MARITIME TRANSPORT VII

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UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

7th INTERNATIONAL CONFERENCE ON MARITIME TRANSPORT

Technological, Innovation and Research

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Departament de Ciència i Enginyeria Nàutiques

With the support of:

Sponsored by:

First edition: June 2016

Oficina de Publicacions Acadèmiques Digitals de la UPC
Jordi Girona Salgado 31,
Edificio Torre Girona, Planta 1, 08034 Barcelona
Tel.: 934 015 885
www.upc.edu/idp
E-mail: info.idp@upc.edu

Production: SERVICE POINT
Pau Casals, 161-163
08820 El Prat de Llobregat (Barcelona)

ISBN: 978-84-9880-591-8

OPTIMAL WATER SUPPLY RELATED TO WATER PRODUCTION CAPABILITIES ON BOARD

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Abstract: *This research is based on savings coming from combination of water production and better planning of water bunkering in ports. Such operational research (OR) approach is based on better utilization of ship tank capacity in relation to water production. The efficient heuristic algorithm for optimal decisions for N different water sources (e.g. production by evaporation, production by reverse osmosis process and bunkering in ports + bottled water) for the ship with limited water tanks capacity is being developed. Mathematical model is developed on the basis of capacity expansion problem, same as the Minimum Cost Multi-Commodity Flow Problem (MCMCF).*

Keywords: *Water supply on board, Capacity management for cruisers, Minimum Cost Multi-Commodity Flow Problem, Optimal shipment on multi-stop voyage route*

INTRODUCTION

The cruise industry is the fastest growing segment in the leisure travel market. Since 1980, the industry has experienced a growth of average annual passenger rate of approximately 7.2% per annum. According to the Cruise Lines International Association statistic, total number of cruise ships was 310 and 22.1 million passengers traveled in year 2014.
As the cruise industry is expanding rapidly, cruise lines needs to stay competitive at the market. The key of success is the top quality of the provided services at the lowest costs possible. Cruise line companies are investing a lot of effort in order to operate cruise ships more efficiently. With optimization methods such as route management and fuel optimization method the expenses can be decreased and the saving can be made. One of the crucial things of the cruise ship operation is drinking water supply. The average use of the drinking water on cruise ships is more than 260 000 gallons per day. A sufficient amount of water on board is needed to provide a quality service to the passengers. Water is essential for ship's kitchen activities and for all passengers' activities such as maintaining hygiene, bathing, drinking, so operation management has to track usage of water carefully 24 hours a day.

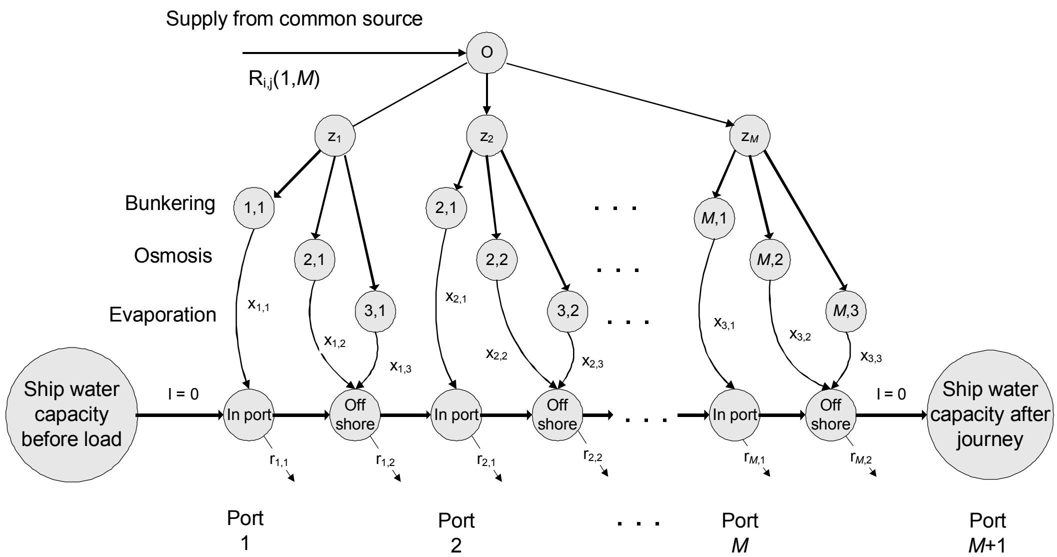
Cruise chips cannot carry all this water from the embarkation port or rely on local ports so the innovative methods for ocean-water desalination process, such as revers osmosis and evaporation, are used. Innovative methods are very expensive to use because lot of energy is needed for that process. On the other hand, the price of the water varies from port to port so it is not profitable to fill the full tank in every port. The major change in water supply on board is firmly in relation to water production but also with better planning of water supply (bunkering) in ports on the voyage, tending to increase operating efficiency, better productivity and profitability. According to our research we can say that optimization of water supply can have a great impact on efficient and profitable operation of cruise ship. In this article we want to ensure better voyage planning with minimization of expenses on the route with multiple loading/unloading ports with intention to ensure enough drinking and sanitary water during voyage.

