

Andrzej Bąk · Stanisław Gucma ·
Marcin Przywarty

Safety of Navigation in Restricted Areas

Methods of Risk Estimation and Analysis

Synthesis Lectures on Ocean Systems Engineering

Series Editor

Nikolas Xiros, University of New Orleans, New Orleans, LA, USA

The series publishes short books on state-of-the-art research and applications in related and interdependent areas of design, construction, maintenance and operation of marine vessels and structures as well as ocean and oceanic engineering.

Andrzej Bąk · Stanisław Gucma ·
Marcin Przywarty

Safety of Navigation in Restricted Areas

Methods of Risk Estimation and Analysis

Andrzej Bąk
Navigational Department
Maritime University of Szczecin
Szczecin, Poland

Stanisław Gucma
Navigational Department
Maritime University of Szczecin
Szczecin, Poland

Marcin Przywarty
Navigational Department
Maritime University of Szczecin
Szczecin, Poland

ISSN 2692-4420 ISSN 2692-4471 (electronic)
Synthesis Lectures on Ocean Systems Engineering
ISBN 978-3-031-49531-1 ISBN 978-3-031-49532-8 (eBook)
<https://doi.org/10.1007/978-3-031-49532-8>

Originally published in Polish language by Wydawnictwo Naukowe

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

Preface

Navigational safety is the state of a marine traffic engineering system, related to accident-free conduct of a ship towards its destination, maintaining required movement parameters, i.e. it is the state of the system related to accident-free performance of specific manoeuvres in a restricted area.

The safety of navigation on sea waterways, particularly on port waterways, is the basic factor limiting the expansion of ports and operations of bigger ships in ports. Navigation risk is a criterion of navigational safety assessment allowing its accurate estimation in port waterways. Methods of navigation risk estimation and analysis is one of the major issues in shipping today.

The themes of this monograph include modern engineering problems of marine traffic engineering, focusing on what this discipline deals with: navigational safety assessment methods. These include:

- criteria of assessing navigational safety in restricted areas,
- navigation risk, as a complex criterion of navigational safety assessment in waterway systems,
- models of navigation risk determination used worldwide,
- conditions of safe operation of ships on waterways determined by using navigation risk,
- minimum safe tug assistance on port waterways and
- navigation risk management in waterway systems with a description of a computer program for model-based tests of navigational safety on Southern Baltic waterways.

Chapter 1 presents the criteria of navigational safety assessment used in restricted waters, focusing on navigation risk determined in various sea waterway systems. It provides the theoretical foundations for determining navigation risk for various types of port waterways, such as anchorage, fairways, port basins and systems combining various types of waterways.

Chapter 2 presents major models of navigation risk currently used worldwide. The described models are those recommended by the IMO, IALA, PIANC and models developed at the Massachusetts Institute of Technology and at the Maritime University of Szczecin.

Chapter 3 looks into methods of determining the conditions of safe ship operation on sea waterways using navigation risk criteria. The risk of moving outside the available navigable area is presented, an event that may occur due to the deterioration of navigational conditions or technical failures of key shipboard machinery and tugs. Also, methods of determining the minimum safe tug assistance are described for various types of port manoeuvres.

Chapter 4 presents a system of navigation risk management in open and restricted areas of the Southern Baltic. NEPTUN is a program for risk management dealing with large amounts of data stored on a server of the Maritime University of Szczecin. The user's computer contains an application allowing the use of data from the server.

This work has been done based on the results of tests conducted by the marine traffic engineering team at the Faculty of Navigation, Maritime University of Szczecin, led by professor S. Gućma, and on the results of up-to-date scientific research performed across the globe.

The said research team has worked out what can be termed Polish school of marine traffic engineering, whose accomplishments include about 50 books, more than ten post-doctoral degrees, dozens of doctoral degrees and one *honoris causa* doctorate in marine traffic engineering.

A number of solutions have been implemented, such as the development of optimal design assumptions for:

- ports of Police, Kołobrzeg, Łeba, Hel;
- the port of Ystad;
- ferry terminal in Świnoujście;
- LNG terminal in Świnoujście;
- currently executed modernisation of the Świnoujście-Szczecin fairway;
- newly designed container terminal in Świnoujście;
- number of port investment projects in Szczecin, Świnoujście and Gdynia.

