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Adriatic Sea Hub Ports Feeder Service Optimization Using Multi-Criteria Decision-Making Methods

Dario Medić [1,*], Srećko Krile [2], Igor Jelaska [3] and Rino Bošnjak [1]

1   Faculty of Maritime Studies, University of Split, Ruđera Boškovića 37, 21000 Split, Croatia; rino.bosnjak@pfst.hr
2   Maritime Department, University of Dubrovnik, Branitelja Dubrovnika 29, 20000 Dubrovnik, Croatia; srecko.krile@unidu.hr
3   Faculty of Kinesiology, University of Split, Teslina 6, 21000 Split, Croatia; igor.jelaska@kifst.hr
*   Correspondence: dario.medic@pfst.hr

Abstract: From a scientific viewpoint, as well as from the perspective of navigation practice, it is clear that the Adriatic Sea feeder service is relatively underdeveloped. Hence, the objective of this study is to suggest a model for selecting the hub port and to optimize the network of seaports engaged in the feeder service. Accordingly, an appropriate hub port has been identified through the methods of multi-criteria decision making and expert assessment, and the optimum shipping route has been calculated by applying the travelling salesman algorithm (TSA). In order to analyze whether there is a possibility of obtaining better optimization results, an integration of a sub-hub port system is suggested. Optimization has been achieved by applying a minimum spanning tree algorithm (MST) and a combination of these algorithms. The proposed methodology for selecting the hub port, sub-hub port and optimizing the feeder network can be implemented globally. The practical application of the achieved model would result in cost minimization, owing to shorter shipping routes or a combination of different transportation means (feeders).

Keywords: feeder service; feeder port; hub port; travelling salesman algorithm; minimum spanning tree

1. Introduction

Sea-borne shipping flows have a great impact on the seaport development trends across the world, as ports cope with the accommodation of ever-larger vessels [1–3]. The choice and development of a viable hub port and the associated feeder service increases the efficiency of global cargo distribution [4]. In addition, inland shipping has been increasing in Europe, heavily affecting the development of feeder service and hub seaports [5,6]. If there are a number of large ports along the major sea-borne shipping routes, it is useful to perform analyses and select one of them as the hub port [7,8]. Various research used for selecting the hub ports is available. In research [9], the possibility of selecting the hub port near the Bay of Bengal (Colombo, Singapore, Kelang and Tanjung Pelepas) was analyzed, where the authors took into consideration the location and traffic in the ports. In research [10], only the economic benefits were analyzed regarding the selection of the hub port. For the selection of building two new hub ports in the Indonesia region, the authors based their selection exclusively on an analysis of the minimization of the total shipping costs [11]. Based on the above, there is a need for a multi-criteria analysis that takes into consideration more variables, such as hierarchical structures, and measures them with suitable algorithms [12,13]. This is why, when selecting a hub port, this research uses the expertise and knowledge of 20 experts from the maritime traffic field of study. Seven key parameters were selected, which are used in the selection of the adequate port, and they will be thoroughly explained in the text. It must be underlined that expert elicitation is considered to be a valid tool for the identification of crucial components of research [14,15].

Due to an increase in container cargo transportation each year, research [16–18] proposes a sub-hub system that can help to lower congestion in the ports. The sub-hub port has a much smaller container throughput, but it can help to solve the demand imbalance and port congestion problems [19–22].

