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MODELS AND METHODS OF OPTIMIZATION OF WATERWAY PARAMETERS

ABSTRACT

The article presents two general models of optimisation of waterway parameters as well as a number of detailed simulated methods of optimisation. It discusses a model with four limitations of manoeuvring safety and a model with one limitation that is a navigational risk.

1. INTRODUCTION

The problems discussed in this article concern the construction of a universal model of optimisation of waterway parameters. An idea underlying such a model is the possibility of its application to testing waterways, which consist of differently, arranged elements. For this reason the article deals with a classical port model comprising all basic elements of waterways in limited areas. These are as follows: anchorage, outer approach channel, port entrance with entrance heads and breakwater protecting them, system of inner fairways, lock, turning basin, port basin with conventional quays and ferry terminals.

Shipping in the areas of such a port should be safe for:

1. Vessels lying in port and at anchor.
2. Vessels performing such port manoeuvres as:
   - anchoring,
   - port entering/ leaving,
   - going along outer and inner fairways,
   - lock entering/ leaving,
   - turning,
   - berthing and unberthing at port quays and ferry terminals.

The article presents and analyses two general (universal) models of optimisation of waterway parameters which can be applied to solving optimisation problems of different elements (and their arrangements) of a model port.

In the first model the manoeuvring safety has been determined by the following conditions: size of manoeuvring basin, amount of water under keel, kinetic energy of vessel's impact on the quay, speed of screw race at bottom.

In the second model the manoeuvring safety has been determined by risk of performing a given manoeuvre (a navigational risk) which must be understood as a product of occurrence probability of a collision and the effects it causes.

The article also discusses some methods of optimisation of waterway parameters, and, which is worth mentioning, while there is a lack of universal methods, there are a lot of detailed simulation methods of optimisation used to examine basic elements of waterways. a number of these detailed methods have been worked out in the Institute of Sea Traffic Engineering of Szczecin Maritime University and have been presented by the author [Gucma, 2000, 1998, 1996].

2. GENERAL MODELS OF OPTIMIZATION OF WATERWAY PARAMETERS

Defining an objective function in the best models of waterway parameters as construction cost (reconstruction cost) of a given element (or elements) of a waterway, its marking and operation, the following initial assumptions have been accepted:

- a vessel tested manoeuvres in a limited area, where the position is defined in rectangular co-ordinates,
- an area tested is presented by means of a set $x \in \mathbf{X}$, $y \in \mathbf{Y}$, where the following subsets are distinguished:
    - of an area (water area) $\mathbf{X1} \subset \mathbf{X}$, $\mathbf{Y1} \subset \mathbf{Y}$
    - quay lines $\mathbf{X2} \subset \mathbf{X}$, $\mathbf{Y2} \subset \mathbf{Y}$
    - breakwater lines $\mathbf{X3} \subset \mathbf{X}$, $\mathbf{Y3} \subset \mathbf{Y}$,
- the co-ordinates describing the subsets are Cartesian products:
    - $\mathbf{X1} \times \mathbf{Y1}$,
    - $\mathbf{X2} \times \mathbf{Y2}$,
    - $\mathbf{X3} \times \mathbf{Y3}$,
- an area tested is for the vessels comprised in the set $i \in \mathbf{I}$. It can refer to both vessel's size (length, breadth, draught) and vessel's type,
- a vessel manoeuvring in the area tested can perform one of the manoeuvres comprised in their set $j \in \mathbf{J}$. It is a set of manoeuvre types performed in the area tested (manoeuvre type, number and power of the tugs used),
- vessel's tested can manoeuvre in the navigational conditions comprised in the set $k \in \mathbf{K}$ It concerns both hydrological and meteorological conditions (speed and direction of wind and current, waving, visibility, icing, state of water etc.) and navigational marking or state of other traffic in the area tested.

2.1 A general model of optimisation of waterway with four limitations of manoeuvring safety

In this model the manoeuvring safety is determined by the following conditions:

- size of a manoeuvring basin,

- amount of water under keel,
- kinetic energy of vessel's impact on the quay or any other hydrotechnical structure (e.g. breakwater heads limiting the port entrance),
- speed of a screw race at bottom or quay walls, or slopes of fairways.

Berthing safety of a vessel at quay or at anchor is determined by a wave height in this position.

