Utilization of the Capacitated Vehicle Routing Problem with the Capacity Limitation of Nodes in Water Transportation

Korištenje kapacitivnog problema usmjeravanja vozila s ograničenjem kapaciteta čvorova u vodnom prometu

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Abstract

The paper discusses the option of using the capacitated vehicle routing problem with the capacity limitation of nodes in water transportation. The problem is used to design circular routes for vehicles of different carriers, each of which services the selected nodes of the transportation network. The goal is to design circular routes where the capacity of vehicles is not exceeded and the value of the objective function is minimal. The limited capacity of nodes is given by the limited number of vehicles that can be operated at a particular node at any given time. The problem allows to design circulation so that the waiting time of vehicles to release the capacity of the node is minimized. This makes it possible to achieve an additional reduction in the total traffic time. The possibility of using the role of the CVRPCLN in water transportation is demonstrated in a case study for the design of circular routes for vessels serving ports. The design of routes is performed using the described problem and using the capacitated vehicle routing problem, which does not take into account the limited capacity of the nodes. To solve both problems, the author uses an evolutionary algorithm, which is part of the optimization module Solver. A comparison of the results indicates that the use of the investigated task can lead to a significant reduction in waiting times in ports for selected tasks in the field of water transportation. This also leads to a significant reduction in the total traffic time.

KEY WORDS
vehicle routing problems
evolutionary algorithm
Solver
port capacity limitations

Sažetak

'U radu se raspravlja o mogućnosti primjene kapacitivnog problema usmjeravanja vozila s ograničenjima kapaciteta čvorova u vodnom prometu. Problemom se koristi za projektiranje kružnih ruta za vozila različitih prijevoznika, od kojih svaki opslužuje odabrana čvorišta prometne mreže. Cilj je projektirati kružne rute, gdje kapacitet vozila nije prekoračen, a vrijednost funkcije cilja je minimalna. Ograničeni kapacitet čvorova je zadan ograničenim brojem vozila kojima se može upravljati u određenom čvoru u bilo kojem trenutku. Problem omogućuje projektiranje cirkulacije tako da vrijeme čekanja vozila za oslobađanje kapaciteta čvora bude minimalizirano. Time je moguće postići dodatno smanjenje ukupnog vremena prometa. Uloga CVRPCLN-a u vodenom prometu prikazana je u studiji slučaja za projektiranje kružnih ruta za plovila koja tiču luke. Projektiranje ruta izvodi se uz pomoć opisanog problema te uz pomoć problema usmjeravanja vozila, koji ne uzima u obzir ograničeni kapacitet čvorova. Za rješavanje oba problema autor se koristi evolucijskim algoritmom koji je dio optimizacijskog modula Solver. Usporedba rezultata pokazuje da se korištenjem istraživanog zadatka može značajno smanjiti vrijeme čekanja u lukama za odabrane zadaće u području vodnog prometa. To također dovodi do značajnog smanjenja ukupnog vremena prometa.

KLJUČNE RIJEČI
problemi usmjeravanja vozila
evolucijski algoritam
Solver
ograničenja kapaciteta luke

1. INTRODUCTION / *Uvod*

During servicing of the transportation nodes on the transport network, the problem of insufficient capacity of the serviced nodes can be encountered in almost all modes of transport [1,2,3,4,5]. The capacity of the nodes is determined by the maximum number of vehicles which can be served simultaneously in the node of the transportation network. In the event of an insufficient capacity, there may be situations

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where the capacity of a node is completely exhausted and new entrants have to wait for service until another transportation vehicle frees the node's capacity [6]. This results in a significant increase in the total time of transportation servicing, which also leads to an increase in the costs of the carriers for the implementation of transportation service.

The paper discusses the possibility of using the capacitated vehicle routing problem with capacity limitation of nodes (CVRPCLN) in water transportation. Some authors are already dealing with the application of circular transportation tasks for the design of vessel transportation routes [7,8,9]. Most of these make it possible to achieve a reduction in the total traffic time only by minimizing the total length of voyage. CVRPCLN also makes it possible to reduce the total traffic time by minimizing the waiting time for service in ports.

The options of using CVRPCLN will be demonstrated on a case study dealing with the design of vessel transportation routes on the transportation network. The case study will first be looked at as a CVRPCLN and then as a capacitated vehicle routing problem (CVRP) [10,11]. CVRP does not take into account the limited capacity of nodes when designing circular routes and thus does not allow to minimize the waiting time for service. Both problems will be solved using an evolutionary algorithm, which is part of the optimization module Solver. The proposals of circular routes obtained by solving both tasks will be compared. The subject of the comparison will be the total time of traffic servicing, the total time of waiting for service in the nodes and the total time of solving the problem. One of the aims of the comparison is to verify whenever the use of the CVRPCLN can lead to significant savings in total traffic time by minimizing the total waiting time. Another goal is to evaluate the applicability of the proposed solution in practice in terms of the time required to solve it using an evolutionary algorithm.

2. CAPACITATED VEHICLE ROUTING PROBLEM WITH CAPACITY LIMITATIONS OF NODES / *Kapacitivni problem usmjeravanja vozila s ograničenjima kapaciteta čvorova*

The CVRPCLN is set by the transportation network and the set of carriers that perform transportation service of the nodes upon the given network. Transportation service is constructed in the form of round trips by the vehicles provided by carriers. Each carrier performs traffic servicing from a certain default node and services only selected nodes upon the given network. During the transportation service, the carriers must satisfy all the requirements of the nodes for the import and export of goods. The goal of the CVRPCLN is to design routes for all the vehicles as not to violate the limitations set forth by the task and to minimize the value of the objective function. The value of the objective function represents the sum of variable and fixed costs incurred for the realization of transport services and penalties for unused capacity of vehicles. The variable costs of the vehicle represent the product of the kilometers traveled and the price per 1 km traveled. Fixed vehicle costs represent the cost of operating a vehicle per unit of time. The penalty for unused capacity of vehicles represents the product of the unused capacity of the vehicle, the number of km traveled with such unused capacity and the penalty coefficient. The higher the value of the penalty coefficient, the higher the effect of non-utilization of vehicle capacity on the value of the objective function. Using the penalty coefficient, it is therefore possible to choose the degree of importance of the use of vehicle capacity during transportation service. The minimization of the objective function makes it possible to minimize the distance traveled by vehicles, to minimize the total time of transportation service and to ensure the maximum load utilization of vehicles.