This problem can be seen as transportation problem represented by a flow diagram of non-oriented acyclic network, see fig.1. The problem can be solved with different techniques but here we applied network optimization technique; see [1] and [2]. The non-linear transportation problem (NTP) with multiple expansion points (sources) and multiple reduction points (sinks) is very hard (NP-hard) problem so it is still the subject of many scientific papers; see [3] and [4]. Figure 1. gives a network flow representation of Minimum Cost Multi-Commodity Flow Problem (MCMCF) for N different water sources on the route with M port. In this paper we applied such network optimization approach; see [5] and [6]. The mathematical model is formulated in section 1. The algorithm development and implementation are explained in section 2. Testing results and explanation of basic heuristic approach can be seen in section 3.

1. THE MATHEMATICAL MODEL

Different kinds of water sources are differentiated with i for i = 1, 2, 3. The objective is to find a loading and production strategy that minimizes the total cost incurred over the whole voyage route consisting of M+1 ports. Today, big cruisers are capable to produce thousand tons of fresh water per day, but it requires extra energy and higher expenses. Cruise ships do not desalinate water near ports or close to land, because coastal waters are the most contaminated.

Figure 1. Mathematical model for water supply. The model is known as Multicomodity Flow Problem. Diagram represents the capacity states for the water sources in each port. Links betwen common source and water capacity states represent the water bunkering or water production.



The transportation problem can be represented by a flow diagram of non-oriented acyclic network. Node "O" is the common source in mathematical model that ensures water loading in ports and water production on board with possible limitations. Some ports can have restriction on loading capacity, but most of them are hub ports with capacity exceeding the ship's earning capacity (water thank of ship). On figure 1. the i-th row of nodes represents the increasing values of water capacity for f i-th type of water source in port m and during voyage between ports m and $m+1$.

The horizontal links between capacity nodes are representing the amounts of water on board on the path. Such transportation problem can be seen as the capacity expansion problem (CEP). For each water load/production we need common ship's tank space so it looks like expansion (load) or reduction (consumption) of spare water in given bounds.
In the mathematical model of CEP the following notation is used:

i, j and k = indices for type of water resources. The N facilities are not ranked, just present different types of water sources from 1, 2, 3 .

m = indices the port of water loading or consumption. The number of ports on the voyage including departure port is $M+1$ ($m = 1, .. , M+1$) .

u, v = indices for ports in sub-problem, $1 \leq u, ... , v \leq M+1$.

$t_{i,m}$ = indices the maximal time of water loading/production where $t_{1,m}$ is time of stay in port m, while $t_{2,m}$ represents shipping off shore.

Effective time of production by reverse osmosis and evaporation process between ports m and $m+1$ could be significantly smaller because it is acceptable only in clean open sea water.

$x_{i,m}$ = quantity of i-th load of water amounts/hour being loaded in ports or produced on board. For convenience, the $x_{i,m}$ is assumed to be integer. Total loading/production amount in port m :

$$X_m = x_{1.m} \cdot t_{1,m} + (x_{2,m} + x_{3,m}) \cdot t_{2,m} \tag{1.1}$$

L = limitations of water tank.