Once a hub port has been selected, it is necessary to optimize the feeder service shipping route [23,24]. Various scientific methods are used to optimize the feeder service. To optimize the route between feeder services in the Pearl River Delta region of China, the authors have made a genetic algorithm model that optimizes the total voyage costs [25]. In the Black Sea region, research has been developed on the optimization of the feeder service, as well as an adaptive neighborhood search algorithm, which is adapted to the mentioned region. In research [26], feeder service network optimization was analyzed in the Ireland region, taking traffic frequency into consideration due to the uniqueness of the region. However, there is no relevant research for the selection of hub ports or the feeder network in the Adriatic Sea. The Adriatic Sea has several routes that are being used, which indicates that there is no coherence of the network, and its feeder service remains relatively underdeveloped [27–33]. In accordance with all previously stated research, the main objective of this study is to find a model for selecting the hub port that can handle the feeder service in the Adriatic Sea, and to optimize the network of service seaports. This can be achieved by applying the method of multi-criteria decision making for selecting an acceptable hub port, and by using two different travelling salesman problem algorithms (TSP) for optimizing the feeder service route, which are most often used in similar research [34–41]. If the sub-hub system is being used, optimization can be achieved using the minimum spanning tree algorithm (MST), which is most often used in similar types of research [42–45]. The mentioned algorithms, if needed, can be incorporated with one of the presented methods when the region is bigger, or for a different feeder service region.

2. Methodology

2.1. Current State of Container Services in the Adriatic Sea

The container services connecting the seaports that are included in the model are:

- CMA CGM: FAS Adriatic Feeder 1 (Malta—Catania—Bar—Ancona—Ravenna—Split—Ploče—Durres—Malta) [27], Adria 1 (Malta—Taranto—Ploče—Split—Rijeka—Koper—Trieste—Venice—Ravenna—Ancona) [28];
- MSC: Asia—Mediterranean (Koper—Trieste—Rijeka—Trieste—Port Said-King Adullah—Salalah) (Gioia Tauro—Bari—Ancona—Ravenna—Venice—Trieste—Rijeka—Ploče) [29];
- Hapag-Lloyd: Adria Express (ADX) (Piraeus—Rijeka—Venice—Ancona—Damietta) [30];
- Evergreen Marine Corporation: Adriatic Levant Service (ADL) (Trieste—Venice—Ravenna—Ancona—Piraeus—Limassol) [31];
- Maersk Line—49T-Adriatic (Piraeus—Bar—Split—Ploče—Piraeus—Durres—Rijeka—Koper—Trieste—Durres) [32].

An analysis of the presented feeder services shows that the above routes involve the following Adriatic seaports: Bar, Ploče, Split, Rijeka, Koper, Trieste, Venice, Ravenna and Ancona. These ports will be included in the model. Figure 1 features the model for the feeder service in the Adriatic Sea.

Figure 1. Distance from the main shipping route of Mediterranean container ports and positions of feeder Adriatic ports. Source: adjusted by the author based on [46].

2.2. Analysis of the Possible Hub Ports for the Adriatic Sea Feeder Service

In line with the model for the Adriatic Sea feeder service, designation of all feeder ports is followed by selection of the hub port. Three major seaports stand out as possible hub ports for our model: Taranto (Italy), Gioia Tauro (Italy) and Marsaxlokk (Malta). Table 1 presents a comparative analysis of these ports. Key parameters need to be defined for selecting the most viable hub port. Communication with twenty relevant experts, who were familiarized with the issue, resulted in identifying a system of possible variables that might be appropriate for defining a seaport as the hub port. Each parameter is followed by the value coefficient k amounting to 1, 2 or 3, depending on the comparative value of a port (1—low, 2—medium, 3—high priority). The selected hub port will have the greatest sum of the value parameters k, where:

$$\max_j \sum_{i=1}^{7} k_{i,j}; (j = 1, 2, 3)$$

(1)

The value of the parameters k in Table 1 is given in boldface and in parentheses.

Table 1. Key parameters and comparative analyses of the ports Gioia Tauro, Marsaxlokk and Taranto—Container terminal.

