by the normal standardized distribution (Gucma S. et al. 2015):

$$P_{nj} = P\left(\frac{X_j - \bar{x}_j}{\delta_j} \leq \frac{d_j - \bar{x}_j}{\delta_j}\right) = 1 - \alpha \quad (12)$$

where

X_j – maximum distance of the extreme ship point in j -th direction from a reference area point or from the fairway centre line (random variable),

\bar{x}_j, δ_j – mean value and standard deviation of the maximum distances of extreme points of a ship in j -th direction from the reference point of the area or the fairway centre line,

d_j – minimum distance from a danger in j -th direction from the reference point of the area or the fairway centre line,

$1 - \alpha$ – confidence level.

The distribution parameters \bar{x}_j, δ_j are calculated from real, simulation or empirical tests of a given manoeuvre that are intended for the determination of the parameters of the safe manoeuvring area. Calculations of safe manoeuvring area parameters performed by simulation or METC deterministic-probabilistic methods are made at the specific confidence level.

On waterways such as fairway or port entrance the random variable X_j is the maximum distance of the ship's extreme point from the fairway centre line. On port waterways such as a turning basin or quayside basin, the random variable X_j is the maximum distance of the extreme point of a ship in j -th direction from the reference point of the area, according to which the safe manoeuvring area is determined.

The basic condition of navigational safety in the available navigable area of i -th port waterway can be written as:

$$\forall_{p(x,y) \in D} \left. \begin{array}{l} d_{jk(1-\alpha)} \subset D_i(t) \\ h_i(t) \geq T_k + \Delta_{ij} \end{array} \right\} \quad (13)$$

where

$D_i(t)$ – available navigable area of i -th waterway (the condition of safe depth at instant t is satisfied);

$d_{ik(1-\alpha)}$ – safe manoeuvring area of k -th ship on i -th waterway in allowable navigational conditions determined at the confidence level ($1 - \alpha$);

$h_i(t)$ – minimum depth of i -th waterway at instant t ;

T_k – maximum draft of k -th ship;

Δ_{ik} – underkeel clearance of k -th ship on i -th waterway.

Safe parameters of ship's manoeuvring area depend on the speed and direction of wind and current, and visibility. For the least favourable wind and current directions programmed in the simulation tests, it was found out that:

$$d_{ik \alpha(1-\alpha)} = f(V_w, V_p) \quad (14)$$

For operating conditions of commercial vessels the following was adopted:

– the ship is not allowed to navigate on the fairway when wind speed exceeds the maximum value

$$V_w > V_w^{dop}$$

– during ship's passage through the waterway system, wind speed may increase,

– simulation tests showed that statistically significant reduction of safe manoeuvring area width occurs when wind speed increases by about 2.5 m/s (Gucma S. et al. 2015).

4.2. The probability of an accident due to deteriorated navigational conditions

The probability of an accident caused by sailing outside the available navigable area by a maximum ship in i -th section of the waterway due to the deterioration of navigational conditions is determined by the following relationship:

$$P_{wi} = P_{ai} \cdot P_{hi} \cdot I_r \cdot \Delta t_i / G_r \quad (15)$$

whereas the probability that the navigable area will not comprise the whole safe manoeuvring area of a tested ship on i -th waterway in j -th direction from the adopted reference point of the area or from the fairway centre line is:

$$P_{aij} = 1 - P_{nij} \quad (16)$$

while to calculate the accident probability the maximum probability of moving outside the available

navigable area is chosen from a set of dangerous directions:

$$P_{ai} = \max_j P_{aij} \quad (17)$$

where

P_{wi} – probability of an accident caused by moving outside the available navigable area by the examined ship on i -th waterway due to the deterioration of navigational conditions;

P_{ai} – maximum probability that the safe manoeuvring area of the tested ship goes beyond the available navigable area;

P_h – annual occurrence of wind in the maximum range;

I_r – mean annual intensity of ship's passages through i -th section of the fairway;

Δt_i – mean time of ship passage through i -th fairway section by the tested ship [h];

G_r – hours per year (8760 h);

P_{nij} – the probability that the navigable area will comprise the safe manoeuvring area of a tested ship on i -th waterway in j -th direction from the adopted point of the area or from the fairway centre line.