The book is intended for:

- researchers dealing with marine traffic engineering, navigation, marine structures;
- designers of waterways and marine structures;
- waterway operators;
- specialists of ship operation, including maritime administration personnel;
- students who choose to specialize in marine traffic engineering, marine navigation, transport and offshore structure engineering.

Szczecin, Poland

Andrzej Bąk
Stanisław Gucma
Marcin Przywarty

Contents

1	Safety of Navigation in Restricted Areas	1
1.1	Conditions of Safe Operation of Ships in Restricted Areas	5
1.2	Criteria of Assessing Navigational Safety in Restricted Areas	8
1.2.1	Probability of Accident-Free Performance of a Specific Manoeuvre	9
1.2.2	Underkeel Clearance	10
1.2.3	Safe Manoeuvring Area	14
1.2.4	Kinetic Energy of Berthing Impact	16
1.2.5	Speed of Ship's Propeller Streams	19
1.2.6	Duration of Manoeuvre Execution	21
1.3	Navigation Risk as Complex Criterion of Navigational Safety Assessment in Restricted Areas	22
1.3.1	Probability of Accidents in Sea Waterways	25
1.3.2	Consequences of Accidents in Restricted Areas	32
1.4	Navigation Risk in Sea Waterway Systems	39
1.4.1	Navigation Risk on Various Types of Port Waterways	40
1.4.2	The Turning Basin, Port Basin (Turning Manoeuvre)	49
1.4.3	Port Basin (Berthing Manoeuvre)	50
1.4.4	Navigation Risk of the Port as a System of Various Types of Waterways	55
2	Models of Navigation Risk Used in Restricted Areas	57
2.1	Matrix Methods	59
2.2	Logical Tree Methods	59
2.2.1	Fault Trees	60
2.2.2	Event Trees	60
2.3	Simulation Methods	60
2.4	Model of the Navigational Risk Recommended by the IMO	63
2.4.1	Definition of the Problem	65
2.4.2	Identification of Hazards	66

2.4.3	Risk Analysis	68
2.4.4	Identification of Risk Control Methods	69
2.4.5	Cost–Benefit Assessment	70
2.4.6	Recommendations for Decision Makers	71
2.5	Model of Navigation Risk Recommended by the IALA	72
2.5.1	Qualitative Risk Assessment	72
2.5.2	Quantitative Risk Assessment	74
2.6	Model of Navigational Risk Developed by the Massachusetts Institute of Technology	82
2.7	Model of Navigation Risk Assessment Developed by the PIANC	86
2.8	Model of Navigation Risk Developed by the Maritime University of Szczecin	91
3	Conditions of Safe Ship Operation in Restricted Areas Determined by Navigation Risk Assessment Methods	99
3.1	Conditions of Safe Operation of Ships in Various Types of Port Waterways Determined by Using Navigation Risk	99
3.2	Conditions of Safe Operation of Ships Determined by Using Navigational Risk on Fairways	106
3.2.1	Risk of Moving out of Available Navigable Fairway Area Due to Deterioration of Navigational Conditions	107
3.2.2	Risk of Moving out of Available Navigable Fairway Area Due to Technical Failures of Machinery	119
3.2.3	Estimation of Navigational Risk on Fairways	127
3.3	Conditions of Safe Operation of Ships in Port Basins Determined by Using Navigational Risk	129
3.3.1	Risk of Moving out of Available Navigable Area of Port Basin Due to Deteriorated Navigational Conditions	129
3.3.2	Risk of Moving out of the Available Navigable Area of the Port Basin Due to Technical Failures of Shipboard Machinery or Tugs	132
3.3.3	Accident Risk During Berthing	134
3.4	Conditions of Safe Ship Operation Determined by Using Relative Risk Methods	135
3.5	Minimum Safe Tug Assistance in Ship Manoeuvres in Port Waterways	137
3.5.1	Minimum Safe Tug Assistance at Port Entrances and Basins	139
3.5.2	Tug Assistance in Approach Channels	143

