This article introduces a model providing an assessment of interdependence of the marine traffic and dredging activity in a port’s areas. This assessment in turn enables to optimize the time schedule of dredging works by coordinating them with a given schedule or with the random pattern of ship’s arrivals. The effectiveness of this type of project (dredging works) depends to a great extent on the proper analysis of the factors hindering the implementation of the project, such as: the vessels traffic, and uninterrupted operation of port terminals. For a better understanding of the problem, the article describes only correlation between dredging works and vessels calling at the harbor. Full form of this issue should describe the interference of the total ship's traffic in port areas, i.e. arrivals and departures. That model is currently under construction and will be described in the following article.

Keywords: dredging, modeling, marine traffic.

INTRODUCTION

Ports are a very important elements of transportation networks, which strongly influence the efficiency of freights handling. Port productivity greatly depends on proper exploitation and unhindered access to the terminals. That way ports must maintain its operability all the time, since any small break would send a heavy shockwave along the whole delivery network connected to it. On the other hand, the port needs to develop constantly to comply with the ship owner’s demands to introduce vessels of permanently growing size and handling them in the shortest time possible. This contradiction boosts the importance of the investment program as a part of port management, in order to enhance its availability and competitiveness. Simple and short-term modernization works might not affect the port operation significantly, while long-term activities dramatically reduce its efficiency, which necessitates a sophisticated planning. Dredging is and important aspect of port development strategies. Analysis of several factors is required to be conducted beforehand, among them the vessel traffic, the proper type of equipment and the level of its efficiency. High costs of dredging pair with the costs of losses of port operators and ship-owners incurred by vessels waiting in queues to pass the areas of development works. To optimize the efficiency of a dredging project it is necessary to assess the interference between the dredging activity schedule and traffic pattern in terms of the costs. This paper presents a simulation model which enables to estimate this impact of dredging activities on the vessel traffic in the port and thus provides a way to find a required optimum.
1. THE MODELING OF DREDGING WORKS IN PORTS

Modern trends in operating terminals put strong emphasis on directly handling huge ocean vessels, which means giving up feeder shipping. Fulfilling the demands of ship owners is possible only by completing a number of development investments, which require a strong expansion into the area around the port and deepening of the port canals. A significant developmental problem in the modern ports is limitation to handle the biggest vessels, which is caused by the depth of the port canals.

The modeling of dredging works in the sea-ports is strongly dependent on the vessel traffic stream in a specific port area, digging performance and maneuverability of dredgers used for the project accessibility for vessels with significant draught. Following the analysis of equipment appropriate for the purpose of deepening the ports, it is a difficult propose to choice is an optimal solution in terms of maneuverability and dredging efficiency. Especially when is used bucket dredge or cutter suction dredger where a big technological impediment in case of the operation of this type of equipment is the anchorage system (Fig. 1), which does not allow to bypass a working dredger during its operation [1, 6].

Fig. 1. The draft of bucket dredger working at internal canal in port of Gdynia

1.1. The proposed model

For a better understanding of the problem, the model describes only correlation between dredging works and vessels calling at the harbor. Full form should describe the interference of the total ship's traffic in port areas, like a arrivals and departures [2].
The channel in some periods of time might be blocked by the dredging works performing in it. In this case a ship arrived to port will join the queue in front of the entry point of the channel (anchorage) waiting for the break in dredging works (Fig. 2).