4.3. The probability of an accident due to technical failure of ship or tug equipment.

Moving outside the available navigable area by a ship due to technical failure of shipboard equipment or tugs depends on their reliability. Technical reliability is understood as failure free performance of a specific manoeuvre. Technical reliability depends on the reliable operation of the main engine, generating sets, steering gear and tugs. Each of the above listed machines is characterized by a specific probability of reliable work during the manoeuvre performance.

To calculate the probability of reliable work of the above machinery, the failure rate function $\lambda(t)$ at instant t is used, that is the failure density function, provided a failure has not occurred till that instant. By considering only the stable phase of operation of the equipment concerned (surveyed by classification societies), it was established that the risk function $\lambda(t)$ is not time-dependent and is constant (Gucma S. et al. 2015).

Some of the failures of the machines under consideration during manoeuvring in the examined area

will not result in an accident. This depends on additional factors:

– place where the failure occurred in the tested area (waterway);

– hydrometeorological conditions prevailing during the performed manoeuvre;

– the scope of the failure of a specific machine.

Considering the individual factors, we can conclude that:

1) Only in certain locations in the examined area (waterway) a failure of a given machine or device leads to a ship's accident. This is taken into account by determining specific time intervals for a given area;

2) Only under some hydrometeorological conditions, prevailing during the performance of a manoeuvre, an accident may occur due to a failure of a given machine;

3) Only a certain extent of a failure of some machines may cause an accident (e.g. jamming of the rudder at some of its deflection angles).

The probability of an accident caused by ship's moving outside the available navigable area due to technical failures of ship equipment or tugs is determined, depending on the type of port waterway and the manoeuvres performed and prevailing hydrometeorological conditions in the area (wind direction and speed). Specific characteristics of manoeuvring on various port waterways and existing risks lead to their division into groups, in which the probability of accidents and the consequences are determined by various methods. These are:

1) fairways and port entrances (without tug assistance)

2) port entrances, turning basin and port basin (tug assistance).

4.4. The probability of an accident in the fairway or port entrance without tug assistance

This probability is determined for three types of failure, which differ for straight fairway sections and bends.

1) Straight fairway or port entrance:

– jamming of the rudder at 5° angle to ship's side (this reflects the manoeuvring technique in fairways where larger rudder angles are rarely used),

– engine failure,

– blackout, i.e. failure of generator sets.

- 2) The fairway bend or port entrance bend.
- jamming of the rudder set 10° to 20° to the side of turning (depending on the turning angle of the bend) to 5° to 10° to the other side (reduction of the rate of turn while turning),
 - engine failure,
 - blackout, i.e. failure of generator sets.

The least favourable hydrometeorological conditions occurring in emergency manoeuvres induce the largest safe emergency widths of the manoeuvring area of the tested ship ($d_{a(1-a)}$). These are the least favourable scenarios of accidents, the probability of which is determined by the computer simulation method or MTEC (Marine Traffic Engineering Centre) method.

Probabilities of accidents of a ship passing through the fairway under least favourable hydrometeorological conditions without tug assistance due to failure of the rudder, engine or generator sets can be written as follows:

- rudder jamming

$$P_{as} = P_{ai} \cdot \lambda_s \cdot \Delta t \cdot I_r \cdot p_z \cdot p_{ws} \quad (18)$$

- engine failure

$$P_{am} = P_{ai} \cdot \lambda_m \cdot \Delta t \cdot I_r \cdot p_{wm} \quad (19)$$

- blackout (failure of generator sets)

$$P_{aa} = P_{ai} \cdot \lambda_{ap}^2 \cdot \Delta t \cdot I_r \cdot p_{ws} \quad (20)$$

where

P_{as} – probability of the ship's accident due to the rudder jamming at 5° (straight fairway section);

