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MULTI-CRITERIA OPTIMISATION OF LIQUID CARGO TRANSPORT ACCORDING TO LINGUISTIC APPROACH TO THE ROUTE SELECTION TASK

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ABSTRACT

The main aim of the paper is to present the possibility of use of the multi-criteria optimization method Analytical Hierarchy Process (AHP) to liquid cargo transportation by sea. Finding the optimal solution is not simple. There are many factors influencing the shipping process. In the case of liquid cargo, the most important thing is the safety of the crew, ship, and environment. Therefore, the Mathematical Theory of Evidence is introduced and used to determine the optimal path in terms of time and safety of transport. Moreover, the details of liquid cargo transport process are described with particular attention to ship to ship operations. Besides, the basic concept of the AHP method, steps of the algorithm are introduced. Finally, the multicriteria optimization of the transport of the liquid cargo from the Persian Gulf to Port of Gdansk is done. It is based on the experts' opinions.

Keywords: liquid cargo transport, Dempster-Shaffer Theory, STS, AHP, multi-criteria optimization

INTRODUCTION

Maritime transport, like air, is exposed to several unfavorable factors from the environment. These includes, among other, time varying hydro-meteorological conditions. Thus, it is crucial to neutralize or to resist these negative factors. Considering the liquid cargo like oil, gas, chemicals, etc., the problem of transport via sea is more complicated. Due to the deep draft of tankers, not every destination can be reached. Thus, the current trends in the industry of carriage demonstrate its strong connection to the decision and optimization theory.

The first step of the process takes place already during the designing and ship building. One of the important thing in these processes are the decision about materials, ship equipment, i.e., navigational, electrical or handling [14], and detailed construction solution. This area concerns research not only on a new composite structure for a ship hull what should increase structural safety during a collision [18], [21]. Also, it concerns the processing technologies of various parts of the ship to reduce the impact of adverse factors [7], [9], [21]. Moreover, the significant field of interest is also the effectiveness and fuel consumption of ship engines [13]. The international regulations on emission become more restrictive, so it is important to seek such solutions of marine engines that the vessels comply with these strict standards.

The next step after designing and building of the ship is its exploitation process. A distinctive feature of the transport of liquid cargo is possible to do ship-to-ship operations (STS) [24]. Performing these operations is possible after meeting very strict rules related to the place, hydro-meteorological conditions, handling technology and qualifications of the crew [6], [20], [24]. Transportation of liquid cargo by sea demands ensuring an appropriate monitoring level to prevent an accident or find the source of the environment pollution. Nowadays, such control is possible using mobile units, including flying or floating drones. The research on usage of mobile laser scanning is introduced in [3].

In the research on transportation systems, a lot of papers are devoted to the mathematical method of analysis, modeling, and optimization. Many research teams conduct their studies of the analysis, modeling, and optimization of the safety and reliability of transportation systems [4], also taking into account the operation process and semi-Markov approach [4], [10] – [12]. The different way of transportation systems' safety description is used in the time series analysis [1].

The second group of mathematical tools is those related to improving and optimization of the objectives for operation transportation systems. A lot of attention is paid to the optimization methods and tools on algorithms for determining safe ship trajectories [15], [16], [17], [23], and the analysis and optimizing of the flow of people or cargo transportation system with accordance to graph theory methods [5].

As it was mentioned above, the problem of liquid cargo is complicated. Thus, one criterion optimization is not enough. In the paper, the Analytic Hierarchy Process method of multi-criteria optimization, [19], [22], is used to solve the problem of liquid cargo transport per route selection task according to costs. This approach is described in the Subsection 2.4. To realize this goal, the Dempster-Shafer Theory combined with fuzzy modeling as the tool to find the safe ship's trajectory is introduced. Furthermore, the description of the liquid cargo transport is presented in Section 3. There is some information about the fleet used in liquid cargo transportation and about realization for the STS operations. Chapter 5 describes the results on multi-criteria optimization with AHP (the Analytical Hierarchy Process)method for the Persian Gulf – Port of Gdansk route.