	Gioia Tauro, Italy [47]	Marsaxlokk, Malta [47]	Taranto, Italy [48]	Defining the Priority of the Parameter *K*
Vicinity of feeder ports in the Adriatic (bf)	425 NM (2)	515 NM (1)	263 NM (3)	Lower value = higher *k*
Current maximum annual capacity (gk)	4,200,000 TEU (3)	4,200,000 TEU (3)	2,000,000 TEU (1)	Higher value = higher *k*
Quay length (do)	3391 m (3)	2173 m (2)	1500 m (1)	Higher value = higher *k*
Draft (dm)	18 m (3)	17 m (2)	15.5 m (1)	Higher value = higher *k*
Total surface (pt)	1.6 mil. m^2 (3)	0.771 mil. m^2 (1)	1 mil. m^2 (2)	Higher value = higher *k*
Joints for frigo containers (fk)	2300 (3)	1658 (2)	900 (1)	Higher value = higher *k*

Table 1. *Cont.*

	Gioia Tauro, Italy [47]	Marsaxlokk, Malta [47]	Taranto, Italy [48]	Defining the Priority of the Parameter *K*
Quayside machinery/cranes (m)	22 quay cranes, 1 mobile crane, 13 reach stackers (2)	Quayside cranes: 18 post-Panamax, 4 super post-Panamax, 15 reach stackers, 65 konecranes RTGs (3)	10 ship-to-shore gantry cranes, 20 rail-mounted gantry cranes (1)	Higher value = higher *k*
Sum of all values of the parameters *k*	(19)	(14)	(10)	

The research produced the sum of the values of seven key parameters for each individual port, and it can be concluded that the Port of Gioia Tauro in Italy has the greatest overall sum of the values of the relevant parameters k. Accordingly, the Port of Gioia Tauro will be selected as the hub port in this model, i.e., as the starting point of all optimization calculations.

The feeder ports (Bar, Ploče, Split, Rijeka, Koper, Trieste, Venice, Ravenna and Ancona) are marked as bullets and, together with their hub port, will make up part of the problem to be studied and optimized in the following chapter.

2.3. Optimization of the Feeder Service Model

The Travelling Salesman Problem (TSP) algorithm is a method that is most frequently used when solving the problem of route optimization, and it can be incorporated together with new methods that are suitable when there is a larger number of ports/cities, such as ant colony optimization (ACO), genetic algorithm (GA), particle swarm optimization (PSO), k-means clustering, shrink wrap algorithm and meta-heuristics [35,49–52]. When solving the optimization problem, using TSP, the branch and bound and the nearest neighbor algorithm are the most frequently used, and they give, in comparison with other algorithms, better results [34–41]. This is why these two algorithms will be used in solving the feeder service optimization problem of the Adriatic Sea.

2.3.1. Settings of the Key Parameters during Optimization

Distances among all seaports involved in the service network have to be defined prior to solving the problem of optimizing the Adriatic Sea feeder network. The distances between individual ports are shown in Table 2. As it has already been explained, the Port of Gioia Tauro in Italy represents the hub port. The ports forming the feeder service network include Bar, Ploče, Split, Rijeka, Koper, Trieste, Venice, Ravenna and Ancona.

Table 2. Distances in nautical miles (NM) between the hub port and feeder ports and among the individual feeder ports included in the model. Source: author.

PORTS									
1. Gioia Tauro	0								
2. Bar	370	0							
3. Ploče	489	169	0						
4. Split	488	168	73	0					
5. Rijeka	644	328	235	182	0				
6. Koper	674	358	265	212	118	0			
7. Trieste	677	360	268	214	121	9	0		
8. Venice	684	368	275	222	128	65	66	0	
9. Ravenna	644	337	250	203	121	100	102	76	0
10. Ancona	571	278	185	132	112	129	132	126	79	0

Considering that the model involves ten seaports and a symmetrical matrix, it can be concluded that there are $\frac{9!}{2}$ possible calls at ports, i.e., 181,440 possible rotation travels.

2.3.2. Optimization by Applying the Nearest Neighbor Method

The following steps are taken for solving the travelling salesman problem through the nearest neighbor method [53]:

- Step 1: Choose any starting node;
- Step 2: Analyze all edges / arcs emerging from the starting node and choose the node that is closest;
- Step 3: Repeat Step 2 until all nodes are visited at least once;
- Step 4: Check whether all nodes are visited, and, if so, return to the starting point to complete the cycle;
- Step 5: Draw the travel and calculate the distance of the travel made.