P_{am} – probability of a ship's accident due to engine failure;

P_{aa} – probability of an accident due to failure of generator sets (blackout);

P_{ai} – maximum probability that the ship moves outside the available fairway width to either side for allowable wind speed blowing from a dangerous direction;

λ_s – failure rate of the rudder;

λ_{ap} – failure rate of generator sets;

λ_m – failure rate of the main engine;

Δt – mean time of passing the examined fairway section or manoeuvre performed;

p_z – probability of rudder jamming on one side ($p_z = 0.67$ - fairway limited on both sides);

p_{ws} – probability of the occurrence of maximum allowable speed wind from the side (range 90°);

p_{wm} – probability of the occurrence of maximum allowable speed wind from the stern (range 90°);

The failure rate for machines affecting manoeuvring safety is shown in Table 1. These data are based on studies conducted in the 1990s (Gucma S. et al. 1995), later revised using data from research done in the years after 2000 (Gucma L., Gralak R. 2008, Matuszak Z. 2012).

Table 1. The failure rate and estimated mean value of failure-free working time of shipboard machinery and tugs

Type of machine	Estimated mean failure-free working time T [h]	Failure rate λ [1/h]
main engine	6000	$1.7 \cdot 10^{-4}$
generator set	2000	$5 \cdot 10^{-4}$
steering gear	13000	$7.7 \cdot 10^{-5}$
tug	1300	$7.7 \cdot 10^{-4}$

4.5. The probability of an accident of a manoeuvring ship assisted by tugs at the port entrance, turning area or port basin

Such probability is determined for the least favourable emergency scenarios occurring in case:

- no reserve tug in a port standing by during manoeuvres of the examined ship,
- direction of allowable speed wind blowing towards the danger (the nearest port structure or moored ship),
- current from the stern (at port entrance or turning basin).

Given the above assumptions, the probability of a ship accident due to a tug failure at port entrance, turning area or port basin can be determined as follows:

$$P_{ah} = P_{ai} \cdot \lambda_h \cdot \Delta t \cdot I_r \cdot p_w \quad (21)$$

where

P_{ah} – probability of ship's accident due to a failure of one of the assisting tugs;

P_{ai} – maximum probability that the safe manoeuvring area will extend beyond the available navigable area of the tested ship for allowable speed of wind blowing towards the danger;

λ_h – failure rate of tug;

- A_T – mean time of passage through the tested fairway section or performed manoeuvre (port entry, turning, berthing);
- p_w – probability of wind occurrence with allowable speed and direction toward a danger.

5. The consequences of accidents on waterways

The consequences of accidents are defined as costs of:

- salvage operation after an accident,
- shipping losses related to the restriction of traffic on the waterway,
- repairs of ships involved,
- repairs of port infrastructure.

The acceptable annual consequences of accidents depend on the size and intensity of the traffic of tested ships on a specific waterway and type of cargo carried.

For a single ship passing through a waterway the acceptable annual consequences are adopted at the level of 20,000 USD (after revaluation) (Gucma L. 2009).

The acceptable consequences of accidents involving LNG tankers with cargo capacity of 100,000 m³ ÷ 220,000 m³ passing through port waterways (port entrance), with a frequency of 100 loaded ships per year, are adopted at one million USD per year (Report...2015).

The acceptable consequences of accidents of bulk carriers with a capacity of more than 50,000 DWT passing through port waterway, with a frequency of 100 entries of loaded ships per year are adopted at 250,000 USD (Gucma S., Ślącza W. 2019).

Taking into account the above assumptions referring to the port waterway system, at the annual rate of

100 ships with cargo capacity above 50,000 DWT, based on an analysis of literature data (Gucma S. et al. 2017, Gućma S., Ślącza W. 2019) the authors propose four-state scale of consequences that accounts only for economic safety – losses (Table 2).