METHODOLOGY

The three methods of research: Mathematical Theory of Evidence, fuzzy modelling, and AHP method are discussed in detail as the basic tools used in the paper. The first two of these are used to determine the shortest in terms of time, and the safest route of the ship. The third one is used to perform multi-criteria optimization based on the opinions of the experts.

The input data is based on the exemplary record vessel properties, motion report data, and digital climate prognosis data. Furthermore, the case in the paper will join consumption curves, velocity diminution curves, vessel class, ship wind and weather sea borders, motion statement velocity, maximal permitted speed, motion statement trace data to contain waypoints, their latitude, and longitude. On top of data related to the motion of the ship, it is indispensable to include the specification of the surroundings. In particular, significant is the specification of the practicable routes between the first point and the last one. This approach was also presented in [15], [16].

The approach presented in this paper can be the conception of accident risk on each curve of the transportation network by taking account of the sensitivity of the curve in question and of the cost created in the event of the accident on this curve with respect to the various impacts considered. To model these, the authors proposed Dempster-Shafer Theory.

DEMPSTER-SHAFER THEORY

The Dempster-Shafer Theory, also called Mathematical Theory of Evidence, deals with function combining information contained in two sets of assignments, subjective expert ratings. This process may be interpreted as a knowledge update. Combining sets results in forming of new subsets of possible hypotheses with new values characterising probability of specific options occurrence. The aforementioned process may continue as long as provided with new propositions. This function is known as Dempster's rule of combination. If more than one factor appears on an edge, then it is possible to cumulate them based on the following formula, where A is the investigated set, B, C are elements of P(Ω).

This equation is proposed by Dempster:

$$m(C)=\frac{\sum_{A\cap B=C} m_1(A)m_2(B)}{1-\sum_{A\cap B=\phi} m_1(A)m_2(B)} \tag{1}$$

where m(A), m(B) are probability mass assignments.

Combination rules specify how two mass functions, presented as m1 and m2, are fused into one combined belief measure. Many combination rules have been suggested (several are presented in [2]).

For a published source apex (node) in the graph, the algorithm discovers the way with smallest cost (i.e. the shortest path) among that vertex and every other one. It could also be used for discovering the smallest cost way from one vertex to a goal vertex by the stoppage algorithm is intended by the smallest way to the goal vertex. For instance, if the apexes of the graph describe the cities and there are given costs of flowing ways distances among pairs of points combined immediately to the road, Dijkstra's algorithm can be used to discover the briefest route between one city and all other cities. Consequently, the briefest path algorithm is highly used in routing protocols in a web network, in particular the IS-IS and Open Shortest Path First [15].

For a given source vertex (node) in the graph, the algorithm finds the path with lowest cost (i.e. the shortest path) between that vertex and every other vertex. It can also be used for finding the shortest cost path from one vertex to a destination vertex by the stopping algorithm which is determined by the shortest path to the destination node. For example, if the vertices of the graph represent the waypoints and are the costs of running paths edge distances between pairs of waypoints connected directly, Dijkstra's algorithm can be used to find the shortest route between start and the exit point in the maritime area (see Figure 1). This approach was presented in [17].