The problem constraints are the basic constraints of circular traffic tasks [2] and other constraints that are specific to this problem. The specific constraints are as follows:

1. The capacity of each vehicle cannot be exceeded.This limitation represents the maximum amount of cargo that can be placed upon one vehicle. As vehicles perform both loading and unloading, it is necessary to ensure that this restriction is observed at each node on the transport route.

2. The capacity of each node cannot be exceeded. This limitation represents the maximum number of vehicles that can be serviced at any given time within the same node. CVRPCLN allows to comply with node capacity limitations in two ways. The first method consists of the vehicles waiting until capacity is released before entering the node. This method makes it possible to design the routes of vehicles to minimize the total travel time of vehicles. However, this increases the total waiting time for service at the nodes. The second method involves the design of vehicle routes in such a way that no more vehicles than the specified capacity of the node meet at the serviced nodes. This method makes it possible to minimize the waiting time for service at the nodes, but usually leads to an increase in the total travel time. This is due to the fact that this method usually requires the vehicles to travel a longer route.

3. Each serviced node has set time windows in which it can services incoming vehicles.

It follows from the above that the CVRPCLN makes it possible to minimize the value of the objective function by minimizing the total travel time of the vehicles and by minimizing the total waiting time of the vehicles for service at the nodes. When designing the circular routes using CVRPCLN, such a combination of both minimization options is used, which will lead to the lowest value of the objective function. CVRPCLN is described in detail using a mathematical model in the subchapter 2.1.

2.1. Mathematical model CVRPCLN / *Matematički model CVRPCLN*

The role of CVRPCLN can be defined as follows: Graph $G = (V, E)$, where V represents the nodes of the transportation network and E its edges. Nodes V are divided into two subsets: $V_o = \{v_0, v_1, \ldots, v_K\}$ represents default nodes and $V_p = \{v_{K+1}, v_{K+2}, \ldots, v_{K+n}\}$ represents serviced nodes, K is the number of default nodes (carriers) and n is the number of nodes served. R represents the set of all vehicles; t^o_{jr} represents the service time of the vehicle r at node j; t^c_{jr} represents the waiting time of the vehicle r for service at the node j; t^t_{ijr} represents the travel time of vehicle r between nodes i and j; c_{ij} represents the distance between node i and j; vc_r represents the cost of the vehicle r per km traveled, fc_r represents the fixed cost of operating the vehicle r for a given time unit, cp represents the penalty coefficient for unused vehicle capacity, Q_r represents the vehicle capacity r, q_{ijr} represents the amount of load transported by vehicle r between nodes i and j, x_{ijr} is a bivalent variable to which:

$$x_{ijr} = \begin{cases} 1, \text{vehicle } r \text{ travelles between nodes } i \text{ and } j \\ 0, \text{else} \end{cases} \tag{1}$$

y_{jrt} is a bivalent variable to which the following apply:

$$y_{jrt} = \begin{cases} 1, \text{service of the node } j \text{ by the vehicle } r \text{ interferes with the interval } t \\ 0, \text{else} \end{cases} \quad (2)$$

In the problem, it is necessary to minimize the objective function (3) while observing the constraints (4 -13).

Objective function:

$$Min \sum_{i=1}^{K+n} \sum_{j=1}^{K+n} \sum_{r=1}^{R} c_{ij} \cdot x_{ijr} \cdot vc_r + (t_{jr}^o + t_{jr}^c + t_{ijr}^t) \cdot x_{ijr} \cdot fc_r + (Q_r - q_{ijr}) \cdot cp \quad (3)$$

Constraints:

Constraint (4) applies to each carrier $k \in K$. The constraint ensures that exactly 1 carrier's vehicle k will depart from each node served by carrier k. D_k is a subset of all nodes served by carrier k, R_k is a subset of carrier's vehicles k.

$$\sum_{i \in D_k} \sum_{r \in R_k} x_{ijr} = 1, \qquad \forall j \in D_k \quad (4)$$

Constraint (5) applies to each carrier $k \in K$. The constraint ensures that exactly 1 carrier's vehicle k will drive into each node served by carrier k.

$$\sum_{j \in D_k} \sum_{r \in R_k} x_{ijr} = 1, \qquad \forall i \in D_k \quad (5)$$

Constraint (6) applies to each vehicle r. The constraint prevents partial cycles. The variable u_{ir} is the natural number assigned to node i served by the vehicle r, the variable u_{jr} is the natural number assigned to node j *served by the vehicle* r, n_r is the number of nodes served by the vehicle r. D_r is a subset of all nodes served by vehicle r.

$$u_{ir} - u_{jr} + n_r x_{ijr} \leq n_r - 1 \quad \forall (i,j) \in D_r, i \neq j \quad (6)$$

Constraint (7) ensures that vehicles arriving at node j also leave that node. x_{jir} is the equivalent of x_{ijr} for the case that vehicle r travels from node j to node i.

$$\sum_{i=1}^{K+n} x_{ijr} = \sum_{i=1}^{K+n} x_{jir}, \qquad \forall j \in (1,2,\ldots,K+n), \forall\, r \in (1,2,\ldots,R) \quad (7)$$

The constraint (8) ensures that the capacity of the vehicle Qr is not exceeded. bj represents the request of node j for goods from the carrier $k \in K$; bi represents the quantity of goods in the vehicle r before visiting the node *j, dj* represents the requirement of node *j* for the removal of goods by the carrier *k*.

$$b_i - b_j + d_j \leq Q_r, \qquad \forall j \in (1,2,\ldots,K+n), \forall\, r \in (1,2,\ldots,R) \quad (8)$$

Constraint (9) applies for each time interval t in which the vehicle r is served in node j. p_j is the maximum number of simultaneously served vehicles in node j, T is the set of all intervals t. The contraint ensures that the maximum number of vehicles served does not exceed the customer's capacity.

$$\sum_{j=1}^{K+n} \sum_{r=1}^{R} y_{jrt} \leq p_j, \qquad \forall\, t \in T \quad (9)$$

