Locating Log Depots and Forest Roads Using a Weighted-Graph Optimization Algorithm

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Abstract – Nacrtak

Sustainable management of commercial forests can be achieved within the limits provided by an optimal, well-designed haul network with low-cost roads and skidding. In this study, a weighted-graph algorithm consisting of nodes (candidate log depots) and links (candidate forest roads) was used to optimize the haul network. The value of each link and node was calculated for thirty six candidate road in harvesting units of an Iranian forestry plan. The analysis of the nodes revealed different skidding costs because of different skidding and winching distances as well as number of logs. Total skidding cost for each node allowed identifying the least-cost depots and designing the links as a support to decisions on road network location. Road cost depends on the length and longitudinal gradient of links, side slope of terrain and unit cost of link construction. In general, the construction cost of each link increased by increasing the link length, side slope gradient and longitudinal gradient. According to our findings, the nodes and links constructed on low slope terrain are the least-costly. The information provided in this paper contributes to the development of knowledge about the usefulness of GIS-based weighted-graph algorithm in determining optimal road network in a forest. Total skidding cost is less for a log depot if there are more marked trees in the related cell. So, if the number of marked trees in the vicinity of the depot is higher and the distance to the depot is lower, the total skidding cost of the depot becomes lower.

Keywords: weighted-graph, forest road, log depot, least-cost, optimization, GIS

1. Introduction – *Uvod*

The forest road network plays a critical role in providing both access to forest products and human mobility (Lee and Lee 1998, Stefanović et al. 2015). Forest road is important in harvesting operations, because it can affect total cost of forestry plans (Taiwo and Kumi 2013). Although the presence of road infrastructure network is essential for forest life, scarce literature is available on concurrent optimization of harvesting and road network layouts on steep terrain of Hyrcanian zone. In traditional optimization methods, the evaluation systems cannot be adapted to the needs of sustainable development of forest (Dahlin et al. 1992, Bin 2012, Galatioto et al. 2015). Therefore, nowadays, due to advances in computer sciences and remote sensing softwares, computer optimization models using Geographical Information System (GIS) are becoming practical (Sole and Valverde 2004, Jaafari et al. 2015).

Vector-based model and raster-based model are the two major models in GIS that represent spatial data for optimization algorithms. Vector-based model uses simple geometric designs such as nodes, links and polygons to represent spatial objects, while raster-based model quantizes an area into small discrete grid-cells. Digital elevation model (DEM) and digital terrain models (DTM) are cell format data sets. By using these models, different link patterns can be formulated to solve complex network theory. In a raster-based system, all cells are uniform and cells can represent a graph with nodes, links, polygons and surfaces. Liu and Dong (2008) used road network analysis algorithm with graph theory including corridor density, α circuitry index, β line-node ratio, and γ connectivity index. Watanabe (2010) used a proximity graph to analyze the road network patterns of major cities in the United States. Each link of proximity graphs on a digital map was compared with road links. Xie and Levinson (2007) attempted the graph theoretical analysis of transportation networks.

Networks can be classified into regular networks, random networks and complex network (Albert and

Barabasi 2002). Regular networks, such as those used in the present study, have square lattices. A forest transportation network consists of the winching routes that collect felled and bucked trees from the entire cell (a portion of forest on a raster map) to a skidder on skid trail (Lockwood and Moore 1992). Then, timber is hauled on skid trails to a candidate log depot as a node and finally loaded and transported on the road as a link (Lu and Eriksson 2000). Epstein et al. (1994) made the planning software for optimizing the location of roads and log depots in forest operations. Some researchers used a GlS package for digitizing forest topographic maps and calculating distances from each raster cell to the nearest road on the digital terrain model. Besides, raster-based GIS data can be used to locate an optimal log depot in forest operation planning. This model found skid trails from stump to each candidate log depot and selected the best depot location with minimum total skidding and road costs (Liu and Sessions 1993, Tucek 1994, Contreras and Chung 2007). Naghdi and Mohammadi Limaei (2009) used linear programming model to reduce the skidding costs and to determine the optimal forest road network density.