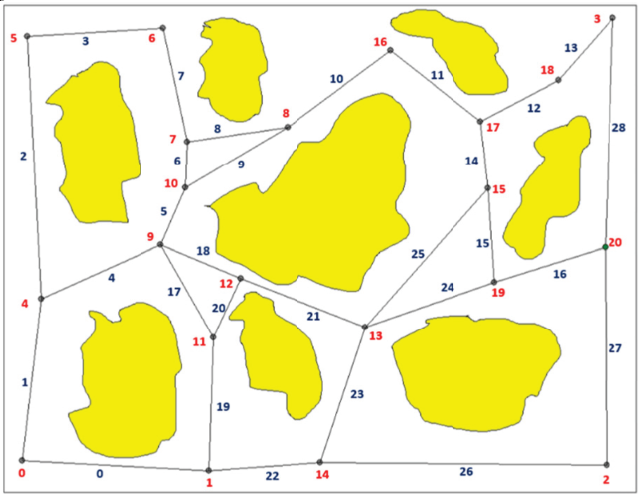

Fig. 1. Scheme of maritime routes among islands

FUZZY MODELLING

The fuzziness shortest path finding problem from start position - specific node of source to the end position - other node is presented in many papers. In the field of maritime transport systems, the suitable networks using fuzzy data of the curves, are supposed to represent time of move from one to another waypoint or economic costs as traffic flow, etc. These data are supple and could be expressed by fuzzy numbers or fuzzy sets [26].

In this approach, one implements the problem of defining a fuzzy data retrieval model. In fuzzy model, queries are defined as linguistic generalizations in the weighted model. To this end, linguistic descriptors are introduced in the query language to express the importance that a term must have in the wished records and in the classification mechanism to label the restored records in relevance classes.

DESCRIPTION OF FUZZY GRAPH

Let Ω be a complete set supposed to be equal to {1, 2, …., n}. The framework G(Ω,σ,μ) can represent valued fuzzy graph on Ω where:

– σ:Ω→[0,1] and means level of membership of any node,

– μ:Ω→[0,1] and means level of membership of any curve

According to the proposed approach, it is possible to use various functions. Most popular are trapezoidal or triangular shaped membership functions. Figure 2 presents typical functions regarding to age of people.

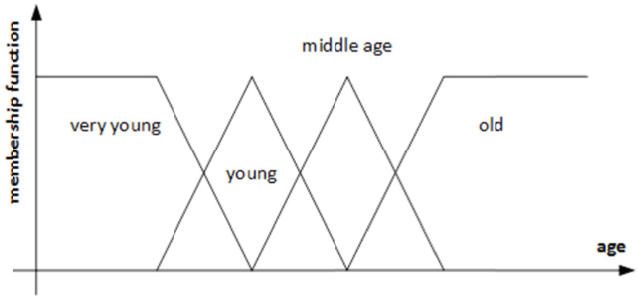

Fig. 2. Typical membership function for the famous age example

Calculations in the fuzzy sets of values can be added to the popular graph algorithms. One of them is presented in Figure 3. We initialize the algorithm source with valued fuzzy graph G(Ω,σ,μ), where σ=δ. The *S* is the sequence of vertices, which is empty at the start algorithm. The *Q* = *G.V* is the set of all unvisited vertices that are to be removed. In this set, *u* represents the vertex with the smallest distance from the source. The *G.Adj*[*u*] describes the neighbour of the vertex *u*.

```
initialize source G(Ω,δ,μ)
S=0
Q= G.V
while Q ≠ 0
    u = extract-min(Q)
    S = S ∪{u}
    for each vertex v∈ G.Adj[u]
        Relax(u,v,δ,μ)
```

Fig. 3. Pseudocode of single shortest path

AHP METHOD DESCRIPTION

In the paper, the authors use one of the most useful multi-criteria optimization methods, i.e. the Analytical Hierarchy Process (AHP) method, which was introduced by Thomas Saaty in the 70s. The general concept of this approach is as follows [19]:

a. the goals' hierarchisation;
b. paired comparison of the objectives being on the same level.

On Figure 4 the general structure of AHP method is presented.

It should be noted that this is a helpful method when the expert opinions are collected during the research.

Let one assume, that there is a set of *n*-variants (options) to consider. Every one of these components take the value for *k*-criteria. Thus, there is the decision matrix $[DM]_{n \times k}$.