It should be noted that when determining the scale of the consequences of specific accidents we need to take into account the conditions of emergency scenarios. These data do not concern ships carrying dangerous goods. In the case of LNG tankers, the annual frequency of passages can be limited by 50% (Report...2015). The analysis of accidents that may occur during ship's port manoeuvring in the waterway system and their consequences shows five general types of accidents, whose consequences (indicators of consequences) are determined differently:

- blocking of the waterway by a ship anchored in an emergency condition,
- grounding,
- hitting a port structure,
- hitting a moored vessel,
- collision with a moving ship.

The consequences of blocking the waterway by a ship anchored in an emergency condition depend on shipping losses related to the traffic restriction during the salvage operation (towing) and the costs of towing the ship in the emergency condition to its anchor/mooring position (outside the waterway system).

The consequences of grounding depend on such factors as: maximum kinetic energy of the ship at the instant of hull-seabed contact and allowable energy of safe contact with the bottom, at which the ship will refloat on its own. The indicator of the consequences can be represented in this form:

Table 2. Consequences scale considering economic safety

Scale of the consequences	1 insignificant	2 slight	3 moderate	4 significant
consequences (losses) [USD]	Up to 0.25 m No accident or accident S < 1	0.25 - 2.5 million Accident S < 1	2.5÷25 million Accident S ≥ 1	25÷50 million Accident S ≥ 2
	–towing –vessel traffic limitation	–towing –vessel traffic limitation –shipyard - up to three days	–towing –salvage operation –shipyard 3 to 10 days –repair of port infrastructure	–towing –rescue operation –shipyard - over one month –repair of port infrastructure

$$S_m = \frac{E(t)}{E_{dop}^m} \quad (22)$$

where

$E(t)$ – kinetic energy of the ship at the instant of the hull-seabed contact,

E_{dop}^m – allowable energy of safe ship-bottom contact at which the ship will manage to refloat.

Kinetic energy of the ship at the instant it contacts the bottom accounting for added mass is determined from the following relationship (Ślącza W. 1999):

$$E(t) = \frac{1}{2} M \left(1 + \frac{2T}{B}\right) V^2 \quad [Nm] \quad (23)$$

The speed of a ship at the instant of grounding (V) is determined depending on the ship speed during its manoeuvring on the waterway, its type, length and loading condition and the parameters of the available navigable area (e.g. available fairway width).

Using the simplified relationships we can determine the allowable kinetic energy at which a ship can refloat on its own as follows (Gucma S. et al. 2015):

$$E_{dop}^m = \frac{3 \cdot U^2}{L_{pp} \cdot B \cdot \gamma \cdot \mu \cdot tg \theta'} \quad [Nm] \quad (24)$$

The maximum pulling force required for ship refloating is a sum of the bollard pull of the ship and that of the tugs assisting the ship in manoeuvring in a given area.

$$U = U_s^{pal} + U_h^{pal} \quad [N] \quad (25)$$

where

M – ship's mass [kNs^2/m];

U – pulling force required for refloating [N];

γ – specific gravity of water [N/m^2];

μ – hull-bottom friction coefficient;

θ' – angle of the slope in relation to grounding ship's centre line.

Using approximate methods of solution, the bollard pull of a ship can be determined by one of the following empirical relationships:

$$U_s^{pal} = kf N_n 7220 [N] \quad (26)$$

where

N_n – total power of main engines [kW];

k – coefficient of pulling force use depends on the engine setting,

CN K = 1,

CN K = 0.3÷0.5 (mean 0.4),

f – empirical conversion factor depending on type of ship and propulsion:

cargo and passenger ships $f=0.005 \div 0.011$ (mean 0.008),

tugs (conventional propeller) $vf=0.010 \div 0.16$ (mean 0.013),

tugs (Kort nozzle) $f =0.017 \div 0.25$ (mean 0.021).