Accepting the above assumptions and conditions, the objective function of optimisation of waterway parameters can be presented as follows:

$$Z = (a \cdot w + b \cdot t + c \cdot r + d \cdot l + e \cdot y + f \cdot s) \rightarrow \min \qquad (1)$$

where: a = $f_1(H_{xy})$, while (x, y) ∈ **X1** x **Y1,**

w = $f_2(D, H_{xy})$

b = $f_3(D, H_{xy})$

r = $f_4(D)$

d = $f_5(H_{xy}, E_{xy})$, while (x, y) ∈ **X2** x **Y2,**

l = $f_6(D)$

e = $f_7(H_{xy}, E_{xy})$, while (x, y) ∈ **X3** x **Y3,**

y = $f_8(D)$

f = $f_8(V_{xy})$, while (x, y) C **X1** x **Y1,**

S = $f_{10}(D)$

with the limitations:

$$D_{ijk} \subset D \qquad (2)$$

where: i ∈ **I,** j ∈ **J,** k ∈ **K**

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \qquad (3)$$

where: (x,y) ∈ **X1** x **Y1** – a subset of areas,

$$E_{ijkxy} \leq E_{xy} \qquad (4)$$

where: (x,y) ∈ **X2** x **Y2** – a subset of quay lines,
(x,y) ∈ **X3** x **Y3** – a subset of breakwater lines.

$$Vijkxy \leq V_{xy} \qquad (5)$$

where: (x,y) ∈ **X1** x **Y1** – a subset of areas.

$$F_{kxy} \leq F_{xy} \qquad (6)$$

where: (x,y) ∈ **X2** x **Y2** – a subset of quay lines:

where:

- Z - Cost of constructing (reconstructing) the port entrance, its marking and operation,
- a - Cost per piece of extracting $1m^3$ of spoil (it depends on bottom type),
- w - Amount of spoil in the process of dredging,
- b - Annual cost of dredging works and cost of maintaining hydrotechnical facilities and navigational marking,
- t - Expected duration of operating the waterway element,
- c - Cost per piece of constructing a navigational mark,
- r - Number of navigational marks in the system
- d - Cost per piece of a running metre of a given quay type together with fender facilities,
- l - Quay length,
- e - Cost per piece of a running metre of a given breakwater type or lock gates,
- y - Length of breakwater or lock gates,
- f - Cost per piece of protecting 1 m^2 of a given bottom type,
- s - Bottom area of a given protection type,
- D_{ijk} - a set of points defining a manoeuvring basin of i type of vessel, j type of manoeuvre and k alternative of navigational conditions,
- D - Accessible manoeuvring basin for a vessel meeting the conditions of acceptable depth (3) for each point p(x, y) of set D,
- I - a set of vessel types tested,
- J - a set of manoeuvre types tested in a given area,
- K - a set of characteristic navigational conditions,
- Δ_{ijkxy} - Safe amount of water under keel of i type of vessel in x, y point of the area for i type of manoeuvre and k alternative of navigational conditions,
- H_{xy} - Depth of area in x, y point,
- T_j - Draught of i vessel type,
- E_{ijkxy} - Kinetic energy of impact of i vessel type on quay (breakwater) in (x, y) point for j manoeuvre type and i k alternative of navigational conditions,
- E_{xy} - Permissible kinetic energy of vessel’s impact on (x, y) point of the quay (breakwater),
- F_{kxy} - Maximum wave height from k direction of wind in (x, y) point of the quay,
- F_{xy} - Wave height safe for the vessel berthing in (x, y) point of the quay.

2.2 A general model of waterway's optimisation with one limitation of manoeuvring safety

In this model the manoeuvring safety is determined by a navigational risk, and the berthing safety of a vessel at quay or at anchor is like in the above model, determined by a wave height in this position.

Accepting the above assumptions and conditions, the objective function is presented analogically to that in the first model (1):

$$Z = \left(a \cdot w + b \cdot t + c \cdot r + d \cdot l + e \cdot y + f \cdot s\right) \rightarrow \min \tag{7}$$

with the limitations:

$$\text{Rijkxy} \leq \text{Rdop} \tag{8}$$

Where i $\in$**I,** j $\in$**J,** k $\in$**K**, x $\in$**X,** y $\in$**Y**

$$\text{hFkxy} \leq \text{hFxy} \tag{9}$$

while:

(x, y) $\in$ **X2** x **Y2** – is a subset of quay lines,

where: R_{ijkxy} – a risk of performing j manoeuvre type by i vessel type in k alternative of navigational conditions in x, y point of the area,
R_{dop} – acceptable navigational risk.