Analysis of graph algorithm, including node and link characteristics of cells, is considered to improve strategic planning of forest road network (Anderson and Nelson 2004). Most existing optimization models for forest road planning do not work well as they assume that road construction costs are homogenous over the entire project area and neglect the total skidding costs for different candidate log depots at a raster cell size scale, whereas in this study construction cost of road and skidding cost of depot are separately calculated for each link and node. Log depots are temporary timber storage areas at forest road landings (Jourgholami et al. 2013). This study has shown the ability of application of computer techniques and methods in the analysis of the most important factors affecting the total logging costs and selection of optimum density of forest roads in the forest area. Moreover, attempts were made to complete and improve the proposed road network in a forest area taking into consideration various link patterns. This problem was mapped on a graph. The graph consists of a set of nodes and a set of road links between two nodes. The weight of a link represents road costs. Indeed, the objective of this research was to provide a weighted-graph algorithm so that planners could locate the least-cost road variant and log depot. Finally, comments are given on advantages, limitations and improvements of the presented optimization algorithm.

2. Materials and Methods – *Materijal i metode*

2.1 Creating a graph with nodes and links *Izrada grafikona s* čvorovima *i vezama*

Bahramnia forest is located in Golestan province and in watershed number 85. This forest is divided into two districts. District I with an area of 1713.3 ha is extended from 36°43′27″ to 36°45′6″ N and 54°21′26″ to 54°24′57″ E. District II with an area of 1992 ha is located from 36°42′30″ to 36°43′30″ N and 54°21′6″ to 54°23′30″ E.

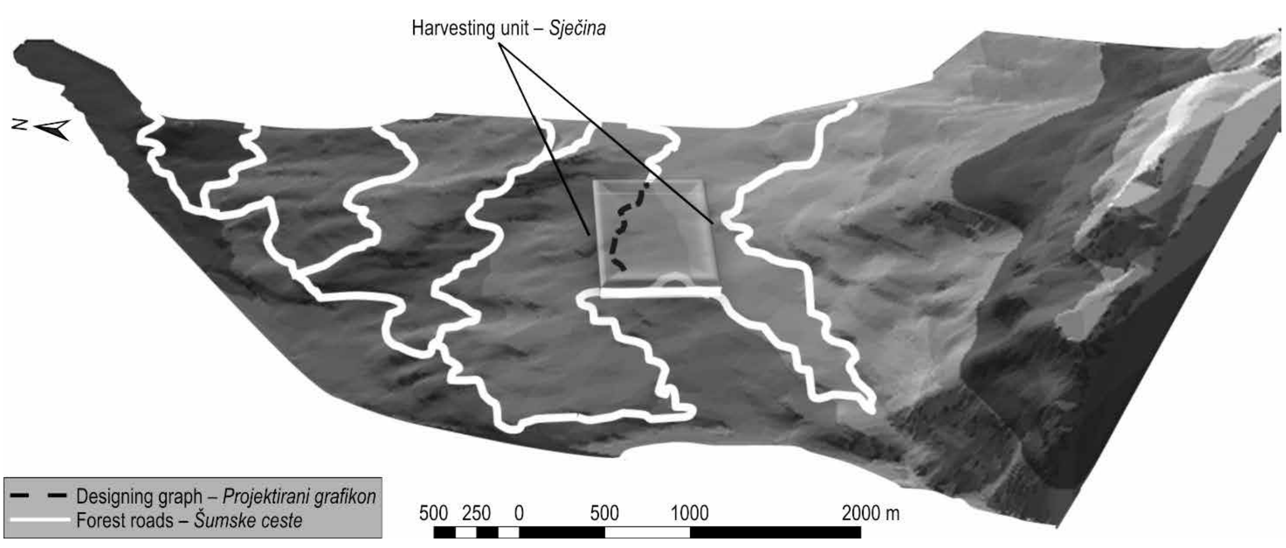

Fig. 1 Study area located in northern forests of Iran

Slika 1. *Područje istraživanja smješteno u sjevernim šumama u Iranu*

The total length of forest roads in districts I and II is 30.3 and 28 km, respectively (21 km is located in timber compartments with an area of 995 ha). In our study area, single-tree selection method was applied in timber compartments at 10-year intervals. Two cycles of operations have already been done in district I. District II has not been harvested yet. The tree species of the case study are *Parrotia persica*, *Carpinus betulus*, *Fagus orientalis*, *Quercus castaneifolia* and *Zelkova carpinifolia*. The mean density of trees per hectare was 214.92 and the canopy cover was 75–85% (Fig. 1).