4	Navigation Risk Management in Waterway Systems	147
4.1	Enhancing Waterway Safety	147
4.1.1	Methodology of Formal Safety Assessment Used in Risk Management Systems	148
4.1.2	General Assumptions of Risk Management System in Southern Baltic Waterways	151
4.1.3	Subsystem of Navigational Safety Management in Open Sea Areas	153
4.1.4	Subsystem of Navigational Safety Management in Restricted Areas	161
4.1.5	Module of Determining Safe Manoeuvring Area and Navigation Risk in Individual Sections of Restricted Area Waterways	174
4.1.6	Safety Management Program NEPTUN for Model-Based Research into Navigational Safety in Southern Baltic Sea Waterways	176
4.2	Working with the Safety Management System NEPTUN	179
4.2.1	Module of Calculating Safe Manoeuvring Area Width (Restricted Area)	180
4.2.2	Risk Calculation Module	180
4.2.3	Module of Trajectory Recommendations Based on Incident Analysis	180
4.2.4	Module of Legal Regulations Analysis	180
4.2.5	Electronic Navigational Chart	182
4.2.6	Display of Incidents	183
4.2.7	Display of Accidents	183
4.2.8	Risk Calculation	184
	Appendix	189
	References	203

Symbols

A_i	Area parameters (–)
A	Waterway subsystem (–)
b	Width between shores of inner fairway or channel (m)
B	Ship's breadth (m)
d	Width of safe manoeuvring area (m)
d_m	Manoeuvring width component of safe manoeuvring area or swept path (m)
d_n	Navigational width component of safe manoeuvring area or swept path (m)
d_p	Width of separation lane (m)
d_r	Reserve of manoeuvring area width (m)
$d_{(1-\alpha)}$	Safe manoeuvring area at confidence level $(1-\alpha)$ (m ²)
D	Width of available navigable area (m)
D_k	Fairway width at bottom (m)
D	Available navigable area (m ²)
E	Kinetic energy of ship (kNm)
E_{dop}	Allowable kinetic energy of ship (kNm)
F	Lateral windage (m ²)
F_n	Froude number (–)
h	Water depth (m)
h_F	Wave height (m)
h	Set of conditions related to tug assistance (–)
H_{st}	Aircraft (m)
H_i	Hydrometeorological parameters (–)
H	Vector of hydrometeorological conditions (–)
I	Number of navigational incidents (–)
I_R	Mean annual intensity of manoeuvres (year ^{–1})
I	Set of vessel traffic intensity (–)
KD_d	Course made good (°)
KR, Ψ	Heading (°)

KR_w, KR_p, KR_f	Direction of wind, current, waves ($^{\circ}$)
K	Subsystem of mooring facility (–)
l	Length of waterway (Nm)
L, L_c	Length overall (m)
L_{pp}	Length between perpendiculars [m] (m)
L_D	Bow-to-bridge distance (m)
m	Ship mass (kg)
m_{KDD}	Mean square error of course made good ($^{\circ}$)
m_{KR}	Error of course determination ($^{\circ}$)
M	Power of ship propulsion (kW)
M_i	Parameters of executed manoeuvre (–)
M_{st}	Power of bow thrusters (kW)
M_o	Circular error of position (m)
Nm	Nautical mile = 1852 m (Nm)
M	Set of conditions of safe operation of ships in waterway (–)
N_i	Parameters of position determination systems (–)
NR	True bearing ($^{\circ}$)
N	Navigational subsystem (–)
p_y	Directional error of position determination (m)
p_{yB}	Directional error of ship's side position (m)
p_{yD}	Directional error of ship's bow position (m)
P_{At}, P_w	Probability of accident (–)
q	Vessel traffic intensity (number of vessels per time unit) (1/h)
r	Arc radius of waterway bend (m)
R	Navigation risk (–)
R_{akc}	Acceptable manoeuvring risk (–)
R_i	Parameters of vessel traffic control system (–)
s	Determinant of consequences (–)
s_h	Stopping distance (Nm)
S	Consequences of accident (indicator) (–)
Q	Ship parameters (–)
t	Time (s)
T	Draft (m)
u_n	Ship's speed component on impact (m/s)
U	Bollard pull (kN)
V	Ship's speed (m/s)
V_p, V_w	Current speed, wind speed (m/s)
W	Number of navigational accidents (–)
W	Vector of conditions of safe operation of ships in waterway (–)
z	Visibility (Nm; m)
Z_i	Parameters of vessel traffic control system (–)