These consequences are calculated differently depending on the type of manoeuvre and the causes of an accident (Woodward J. Pitblado R. 2010). The differences consist in the adoption of various speeds of the ship running aground and the slope angle relative to the centre line of the ship running aground (Gucma S. et al. 2017).

The losses due to grounding (economic consequences) are estimated as the function of the indicator S_m and the conditions of an emergency scenario (Table 3).

Table 3. Grounding (scale of consequences)

Scale of consequences	1	1	2
Indicator of the consequences	$S_m < 1$	$S_m \geq 1$	$S_m \geq 1$
Conditions of emergency scenarios		soft bottom	hard bottom

The consequences of an unintended impact against an offshore-port structure or moored ship depend on such factors as maximum impact energy and allowable impact energy that will not damage the hull plating. The indicator of the consequences can be represented in this form:

$$S_u = \frac{E(t)}{E_{dop}^u} \quad (27)$$

where

S_u – indicator of the consequences of ship's impact on the structure, shore or moored vessel.

$E(t)$ – maximum kinetic energy of the ship at impact against an offshore/port structure or moored ship;

E_{dop}^u – allowable energy of an impact against an offshore/port structure that will not damage the hull plating.

The maximum kinetic energy of the ship at an unintended impact against an offshore/port structure or moored vessel is determined using the approximate relationship (Gucma S. et al. 2017):

$$E(t) = \frac{M \cdot u^2}{4} \quad [kNm] \quad (28)$$

where

M – ship's mass and added mass $[kNs^2/m]$;

u – ship's speed at impact (normal to the line of the structure or to moored ship side) $[m/s]$.

The speed of a ship at the instant of impact (u) is determined depending on the ship speed during its manoeuvring on the waterway, its type, length and loading condition and the parameters of the available navigable area (e.g. available fairway width).

The allowable kinetic energy of an impact against a structure or moored vessel can be estimated using the fender factors. The fender factor is the ratio of maximum reaction force to kinetic energy of the impact against berth or fender. If a berth is not protected by fenders, the equivalent factor can be adopted as equal to $k = 150 \text{ kN/kNm}$ (PIANC 2002). Knowing the allowable load of the hull (q) and approximate surface area of the ship-berth contact (f), we can determine the allowable impact energy:

$$E_{dop}^u = q \cdot f/k \quad [kNm] \quad (29)$$

where

q – allowable load on the hull, depending on the size and type of vessel $[kN/m^2]$; [PIANC 2002]

F – approximate surface area of ship-berth contact $[m^2]$;

k – fender factor $[kN/kNm]$.

The losses caused by ship's impact on a structure or moored vessel due to the deterioration of navigational conditions and the failure of technical equipment or assisting tugs are estimated as the function of the indicator S_u (Table 4).

Table 4. Ship's impact on a structure (scale of consequences)

The scale of consequences of impact on the structure	1	2	3
The scale of consequences of impact on a moored vessel	1	3	4
The indicator of the consequences	$S_u \leq 1$	$1 \leq S_u < 2$	$S_u \geq 2$

The consequences of collision with a ship in motion are the function of kinetic energy induced at the point of first contact (Gucma S. et al. 2017).

$$E_{K-I} = 0,5M_{sr}(V_{sr} \sin \beta)^2 - 0,5\left(\frac{M_{sr}^2(V_{sr} \sin \beta)^2}{M_{sr} + M_{su}(1 + C_{sr})}\right) \quad [Nm] \quad (30)$$

where

E_{K-I} – kinetic energy induced in the place of both hulls contact during a collision in a two-way fairway $[Nm]$;

M_{sr}, M_{su} – masses of the ships involved in a collision $[kNs^2/m]$;

C_{sr} – added mass coefficient of the striking ship;

β – impact angle of the striking ship in relation to the course made good of the struck ship $[^\circ]$;

V_{sr} – striking ship speed $[m/s]$.