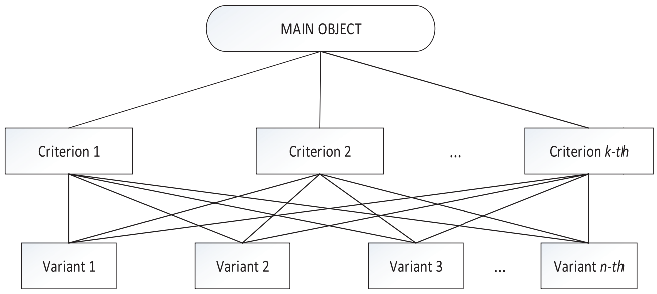

Fig. 4. General diagram of the AHP method [19]

The steps of the AHP algorithm are as follows [19], [22]:
1. *Hierarchization of the problem.*
2. *Paired comparison of the objectives being on the same level – matrixes of the paired comparisons.*
3. *Definition of the mutual weight of the criteria and decision variants.*
4. *Choosing the best options.*

In step 1, the detailed description of a problem, definition of the primary goal and expectations of them is done. The decomposition of the problem in the form of the principal criteria and the main options considered, which generate a certain degree of fulfillment of objectives of the function at different levels of the hierarchical model is defined (see Fig. 4).

In step 2, the decision maker compares together in pairs criteria in relation to the primary goal and the options to the specific guidelines. A subjective determination indicates which of the criteria and options, and to what extent are more important than the other.

Relations between the elements is determined based on a 9-point scale [19], [22]:

a. 1 – a same significance;
b. 3 - a small advantage;
c. 5 - a strong advantage;
d. 7 – a very strong advantage;
e. 9 – an absolute advantage;
f. 2, 4, 6, 8 – an intermediate value.

Evaluation of the inverse relations is determined as a reciprocal of integers.

This step completes the formation of a matrix $\mathbf{B}^{level}$, $level = 2,3$, size $k \times k$ and $n \times n$ in case of the second and third levels, respectively, which is made of $k(k-1)/2$ and $n(n-1)/2$ of these comparisons. The characteristic feature of this matrix is a diagonal equal to 1, which consists of the following property [19]:

$$b_{ij} = \frac{1}{b_{ji}}. \tag{2}$$

where b_{ij} is element in *i-th* row and *j-th* column and b_{ji} is element in *j-th* row and *i-th* column.

In step 3, the mutual weights for criteria and variants (options) are calculated. The normalized rows of the matrix $\mathbf{B}^{level}$, *level=2,3*, are summed and the eigenvector of it is found. Furthermore, the matrix $\mathbf{B}^{level}$, *level=2,3*, satisfies [19]:

$$\mathbf{B}^{level} \cdot \mathbf{w} = \lambda \cdot \mathbf{w}, \tag{3}$$

where
$\mathbf{w}$ - the eigenvector of matrix $\mathbf{B}^{level}$,
λ - the eigenvalue of matrix $\mathbf{B}^{level}$.

The experts' assessments are not always completely neutral, so it is necessary to introduce the inconsistency coefficient *IF* defined as follows [19]

$$IF = \frac{CI}{RI}, \tag{4}$$

where
CI - consequence ratio,
RI - random index.

It should be less than or equal to 0.2. In the case when $CI = 0$, then the value of coefficient *IF* is calculated in respect to the random index RI. It is the average CI for a large number of randomly generated matrix of comparisons.

Moreover, the consequence ratio *CI* for matrix size *n* is given by [19]:

$$CI = \frac{\lambda_{\max} - n}{n-1}, \tag{5}$$

where $\lambda_{\max}$ is maximal eigenvalue of matrix $\mathbf{B}^{level}$, $level = 2,3$, calculated with equation (3).

It is believed that the data are consistent to the value of the ratio *CI*, given in (5), which is less than 0.1 [19].

Finally, in the step 4, the decision-maker chooses the optimal option for established criteria.

LIQUID CARGO TRANSPORT

Sea transport of crude oil & oil products generally covers all sea routes between sources of crude oil in the world and the places where refineries producing various type of fuels, lubricating oils and others are located. There are many places in the world where crude oil is produced on shore & also at the off shore - oil field.

