Methods of waterway and ship parameters optimization, their limitations and criteria

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Abstract

The article describes methods of marine traffic engineering used for restricted areas.

These methods have been developed at the Institute of Sea Navigation, Szczecin Maritime University. Their credibility depends mainly on criteria and limitations used.

To determine the parameters of waterways a number of simulation optimization methods have been applied depending upon area type, mainly fairways, turning basins and harbour basins. The method of ship parameters optimization, in turn, is concerned only with ships which in ports manoeuvre by themselves, such as sea ferries or river/channel ferries, designed for specific ports.

1 Introduction

Simulation methods of waterway and ship parameters optimization take their roots in general simulation methods. The latter consist in computing parameters of waterways or ships on the basis of the statistically processed results of simulation studies which, in turn, depend on performing a series of trials (passings) of a reliable number for the examined version of waterway or a specific ship. A disadvantage of this method is that only specific solutions imposed by the designer are examined. Simulation methods of waterway or ship parameters optimization allow to avoid the short-
comings of the traditional simulation method and determine optimal parameters of a waterway or ship for the set conditions.

The reliability of these methods mainly depends on the quality of models used, criteria and limitations. This article presents limitation models currently used in the methods of waterway and ship parameters optimization.

2 Simulation methods of waterway parameters optimization

The staff at the Sea Navigation Institute in Szczecin have developed simulation methods of parameter optimization for the following types of waterways:
- turning basins [3]
- fairways [3]
- ferry terminals [2]
- multi-berth port basins [1,4].

This paper presents simulation methods of fairway and port basin optimization. In the case of parameters optimization of fairways and their navigational aids the objective function can have this form:

\[ \text{Min. } Z = a \cdot k + b l + cm \]  

where:

\[ k = f_1(H_j), \ j = 1,\ldots,n \]

\[ l = f_2(H_j), \ j = 1,\ldots,n \]

with limitations connected with the fulfillment of the basic shipping safety criterion:

\[ h_j \leq H_j , \ j = 1,\ldots,n \]

where:

\( Z \) - cost of building a navigational system and fairway plus their maintenance,
\( k \) - quantity of spoil excavated while dredging
\( a \) - unit cost of dredging 1 m³ of spoil,
\( l \) - anticipated time of fairway operation,
\( b \) - annual cost of maintaining a fairway and navigational system,
\( m \) - number of navigational marks (beacons, buoys) in the system,
\( c \) - unit cost of a navigational mark,
\( H_j \) - accessible width of the j-th axis point of a fairway in the bottom for safe depth,
\( h_j \) - width of swept path at the j-th point of the fairway axis at 95% confidence level.
The widths of swept paths are determined from simulation research for the maximum ship expected to be in operation, various visibility conditions and various directions and speeds of wind and current (their respective distributions). The research is done in series of passings of a reliable number; their results are statistically processed to determine the value $h_{ij}$ - width of swept path at 95% confidence level in the $j$-th point of the fairway axis for $i$-th version of the navigational system and markings.

This investigation is executed in two stages. The first stage excludes the action of bank forces (unrestricted navigation area). After establishing the fairway shape at stage 1, stage 2 of the investigation is carried out including the bank reaction for an established fairway shape. Fig. 1 shows an example of traffic lane width for two versions of navigational markings at Zakole Mankow (Mankow Bend), part of the Szczecin-Swinoujscie fairway [2,3]:

- version 1 assumes the existence of one beacon (No 1)
- version 2 assumes the existence of two beacons (No 2 and 3).

In the case of parameters optimization for multi-berth port basins the objective function can be written as:

$$\text{Min } Z = f \left( H_j, A_l, B_k, C'_k \right)$$

with these limitations:

- $h_{ij} \leq H_j \quad (j = 1, ..., m; \ i = 1, ..., n)$
- $e_{lj} \leq E_l \quad (l = 1, ..., o; \ i = 1, ..., n)$
- $v_{ki} \leq V_k \quad (k = 1, ..., p; \ i = 1, ..., n)$

where:

- $Z$ - costs of building a two-berth basin,
- $H_j$ - accessible width of a manoeuvring area in the bottom for $j$-th point of a theoretical basin axis,
- $A_l$ - length of individual quays having specific strength parameters and fenders for $l$-th point of the quay,
- $B_k$ - depth at $k$-th point of the manoeuvring basin,
- $C'_k$ - parameters of bottom strengthening at $k$-th point of the manoeuvring basin,
- $h_{ij}$ - swept path width at $j$-th point of a theoretical basin axis for $i$-th function of the terminal, at 95% level of confidence,
- $E_l$ - critical energy of the impact of a ship hitting a quay resulting from the strength of the quay and ship hull and from the selection of fenders for $l$-th point of the quay.
\( e_{ij} \) - kinetic energy of the impact on \( i \)-th point of the quay and \( j \)-th terminal function at 95 % level of confidence,

\( V_k \) - critical speed of the propeller race (current) at the bottom resulting from the type of ground and bottom strengthening at \( k \)-th point of the manoeuvring area,

\( v_{ki} \) - propeller race speed at the bottom at \( k \)-th point of the manoeuvring area for \( i \)-th terminal function at 95 % level of confidence.