Constraint (10) ensures that vehicles from one default node will not arrive to another default node.

$$x_{ijr} = 0, \quad \forall (i,j) \in (1,2,\ldots,K), \forall\, r \in (1,2,\ldots,R) \quad (10)$$

Constraint (11) ensures that a route from node i to node i is not to be planned.

$$x_{iir} = 0, \quad \forall i \in (K+1, K+2, \ldots, K+n) \quad (11)$$

The constraints (12) and (13) ensures that each vehicle r serves node j in the time window designated to the node service. e_{ja} represents the earliest possible start of vehicle operation r at node j. l_{ja} represents the latest possible end of vehicle operation r at node j. t^z_{jr} represents start of vehicle operation r at node j. t^k_{jr} represents end of vehicle operation r at node j. A is a set of time windows a in which the operation of vehicles at node j is possible.

$$e_{ja} \leq t_{jr}^z \qquad \forall j \in (1,2,\ldots,K+n), \forall\, r \in (1,2,\ldots,R), \forall a \in A \quad (12)$$

$$t_{jr}^k \leq l_{ja} \qquad \forall j \in (1,2,\ldots,K+n), \forall\, r \in (1,2,\ldots,R), \forall a \in A \quad (13)$$

Constraint (14) ensures that the bivalent variable x_{ijr} takes the values 0 or 1.

$$x_{ijr} = \{0,1\}, \qquad \forall\, i,j \in (1,2,\ldots,K+n), \forall\, r \in (1,2,\ldots,R) \quad (14)$$

Constraint (15) ensures that the bivalent variable y_{jrt} takes the values 0 or 1.

$$y_{jrt} = \{0,1\}, \quad \forall j \in (1,2,\ldots,K+n), \forall\, r \in R, \forall t \in T \quad (15)$$

3. EVOLUTIONARY ALGORITHM / *Evolucijski algoritam*

The case study will be solved using an evolutionary algorithm. Evolutionary algorithms are metaheuristic iterative optimization methods that are inspired by the principles of natural evolution. This inspiration consists in the use of 3 basic principles of evolutionary theory: selection, cross-breeding and mutation. Evolutionary algorithms translate these principles into computer-generated optimization procedures. In this paper, an evolutionary algorithm will be used, which is part of the Solver optimization module. The Solver tool is part of the Excel spreadsheet and is used to solve mathematical programming problems [12]. When solving problems using the Solver, a cell is selected in the spreadsheet that contains a formula for calculating the objective function of the mathematical model of the problem. Variables are specified in the formula in the form of references to cells whose value represents the value of the variables [6]. Based upon the value of the cells containing the variables, the value of the cell containing the objective function changes. The required extreme of the objective function is achieved through the Solver, which uses the selected optimization method to find the optimal or suboptimal values of the cells representing the variables. The Solver can use several methods to optimize the objective function. The mentioned evolutionary algorithm will be used in this paper. A detailed procedure for solving problems using the Solver is given by Fystra et al. [13].

3.1. Algorithm for CVRPCLN resolution / *Algoritam za CVRPCLN rješenje*

The following procedure illustrates the use of an evolutionary algorithm within the Solver to solve the CVRPCLN. The procedure is divided into 3 steps, which are shown in Figures 1, 2 and 3. Figure 1 shows the creation of a objective function and variables in a spreadsheet. Figure 2 shows the preparation of the data necessary to enter all the constraint. Figure 3 shows entering parameters into the Solver. In the example shown in Figures 1-3, a time matrix instead of a distance matrix was used to calculate the variable costs.

Step 1:

1. Into the Excel spreadsheet, a time matrix is inserted for each carrier expressing the travel time between nodes of

the transportation network. Furthermore, requirements of serviced nodes for import and export of cargo, data on capacity, variable costs of vehicles per 1 time unit, fixed costs of vehicles per time unit, data on time windows in which it is possible to service individual nodes and data on the service time of vehicles of individual carriers within the serviced nodes are inserted.

2. For each carrier, 3 columns representing the variables of the mathematical model are selected, for reference, see the table "Variables-carrier A" in Figure 1. Column G contains the numbers of the serviced nodes. The numerical order in the column determines the arrangement of the nodes on route of their respective vehicle. Column H contains the numerical designation of the vehicles that services the nodes on the corresponding row of column G. Column I contains the waiting time of the vehicle for servicing at the node from the corresponding row of column G.
3. For each carrier, a table is created for calculating the journey time between nodes on the transportation route of each carrier vehicle, see the table "Carier A - vehicle routes" in Figure 1.
4. A formula for calculating the objective function is inserted into the selected cell, see cell P27 in Figure 1.

Step 2:

1. A table is created in which the maximum capacity of all vehicles and the used capacity of all the vehicles are employed within the specific design of circularity, see the table "Capacity limitations of vehicles" in Figure 2.
2. A table is created for calculating the timing the arrivals and departures of vehicles to each serviced node, see the table "Service time in nodes" in Figure 2. Next, a table is created in which the arrival and departure times of carriers' vehicles to a particular node are arranged within one line, see table "Service time in nodes - orderly".
3. A table is created, which determinates for each carrier how many vehicles are simultaneously served in each node at the time when the vehicle of a given carrier is served in the node, see the table "Collisions at the time of operation"
4. The maximum capacity for each node is entered into the selected column, see the "Node capacity" column in Figure 2.
5. A table for calculating the penalty for unused capacity of vehicles is created, see the table „Penalty for unused capacity" in Figure 2.
6. A table is created to check compliance with time windows for node operation, see the „Time windows control" table. If the values in the table represent only zeros, the nodes are serviced in the specified time windows.

Step 3:

1. The "Solver Parameters" dialog box opens, see Figure 3. A link to the cell containing the objective function and to the cells containing the variables is entered here. Next, the minimization of the objective function is chosen and the evolutionary algorithm is chosen as the solution method.
2. The following constraints are created in the "Solver parameters" dialog box: variables indicating individual nodes can take only values intended for their designation, variables indicating vehicles can take only values intended for their designation, variables determining the waiting time of vehicles for service at the node can only acquire integers from the specified interval, the value in the cell representing the used capacity of the vehicle must not exceed the value in the cell representing the maximum capacity of the vehicle, the value in the cell representing the number of served vehicles in the node at the time of operating the vehicle of a certain carrier must not exceed the value in the cell representing maximum node capacity. All values in the "Time windows control" table must be equal to 0. The specified constraints are shown within the Figure 3
3. The "Solve" button in the "Solver Parameters" dialog box starts the optimization.