Z	Subsystem of traffic control (–)
Δ	Underkeel clearance (m)
Δh	Drop of water level (–)
$\Delta\Psi$	Angle of turn in bend (°)
α	Drift angle (°)
β	Leeway angle (°)
δ	Rudder angle (°)
v	Speed of propeller stream at bottom (m/s)
λ	Intensity of failures (1/h)
$\sigma, \sigma_o, \sigma_x, \sigma_y, \sigma_z$	Standard deviations (–)
φ, λ	Geographical coordinates (φ –latitude, λ –longitude) (°)
ω	Rate of turn (°/s)
τ	Maximum time interval between positions (s)



The safety of navigation is defined as the state of the ship-human-environment system, in which none of its elements due to certain reasons/causes threatens any other element of the system (Gucma et al., 2008). In shipping, the state of danger is caused by a marine accident, understood as an undesired event bringing damage and losses (material and human).

Navigational safety is a component of shipping safety (Urbański, 1994; Walczak & Hajduk, 1994), which apart from navigational dangers, also takes into account hazards related to fire, stability, intact stability, non-sinkability, cargo, etc.

Navigational safety includes all issues related to accident-free ship conduct from point A to point B of a sea waterway (Gucma, 2001). The term accident is to be understood as a navigational or manoeuvring accident, such as:

1. Grounding, broadly understood as unintentional contact of the hull, rudder or propeller with the bottom.
2. Damage to the hull through ship contact with the shore (collision with shore element at which the water depth is larger than the ship's draft).
3. Damage to offshore or port structure by ship's direct contact or as indirect effect of the propeller stream.
4. Collision with another ship moored to the berth or lying at anchor.
5. Collision with another vessel in motion.
6. Damage to a tug assisting the manoeuvring ship.
7. Damage to the floating seamark.

In the context of navigational safety, marine traffic engineering defines a restricted area as an area where the ship cannot manoeuvre in a free, unrestricted manner (Dzwonkowski et al., 2019). In the light of this definition, marine waterways also belong to restricted areas. Marine traffic engineers classify sea waterways depending on the type of manoeuvres that the ship performs: The following types of waterways and manoeuvres are distinguished (Gucma, 2001).

Types of waterway	Type of manoeuvre
1. Fairway:	– fairway passage
• straight section	
• bend	
2. Port entrance	– port entry manoeuvre
3. Turning basin	– turning manoeuvre
4. Port basin	
• berth approach	– berthing manoeuvre
• berth	– mooring, unmooring
5. Lock	– lock entry, exit and mooring
6. Anchorage	– anchoring manoeuvre

The sea waterway is adjusted to the navigation performed by specific types of vessels characterised by specific parameters. The basic condition of navigation on sea waterways is the safety of navigation, understood as the safety of a specific ship and its environment during manoeuvres in such areas, in view of the possibility of a navigational accident (undesired event causing damage and losses) (Gucma et al., 2008).

Navigation safety can be assessed by means of navigation risk (manoeuvring risk). Navigation risk is understood as the risk of ship accident during manoeuvring in a restricted area. The risk of manoeuvring for all types of waterways (i.e. manoeuvres performed on them) be presented as a function (Gucma, 2001; Gućma et al., 2013, 2015):