In this study, portions of the forest, with trees marked for felling, were selected as harvesting units. A harvesting unit is an area to be harvested by ground-based skidding system and all logs hauled into depots by skidders. To produce the raster-base slope map of this area, the DEM of harvesting units was prepared from topography map and then the slope layer was produced by surface analysis tool. The slope layer of this portion was converted into raster format to use the cell size and cover it with a set of nodes and links. Each three cells on a vertical line were considered as a harvesting unit. Nodes as candidate log depots were placed on a regular grid and links that represented potential roads were projected to connect the nodes. Links with maximum length of 75 m were connected from a node to eight adjacent nodes (Fig. 2).

2.2 Total Skidding Cost (TSC) – *Ukupni troškovi privlačenja (TSC)*

The aim of the optimization algorithm used in this study was to create a graph with several candidate log depots within each harvesting unit. This algorithm can solve the haul network problem by minimizing the sum of road construction plus skidding costs. Depots were located on a slope less than 10% for loading by crane. Candidate depots were arranged on a line in a harvesting unit. The distance between two lines was 150 meters. Indeed, this distance indicates the sum of winch cable length (50 m) and trees average length (25 m) at each side of the skid trail. The model calculates total skidding cost for a candidate depot *k* by adding

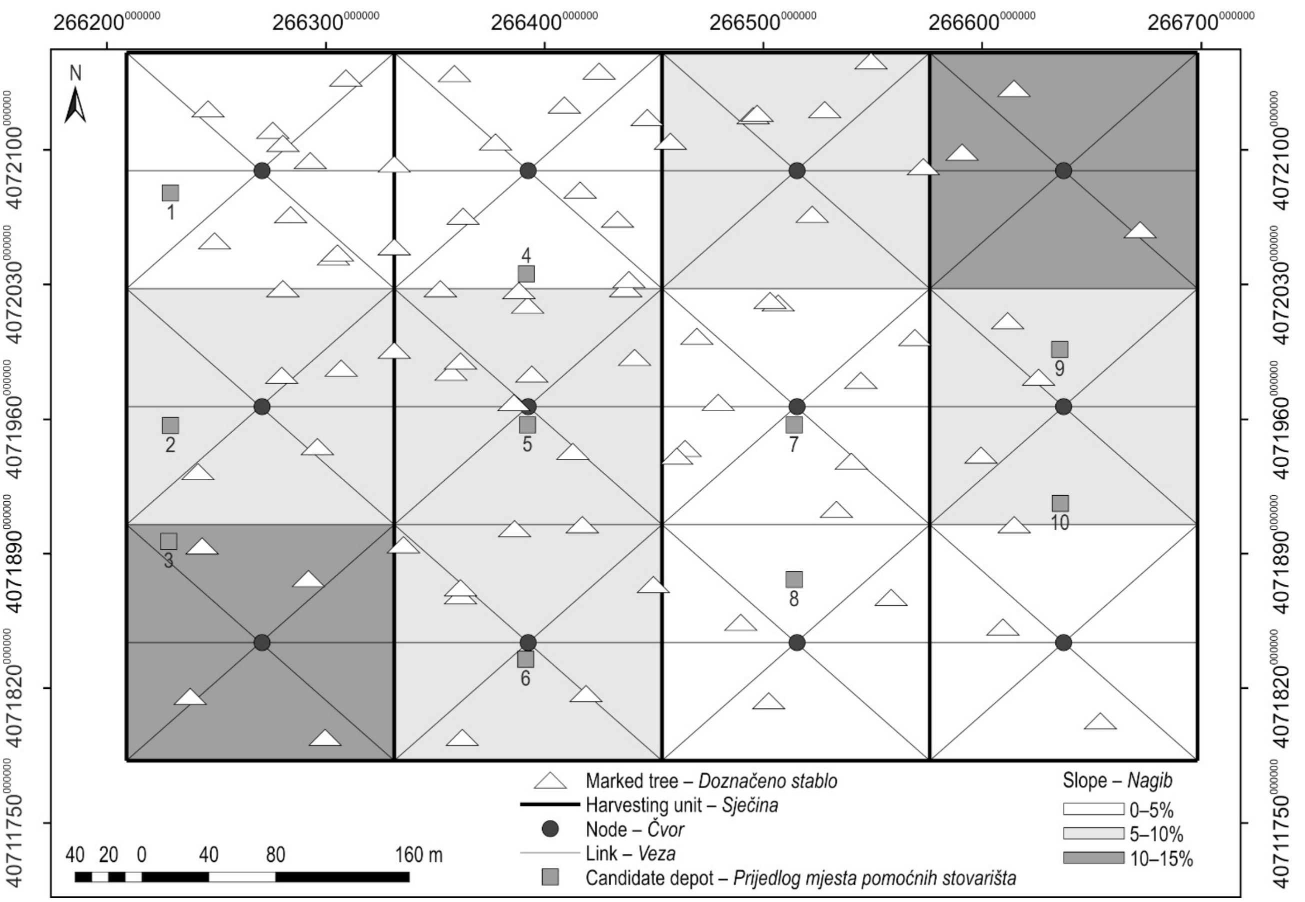

Fig. 2 Graph created by links and nodes for a given harvesting unit

Slika 2. *Grafikon izrađen pomoću veza i čvorišta za istraživanu sječinu* up all the skidding costs from each cell to the candidate log depot *k* (Eq. 1) (Contreras and Chung 2007):

$$TSC_k = \sum_{i=1}^{m} SC_i \qquad (1)$$

Where:

TSC_k total skidding cost for a candidate depot *k*, $

m total number of cells within the harvesting unit

SC_i skidding cost from the *i*th cell to log depot *k*.

The skidding cost for each cell is calculated using Eq. 2 (Contreras and Chung 2007):

$$SC_i = \left[\left(\frac{CT_i}{60}\right) \times R\right] \times N_i \qquad (2)$$

Where:

CT_i overall time consumption for a skidding cycle (min) from i^{th} cell to log depot

K is calculated using Eq. 3 (Mousavi 2012)

R represents the rental rate of a skidder which was 18.9 $ hr^{-1},

N_i number of turns for skidding all timber from *i*th cell to log depot *k*.

The average timber volume per turn was 1.85 m^3.

$$CT_i = -2.598 + 0.023\,X + 2.187\,X_n + 0.122\,X_W + 0.279\,K_L \qquad (3)$$

Where:

X skidding distance, m

X_n number of logs

X_W winching distance, m

X_L log length, m.

2.3 Total Road Cost (TRC) – *Ukupni troškovi šumske ceste (TRC)*

A set of links were created to connect a forest road from one depot back to the existing network. Once this new road is connected, it is added to the road network. Then the next depot is selected and connected to the road network. The procedure is repeated until all depots are connected. The total road cost for road candidate *k* is calculated using Eq. 4 (Contreras and Chung 2007):

$$TRC_k = \sum_{i=1}^{e} RC_i \qquad (4)$$

Table 1 Road gradient and side slope factors (Contreras and Chung 2007)

Tablica 1. *Faktori uzdužnoga nagiba šumske ceste i nagiba terena*

Road gradient, % *Uzdužni nagib šumske ceste, %*	Road gradient factor *Faktor uzdužnoga nagiba šumske ceste*	Side slope, % *Nagib terena, %*	Side slope factor *Faktor nagiba terena*
0–5	1.0	0–15	1.0
5–10	1.5	15–30	1.5
10–15	2.5	30–45	2.5
15–20	3.5	45–60	3.5

Where:

TRC_k total road construction cost for road candidate *k* ($)

e total number of links for road *k*

RC_i construction cost of i^{th} link calculated using Eq. 5 (Contreras and Chung 2007):

$$RC_i = LD_i \times RC \times LS_i \times SS_i \qquad (5)$$

Where:

LD_i length of the link (m)

RC unit cost of road construction ($ m^{-1}) assumed to be 16.22 $ m^{-1} in this study

LS_i longitudinal road gradient factor and SS_i is side slope factor (Table 1).

The road gradient must be less than 12%.

2.4 Optimization by graph analysis *Optimizacija grafičkom analizom*

Total Harvesting Cost (*THC*) for candidate depot and road *k* was calculated using Eq. 6 and finally the least-cost variant was selected as the optimal depot and road location in the harvesting unit. Fig. 3 shows the procedure used to find the least-cost route from depots to the existing road in a flow chart.