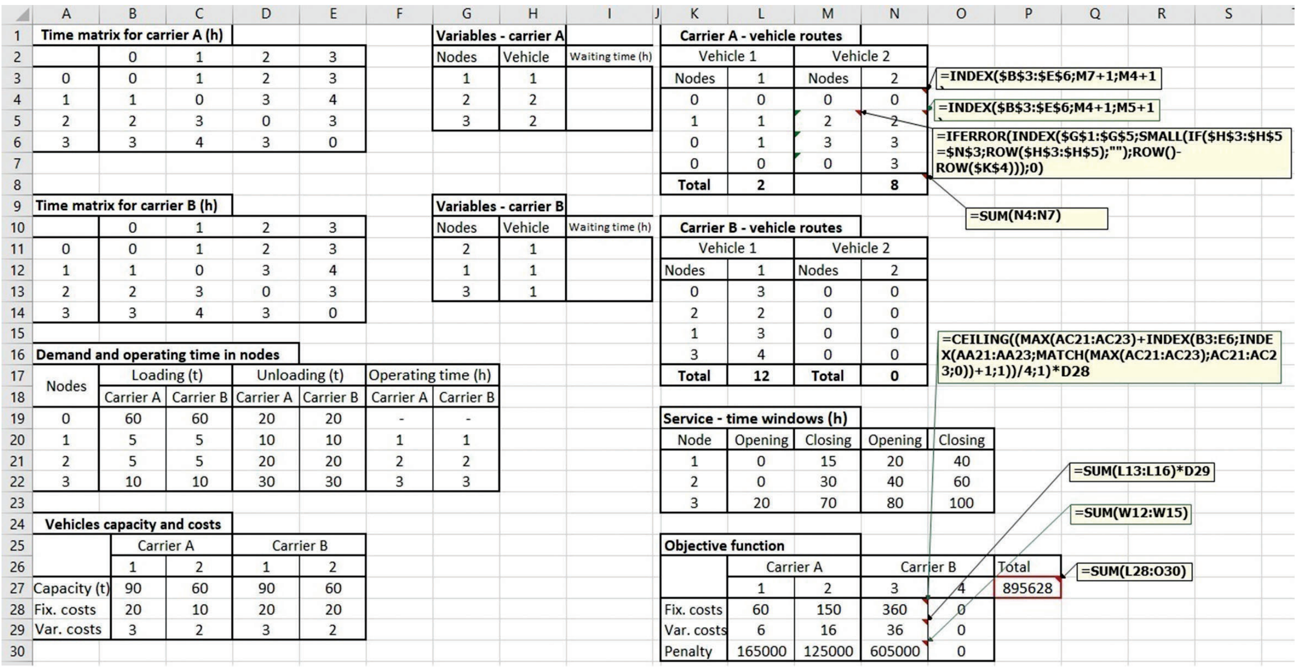

Figure 1 Objective function and variables CVRPCLN

Slika 1. Funkcija cilja i varijable CVRPCLN

Source: Author

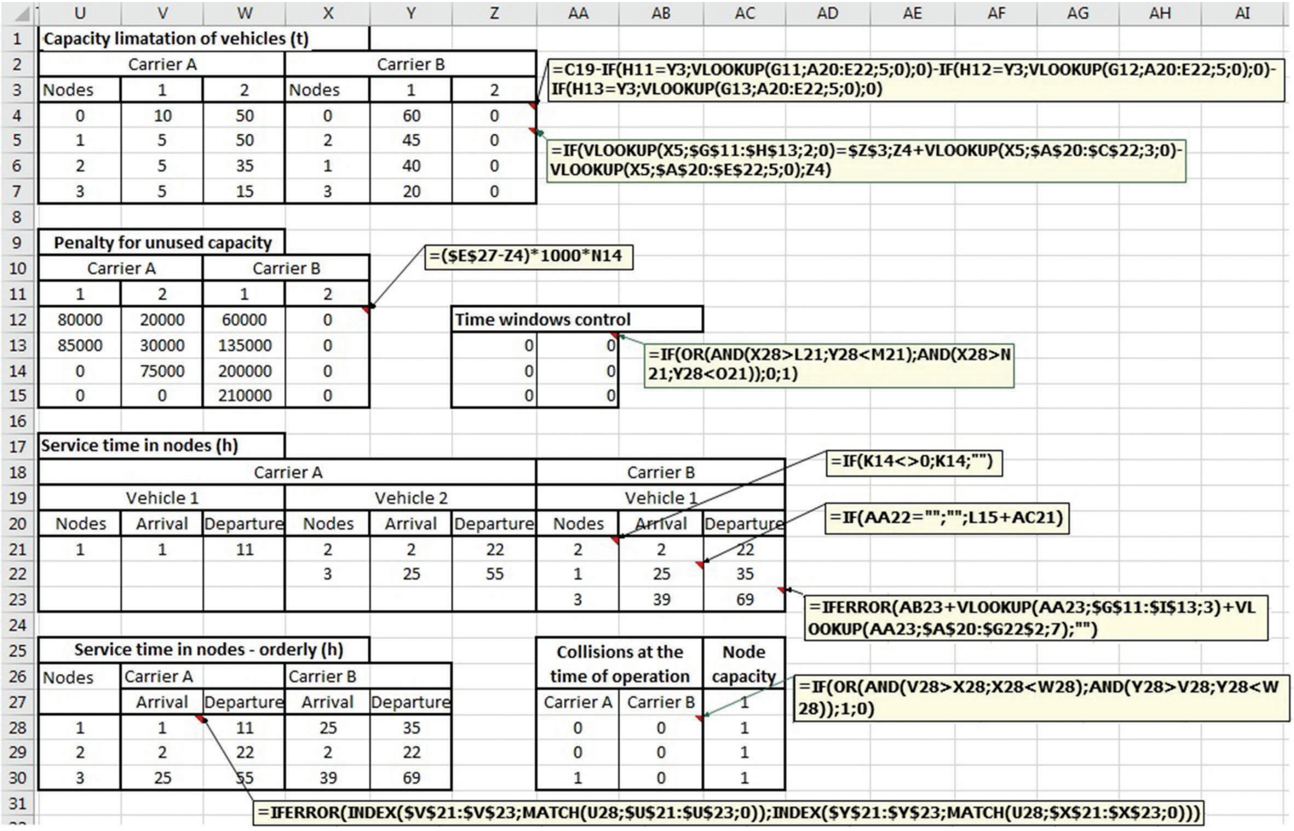

Figure 2 CVRPCLN constraints

Slika 2. CVRPCLN ograničenja

Source: Author

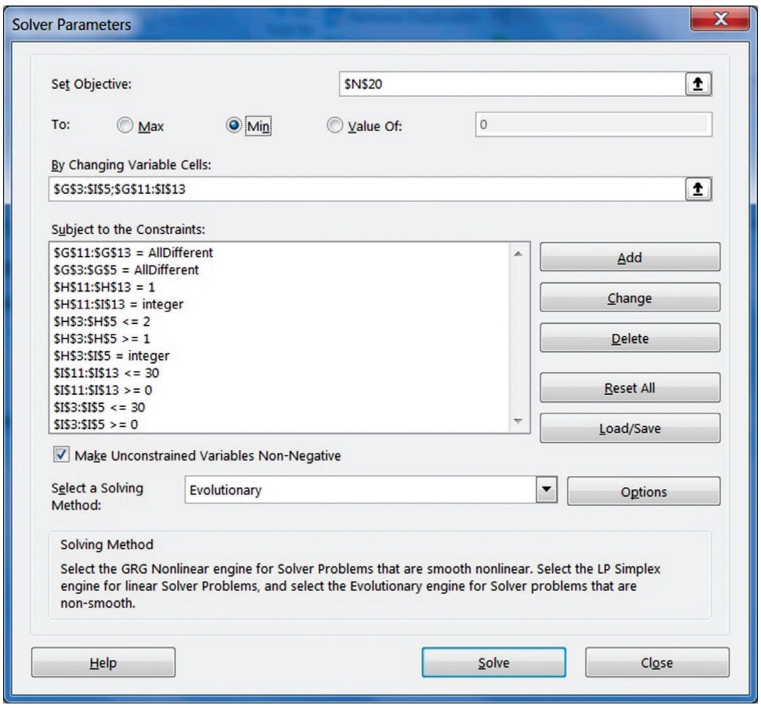

Figure 3 Solver parameters

Slika 3. Solver parametri

Source: Author

4. CASE STUDY / *Studija slučaja*

In the case study, a design of circular routes for vessels of 3 fictitious carriers will be performed. These carriers operate maritime transport of bulk shipments. Each carrier operates ports upon the transportation network from a different port of departure. To ensure transportation service, each carrier has 2 vessels. Carriers use the same types of vessels. The first type of vessel has a capacity of 110 tons and the second type has a capacity of 60 tons. The total cost of operating a vessel type

1 is 1000 monetary units and the cost of operating a vessel type 2 is 800 monetary units. Fixed costs are calculated for every 24 hours of operation. To simplify the case study, it will be considered that the vessels move at the same speed and have the same cost per 1 km of sailing. Variable costs will be calculated based on the voyage time of the vessels. One hour of the voyage will correspond to the price of 1monetary units [14]. The coefficient for calculating the penalty for the unused capacity of the vessels is equal to 1. The capacity of all the serviced ports is 1 vessel, which can be serviced in the port at any given time. The transportation network consists of 3 ports of departure and 10 serviced ports. Each carrier must service all 10 servicing ports. At the same time, the capacity of the vessels used and the nodes serviced must not be exceeded. Table 1 presents a time matrix showing the length of voyages between all ports on the transport network in units of hours. The default ports are marked V0 - V2 and the serviced ports V3 - V12.