$$R_i = f(A_i, Q_i, N_i, H_i, M_i, I_i, Z_i) \quad (1.1)$$

where

R_i navigation risk in i th section of the waterway,

A_i area parameters,

Q_i ship parameters,

N_i parameters of position determination systems,

H_i hydrometeorological parameters,

M_i parameters of the manoeuvre,

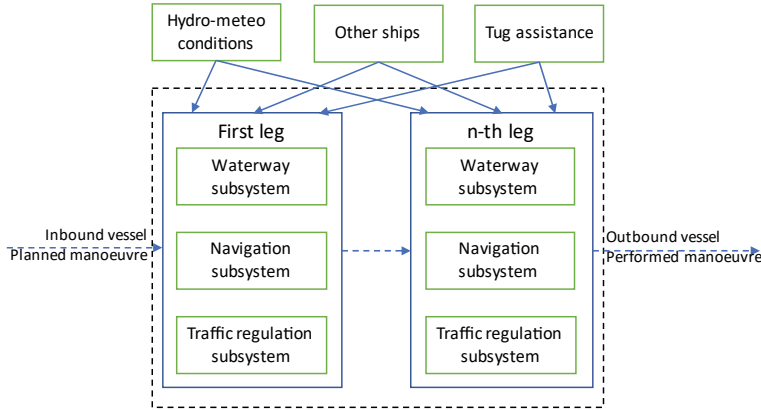


Fig. 1.1 A general model of the waterway system with n sections

I_i parameters of traffic intensity,

Z_i parameters of the traffic control system.

The function of navigation safety (navigation risk) R_i is a variable dependent on independent variables $A_i, Q_i, N_i, H_i, M_i, I_i, Z_i$, representing factors describing the system: ship–area–position determination system—prevailing hydrometeorological conditions—traffic intensity—traffic control system—manoeuvring tactics.

Types of sea waterway differ in the parameters of:

- area, such as minimum depth and available navigable area and the type of manoeuvres performed,
- position determination systems,
- traffic control system and waterway capacity.

The system of waterways in terms of marine traffic engineering is composed of a number of sections. Each of the isolated sections of the waterway is composed of three basic elements:

1. subsystem of the waterway characterised by the parameters of the area and the type of manoeuvre performed there;
2. system of ship position determination, i.e. navigational subsystem, characterised by the parameters of navigational systems used in it;
3. subsystem of traffic control is characterised by its parameters and waterway capacity.

A general model of the waterway system is presented in Fig. 1.1.

Every sea waterway has restrictions on the movement of vessels using it. These restrictions, called conditions of sea waterway operation or conditions of ship operation on a sea waterway, refer to:

- parameters of ships using the waterway;
- hydrometeorological conditions, where the traffic includes specific type ships;
- parameters of vessel traffic intensity;
- conditions of ship manoeuvring in the waterway, such as tug assistance or allowable speed.

Given the above restrictions, we can present the navigation risk in i th section of a specific waterway defined by the area, navigational and traffic control subsystems, as a simplified function:

$$R_i = f(Q_i, H_i, M_i, I_i) \quad (1.2)$$

with restrictions related to the waterway:

A_i const;

N_i const;

Z_i const.

The parameters of the sea waterway restrict the movement of ships using it.

The construction and operation of sea waterway and port area systems create two basic research problems (Gucma et al., 2015; PIANC, 2014):

1. determine conditions of safe operation of ships in the existing sea waterway system with known parameters, i.e. the state vector of safe ship operation conditions—a function of waterway system parameters:

$$W_i = F_1 \begin{bmatrix} A_i \\ N_{in} \\ Z_{im} \end{bmatrix} \quad (1.3)$$

2. determine basic parameters of the built or modified sea waterway system (waterway, navigational subsystem, traffic control subsystem). The parameters of the sea waterway system are a function of designed conditions of safe ship operation (vector of safe ship operation conditions):

$$\begin{bmatrix} A_i \\ N_{in} \\ Z_{im} \end{bmatrix} = F_2(W_i) \quad (1.4)$$

where

- W_i conditions of safe ship operation (state vector);
- A_i subsystem of i th section of the waterway, determining the area parameters and the type of manoeuvre performed (area subsystem);
- N_i subsystem of ship position determination, characterising parameters of navigational systems in use (navigational system);
- Z_i subsystem of traffic control, characterising its parameters and waterway capacity.

The general topic of this monograph includes the former of the two research problems, discussed in more detail in Sect. 1.1.

1.1 Conditions of Safe Operation of Ships in Restricted Areas

Sea waterway systems and conditions of safe operation of ships manoeuvring in such systems are defined depending on the type of waterway and performed manoeuvres (Gucma et al., 2015, 2017; Kulczyk & Winter, 2003; PIANC 1997). Therefore, sea waterway systems can be divided into:

- fairway (fairway passage manoeuvre) and port entrance (port entry manoeuvre);
- turning basin (turning manoeuvre), port basin (berthing and mooring manoeuvres), lock (entry, departure, mooring).