3. Results – Rezultati

3.1 Total skidding cost for candidate depots *Ukupni troškovi privlačenja do predloženih mjesta pomoćnih stovarišta*

Different distribution of marked trees in a harvesting unit has large effects on log depot location. In this study, two terminals have been located as log depots 9 and 10. Links and nodes were routed in zigzag shape

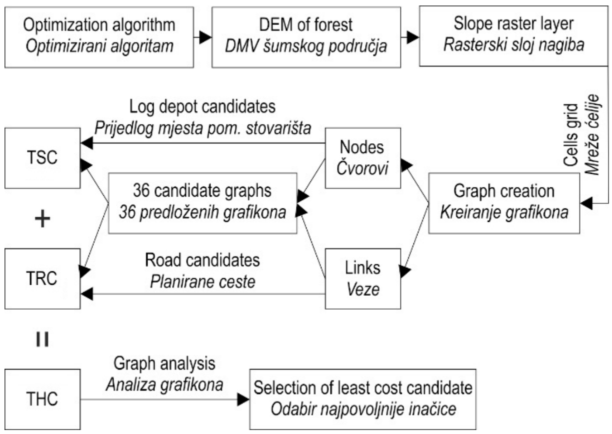

Fig. 3 Diagram of the optimization algorithm used in the present study

Slika 3. *Dijagram optimiziranoga algoritma uporabljena u istraživanju*

to access terminal depots without considering curve design. Indeed, all links were assumed to be straight lines. The total skidding cost for a depot is limited by the overall time spent for a skidding cycle and the number of trips for skidding all timber. The skidding cycle time depends on log size, number of logs, winching and skidding distances. The influence of variables is not the same. Skidding cost in lower slope is less than that of higher side slope. Therefore, log depot location was shifted to lower slopes. Total skidding cost at four harvesting units in depots 1, 5, 7 and 9 were 72.80 $, 92.60 $, 65.75 $ and 29.23 $. These are the optimal log depot locations without considering road construction cost. Table 2 shows the skidding parameters of candidate log depots for locating the least-cost depot. Total skidding cost is less for a log depot having more marked trees in the related cell. So, if the number of marked trees in the vicinity of the depot is higher and the distance to the depot is lower, the total skidding cost of the depot becomes lower.

3.2 Total road cost for candidate roads – *Ukupni troškovi predloženih šumskih cesta*

36 access roads were analyzed considering their accessibility to a depot in each harvest units (Fig. 4). Each road was evaluated by calculating the construction cost of links that make a road. The present investigation takes account of the varying road construction cost over different kinds of terrain slope. Road cost depends on the length of links, longitudinal gradient of links, side slope of terrain and unit cost of link construction. Results show that, in general, the construction cost of each link increased by increasing the link length, side slope gradient and longitudinal gradient. Therefore, the construction cost of candidate roads 6, 12, 31 and 32 is higher than the cost of other candidate roads. These cases consider a road construction cost of 16,139$, 16,187$, 16,686$ and 16,637$, respectively. In addition, the construction cost of candidate roads 2, 8, 14 and 20 are the lowest (Table 3). These cases consider a road construction of 9435$, 9483$, 9848$ and 9896$, respectively. As shown in Table 2 and Table 3, total harvesting cost is relatively insensitive to skidding costs of depots in the study area. As the log depots are only located on slopes less than 15%, the number of candidate depots for a given harvesting unit varies. As the

Table 2 Values of skidding time (CT_i), number of skidding turns (N_i) and skidding cost from each cells to candidate depots (SC_i) as well as the total skidding cost for candidate depots in harvesting units (TSC_k)

Tablica 2. *Vrijednosti vremena privlačenja (CT_i), broj turnusa privlačenja (N_i) i troškovi privlačenja od svake ćelije do predloženih mjesta pomoćnih stovarišta (SC_i) te ukupni troškovi privlačenja za predoložena mjesta pomoćnih stovarišta u sječini (TSC_k)*