This is the route obtained through the nearest neighbor method:

T_{min} = 1→2→4→3→10→9→8→6→7→5→1 = Gioia Tauro→Bar→Split→Ploče→ Ancona→Ravenna→Venice→Koper →Trieste→Rijeka→Gioia Tauro, shown in Figure 2.

The length of the travel:

T_{min} = c1,2 + c2,4 + c4,3 + c3,10 + c10,9 + c9,8 + c8,6 + c6,7 + c7,5 + c5,1 = 370 + 168 + 73 + 185 + 79 + 76 + 65 + 9+121 + 644 = 1790 NM
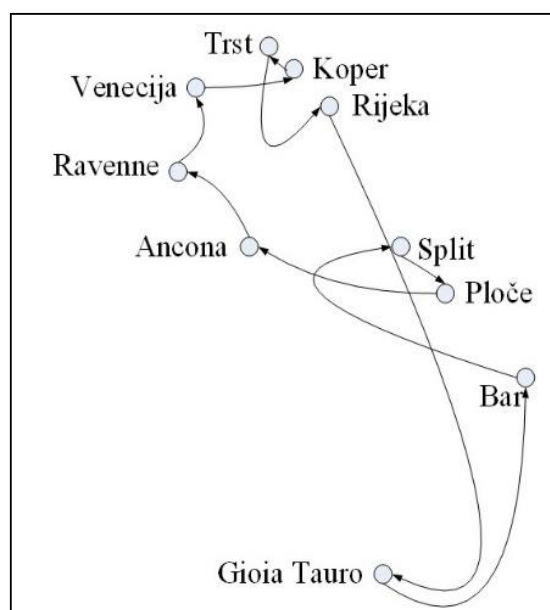
Figure 2. Route obtained through the nearest neighbor method. Source: author.

2.3.3. Optimization by Applying the Branch and Bound Method

The branch and bound method divides the set of all rotation travels into two disjoint subsets (branching). The lower cost limit (bound) for a given length of travel is calculated for each of the subsets [54]. The first step is to set the requirement cii = ∞ in order to prevent the travelling salesman from selecting the shortest route as 1→1, 2→2, 3→3, 4→4, 5→5, 6→6, 7→7, 8→8, 9→9 or 10→10. The next step is to resume branching by dividing the subset with the lower bound into two parts. The procedure is repeated until a subset is obtained with only one rotation travel whose bound is smaller than or equal to the bounds in other subsets. In this procedure, the subsets are described as nodes, and the partition process is presented as branching of a tree—hence the name. Figure 3 presents a completed tree obtained through the branch and bound method.
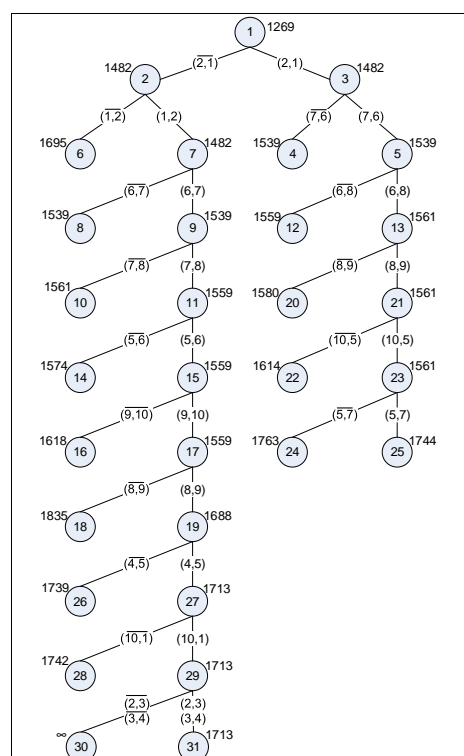
Figure 3. Branching of the tree obtained by applying the branch and bound method. Source: author.