Table 2 shows the port requirements for the import and export of goods by individual carriers and the estimated time of servicing of the vessels owned by the carriers in the ports. The requirements for the goods of the carriers and the service time are the same for all the carriers.

Table 3 shows the time windows in which it is possible to operate individual ports. Data on time windows are given in time from the beginning of the traffic service in units of hours.

The case study will first be addressed as a CVRPCLN and then as a CVRP that does not take into account the limited capacity of the nodes. In both methods, the value of the objective function is the sum of variable costs, fixed costs and the value of the penalty for unused capacity of vessels. In the case of CVRP, the waiting time for service in ports is not included in the calculation of the objective function, because the method does not take into account the limited capacity of the ports. The waiting time for the service will be included in the objective function only after the traffic service plan has been drafted.

Table 1 Time matrix

Tablica 1. Vremenska matrica

	V0	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12
V0	0	-	-	37	27	22	21	18	37	18	29	35	10
V1	-	0	-	20	11	19	19	33	32	9	16	34	23
V2	-	-	0	14	44	53	25	61	13	32	19	19	37
V3	37	20	14	0	31	39	18	50	12	20	9	21	29
V4	27	11	44	31	0	11	29	27	42	17	27	44	29
V5	22	19	53	39	11	0	32	17	48	21	34	49	27
V6	21	19	25	18	29	32	0	37	17	12	9	17	12
V7	18	33	61	50	27	17	37	0	54	29	42	52	27
V8	37	32	13	12	42	48	17	54	0	27	15	6	27
V9	18	9	32	20	17	21	12	29	27	0	13	28	14
V10	29	16	19	9	27	34	9	42	15	13	0	18	20
V11	35	34	19	21	44	49	17	52	6	28	18	0	25
V12	10	23	37	29	29	27	12	27	27	14	20	25	0

Source: Author

Table 2 Port requirements and port service times

Tablica 2. Zahtjevi luka i vremena u luci

	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12
Unloading (t)	15	10	16	18	12	18	20	14	13	10
Loading (t)	10	13	16	14	11	16	16	10	11	12
Servicing time (h)	30	20	32	36	24	36	40	28	26	20