Skidding cycle time – *Vrijeme turnusa privlačenja*	Candidate depots – *Predložena mjesta pomoćnih stovarišta*									
	1	2	3	4	5	6	7	8	9	10
CT_1, min	9.35	12.15	13.51	10.36	12.18	14.92	11.32	13.16	10.54	12.40
CT_2, min	11.58	8.86	10.22	8.92	7.10	9.84	9.02	10.86	8.32	8.38
CT_3, min	15.26	12.54	11.20	14.09	12.25	9.52	10.11	8.27	12.07	10.20
N_1	12.00	12.00	12.00	12.00	12.00	12.00	7.00	7.00	3.00	3.00
N_2	5.00	5.00	5.00	7.00	7.00	7.00	11.00	11.00	3.00	3.00
N_3	4.00	4.00	4.00	8.00	8.00	8.00	3.00	3.00	3.00	3.00
SC_1, $	35.34	45.92	51.09	39.18	46.05	56.40	24.95	29.02	9.96	11.72
SC_2, $	18.24	13.95	16.10	19.67	15.66	21.70	31.24	37.64	7.86	7.92
SC_3, $	19.22	15.79	14.11	35.51	30.88	23.99	9.56	7.81	11.40	9.64
TSC_k, $	72.80	75.67	81.30	94.36	92.60	102.09	65.75	74.48	29.23	29.27

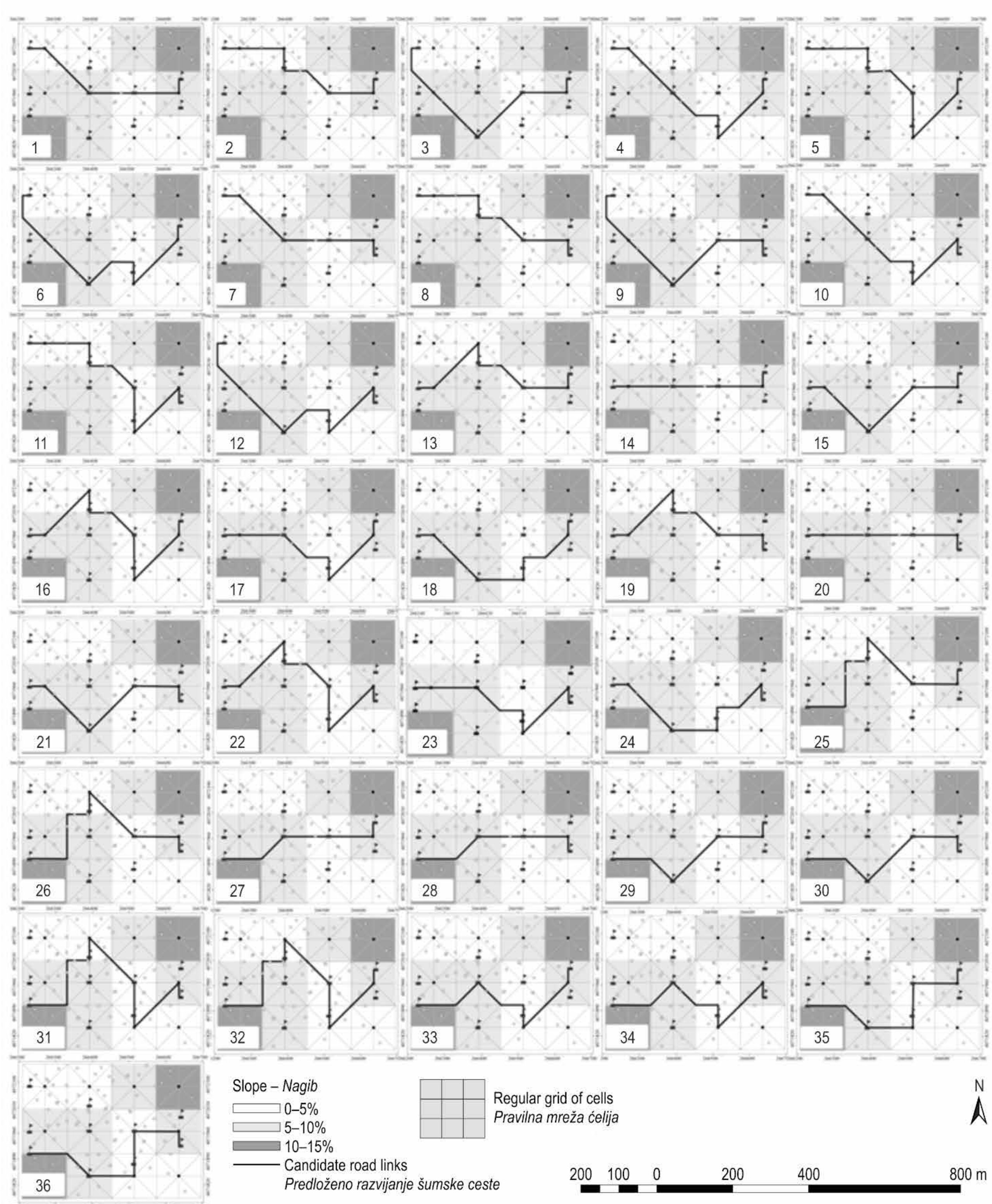

Fig. 4 Different road network candidates developed by connecting log depots in harvesting units. Shaded grid cells represent different slope percentages (0–5%, 5–10% and 10–15%)