$r_{i,m}$ = water consumption in port m (i=1) or during voyage between port m and port $m+1$ (i=2). For convenience, the $r_{i,m}$ is assumed to be integer. Total consumption amount (reduction) including staying in port m and during voyage to the neighbor port $m+1$.

$$R_m = r_{1,m} \cdot t_{1,m} + r_{2,m} \cdot t_{2,m} \tag{1.2}$$

All water demands must be satisfied during voyage reaching the last port on the route.

$$\sum_{m=1}^{M} X_m = \sum_{m=1}^{M} R_m \tag{1.3}$$

I_m = the relative amount of water in any moment on the voyage. Horizontal links (I_m) on fig. 1. are representing the water amount between two neighbor ports. Before the first port of loading, $I_1 = 0$. After last port $I_{M+1} = 0$. Capacity values cannot be negative.

step I_i = the lowest step of possible capacity change (load and reduction) for water source i. In numerical examples it can be set e.g. *step* I_i = 5% of total ship's capacity.
The total cost over time includes:

a) f_m - loading cost in port m in relation to amount.

$$f_m = A_{1,m} + B_{1,m} \cdot x_{1,m} \cdot t_{1,m}^{\;a_{1,m} \cdot t_{1,m}} \tag{1.4}$$

b) f_m – water production cost by reverse osmosis process between port m and port m+1 in relation to amount.

$$h_m = A_{2,m} + B_{2,m} \cdot x_{2,m} \cdot t_{2,m}^{\;a_{2,m} \cdot t_{2.m}} \tag{1.5}$$

c) g_m – water production cost by evaporation process between port m and port m+1 in relation to the amount.

$$g_m = A_{3,m} + B_{3,m} \cdot x_{3,m} \cdot t_{2,m}^{\;a_{3,m} \cdot t_{2.m}} \tag{1.6}$$

where $a_{i,m}$ represents the factor of concavity for appropriate water source i and for appropriate conditions on the route (m=1, …, u, v, ..., M+1). In some cases the constant value $A_{i,m}$ (fix cost) could be avoided.

d) p_m – penalty cost taking in account I_m, the water surplus during voyage. It should be assumed that all function costs are concave and non-decreasing (most of them reflecting economies of scale) and they differ from one port to another; see [6]. The objective function is necessarily non-linear cost. With variation of cost parameters the optimization process could be easily managed, looking for benefits of the most appropriate loading/production solutions; see [7].

The optimization process should find out the most attractive water loading/production sequence. It can be formulated as minimization of the objective cost function:

$$\min \sum_{m=1}^{M} \{ f_m(x_{1,m}, t_{1,m}) + h_m(x_{2,m}, t_{2,m}) + g_m(x_{3,m}, t_{2,m}) - p_m(I_m) \} \tag{1.7}$$

where:

$$I_{m+1} = I_m + D_m(x_{i,m}, r_{i,m}, t_{i,m}) \tag{1.8}$$

$$D_m = X_m(x_{1,m}, t_{1,m}) - R_m(x_{2,m}, x_{3,m}, t_{2,m}) \tag{1.9}$$

$$I_1 = I_{M+1} = 0 \tag{1.10}$$

for m = 1, 2, .. , M ; i = 1, 2, 3

2. ALGORITHM DEVELOPMENT

Instead of a nonlinear convex optimization, that may be very complicated and time-consuming, the network optimization methodology is efficiently applied. The main reason of such approach is the possibility of definition of many discrete capacity values for limited number of water resources in any moment of the voyage; see [11]. The multi-constrained problem (MCP) can be formulated as Minimum Cost Multi-Commodity Flow Problem (MCMCF). Such problem (NP-complete) can be easily represented by multi-commodity the single (common) source multiple destination network; see [8], [9] and [10].

Definition of the single-constrained problem for CEP is to find a path P from starting to end port such that:

$$w(P) = \min \sum_{m=1}^{M+1} \sum_{i=1}^{N} w_m(I_m, x_{i,m}, r_{i,m}, t_{i,m}) \tag{2.1}$$

where: $I_m \leq L$ (2.2)
for $i = 1, \ldots, N$; $m = 1, \ldots, M+1$

A path obeying the above conditions is feasible. Note that there may be multiple feasible paths between starting and ending port (node).