The state of the model at any time interval is defined by the number of ships arrived to the entrance channel, number of ships waiting in the queue and these entered the approaching channel. In other words, the state of the model is determined by the state and events at the previous interval (i-1). These reason-sequence connections could be described by the following rules: if there is no dredging activity in the channel, the ship waiting in the queue or just arrived to the port could enter the channel. If there is the dredging activity, no ship can move. On the other hand, if a ship entered the entrance channel, the queue length is diminished by 1, if it was not zero. If a new ship arrived to the port and did not pass straight to the channel, the queue length is increased by 1 [4]. The Algorithm of the proposed model is shown by Figure 3.
The state of the model at every time is described by two variables: length of the queue $Q[i]$ and the number of ships in the approaching channel $C[i]$. These state depend on the values of those variables at previous quantum $[i]$, i.e. $Q[i-1]$ and $C[i-1]$. In additions, the current state of the model is affected by external events of two categories: the ship arrival at this quantum $A[i]$ and the dredging activity at this quantum $D[i]$, blocking the approach channel for ships [1]. The ships arrival and the schedule of dredging activity form to reference flow of events, causing the state of the model to change by time. This changing of the state by time is the dynamic behavior of the system under study. The interference of traffic and dredging leads to appearance of the queue. The waiting time in the queue is connected with direct financial losses for the ship owner and indirect losses for port operator. In order to make a judgment about these losses, it is necessary to estimate the cost of dredging activity under different scenarios.

Fig. 3. Algorithm of the model
2. COST OF DREDGING WORKS

First of all cost of dredging works depend on constant and variable cost of the used dredgers. Also cost of dredging works strongly change if traffic vessels interfere at work schedule. So it is possible to calculate costs if we know the unit cost of dredging, the unit variable costs (when working) and also the cost of moving the dredging caravan when ships need pass channel.

Table 1

An example of dredging schedule module

<table>
<thead>
<tr>
<th></th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>WH</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Working hours

Adopted dredging schedule

1 – dredging activity
0 – no dredging activity (vessels can pass canal)

For example proposed working module presented by Table 1 consists of 10 hours, 5 of which are working and another 5 are inactive. This particular schedule required 4 moves of the dredger to the dredging activity area and 4 moves back (the vessels can pass canal). Total amount of working hours required to perform the dredging task, it is possible to calculate the amount of modules needed and, eventually, the cost of the total dredging project. The calculated cost depends on the amount of working hours in this 10-hour module and number of the dredging caravan moves. Different utilization of module time resource and different organization of continue work periods would leave to different costs of dredging. During experiments with the model will enable to assess tendency of time spent by ships in the queue during the dredging activities (Fig. 4).

![Fig. 4. Total time ships spend in the queue](image-url)
If the cost of working a vessels is known (hourly), it makes possible to calculate the ship losses. The multiple and detailed study of different scenarios will enable to compare the costs with the losses caused by the ship waiting time.

3. SCENARIOS OF THE MODEL

Modeling of dredging works give a wide specter of possible variants with different combinations of traffic patterns and dredging scheduling. On one side of this specter there is a solution when all the traffic is hold until the dredging works are over. In this case the cost of the dredging works is minimal, but the traffic losses are maximum. On the other side of this specter there is a solution when the dredging activity is performed so that it does not affect the port traffic, i.e. the dredging is performed only in the time intervals between the ship arrivals long enough to do it. In this case the traffic is not affected by the dredging, but the dredging works will take a longer time and cost more. Between these two extreme variants there is an optimal solution [3].

3.1. Dredging priority

Priority for a dredging does not require any specific simulation, since the scenario simply implies that all the ships are not permitted to enter the port, they will have to wait in the outer anchorage or not call at the port at all. Still, the simulation in this case could give an informative picture about the losses caused by this situation. An example of simulation of this scenario is given by Figure 5.

Fig. 5. Growth of the queue length in case of vessel traffic is closed
The area under the curve on this figure gives the total amount of hours ships spent in the queue. The cost of dredging in this case is easy to calculate multiplying the unit hour cost by total amount of hours needed to perform dredging and adding two move costs of the dredging caravan, thus also needing no simulation. In fact, such scenario in a long term, cannot take place due to the strong fast growing financial losses for ships and port terminals.