Source: Author

Table 3 Time windows for port operations

Tablica 3. Vremenski prozori za lučke operacije

Time window	V3	V4	V5	V6	V7	V8	V9	V10	V11	V12
1	10 -85	0 - 100	20 -140	80-260	0 - 190	0 - 140	5 - 150	10 - 130	20 - 200	10 -100
2	130 -180	115 -180	170 - 250	300-400	200-320	170-270	200 - 350	160 - 220	250 - 340	130 - 200
3	215 - 260	-	-	-	-	-	-	250 - 320	-	220 - 380

Source: Author

4.1. Solution CVRPCLN / *CVRPCLN rješenje*

The algorithm described in chapter 3.1 was used for solution CVRPCLN. The resulting design of circulation is shown in Table 4. The "Port" column lists the serviced nodes. The columns with the designation of the carrier show which vessel of the given carrier performs the servicing of the node from the corresponding row in the column "Port" and at what time from the beginning of the servicing it performs this action. The "Waiting time" column shows the total waiting time of vessels for service in ports.

Based upon the data collected from the Tables 1 and 4, it is possible to determine the total length of voyage as 602 hours, the total waiting time of vessels for servicing is 14 hours, the total time of servicing in ports is 876 hours and the total time of transportation service is 1 492 hours. The value of the objective function is 71778. All vessels were used for transportation service. The capacity of vessels was used on average at 80.28%. No vessel's capacity has been exceeded and no port capacity has been exceeded in any port. All ports were served within the specified time windows. Therefore, none of the proposed circular routes violate the set constraints.

4.2. Solution CVRP / *CVRP rješenje*

A modified algorithm from chapter 3.1 was used for solution CVRP. For CVRP, the waiting time for service in ports is not included in the objective function. This ensures that circulations are designed only on the basis of minimizing the total length of voyage. The resulting design of the circular routes is shown in Table 5. The table shows the data in the same way as the Table 4 did.

Based upon the data from Tables 1 and 5, it is possible to determine that the total length of voyage is 564 hours, the total waiting time of vessels for servicing is 114 hours, the total time of servicing at the ports is 876 hours and the total time of transportation service is 1 554 hours. The value of the objective function is 72923. In this case, all vessels were used for transportation service. The capacity of vessels was used on average at 78.71%. The capacity of any vessel has not been exceeded and no maximum capacity has been exceeded in any port. All ports were served within the specified time windows. Therefore, none of the circular routes violate the set constraints.

Table 4 Design of circular routes using CVRPCLN
Tablica 4. Projektiranje kružnih ruta uz pomoć CVRPCLN-a

Port	Carrier 1		Carrier2		Carrier 3		Waiting time (h)
	Vessel	Servicing time (h)	Vessel	Servicing time (h)	Vessel	Servicing time (h)	
V3	1	138 -168	1	53 -83	2	14 - 44	0
V4	2	75 -95	2	11 - 31	2	151 - 171	0
V5	2	106 - 138	2	42 - 74	1	193 - 225	0
V6	1	216 - 252	1	180 - 216	1	98 - 134	2
V7	2	155 - 179	2	91 - 115	1	242 - 266	0
V8	1	49 - 85	1	95 - 131	1	13 - 49	12
V9	2	18 - 58	1	262 - 302	2	94 - 134	0
V10	1	177 - 205	1	16 – 44	2	53 - 81	0
V11	1	91 - 117	1	137 - 163	1	55 - 81	0
V12	1	264 - 284	1	228 - 248	1	146 - 166	0

Source: Author

Table 5 Design of circular routes using CVRP
Tablica 5. Projektiranje kružnih ruta pomoću CVRP-a

Port	Carrier 1		Carrier 2		Carrier 3		Waiting time (h)
	Vessel	Servicing time (h)	Vessel	Servicing time (h)	Vessel	Servicing time (h)	
V3	1	139 -169	1	228 - 258	1	14 - 44	0
V4	2	117 - 137	2	11 -31	1	151 -171	0
V5	2	74 - 106	2	42 -74	1	182 - 214	15
V6	1	301 - 337	1	95 -131	2	131 - 167	33
V7	2	18 -42	2	91 - 115	1	231 - 255	0
V8	1	216 - 252	1	180 - 216	2	13 -49	35
V9	1	49 - 89	1	9 - 49	1	94 - 134	31
V10	1	102 -130	1	267 - 295	1	53 - 81	0
V11	1	258 - 284	1	148 - 174	2	55 - 81	0
V12	1	349 - 369	1	63 -83	2	179 - 199	0

Source: Author

4.3. CVRPCLN and CVRP complexity comparison / *Usporedba složenosti CVRPCLN-a i CVRP-a*

To solve the case study, a maximum limit of 100,000 evolution algorithm iterations was set for both tasks. During these iterations, the process of improving the objective function with both evolutionary algorithms took place in both tasks. After the set limit, the evolutionary algorithm was terminated. Figure 4 shows the gradual improvement of the objective function value using the evolutionary algorithm for CVRPCLN and CVRP in individual iterations. In order to make the values of the objective function comparable to each other, the final waiting time of vessels for servicing was added to the value of the objective function in the CVRP. The number of iterations is shown on the x-axis and the value of the objective function on the y-axis.

In Figure 4, we can see that in the case of CVRPCLN, the default solution to the problem was found after 1 084 iterations. The value of the objective function of this solution is 71 778. For CVRPCLN, it can be observed that the value of the objective function decreases linearly depending on the number of iterations. From iteration 43 000, the rate of degradation of the objective function value gradually decreases. Starting with iteration 48 933, the final solution was found that did not improve until the 100 000 iteration.

For CVRP, the default solution was found after 575 iterations.The value of the objective function for this solution is 72 923. For CVRP, the relationship between the value of the objective function and the elapsed time is logarithmic. Thus, the value of the objective function at first decreases rapidly and then the rate of the degradation slows down sharply. The decrease rate of the objective function slows down after 5 730 iterations. In iteration 12885, the final solution was found that did not improve until the 100 000 iteration.