Crude oil is carried by large tankers (size ULCC or VLCC) to minimize cost of the transport cargo between continents to deliver cargo to the shore storage tanks or to the fix installations like the pipelines, connecting oil terminals with the refinery.

Ultra Large Crude Carriers (ULCCs), are tankers able to transport very large volumes of oil, up to three million barrel cargoes. A typical Double Hull Ship is of 410.000 Dwt. LOA 337 m Breadth 68 m Draft 23 m, Light ship 45.000 tons.

Very Large Crude Carriers (VLCCs), are tankers able to transport large volumes of oil, including two million barrel cargoes, over relatively long distances. Typical Double Hull

Ship is of 280.000 Dwt. LOA 335 m, Breadth 57 m Draft 21 m, Light ship 35.000 tons (see Figure 5).

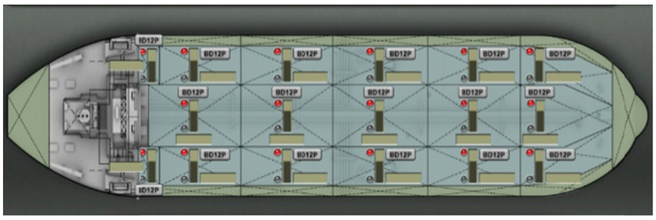

Fig. 5. VLCC Typical Double Hull Tanker [25]

However, some destinations for tankers are restricted by maneuverability and draft of the large ships. One of the solution is to reduce the size of a tanker, but quantity of cargo is automatically reduced too and the cost of the transport is arises.

Maximum size for Baltic Sea are Suez Max tankers generally identified as those capable of transporting one million barrel cargoes. Typical Double Hull Ship is of 150.000 Dwt. LOA 274 m, Breadth 50 m, Draft 14,5 m, Light ship 20.000 tons.

Another solution to achieve the same volume of delivered cargo to a destination and to reduce the cost to a reasonable level is to organize the STS operation before the port of destination.

Generally, STS operations take place at open sea or on the road before restricted draft approaches to ports, rivers, straits for large vessel. The main goal of an STS operation is to reduce the draft of the large tankers up to accepted value, which allows them to enter such areas. Part of the liquid cargo from a large tanker is discharged to a smaller size tanker to reduced draft. Discharging a quantity of liquid cargo should always correspond to minimum numbers of small size tankers. Liquid cargo that remains on onboard should be distributed on board in such way to keep large tanker always on even keel without heel and avoid forming free surface in the cargo tank (see Figure 6).

Fig. 6. Example of lightering operation La Plata river [photo P. Wilczyński]

The size of small tankers designated to STS operation should be adjusted to the quantity of cargo to be discharged (exemplary see Figure 7). All ship's parameters like deadweight, draft, mooring arrangement, max. loading rate etc. contain Q88 form exchanged between vessels involved in STS operation. On the base of Q88 tanker's operators and masters take the decision which ship could be used for planned STS.

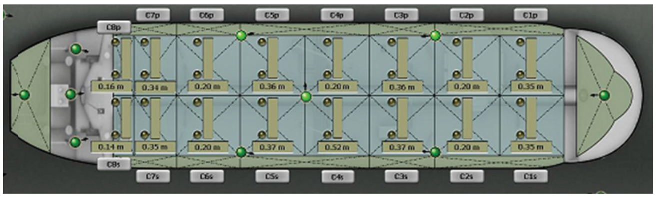

Fig. 7. Typical Double Hull tankers of 60.000 Dwt. LOA 228,6 m, Breadth 32,2 m Draft 12,6 m, Light ship 12.000 tons [25]

Also distance between place where STS is planned to the port of cargo destination is a very important factor to take decision, how many small tankers should be involved in such operation.

There are not so many places where STS operation could be performed for VLCC proceeding to the Baltic Sea. Such an area should provide enough space and depth for both maneuvering vessels, additional support and service should be available to fulfill all national regulation.