Generalizing the concept of the capacity states after loading/production in any moment between ports *m and m* +1 we define as *a capacity point* - α_m.

$$\alpha_m = (I_{m,}, x_{i,m}, r_{i,m}, t_{i,m}) \quad (2.3)$$

$$\alpha_1 = \alpha_{M+1} = 0 \quad (2.4)$$

Let C_m be the number of capacity point values at port *m* (load/production value for each water source after departure from the port *m* and before arrival in port *m*+1; see fig. 2. Only one capacity point is for starting port (before bunkering) and one for end port on the route: $C_1 = C_{M+1} = 1$; see. Formulation (2.4) implies that relative value for water amount is zero before loading on the starting point, same as after consumption on the ending point. For absolute value we can limited it on some minimal amount, e.g. 20% of water tank.

The total number of capacity points is:

$$C_p = \sum_{m=1}^{M+1} C_m \quad (2.5)$$

The network optimization can be divided in two steps; see [11]. At first step the minimal transportation weights $d_{u,v}$ between all pairs of capacity points (neighbor ports on the route) are calculated. It is obvious that in CEP we have to find many cost values $d_{u,v}(\alpha_u, \alpha_{v+1})$ that emanate two capacity points of neighbor ports: from each node (u, α_u) to node $(v+1, \alpha_{v+1})$ for $v \geq u$. Calculation of such value is the capacity expansion sub-problem (CES). The objective function for CES can be formulated as follows:

$$d_{u,v} = \min\left\{ \sum_{m=u}^{v} \left[\sum_{i=1}^{N} f_m + h_m + g_m - p_m \right] \right\} \quad (2.6)$$

The most of the computational effort is spent on computing of many sub-problem values. That number depends on the total number of capacity points, see (2.5). The total number of all possible $d_{u,v}(\alpha_u, \alpha_{v+1})$ values representing CES between two capacity points is:

$$N_d = \sum_{m=1}^{M} C_m \cdot C_{m+1} \quad (2.7)$$

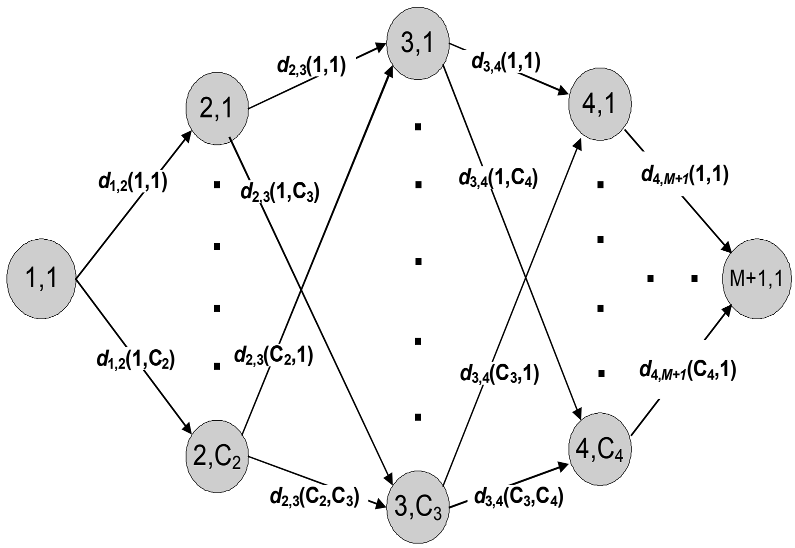
At second step we are looking for the shortest path in the network with former calculated weights (CES values), see fig. 2. As the number of all possible $d_{u,v}(\alpha_u, \alpha_{v+1})$ values depends on the total number of capacity points it is very important to reduce that number (C_p) and that can be done through imposing of appropriate capacity bounds or by introduction of adding constraints (e.g. max. loading/production time). Through numerical test-examples we will see that many loading/reduction solutions cannot be a part of the optimal expansion sequence. It is the way how this algorithm can be significantly improved without significant degradation of final result. According to this the heuristic approach can obtain the near-optimal result with significant computational savings.