Slika 4. *Predloženo razvijanje šumske ceste dobivene povezivanjem mjesta pomoćnih stovarišta u sječinama; tamnije ćelije predstavljaju različite nagibe terena u postocima (0–5 %, 5–10 %, 10–15 %)*

depot spacing increases, fewer depots are present, and therefore the supplementary network (skid trail) length increases. As the log depots spacing increases, roads are able to avoid steep slope and the average longitudinal gradient is improved.

3.3 Total harvesting cost for candidate depots and roads – *Ukupni troškovi privlačenja pri predloženim šumskim cestama i mjestima pomoćnih stovarišta*

In this study, the total area of the selected harvesting units is 18 ha with a mean volume of 350 m^3 logs. Some areas within the harvesting unit with the slope of more than 10% have not been taken into consideration for locating log depots. In addition, the road gradient must be less than 9% for safe truck driving according to the standard limit value. If the gradient is higher than 9%, the link becomes unacceptable for road construction. The mean road gradient of optimal road is 4% or 5% less than the road gradient limit. Total harvesting cost is computed by adding total skidding cost to road construction cost. An optimal road candidate is the variant with the least total harvesting cost. So, road candidate 2 was chosen as the optimal variant (Table 4). Fig. 5 presents the optimal graph of road network as the least-cost candidate road. The weights of links in the network are determined according to construction cost. The lower the cost, the greater the chance that link will get routed. The total skidding cost of depots and construction cost of optimal road are 262.14$ and 17.73$ m^{-1}, respectively. Total length and total harvesting cost of the optimal graph are 532 m and 9697.14$, respectively. The analysis shows that the algorithm is feasible in selecting the optimal road according to the depots variable and construction cost.

Table 3 Construction cost of links and total road construction cost attributes of 36 candidate roads examined in this research

Tablica 3. *Troškovi izgradnje veza i ukupni troškovi izgradnje za 36 predloženih inačica šumskih cesta ispitanih u ovom istraživanju*