STS operations required proper hydro-meteorological conditions to perform safe transfer of cargo between the tankers. Sea current, wind and waves above the certain limits do not allow to start the STS operation.

RESULTS

For consideration, the authors took into account the oil transport from the Persian Gulf to the Port of Gdansk. After discussion with experts, in transport of oil and oil products, the following optimization criteria are fixed:

a. C1 - number of STS operation,
b. C2 - total load [mt],
c. C3 - time route [h],
d. C4 - total cost [USD].

As it was mentioned in the first step of AHP algorithm, the first step and taking into account experts' opinions gives the hierarchization which is presented in Figure 8.

As it is presented above on the AHP method schema, six options are under investigation. The decision matrix of the considered problem is given in Table 1. Calculations find the data for time route column based on Mathematical Theory of Evidence and fuzzy modeling, which is described in Section 2. According to information mentioned in Section 3, the two main routes are possible to realize the transport between the Persian Gulf and Port of Gdansk. The shortest path goes through the Suez Canal and its time length is 514 [h]. The second route runs around Africa with length equal to 837 [h]. Both results are calculated numerically.

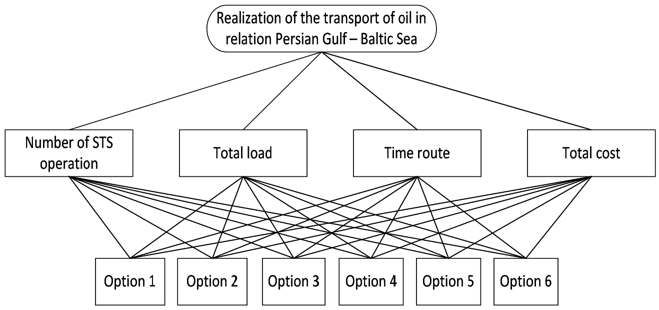

Fig. 8. AHP schema for liquid cargo transport

Tab. 1. Decision matrix

	Number of STS operation (C1)	Total Load [mt] (C2)	TIME ROUTE [h] (C3)	TOTAL COST [$] (C4)
Option 1	0	140 000	514.00	2178333.33
Option 2	1	200 000	586.00	2512500.00
Option 3	2	200 000	646.00	2567500.00
Option 4	3	300 000	1047.00	3825000.00
Option 5	3	320 000	1053.00	3862500.00
Option 6	4	320 000	1011.00	3875000.00

The second step of AHP algorithm is to build the matrix of criteria comparison according to the formula (2), i.e. the matrix $\mathbf{B}^2$. It is given in Table 2.

Tab. 2. Matrix of comparisons for second level

		b_j			
		C1	C2	C3	C4
b_i	C1	1.0000	0.3333	0.2000	0.1111
	C2	3.0000	1.0000	0.3333	0.1429
	C3	5.0000	3.0000	1.0000	0.5000
	C4	9.0000	7.0000	2.0000	1.0000

Moreover, the four matrices $\mathbf{B}^3$ of third level are obtained for criteria C1, C2, C3 and C4 from experts and filled in accordance to formula (2). The matrixes of comparisons are presented in Table 3 (for C1), Table 4 (for C2), Table 5 (for C3), Table 6 (for C4). The results are as follows:

a) in case of the criterion C1

Tab. 3. Matrix of comparisons of third level for criterion C1

C1	O1	O2	O3	O4	O5	O6
O1	1.0000	3.0000	5.0000	7.0000	7.0000	9.0000
O2	0.3333	1.0000	3.0000	5.0000	5.0000	7.0000
O3	0.2000	0.3333	1.0000	3.0000	3.0000	5.0000
O4	0.1429	0.2000	0.3333	1.0000	1.0000	3.0000
O5	0.1429	0.2000	0.3333	1.0000	1.0000	3.0000
O6	0.1111	0.1429	0.2000	0.3333	0.3333	1.0000