A navigational risk is defined as a product of probability of collision accurrence and the effects it causes during a given manoeuvre [3], where a manoeuvre is to be understood as a movement process of a given vessel type an a specified waterway type in specified navigational conditions. The definition is additionally completed by relative frequency of performing a given manoeuvre and it can be presented in the following form:

$$R_{ijkxy} = I_{ijkxy} \cdot P_{ijkxy} \cdot S_{ijkxy} \tag{10}$$

where: I_{ijkxy} – mean annual intensity of performing j type of a manoeuvre in a specified area defined by means of (x, y) co-ordinates by i vessel type in k navigational conditions,
P_{ijkxy} – probability of collision occurrence while performing j type of a manoeuvre by i vessel type in k navigational conditions in x, y point of the area.
S_{ijkxy} – the effects caused by the collision of i type of the vessel performing j type of a manoeuvre in k navigational conditions in x, y point of the area.

3. DETAILED METHODS OF OPTIMIZATION OF WATERWAY PARAMETERS

The exiting detailed methods of optimization of waterway parameters are simulation methods. They refer to optimization of specific elements of waterways or their specified arrangement. The methods have been worked out on the basis of a model with four limitations of manoeuvring safety. At the moment there are also carried out some works on constructing methods based on a model with another limitation of manoeuvring safety and the research results are presented here as well.

3.1 Detailed methods of optimization constructed on the basis of a model with four limitations of manoeuvring safety

Below there are presented some simulation methods of parameter optimization for the following sections (elements) of waterway:

1. Turning basins
2. Fairways
3. Ferry Terminals
4. Port basins
5. Port entrances
6. Locks.

Methods 1÷ 5 have been worked out by a team of sea traffic engineering of Szczecin, Maritime University, method no. 6 by a team of scientists of Delft University.

3.1.1 A simulation's method of optimization of turning basin parameters.

The objective function is presented as follows:

$$Z = (a \cdot w + b \cdot t) \rightarrow \min \tag{11}$$

with the limitations

$$D_{ijk} \subset D \tag{12}$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \tag{13}$$

where: $(x,y) \in \mathbf{X1} \times \mathbf{Y1}$ – a subset of areas.

In a practical method of optimization of turning basin parameters the limitations are presented in the following form [4,5]:

$$R^{s}_{\alpha ijk} \leq R^{s}_{\alpha} \tag{14}$$

$$R^{h}_{\alpha ijk} \leq R^{h}_{\alpha} \tag{15}$$

in bearing divisions $\alpha = 1^0,...,360^0$, where:

- R^s_α - a minimum leading radius of a turning basin for safe depth at bottom (h_s) for vessels,
- R^h_α - a minimum leading radius of a turning basin for safe depth at bottom (h_s) for tugs,
- $R^s_{\alpha ijk}$ - a leading radius of a safe manoeuvring area in the turning basin for i vessel type, j manoeuvre type and k alternative of navigational conditions at 95% of confidence level,
- $R^h_{\alpha ijk}$ - a leading radius of a safe manoeuvring area in the turning basin for tugs for i vessel type, j manoeuvre type and k alternative of navigational conditions at 95% of confidence level.

The values $R^s_{\alpha ijk}$ and $R^s_{\alpha ijk}$ are defined on the basis of simulation research using real time models carried out for maximum operated vessel types at different existing speeds as well as current and wind directions. The research is carried out in sets of voyages (simulation manoeuvres) of a credible number for different navigational conditions.

3.1.2 A simulation's method of optimization of fairway parameters.

The objective function can be presented as follows:

$$Z = (a \cdot w + b \cdot t + c \cdot r) \rightarrow \min \qquad (16)$$

with the limitations

$$D_{ijk} \subset D \qquad (17)$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \qquad (18)$$

where (x, y) ∈ **X1** x **Y1** – a subset of areas.

In practice the simulation method of optimization of fairway parameters takes advantage of models of real time and limits itself to defining widths of traffic lanes for subsequent points of a fairway axis (the distance between points is usually 10 m). The width of a traffic lane is specified to the right and left of a fairway axis, and the limitations are presented as follows [4,5]:

$$B_{pijkn} \leq B_{pn} \qquad (19)$$

$$B_{lijkn} \leq B_{ln} \qquad (20)$$

where: B_{prj}; B_{ln} – accessible width of n point of a fairway axis to the right (p) and to the left (l) from the fairway axis for its n point,

B_{pijkn}; B_{lijkn} – the width of right (p) and left (l) traffic lanes of i vessel and j vessel manoeuvre type for k navigational conditions in a point of fairway axis.

Width of traffic lanes is defined by means of simulation tests using the method of real time for maximum vessels to be operated in different navigational conditions. The tests are carried out in sets of voyages of credible number, for which there are specified (after statistical processing of results) values B_{pijkn} i B_{lijkn} calculated on the level of 95% of confidence. The method is a two-level one [ ] where, on the first level there are specified rail shapes, and then bank effect does not take place. After deciding about rail shape, on the second level. There are defined its detailed parameters and then bank effect forces start working again.