For every CES many different solutions can be derived depending on D_m value; see (1.9). Each of them represents the capacity state of each water source onboard (loading/production) in appropriate port or on journey between neighbor ports.

Suppose that all links (sub-problems) in diagram 2. are calculated, the optimal solution for CEP can be found by searching for the optimal sequence of capacity points and their associated link state values; see fig 2. Then Dijkstra's or Floyd's algorithm or any similar algorithm can be applied; see [13] and [14].

The complexity of the proposed algorithm is $O(C_p^2)$. As we mentioned before C_p is in a strong correlation with number of ports M and number of water sources N but also with minimal capacity increment *step* I_i that can be variable.

Figure 2. The CEP problem can be seen as the shortest path problem for an acyclic network in which the nodes represent all possible values of capacity points. The links connecting neighbor capacity are representing CES values.



3. TESTING RESULTS OF BASIC HEURISTIC

In route definition from example in fig. 3 we have starting port 1 and ending port 7, and any of 5 middle ports can be used for water load. We are looking for distribution plan of water loading/production amounts, showing water capacity state and consumption rates. The water consumption demands are presented in the percentage of the total ship capacity, see figure 5. (green column). Water consumption is generally smaller in ports in relation to voyage periods, because the passengers are out. That input information is gathered from statistics.

Water loadings are in relation to ship stay in each port and it is limited respectively to ship tank amount; see table 1. Production is dependent of many factors and their correlations, but generally it is limited by duration (time), see table 2. Production amounts by reverse osmosis is generally higher than by evaporation because it is much cheaper. The problem is the low temperature of sea water. Sometimes the evaporation process can be a good way of energy savings, utilizing the surplus of energy produced in another process on board [15], [16].

Table 1. Capacity limitations in ports during voyage. That values are in relation to loading/production conditions, mostly in dependence of time. For this example spare water amount has to be min 20 %.

Water source	Port 1 % of tank	Port 2 % of tank	Port 3 % of tank	Port 4 % of tank	Port 5 % of tank	Port 6 % of tank
bunkering	80	80	80	80	60	70
osmosis	40 (1-2)	30 (2-3)	20 (3-4)	30 (4-5)	20 (5-6)	20 (6-7)
evaporation	20 (1-2)	15 (2-3)	10 (3-4)	15 (4-5)	10 (5-6)	10 (6-7)

Table 2. Time limitations staying in port and during voyage. That values are in relation to loading/production conditions.

	Port 1 % of tank	Port 2 % of tank	Port 3 % of tank	Port 4 % of tank	Port 5 % of tank	Port 6 % of tank
In port	12	10	13	15	10	10
Off shore	20 (1-2)	15 (2-3)	10 (3-4)	15 (4-5)	10 (5-6)	10 (6-7)

For simplicity some costs elements are equal: $A_{1,m}$= 0.0; $B_{1,m}$ = (2.5; 4.0; 2.0; 5.0; 3.0; 4.0); $B_{2,m}$ =1.7; $B_{3,m}$ =2.5; p_m=0.0; and concavity for all costs $a_{i,m}$= 0.85, for m=1,…,6.

According to all loading/production costs we can calculate the optimal plan for water supply distribution. From figure 3. it is obvious that loads/productions are: 1-2 (65+30 %); 2-3 (0 + 20 %); 3-4 (80 + 30 %); 4-5 (0 + 20 %); 5-6 (60 + 20 + 5 %), 6-7 (5 %).

For our test-example the best loading/production strategy (near optimal) is shown on figures 3. and 4. For the basic option we used the same minimal capacity increment *step* $I_{i,m}$ = 5 % for all changes of water resources. We know that such capacity resolution is not satisfactorily and, in general, we should be far away from optimal result. In this case we have 3181 capacity states and 3181x3181 CES values. We can decrease value *step* $I_{i,m}$ but the complexity drastically rises. Water loading/production amounts can be seen in diagram on fig. 5. In this figure we unified the load amounts in port and production off shore, just to show importance of each water source.