Quantities \( h_{ij} \), \( e_{ij} \), \( v_{ki} \) are determined by simulation research at 95 % level of confidence at both stages. The scope of these stages depends on an assumed model of terminal operation, where the following two models of operation are distinguished:

- one function of the basin is predominant over the others (priority of one of the berths),
- functions of the port basin are equally important.

This article discusses only the former model of port basin operation.

In stage 1 the simulation is performed for preliminarily established arrangement of basins with the reaction of bank forces excluded. The investigation is carried out exclusively for the basic terminal function at assumed hydrometeorological and operating conditions. At this stage an arrangement of a port basin is defined for which this condition has to be met:

\[ h_{ij} \leq H_j \quad (i = 1; j = 1, \ldots, m) \]

At stage 2 the new basin arrangement is examined with bank forces reaction included. All terminal functions are investigated in various hydrometeorological conditions for which the values of kinetic energy \( e \) and propeller race speeds \( v \) are determined. From these values allowable terminal operating conditions are determined. These are:

- maximum size of ships for a secondary function of the terminal,
- maximum hydrometeorological conditions for particular functions,
- indispensable number and output of tugs for particular functions etc.

This method was used for the designing of port basin parameters of the Pomeranian Fuel Terminal at Swinoujscie [1], whose traffic lanes and the basin arrangement upon the completion of stage 1 are shown in Fig. 2.

Basic limitations applied in simulations by waterway parameters optimization methods are these:

- limitation of swepth path width
  \[ h_j \leq H_j \]

- limitation of impact energy of a ship hitting the quay
  \[ e_i \leq E_i \]

- limitation of propeller race speed at the bottom
These limitations satisfy the safety conditions for ships and hydro-technical structures when a manoeuvre is carried out (turning, fairway passage, mooring etc.). The values $h, e, v$ are determined on the basis of results of the simulation research at 95% level of confidence. The swepth path width for $j$-th point of the theoretical basin axis is calculated according to this relation:

$$h_j = h_{ji} + c\delta_{ji} + h_{jp} + c \cdot \delta_{jp}$$

where:

- $h_{ji}$ - average of maximum distances of ship's extremes to the left of the axis at its $j$-th point
- $h_{jp}$ - average of maximum distances of ship's extremes to the left of the axis at its $j$-th point,
- $\delta_{ji}, \delta_{jp}$ - standard deviations from maximum distances of ship's extremes to the left and right of the axis at its $j$-th point,
- $c$ - factor determining a level of confidence.

The random variable is the maximum distance of the ship's extreme points to the left or right from the theoretical fairway axis ($h_{ji}, h_{jp}$); the model best describing this variable is a normal distribution (Fig. 1,2) [5]. Kinetic energy of the ship impact on the $l$-th point (range) of the quay is calculated at 95% level of confidence. While calculating one should use a gamma distribution as an optimal model describing the random variable, i.e. kinetic energy of the first impact released on the quay. This energy for each simulated mooring is calculated from this relation:

$$e = \frac{1}{2} m u_0^2 \left( 1 - \frac{a^2}{k^2 + r^2} \right) - m u_0 \omega_0 \frac{k_1 \cdot a}{k_2 + r^2} + \frac{1}{2} m \omega_0^2 \frac{k_2 \cdot r^2}{k_2 + r^2}$$

where:

- $m$ - ship's virtual mass,
- $u_0$ - linear speed of the ship,
- $\omega_0$ - angular speed of the ship,
- $r, a, b$ - indicators describing the geometry of ship's approach to the quay.

The speed of propeller race over the bottom at $k$-th point of the manoeuvring area is calculated at 95% level of confidence with a normal distribution as a statistical model (Fig. 3.) [7]. The random variable is the
maximum propeller race speed at the bottom in a particular discrete area for a separate simulated passage (mooring manoeuvre), calculated according to this relation:

\[ V_{\text{max}} = V \cdot S_e \left( \frac{d}{h_p} \right) \]  

(5)

where:

- \( V \) - propeller race speed in direct vicinity of the propeller plane,
- \( d \) - propeller diameter,
- \( h_p \) - distance of the propeller shaft from the bottom,
- \( S_e \) - empirical coefficient.

### 3 Simulation methods of ship parameters optimization

The method presented below refers only to ships capable of port manoeuvres by themselves, such as sea ferries and channel/river ferries. It comes down to the determination of parameters of an optimal ship for a particular area. The requirement these ships are expected by shipowners to meet is the maximum profit gained within a specified operation time with the building costs taken into account. It is an economic problem going beyond the interest of engineers; nevertheless, putting the aspects of transport economics aside we can formulate the task these ships have to face as follows: maximization of cargo carrying capacity at minimum construction costs for specified hydrometeorological conditions and ensuring an assumed safety standard.