3.1.3 Simulation's methods of optimization of ferry terminals and port basins

The objective function can be written as follows:

$$Z = (aw + b \cdot t + c \cdot r + d \cdot l + f \cdot s) \rightarrow \min \tag{21}$$

with the limitations:

$$D_{ijk} \subset D \tag{22}$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \tag{23}$$

$$V_{ijkxy} \geq V_{xy} \tag{24}$$

where, in both above cases:

$(x,y) \in$ **X1** x **Y1** – a subset of areas.

$$E_{ijkxy} \leq E_{xy} \tag{25}$$

where: $(x,y) \in$ **X2** x **Y2** – a subset of quays.

In practical methods of parameter optimization of ferry terminals and port basins the limitations are presented as follows [4,5]:

$$B_{pijkn} \leq B_{pn} \tag{26}$$

$$B_{lijkn} \leq B_{ln} \tag{27}$$

$$E_{ijkqm} \leq E_{qm} \tag{28}$$

$$V_{ijkxy} \leq V_{xy} \qquad ((x, y) \in \mathbf{X1} \text{ x } \mathbf{Y1}) \tag{29}$$

where: n – points of arbitrarily selected area axis(one or more),
q – quay number,
m – line point of q quay,
E_{ijkqm} – kinetic energy of impact of i vessel type for j manoeuvre type in k navigational conditions on m point of q quay calculated at 95% of confidence level using gamma distribution,
E_{qm} – permissible kinetic energy of vessel's impact on m point for q quay.

They are 2-level methods, where on the basis of research on level 1 it is possible to define terminal or area arrangement. On this level, quay reaction forces do not work at all or work partly. On level 2 the research is done for new arrangement of terminals or areas (defined on level 1) with quay reaction forces working. On this level, limitation (28) and (29) are examined. There is also defined kinetic energy of vessel's impact on the quay taking into consideration the vessels berthed and speed of screw race.

3.1.4 A simulation method of optimization of port entrance

The objective function can be written here as follow [6]:

$$Z = \left(aw + b \cdot t + c \cdot r + e \cdot y\right) \rightarrow \min \qquad (30)$$

with the limitations

$$D_{ijk} \subset D \qquad (31)$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \qquad (32)$$

where: (x, y) ∈ **X1** x **Y1** – a subset of areas,

$$E_{ijkxy} \leq E_{xy} \qquad (31)$$

where: (x, y) ∈ **X3** x **Y3** – a subset of breakwaters,

$$F_{kxy} \leq F_{xy} \qquad (32)$$

where: (x, y) ∈ **X2** x **Y2** – a subset of quays.

In a practical method of optimization of port entrance the limitations are presented as follows [6]:

$$B_{pijkn} \leq B_{pn} \qquad (33)$$

$$B_{lijkn} \leq B_{ln} \qquad (34)$$

$$E_{ijko} \leq E_o \qquad (35)$$

$$F_{kq} \leq V_q \qquad (36)$$

where: o – line point of breakwater,
E_O – permissible kinetic energy of vessel's impact on o point of the breakwater,
F_q – wave height safe for a vessel berthing at q quay.

This is a 2-level method where, on level 1, there is initially defined an entrance shape meeting the safety criterion of the vessels lying in port (limitation (36)). Level 1 also comprises an expected movement of rubble in terms of siltation of port entrance. There are a few alternatives selected on this level. On level 2, there is selected the most profitable alternative of an entrance shape out of the alternatives defined on level I. It is followed by carrying out the modification of its shape. On this level, limitations (33), (34), and (35) were used. Values B_{pijkn}, B_{lijkn} and E_{ijko} have been defined by means of simulation methods of real time.

3.1.5 A simulation method of optimization of lock parameters

The objective function can be written down as follows:

$$Z = \left(aw + b \cdot t + d \cdot l + e \cdot y + f \cdot s\right) \tag{37}$$

with the limitations

$$D_{ijk} \subset D \tag{38}$$

$$\bigwedge_{p(x,y) \in D} \Delta_{ijkxy} \geq H_{xy} - T_i \tag{39}$$

$$V_{ijkxy} \leq V_{xy} \tag{40}$$

where: $(x, y) \in \mathbf{X1} \times \mathbf{Y1}$ – a subset of areas.

$$E_{ijkxy} \leq E_{xy} \tag{41}$$

where: $(x, y) \in \mathbf{X2} \times \mathbf{Y2}$ – a subset of quay,
$(x, y) \in \mathbf{X3} \times \mathbf{Y3}$ – a subset of lock gates.