5. ANALYSIS OF THE RESULTS / *Analiza rezultata*

By solving a case study as CVRPCLN, the final value of the objective function was 71 778 and by solving a case study as CVRP, the final value of the objective function was 72 923. Thus, in the case of CVRPCLN, the value of the objective function is lower by 1 145. This represents a saving of 1,5%. To justify the savings, it is necessary to analyze the partial values of the objective function for both tasks. These values include variable costs, fixed costs and penalties for unused vessel capacity. The penalty for unused capacity is 1 017 lower in the case of CVRP. Variable costs are given by the total sailing time and fixed costs by the total traffic time. Figure 5 presents a comparison of the total sailing time and the total waiting time for servicing in ports as per the resulting proposals of both problems.

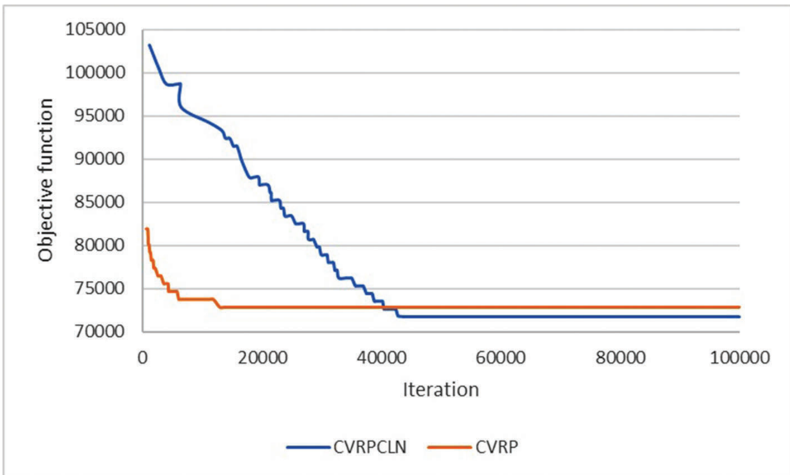

Figure 4 Comparison of CVRPCLN and CVRP in terms of number of iterations
Slika 4. Usporedba CVRPCLN-a i CVRP-a prema broju ponavljanja

Source: Author

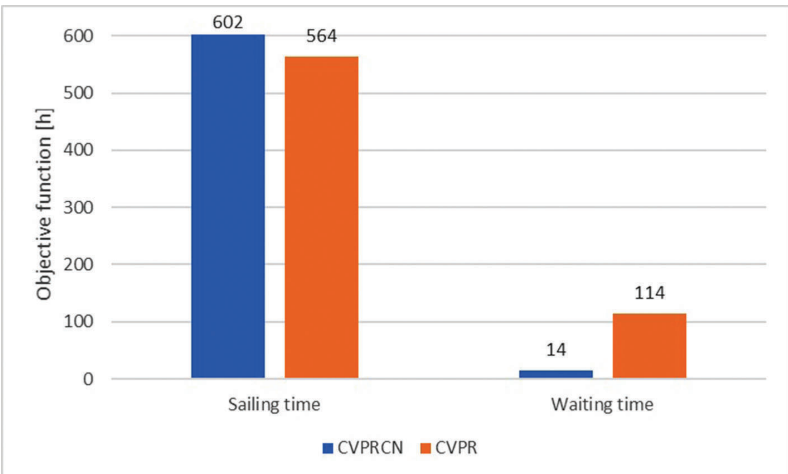

Figure 5 Comparison of CVRPCLN and CVRP in terms of total sailing time and total waiting time for servicing
Slika 5. Usporedba CVRPCLN-a i CVRP-a prema ukupnom vremenu plovidbe i ukupnom vremenu čekanja

Source: Author

Figure 5 shows that the CVRP solution had offered 38 hours shorter sailing times than the CVRPCLN solution. However, the total waiting time of vessels for servicing was 100 hours shorter for the CVRPCLN. The shorter voyage time in the case of CVRP led to a reduction in the value of the objective function by 38 points due to a reduction in variable costs. The shorter waiting time in the case of CVRPCLN led to a reduction in the objective function by 2,200 points due to a reduction in fixed costs. The lower value of the objective function for the CVRPCLN was therefore achieved by minimizing the total waiting time of vessels for servicing at ports that the CVRPCLN permits.

In the case of CVRPCN, the total number of iterations required to find the final solution was 43 203 more than that in the case of CVRP.The difference is mainly due to the fact that in the case of CVRP the reduction of the target value by means of an evolutionary algorithm copies the logarithmic trend line and in the case of CVRPCLN the linear trend line. Decreasing the value of the objective function in CVRP is therefore faster. Due to this fact, the final value of the objective function was found faster. Another cause of the difference in the number of iterations can be found in the higher value of the objective function of the default solution in CVRPCLN. For the CVRPCLN, it was therefore necessary to use an evolutionary algorithm to reduce the value of the objective function of the initial solution in a more significant way, which requires a larger number of iterations.

6. CONCLUSION / *Zaključak*

The paper introduces the author-defined role of the CVRPCLN, which is used to design the circular routes of carriers' vehicles in cases where it is necessary to comply with the capacity limitations of the nodes served. The case study verified the possibility of using CVRPCLN in water transportation. In this study, the CVRPCLN was used to plan the delivery routes of vessels serving ports. The results obtained with CVRPCLN were compared with the results gathered with CVRP, where the limited capacity of the nodes is not taken into account. When comparing the results of both, it was found that the total length of voyage was longer for CVRPCLN, but the waiting time for servicing in ports was significantly shorter. Thus, longer circulation was designed using the CVRPCLN, but this design method led to the minimization of vessel encounters in the ports served. This has also minimized waiting times for servicing in ports. Thanks to this, the total traffic time was significantly shorter at CVRPCLN. The total number of iterations needed to find the final solution was larger in the case of CVRPCLN. This is due to the fact that CVRPCLN has a greater number of restrictions than CVRP. As a result, the rate of decrease of the value for the objective function by the evolutionary algorithm is slower in CVRPCLN, and at the same time the higher value of the objective function of the default solution, which needs to be reduced by the evolutionary algorithm. With the increasing complexity of the problem, it can be assumed that the difference in the number of iterations required to find an acceptable solution between CVRPCLN and CVRP will increase.