In this way, the optimum solution to the problem has been reached. The next step is to define the optimum shipping route and the voyage length.
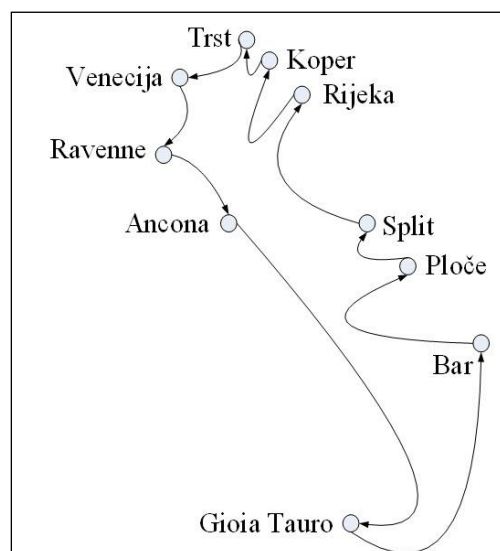
The optimum route:

$T_{min} = 1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7 \rightarrow 8 \rightarrow 9 \rightarrow 10 \rightarrow 1$

T_{min} = Gioia Tauro→Bar→Ploče→Split →Rijeka→Koper →Trieste→Venice→Ravenna →Ancona →Gioia Tauro, shown in Figure 4.

The length of the voyage:

$T_{min} = c_{1,2} + c_{2,3} + c_{3,4} + c_{4,5} + c_{5,6} + c_{6,7} + c_{7,8} + c_{8,9} + c_{9,10} + c_{10,1}$

T_{min} = 370 + 169 + 73 + 182 + 118 + 9+66 + 76 + 79 + 571 = 1713 NM.

Figure 4. Route obtained through the branch and bound method. Source: author.

2.3.4. Optimization by Applying Minimum Spanning Tree

Another idea is to establish some sub-hub ports. Geographical or economic importance of potential sub-hub ports on the route cannot be seen from Figure 4 in the chapter above, nor is the importance to neighbor ports obvious. Each port on the route is connected to two neighbor ports only, and such characteristic is represented with parameter $d = 2$. If the minimum spanning tree (MST) algorithm is applied, the result can be seen in Figure 5. Such graph is denoted with $T = (V,E)$, where V is the set of edges representing ports and E is the set of n–1 edges connecting all edges (ports) between them, so the sum of distances between edges is minimal T_{min}.

There are many algorithms solving the MST problem, though most of them use heuristics, which sometimes does not lead to optimal solutions [55–59]. The following steps are taken for solving the minimum spanning tree by well-known algorithm of Kruskal, and such algorithm is based on the exact approach:

- Step 1: Order all n values of arcs (distances between edges) from the smallest to the biggest in ascending order;
- Step 2: Take the smallest arc and include that arc in the sub-set of arcs forming MST, no matter if there is more of them with the same value;
- Step 3: Check whether it is possible to make a cycle in such sub-set of arcs forming the MST network. Such graph (network) is not necessarily connected during calculation. It only does not need to be checked if there is a first arc in the sub-set. If condition from Step 3 is satisfied, delete that arc from sub-set of arcs in MST network. If not, proceed further;
- Step 4. Repeat Step 2 and Step 3 for each arc until all arcs are visited at least once;
- Step 5: Make a sum of all n–1 arc distances in the MST network.