Figure 3. Water bunkering/production plan on the route as result of optimization. Bunkering is possible only during stay in port, that depends of many factors as loading sped (water throughput), duration of stay in the port and special port taxes.

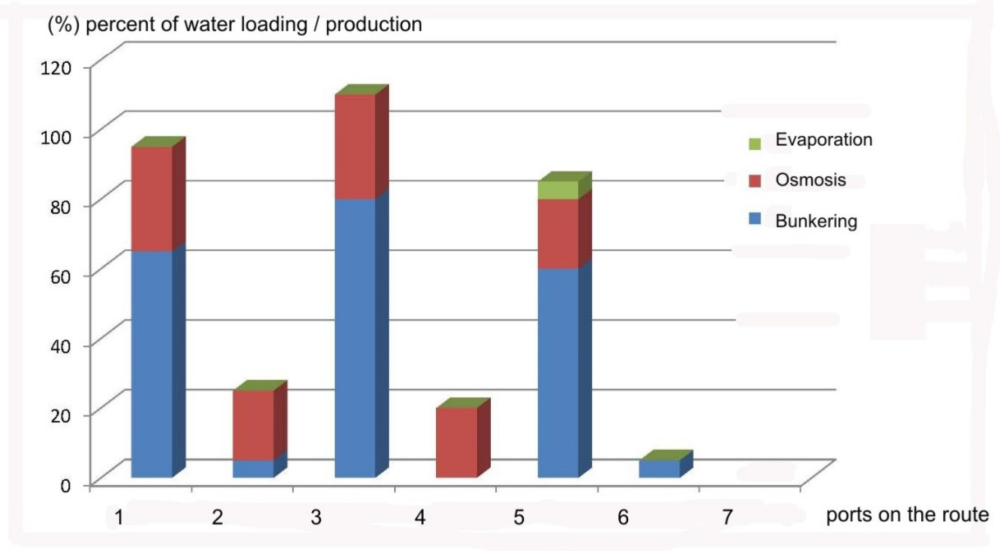
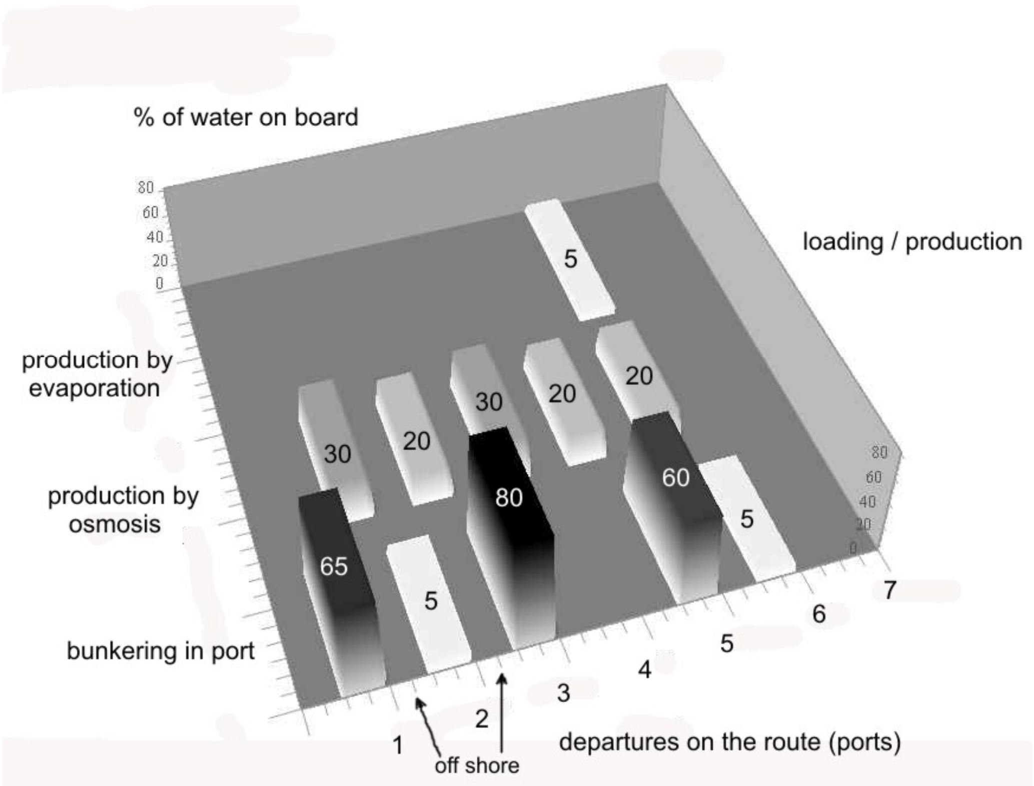