To determine optimal parameters of these ships for a specified port a two-stage simulation method of optimization has been applied.

In the first stage maximum dimensions of a ship are established such that they allow her to enter the port safely at the extreme hydrometeorological conditions assumed by the shipowner and with other parameters assumed to be standard

\[ \text{Max} \mathcal{L} = (L, B, T, F_{\text{now}}) \]  

(6)

with the limitations:

\[ T \leq H_{\text{min}} + \Delta T \]

\[ L \leq L_{\text{crit}} (W, m_{sr}, N_{sr}, m_{ss}, N_{ss}, F_{\text{now}}) \]

\[ \frac{B}{L} = K \]
where:

\( £ \) - ship's net capacity,
\( L, B, T \) - length, breadth and draft of the ship,
\( H_{min} \) - minimum manoeuvring area depth,
\( \Delta T \) - under-keel clearance,
\( W \) - extreme hydrometeorological conditions,
\( m_{sr} \) - number of propellers,
\( N_{sr} \) - output at propellers,
\( m_{ss} \) - number of thrusters,
\( N_{ss} \) - power of thrusters,
\( F_{man} \) - side surface of a ship's manoeuvre,
\( L_{bez} \) - safe length of the ship.

The safe ship's length \( (L_{bez}) \) is determined by the method of subsequent approximations, \((2 \div 4)\) where simulations are realized for a number of ships with length \( L_{bez}^1, L_{bez}^2, L_{bez}^3, L_{bez}^4 \) and standard parameters matched to this length. Stage 1 results in establishing \( L, B, T, F_{man} \) as maximum safe quantities for assumed hydrometeorological conditions and standard solutions of the other parameters. In stage 2 the objective function is

\[
\text{Min } Z = f_i (m_{sr}, N_{sr}, m_{ss}, N_{ss}, F_{st}, t_{st})
\]

with the limitations:

\[
H_j \geq h_j (m_{sr}, N_{sr}, n_{sr}, t_{sr}, m_{ss}, N_{ss}, F_{st}, t_{st}) \quad (j = 1, \ldots, m; i = 1, \ldots, n)
\]

\[
E_l \geq c_l (m_{sr}, N_{sr}, n_{sr}, t_{sr}, m_{ss}, N_{ss}, F_{st}, t_{st}) \quad (l = 1, \ldots, \sigma; i = 1, \ldots, n)
\]

\[
V_k \geq v_k (m_{sr}, N_{sr}, n_{sr}, t_{sr}, m_{ss}, N_{ss}, F_{st}, t_{st}) \quad (k = 1, \ldots, \rho; i = 1, \ldots, n)
\]

where:

\( Z \) - ship's building cost,
\( t_{sr} \) - type of propeller,
\( n_{sr} \) - propeller revolutions,
\( F_{st} \) - surface of rudder(s),
\( t_{st} \) - type of propeller,
\( H_j \) - accessible width of a manoeuvring area in the bottom for \( j \)-th point of a theoretical basin axis,
\( E_l \) - critical energy of the impact of a ship for \( l \)-th point of the quay,
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\( V_k \) - critical speed of the propeller race at k-th point of the manoeuvring area

\( h_{ji} \) - swept path width at j-th point of a theoretical basin axis for i-th version of ship's parameters at 95 % level of confidence,

\( e_{ii} \) - kinetic energy of the impact on l-th point of the quay and i-th version of ship's parameters at 95 % level of confidence,

\( v_{ki} \) - propeller race speed at the bottom at k-th point of the manoeuvring area for i-th version of ship's parameters at 95 % level of confidence.

Quantities \( h_{ji} \), \( e_{ii} \), \( v_{ki} \) are determined by simulations where the number of investigated versions is established upon consulting the naval architect.

The method was used for determining the parameters of the m/f Polonia as the optimal ferry for Ystad; additionally, extreme hydrometeorological conditions for her operation in the ports of Ystad and Swinoujscie were defined [6,7].

4 Conclusions

The article presents:
- Simulation methods of waterway parameters optimization. The methods apply to various types of waterways,
- Simulation method of ship parameters optimization. The method applies to ships manoeuvring by themselves in one particular port.
- Model of limitations satisfying safety conditions for ships and hydrotechnical structures.

It seems worthwhile to continue this direction of research, particularly into the methods of ship parameters optimization as they are not known well and the reliability of limitations satisfying the safety of ship and hydrotechnical structures.

References


6. „Navigational Analysis of Enterens and Port Manouvres in the Port of Ystad for a Newly Designet Universal Ferry (Ystadmaks)”. Maritime University, Szczecin 1993.

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Figure 1: Swept path width for two versions of navigational marking of Mankow Bend (Zakret Mankow).
- version with 1 beacon.
- version with 2 beacon.
Figure 2: Port basin at the Pomeranian Fuel terminal at Swinoujscie after the first optimization stage.
Figure 3: Speeds of propeller races of the m/f Polonia mooring in the Ferry Terminal at Swinoujscie.