The contribution to the case study demonstrated the possibility of using CVRPLN in the design of circular routes of vessels in water transportation. The application can lead to reduction in total traffic time upon the transportation network by minimizing the total waiting time of vessels to be serviced in ports. The quality of the solution found using CVRPCLN is affected by the nature of the problem. If the solved issue does not offer room for planning circular routes so that vehicles do not meet in the serviced nodes, or such a design of circular routes leads to a significant increase in total traffic time, CVRPCLN may not be able to provide a better solution than CVRP. CVRPLN can therefore be considered effective for tasks where there is room to minimize vehicle encounters and at the same time this minimization does not mean a significant increase in total driving time. The application of CVRPCLN solved by means of an evolutionary algorithm seems to be more suitable for less complex tasks, where it can be assumed that a suitable solution will be found within an acceptable timeframe. The issue can also be applied to more complex tasks. Here, however, it is necessary to assume a significantly longer solution time than with CVRP.

The algorithm presented by the authors can be practically used in cases where a set of ports are served by vessels from several ports of departure. This service can be carried out by various types of vessels in the form of round trips. Vessels can pick up and deliver goods at the same time. Ports may require service during specified time windows and have a specified limited capacity for the number of vessels simultaneously serviced. The task is to minimize the total fixed and variable costs for the realization of transport and to maximize the use of the useful weight of the vessels used. These goals can be achieved within the algorithm primarily by a suitable design of transport routes and further by a suitable selection of the vessels used.

As a practical example of the use of the algorithm in water transport, we can mention the ship routing between salmon farms located on the individual islands of Chiloe Island [15]. Salmon feed is transported to these farms from the warehouses of Skretting Chile SA. The transport of feed is provided every day by vessels of 2 companies in the form of round trips. Within one day, one farm can be served by more than one vessel. Most of the serviced farms require service in the time window of 8:00 am to 6:00 pm and are limited by the maximum number of vessels serviced. In the event of a poor traffic service plan, vessels may be waiting for service in ports. For each of the vessels used, it is required that its loading capacity is used at least 80%. When dealing with vessels routing, it is therefore necessary to choose suitable vessels not only with regard to costs, but also with regard to the use of their loading capacity. Route planning is done manually and takes roughly 2 hours per day for planners. The requirements placed on the planning of maritime transport routes in the given example correspond to the algorithm presented in the paper. Since the route planning is done manually, the use of the given algorithm could lead to a more efficient planning of maritime transport routes in salmon feed delivery in terms of cost minimization, maximization of the use of the loading capacity of vessels and minimization of the time required for maritime transport route planning.

REFERENCES / *Literatura*

[1] De Weille, J. & Ray, A. (1974). The optimum port capacity. Journal of Transport Economics and Policy, 8(3), 244-259.

[2] Sheikholeslami, A., Ilati, G. & Yeganeh, Y. E. (2013). Practical solutions for reducing container ships' waiting times at ports using simulation model. *Journal of Marine Science and Application*, 12(4), 434-444. https://doi.org/10.1007/s11804-013-1214-x

[3] Wang, C. N., Dang, T. T., Le & T. Q., Kewcharoenwong, P. (2020). Transportation Optimization Models for Intermodal Networks with Fuzzy Node Capacity, Detour Factor, and Vehicle Utilization Constraints. *Mathematics*, 8(12), 2109. https://doi.org/10.3390/math8122109

[4] Barnhart, C., Fearing, D., Odoni, A. & Vaze, V. (2012). Demand and capacity management in air transportation. *EURO Journal on Transportation and Logistics*, 1(1-2), 135-155. https://doi.org/10.1007/s13676-012-0006-9

[5] Gilbo, E. P. (1997). Optimizing airport capacity utilization in air traffic flow management subject to constraints at arrival and departure fixes. *IEEE Transactions on Control Systems Technology*, 5(5), 490-503. https://doi.org/10.1109/87.623035

[6] Yoon D. (2022). Logistics Strategy Research for Efficient Operation of Airports and Ports. *LOGI - Scientific Journal on Transport and Logistics*, 13(1), 96-107. https://doi.org/10.2478/logi-2022-0009

[7] Chládek, P. & Smetanová, D. (2018). Travelling salesman problem applied to black sea ports used by czech ocean shipping companies. *Naše more: znanstveni časopis za more i pomorstvo*, 65(3), 141-145. https://doi.org/10.17818/NM/2018/3.2

[8] Antoš, K. (2016). The Use of Minimal Spanning Tree for Optimizing Ship Transportation. *Naše more: znanstveni časopis za more i pomorstvo*, 65(3), 81-85. https://doi.org/10.17818/NM/2016/SI1

[9] Fazi, S., Fransoo, J. C., Van Woensel, T. & Dong, J. X. (2020). A variant of the split vehicle routing problem with simultaneous deliveries and pickups for inland container shipping in dry-port based systems. *Transportation Research Part E: Logistics and Transportation Review*, 142. https://doi.org/10.1016/j.tre.2020.102057

[10] Laporte, G. (1992). The vehicle routing problem: An overview of exact and approximate algorithms. *European journal of operational research*, 59(3), 345-358. https://doi.org/10.1016/0377-2217(92)90192-C

[11] Dantzig, G. B. & Ramser, J. H. (1959). The truck dispatching problem. *Management science*, 6(1), 80-91. https://doi.org/10.1287/mnsc.6.1.80

[12] Holoubek, J. (2006). Ekonomicko-matematické metody. Mendelova zemědělská a lesnická univerzita. ISBN 80-7157-970-X

[13] Fylstra, D., Lasdon, L., Watson, J. & Waren, A. (1998). Design and use of the Microsoft Excel Solver. *Interfaces*, 28(5), pp. 29-55. https://doi.org/10.1287/inte.28.5.29

[14] Nwokedi T.,Ndikom O.,Okoroji L., Nwaorgu J. (2021). Determinant Port-related Factors Affecting the Flow of Shipping Trade and Logistics in Nigerian Seaports. *LOGI - Scientific Journal on Transport and Logistics*, 12(1), 261-270. https://doi.org/10.2478/logi-2021-0024

[15] Romero, G., Durán, G., Marenco, J., & Weintraub, A. (2013). An approach for efficient ship routing. *International Transactions in Operational Research,* 20(6), 767-794. https://doi.org/10.1111/itor.12021