Figure 4. Amounts of water loading and water production on the route.

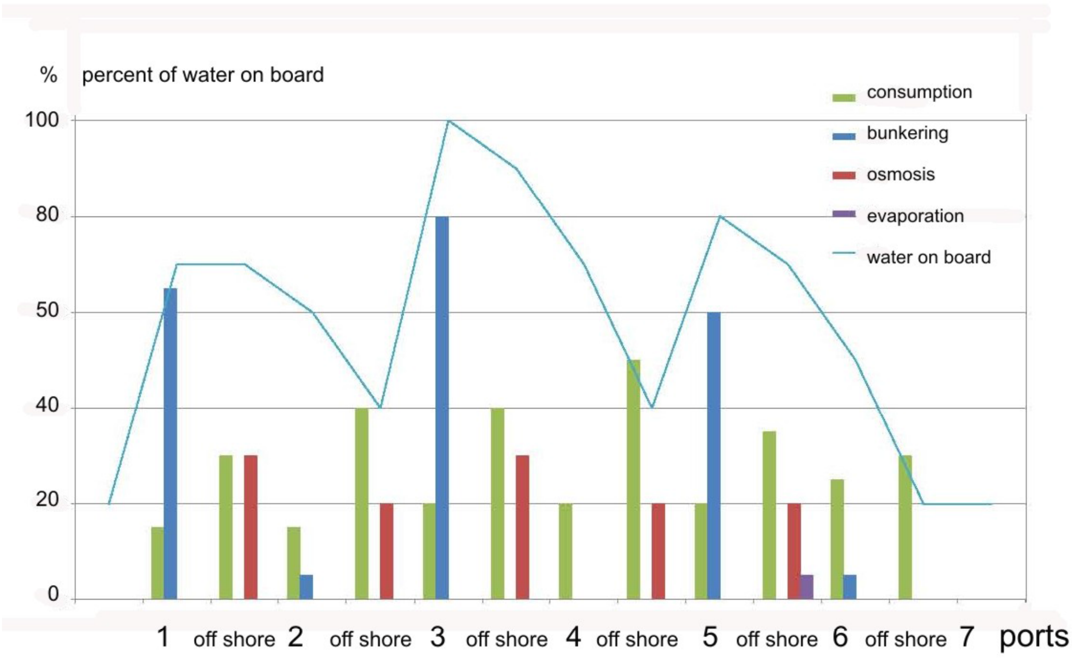


From fig. 5. we can see that absolute amount of spare water (blue line) do not fall below of 20% of total water capacity (tank space). It is mandatory in relation to decisions of ship owner and security of passengers and crew.

4. CONCLUSIONS

The proposed heuristic algorithm shows ability to solve very complex optimization problem with many water loading/production locations (ashore/off shore) on the route. The most important benefit is to be able to solve the nonlinear cost problems that we normally have in practice. Also, the existing calculation power in shipping surrounding is limited so algorithms with huge complexity are useless. This approach can be extended with successive iterations and be able to decrease complexity to acceptable level, looking for the best solution more precisely. In the same time it ensures to planners and managers very fine tool, to modulate many input values, leading optimization process in wanted direction. With such optimization tool the shipping companies can ensure a significant savings on the multiport cruiser routes and be more profitable by following the demands and easily adapt to its changes.

Figure 5. Plan of water loading/production on the route, showing water capacity state and consumption rates. Water consumption is generaly smaller in ports in relation to voyage period, because the passengers are out of board.



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