3.2. Traffic priority

The dredging in this case would be performed only when there long enough time period free of passing vessels. In case of the scheduled traffic pattern this variant also does not require any simulation, since the schedule gives the possibility to calculate the total time available for dredging and number of moves for the caravan during the module of schedule. In its turn, this enables to calculate the required amount of these modules and calculate the total cost of the dredging works [2]. In situation when arrival pattern is random (stochastic), then the simulation experiments are needed to determine the actual number of intervals and their length available to perform the dredging works.

In this example dredging is permitted for 12 hours out of 24 and requires 4 moves of the dredging caravans. The calculation of the total dredging work’s cost in the similar way as described above would give the results presented by Table 2.

<table>
<thead>
<tr>
<th>Characteristic Data</th>
<th>Value/Amount</th>
<th>Unit/Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit constant cost</td>
<td>10</td>
<td>[money/hour]</td>
</tr>
<tr>
<td>Unit variable cost</td>
<td>10</td>
<td>[money/hour]</td>
</tr>
<tr>
<td>Unit cost of moving</td>
<td>50</td>
<td>[money/move]</td>
</tr>
<tr>
<td>Number of hours</td>
<td>24</td>
<td>240</td>
</tr>
<tr>
<td>Number of working hours</td>
<td>12</td>
<td>120</td>
</tr>
<tr>
<td>Number of moves</td>
<td>4</td>
<td>200</td>
</tr>
<tr>
<td>Dredging work utilization</td>
<td>0,5</td>
<td></td>
</tr>
<tr>
<td>Total cost of one module</td>
<td></td>
<td>560</td>
</tr>
<tr>
<td>Required amount of working hours</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td>Number of modules needed</td>
<td>83</td>
<td></td>
</tr>
<tr>
<td>Cost of dredging works</td>
<td></td>
<td>46667</td>
</tr>
</tbody>
</table>
According to the calculations the general total cost of dredging is 46667 arbitrary monetary units (Tab. 2). The practically significant experiments should involve a longer schedule modules and more realistic data on duration and unit costs of dredging works. A sample of simulation with a 24-hour schedule module for one day period is presented on Figure 6.

![Figure 6. One day queue dynamics caused by a given 24-hours schedule of dredging](image)

CONCLUSIONS

A simulation model is introduced to describe the way how the assessment of mutual interdependency of the sea traffic and dredging activity in a port approaching channel could be made. This model enables to assess the ship losses caused by the time spent in the queue while the dredging works are performed.

A way to calculate the total dredging works’ cost in different scenarios of their scheduling is presented. It is shown how simulation performed for different scenarios could help to optimize the time schedule of dredging works by coordination them with a given schedule or random pattern of ship arrivals.

BIBLIOGRAPHY


**MODELOWANIE ROBÓT CZERPALNYCH I OCENA ZAKŁÓCEŃ RUCHU STATKOWEGO**

Streszczenie

Artykuł przedstawia model oceny wzajemnej zależności ruchu jednostek morskich i działalności prac pogłębiarskich na kanale portowym. Analiza ta ma na celu umożliwienie doboru czasu prac pogłębiarskich i koordynacji ich ze stałym harmonogramem lub losową strukturą zawinięć statków. Skuteczność tego typu przedsięwzięcia zależy w dużej mierze od prawidłowej analizy czynników utrudniających realizację projektu, tj. głównie ruchu statków i nieprzerwanego działania terminali portowych. Optymalny harmonogram prac pogłębiarskich, szczegółowo dopasowany do funkcjonowania portu, pozwala zarówno na efektywne wykonywanie zaplanowanych prac, jak i na ograniczenie strat finansowych armatorów i terminali portowych.

Dla wstępnego lepszego zrozumienia problematyki artykuł opisuje zaledwie zakres prac pogłębiarskich wobec jednostek morskich wpływających do portu. Pełna forma niniejszej problematyki powinna opisywać wpływ całkowitego ruchu statków na obszarach portowych, tj. wejścia i wyjścia. Taki model jest obecnie tworzony przez autorów i będzie opisany w kolejnym artykule.

**Słowa kluczowe:** prace czerpalne, modelowanie, ruch statków.