In each of these groups the conditions of safe ship operation are defined differently and, consequently, different methods of defining them are applicable.

Anchorage has been deliberately excluded from this grouping, as the conditions of safe operation are different than in the other waterways in relation to ship parameters and allowable hydrometeorological conditions.

Some systems, like seaports, are composed of a variety of waterways. A typical seaport is composed of the following types of waterways:

- anchorage;
- approach channel;
- entry into port;
- inner fairway (channel, river etc.);
- port basin, including:
 - turning basin;
 - berth approach;
 - berth.

Conditions of safe operation of ships in the waterway are described by a set of conditions of safe operation of a ‘maximum ship’ in i th section of the examined waterway (state vector). The set of conditions of safe ship operation on the waterway depends on the manoeuvre performed there. The following characteristic manoeuvres are distinguished, where conditions of safe operation of ships are defined differently:

- ships manoeuvring unassisted;
- ships manoeuvring with tug assistance.

Sea ferries make up a separate group, always manoeuvring on their own even in much worse hydrometeorological conditions compared to conventional ships.

Ships manoeuvring without tug assistance. Conditions of safe operation of ships manoeuvring unassisted are written as this set (Gucma et al., 2015):

$$W_i = [t_{yp}, L_c, B, T, H_{st}, V_i, M_{st}, H_i] \quad (1.5)$$

where

- t_{yp} type of ‘maximum ship’;
- L_c length overall of ‘maximum ship’;
- B breadth of ‘maximum ship’;
- T draft of ‘maximum ship’;
- H_{st} airdraft of ‘maximum ship’;
- V_i allowable speed of ‘maximum ship’ in i th fairway section;
- M_{st} power of bow thrusters (if any);
- H_i set of hydrometeorological conditions acceptable for ‘maximum ship’ in i th waterway section.

$$H_i = [d/n, \Delta h_i, V_{wi}, KR_{wi}, V_{pi}, KR_{pi}, h_{fi}, KR_{fi}, z] \quad (1.6)$$

where

- d/n allowable time of day (daylight or no restrictions);
- Δh_i allowable drop of water level;
- V_{wi} allowable wind speed in i th section;
- KR_{wi} wind direction restrictions (if any exist in i th section);
- V_{pi} allowable current speed in i th section;
- KR_{pi} restriction of current direction (if any);
- h_{fi} allowable wave height in i th section;
- KR_{fi} wave direction restrictions (if any);

Z minimum visibility.

Notably, main propulsion power (M) is deliberately ignored due to its relatively small impact on the conditions of safe operation of typical cargo ships.

Ships manoeuvring with tug assistance. Conditions of safe operation of ships manoeuvring with tug assistance are written as the set:

$$\mathbf{W}_i = [t_{yp}, L_c, B, T, H_{st}, V_i, n_h, U_h, M_{st}, \mathbf{H}_i] \quad (1.7)$$

where

n_h required number of tugs engaged in manoeuvring;

U_h required minimum total bollard pull of tugs engaged in manoeuvring.

In the case of berthing manoeuvres, the set of conditions of safe ship operation assumes the following form:

$$\mathbf{W}_i^{hc} = [t_{yp}, L_c, B, T, V_n, n_h, U_h, M_{st}, H_i] \quad (1.8)$$

where

V_n allowable berthing speed (normal to the shoreline).

Sea ferries. Conditions of safe operation of sea ferries manoeuvring in ferry terminal basins are written as the set:

$$\mathbf{W}_i^p = [L_c, B, T, H, F, M, M_{st}, H_p] \quad (1.9)$$

where

F lateral windage;

M power of main propulsion;

M_{st} power of bow thrusters;

$\mathbf{H}_p$ set of hydrometeorological conditions acceptable for the considered ferry in a specific ferry terminal.

$$\mathbf{H}_p = [V_{wd}, KR_w, V_p, KR_p, h_{fi}, KR_{fi}] \quad (1.10)$$