Such traffic option proposes that cycles are not being made, but, in MST, there is a different d ($d = 1, 2, 3 \ldots$). For example, if $d = 1$, it means that such port is not appropriate for making cycles toward other ports. It significantly increases travelling distance because it is necessary to return back from such edge port to the starting port, e.g., Ancona—Rijeka (see Figure 5), and to start another route to call all other ports. This solution could be very far from minimal distance route.
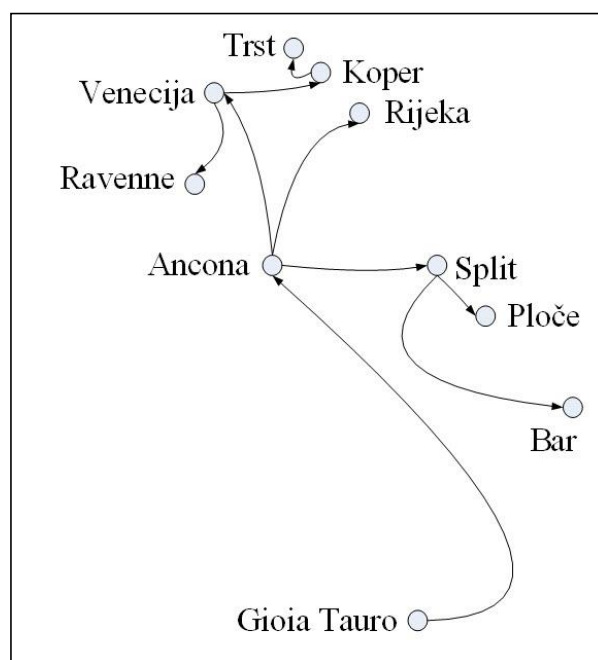

Figure 5. Route obtained through the MST algorithm—Solution 1. Source: author.

3. Results and Discussion

Similarities between the TSP and MST algorithm can be seen. For example, if the longest distance (edge) Ancona—Gioia Tauro from Figure 4 is eliminated, the solution can be presented as a MST problem. In that case, MST has a minimum distance Tmin = 1142NM, which is less optimal than the solution shown in Figure 5, where the best result for MST is Tmin = 1084NM. From such a minimum spanning tree construction, the geographical importance of ports can be seen. Two different facts arise:

- Some ports are connected with many other neighbor ports, $d > 2$;
- Other ports are connected only with one neighbor port, $d \leq 2$.

The first case means that such a port ($d > 2$) is geographically situated to be suitable as a sub-hub port. From Figure 5, it is obvious that the most important port is Ancona ($d = 4$). Other similar ports, but with smaller significances, are Venice and Split, with $d = 3$, and Koper, with d = 2. Compared with Ancona, they are not suitable as sub-hub port. If Ancona is used as sub-hub port, the process of the feeder service can be divided into two cycles (Figure 6). The first cycle could start from Gioia Tauro, calling ports $2\rightarrow3\rightarrow4$, and could be back to 10, using the TSP algorithm, where T_{min} = c10,2 + c2,3 + c3,4 + c4,10 = 1315 NM. This means that the ending port is Ancona (unloading) and that the feeder gets back to Gioia Tauro, with minimum route distance T_{min} = 1315 NM. The second cycle could be $10\rightarrow5\rightarrow-6\rightarrow7\rightarrow8\rightarrow9\rightarrow10$, including loading in Ancona. Using TSP, there is T_{min} = c10,5 + c5,6 + c6,7 + c7,8 + c8,9 + c9,10 = 460 NM. This means that the total distance is 1775 NM, which is slightly less optimal than what is shown in Figure 4. The difference is only 62 NM. The second cycle can be carried out with another, smaller feeder, starting from Ancona. Such a solution could be cost effective, as expenses with smaller feeders could be reduced.
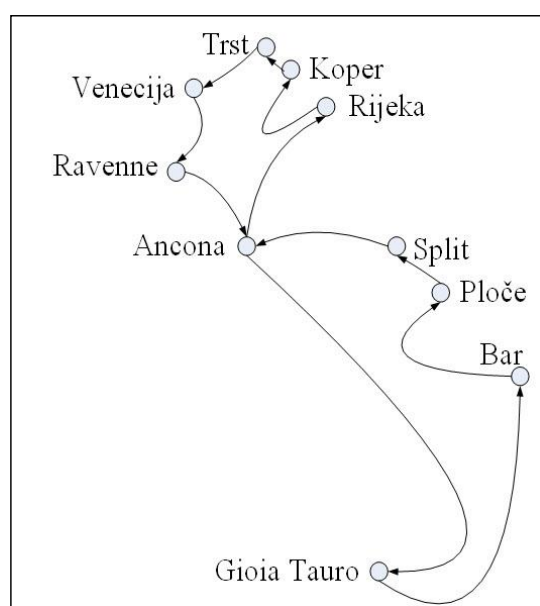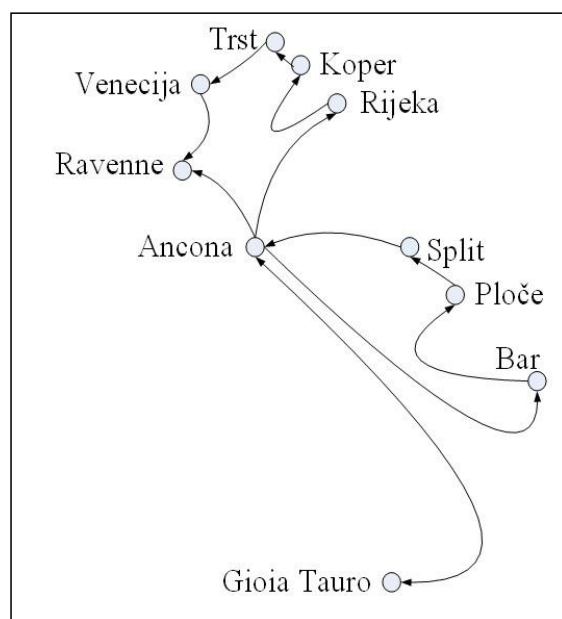