In practice the method used is a 2-level are [Boogard et all, 1998], where, on level 1, there are defined lock dimensions (limitation (38) and (39)). The research on this level is carried out using simulation methods of non-real time. On level 2 the research is done for lock arrangement specified on level 1. On this level the limitations (40) and (41) are tested, and there is also defined kinetic energy of vessel's impact on the quay including the vessels berthed there and speed of screw race. The research on level 2 is carried out in real time. There is also a practical simulation method of optimization of lock parameters using only simulation models of real time [DeRouck et all, 1998].

3.2 Detailed methods of optimization constructed on the basis of a model with one limitation of manoeuvring safety

The attempts at working-out the method were undertaken by the team of sea traffic engineering of Maritime University of Szczecin during designing works connected with modernising a part of the fairway of Szczecin – Świnoujście from entrance heads of the port of Świnoujście to Szczecin Transgression. There was worked out a 2-level simulation method of real time.

On level 1, on the basis of the results of simulation tests, there is defined an initial shape of the area while using the following limitations;

$$B_{pijkn} \le B_{pn} \tag{42}$$

$$B_{lijkn} \le B_{ln} \tag{43}$$

The limitations are similar to the ones in detailed methods of optimization constructed on the basis of model with four limitations of manoeuvring safety. On the basis of the results on this level, there are carried out hydrological tests (as required) and there is created an initial concept of the undertaking.

On level 2 there are carried out simulation tests in real time in the area specified during an initial designing project. On the basis of the test results and using are limitation of manoeuvring safety:

$$R_{ijkxy} \le R_{dop} \tag{44}$$

it is defined an optimum shape of the area tested. Fig 1 presents an optimum shape of the fairway, calculated by means of the above method, at the bottom on turning point of Mielin on Świnoujście – Szczecin fairway depending on the effects of vessel's entering the fairway shape (s) and an annual intensity of traffic (I). The effects of vessel's grounding (a bank i.e. fairway slope) mainly depend on vessel's parameters and her speed.

4. CONSTRUCTIONS

1. Out of the two general models of optimization of waterway parameters presented in the article the one with one limitation is a more modern model because it takes into account collision effects and traffic intensity. It seems that in near future it will be widely used.
2. Detailed simulation methods of optimization working in non-real time are far cheaper than the methods working in real time. The methods can be used directly by designers without forming special research teams and carrying out long-term research. At the moment there are intensive works carried out on constructing such methods.

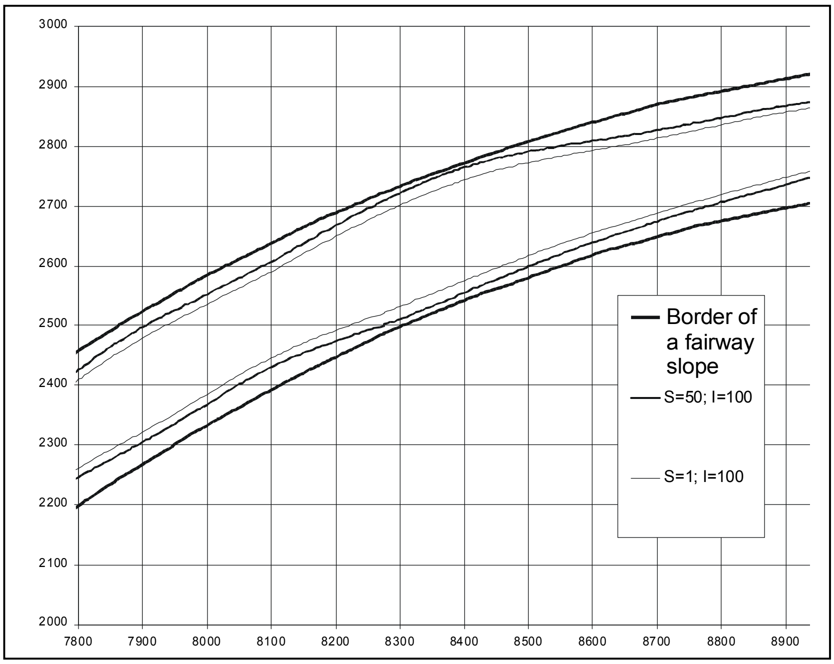

Fig. 1. Minimum safe width of the fairway ot bottom of Mielin bend (total series of 45 trials) depending on collision effects (S) and traffic density (I).

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