The consequences of a collision of vessels manoeuvring in the fairway are calculated following this procedure:

- 1) determination of the impact angle β of the ship approaching the fairway in relation to the course made good of the ship on the two-way fairway or the calculation of the impact angle of ships approaching each other head-on or nearly head-on.
- 2) determination of the striking ship speed.
- 3) calculation of the depth of hull penetration in a ship struck by the other ship's bow (Zhang S. 1999; Kristiansen S. 2005):

$$L_p = 2,67 \ln E_k - 1,97 \ln \left(\frac{M_{sr}}{1000}\right) + 1,66 \quad (31)$$

where

L_p – depth of the hull penetration by the striking ship's bow $[m]$.

The above formula is the result of an analysis of numerical function models of the absorbed energy and penetration depth. The formula, based on the regression analysis, was proposed by Zhang (1999).

- 4) Calculation of the indicator of consequences of a collision of ships proceeding in a two-way fairway:

$$S_k = \frac{L_p}{L_{dop}} \quad (32)$$

where

S_k – consequences of a collision of vessels in the two-way fairway;

L_{dop} – distance between ship' side platings regulated by separate classification society regulations.

Polish Register of Shipping regulations for passenger and cargo vessels (except for tankers) concerning the spacing between plating of double skin hull stipulate that the adopted L_{dop} value shall not be less than 760 mm and need not be greater than 2000 mm. The consequences due to a collision of two ships in motion are estimated as a function of the angle of impact β , speed of the striking ship V_{sr} and the consequences indicator S_k (Table 5).

Table 5. Ship's collision (scale of consequences)

The scale of consequences	1	1	2	3
Indicator of the consequences		$S_k < 1$	$S_k \geq 1$	$S_k \geq 1$
Conditions of an emergency scenario	$\beta < 10^\circ$	$\beta < 10^\circ$ $v_{sr} \leq 4w$	$\beta < 10^\circ$ $V \leq 4w$	$\beta \sim 30^\circ$ $V > 4w$

It should be noted that the angle of impact $\beta < 10^\circ$ is adopted for collisions caused by the deterioration of navigational conditions during ships' passing on a two-way fairway, while the angle of impact $\beta \sim 30^\circ$ is adopted in collisions due to the jamming of the rudder on the side of the ship being passed.

In the presence of an operational VTS system, ship collisions are not expected in other manoeuvring situations.

6. Summary

The article presents the method of assessment of ship manoeuvring safety in the waterway system, using the concept of relative navigational risk.

The safety of ship manoeuvring in sea waterway systems requires the compliance with acceptable restrictions, called conditions of safe ship operation. The presented method is intended for the assessment of navigational safety when the conditions of safe operation of ships change:

- parameters of 'maximum ships' are increased,

- allowable hydrometeorological conditions are increased,

- minimum tug assistance is modified.

The navigational safety assessment when the conditions of safe operation of ships change in a given waterway system is conducted using two indicators: relative navigational risk and the difference of navigational risks.

The determined probability of accidents refers to the ship moving outside the available navigable area due to changes in navigational conditions, technical failure of the ship and tugs. The presented methods are used to calculate the probability for various types of waterways when ships are manoeuvring with or without tug assistance.

The accident consequences are defined as costs of salvage operation, commercial shipping losses related to the vessel traffic restriction, ship and waterway infrastructure repair costs. These consequences are determined for the following accidents:

- blocking of the waterway,

- grounding,

- striking a structure or moored ship,

- collision with another ship.

Presented relative navigational risk is a proposition of the authors for using it in the assessing of navigational safety of ships in waterway systems. Normally navigational safety assessment could be done when the conditions of safe operation of ships change in a given waterway system is conducted using two indicators: relative navigational risk and the difference of navigational risks. Relative navigational risk as the ratio of navigational risks of the passage through a given waterway system under various conditions of its safe operation, while differences of navigational risks can be used for the assessment of the navigational safety of the waterway system when the safe ship operation conditions are changed. A model of navigation safety management was built by authors on the basis of algorithms presented in article and concerning the relative risk and risk difference calculation.

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