Figure 6. Route obtained through the MST algorithm—Solution 2. Source: author.

The third option can be seen in Figure 7. The route starts from Gioia Tauro to Ancona and back, but transshipment (unloading) has to be in Ancona, as it is a sub-hub port. Then, two or more cycles can be organized in order to feed all ports. This could be carried out with a time delay that enables the usage of only one smaller feeder. For example, if there are two routes with a smaller feeder, the total route distance is 1112 NM, the first cycle is $10\rightarrow9\rightarrow8\rightarrow7\rightarrow6\rightarrow5\rightarrow10$ with T_{min} = 460 NM and the second cycle is $10\rightarrow4\rightarrow3\rightarrow2\rightarrow10$ with T_{min} = 652 NM. In addition, the distance from Gioia Tauro to Ancona needs to be added (with a bigger feeder), which is 571 NM $\times$ 2 (in both directions).

Figure 7. Route obtained through the MST algorithm—Solution 3. Source: author.

4. Conclusions

According to relevant scientific databases, there is a lack of research concerning the optimization of the feeder service and selecting a hub port in the Adriatic Sea. From the viewpoint of practical realization, the feeder service in the Adriatic Sea is not optimal. This is the reason for addressing the issue scientifically and finding a solution that could be of great benefit, given the minimization of the shipping cost per cargo unit. This study suggests a multi-criteria analysis model that, based on the expert assessment and featuring seven parameters with associated coefficients, enables the identification of the hub port. The suggested multi-criteria analysis represents one of the key contributions to the mentioned research. Furthermore, expert assessment used in this research is based on multiple years of experience in this field. A sub-hub port system was also suggested as a new element that could upgrade the feeder system.

Two methods have been used in order to define the optimum feeder service route using the hub port system based on the travelling salesman problem (TSP) algorithm: the heuristics of the nearest neighbor and the branch and bound method. Through the comparative analysis of the obtained solutions, it can be concluded that the rotation voyage achieved by the branch and bound method is shorter, i.e., optimal. Therefore, it is suggested that this rotation of the shipping route can be used when implementing the Adriatic Sea feeder service. A minimum spanning tree algorithm was used for selecting the sub-hub port and, combined with the TSP algorithm, optimizing the routes of Adriatic feeder service. It can be concluded that the use of a sub-hub with the presented algorithm can give better or worse optimization results, depending on the multi criteria for the best option definition. In addition, different parameters can influence the evaluation of the most appropriate solution: the type of feeder, the transshipment possibilities, the timing of the feeding process, etc. The methodology suggested in the research can be extended and applied to similar areas, which is why the research stands out. Future research could focus on a broader application of the suggested methodology for selecting the hub ports, sub-hub port and optimal routes among the service network seaports.

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