b) in case the criterion C2

Tab. 4. Matrix of comparisons of third level for criterion C2

C2	O1	O2	O3	O4	O5	O6
O1	1.0000	3.6667	3.6667	8.1111	9.0000	9.0000
O2	0.2727	1.0000	1.0000	5.4444	6.3333	6.3333
O3	0.2727	1.0000	1.0000	5.4444	6.3333	6.3333
O4	0.1233	0.1837	0.1837	1.0000	1.8889	1.8889
O5	0.1111	0.1579	0.1579	0.5294	1.0000	1.0000
O6	0.1111	0.1579	0.1579	0.5294	1.0000	1.0000

c) in case the criterion C3

Tab. 5. Matrix of comparisons of third level for criterion C3

C3	O1	O2	O3	O4	O5	O6
O1	1.0000	2.0686	2.9592	8.9109	9.0000	8.3766
O2	0.4834	1.0000	1.8905	7.8423	7.9314	7.3080
O3	0.3379	0.5289	1.0000	6.9518	7.0408	6.4174
O4	0.1122	0.1275	0.1438	1.0000	1.0891	0.6518
O5	0.1111	0.1261	0.1420	0.9182	1.0000	0.6160
O6	0.1194	0.1368	0.1558	1.5343	1.6234	1.0000

d) in case the criterion C4

Tab. 6. Matrix of comparison of third level for criterion C4

C4	O1	O2	O3	O4	O5	O6
O1	1.0000	2.5756	2.8350	8.7642	8.9411	9.0000
O2	0.3883	1.0000	1.2593	7.1886	7.3654	7.4244
O3	0.3527	0.7941	1.0000	6.9293	7.1061	7.1650
O4	0.1141	0.1391	0.1443	1.0000	1.1768	1.2358
O5	0.1118	0.1358	0.1407	0.8497	1.0000	1.0589
O6	0.1111	0.1347	0.1396	0.8092	0.9443	1.0000

In the third step of the algorithm, the normalized eigenvector of matrix $\mathbf{B}^2$ is calculated via formula (3) and presented in Table 7.

Tab. 7. Normalized weighted vector of matrix $\mathbf{B}^2$

Criterion	C1	C2	C3	C4
Weight	0.0507	0.0955	0.3080	0.5458

The conclusion is that the highest weight has the C4 criterion - total cost (see Table 7).

Finally, the vector of the rank is calculated and given in Table 8.

Tab. 8. Rank vector for choosing the option

Opt.	O1	O2	O3	O4	O5	O6
Rank	0,4256	0,2497	0,2092	0,0408	0,0367	0,0380

The above rank vector indicates that the optimum option for our problem is O1. Thus, we know, that:

a) to transport the liquid cargo, one should use the Suez Max with total load 140000 [mt] without the need of STS operation,
b) the route leads through the Suez Canal and the Mediterranean Sea at total time equal to 514 [h],
c) the cost of transportation is equal to 2178333,33 [USD].

The alternative is the Suez Max with full tanks equal to 200000 [mt] (second in the ranking of options, see Table 8). In this case, before the Danish Straits, it is necessary to unload part of the cargo to a tanker with a capacity of 60000 [mt]. Thus, the cost of transport is higher - about 334166,67 [USD].

The final remark is that the experts' opinions are consistent, because IF = 0.04, with accordance to formulae (4) – (5).

CONCLUSION

The article is devoted to the problem of multi-criteria optimization of liquid cargo transport in relation to the Persian Gulf - Port of Gdansk rout. This objective was made possible by obtaining information from experts. The information has made possible to determine the cost, route and organization of STS operations. Furthermore, the time of passage has been fixed by the linguistic approach to the route selection task taking into account the uncertainties. The ship to ship operations have been described. Moreover, the details of tankers have been introduced.

Finally, the optimization problem has been solved using the AHP method. The steps of the algorithm have been described in details and used to optimize the transport of liquid cargo.

Further work in this area will be aimed to optimize the return route.

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