Link – *Veza*	$	Link – *Veza*	$	Link – *Veza*	$	Link – *Veza*	$	Link – *Veza*	$	Link – *Veza*	$
RC_{1-5}	4157	RC_{1-4}	3339	RC_{1-6}	7605	RC_{1-5}	4157	RC_{1-4}	3339	RC_{1-6}	7605
RC_{5-7}	2475	RC_{4-7}	2671	RC_{6-7}	3500	RC_{5-8}	3403	RC_{4-8}	3975	RC_{6-8}	3406
RC_{7-9}	3425	RC_{7-9}	3425	RC_{7-9}	3425	RC_{8-9}	5128	RC_{8-9}	5128	RC_{8-9}	5128
TRC_1	10,057	TRC_2	9435	TRC_3	14,530	TRC_4	12,688	TRC_5	12,442	TRC_6	16,139
RC_{1-5}	4157	RC_{1-4}	3339	RC_{1-6}	7605	RC_{1-5}	4157	RC_{1-4}	3339	RC_{1-6}	7605
RC_{5-7}	2475	RC_{4-7}	2671	RC_{6-7}	3500	RC_{5-8}	3403	RC_{4-8}	3975	RC_{6-8}	3406
RC_{7-10}	3473	RC_{7-10}	3473	RC_{7-10}	3473	RC_{8-10}	5176	RC_{8-10}	5176	RC_{8-10}	5176
TRC_7	10,105	TRC_8	9483	TRC_9	14,578	TRC_{10}	12,736	TRC_{11}	12,490	TRC_{12}	16,187
RC_{2-4}	5184	RC_{2-5}	3948	RC_{2-6}	5178	RC_{2-4}	5184	RC_{2-5}	3948	RC_{2-6}	5178
RC_{4-7}	2671	RC_{5-7}	2475	RC_{6-7}	3500	RC_{4-8}	3975	RC_{5-8}	3403	RC_{6-8}	3154
RC_{7-9}	3425	RC_{7-9}	3425	RC_{7-9}	3425	RC_{8-9}	5128	RC_{8-9}	5128	RC_{8-9}	4357
TRC_{13}	11,280	TRC_{14}	9848	TRC_{15}	12,103	TRC_{16}	14,287	TRC_{17}	12,479	TRC_{18}	12,689
RC_{2-4}	5184	RC_{2-5}	3948	RC_{2-6}	5178	RC_{2-4}	5184	RC_{2-5}	3948	RC_{2-6}	5178
RC_{4-7}	2671	RC_{5-7}	2475	RC_{6-7}	3500	RC_{4-8}	3975	RC_{5-8}	3403	RC_{6-8}	3154
RC_{7-10}	3473	RC_{7-10}	3473	RC_{7-10}	3473	RC_{8-10}	5176	RC_{8-10}	5176	RC_{8-10}	4405
TRC_{19}	11,328	TRC_{20}	9896	TRC_{21}	12,151	TRC_{22}	14,335	TRC_{23}	12,527	TRC_{24}	12,737
RC_{3-4}	6707	RC_{3-4}	6707	RC_{3-5}	4564	RC_{3-5}	4564	RC_{3-6}	4567	RC_{3-6}	4567
RC_{4-7}	3498	RC_{4-7}	3498	RC_{5-7}	2475	RC_{5-7}	2475	RC_{6-7}	3500	RC_{6-7}	3500
RC_{7-9}	3425	RC_{7-10}	3473	RC_{7-9}	3425	RC_{7-10}	3473	RC_{7-9}	3425	RC_{7-10}	3473
TRC_{25}	13,630	TRC_{26}	13,678	TRC_{27}	10,464	TRC_{28}	10,512	TRC_{29}	11,492	TRC_{30}	11,540
RC_{3-4}	6707	RC_{3-4}	6707	RC_{3-5}	4564	RC_{3-5}	4564	RC_{3-6}	4567	RC_{3-6}	4567
RC_{4-8}	4802	RC_{4-8}	4802	RC_{5-8}	3403	RC_{5-8}	3403	RC_{6-7}	4458	RC_{6-7}	4458
RC_{8-10}	5176	RC_{8-9}	5128	RC_{8-9}	5128	RC_{8-10}	5176	RC_{7-9}	3425	RC_{7-10}	3473
TRC_{31}	16,686	TRC_{32}	16,637	TRC_{33}	13,095	TRC_{34}	13,143	TRC_{35}	12,450	TRC_{306}	12,498

Table 4 Total harvesting cost (THC_k) used for analysis of 36 candidate roads
Tablica 4. *Ukupni troškovi privlačenja (*THC_k*) u analizi 36 predloženih inačica šumskih cesta*

THC_k	$	THC_k	$	THC_k	$
THC_1	10,317.38	THC_{13}	11,545.01	THC_{25}	13,900.64
THC_2	9697.14	THC_{14}	10,111.25	THC_{26}	13,948.68
THC_3	14,799.87	THC_{15}	12,375.74	THC_{27}	10,732.88
THC_4	12,957.11	THC_{16}	14,560.74	THC_{28}	10,780.92
THC_5	12,712.87	THC_{17}	12,750.98	THC_{29}	11,770.37
THC_6	16,417.60	THC_{18}	12,970.47	THC_{30}	11,818.41
THC_7	10,365.42	THC_{19}	11,593.05	THC_{31}	16,964.37
THC_8	9745.18	THC_{20}	10,159.29	THC_{32}	16,916.41
THC_9	14,847.91	THC_{21}	12,423.78	THC_{33}	13,372.61
THC_{10}	13,005.15	THC_{22}	14,608.78	THC_{34}	13,420.65
THC_{11}	12,760.91	THC_{23}	12,799.02	THC_{35}	12,728.37
THC_{12}	16,465.64	THC_{24}	13,018.51	THC_{36}	12,776.41

4. Discussion – *Rasprava*

This study fills a knowledge gap in the application of computer road design in Iranian forestry and shows how weighted–graph algorithm can support decision makers in locating log depots and road network. Minimization of total costs of skidding and road construction was the traditional method to determine the optimal forest road density in a forest area (You et al. 2003, Chung et al. 2004, Żak and Węgliński 2014). This method is very similar to weighted–graph algorithm used in the present study. Ghaffarian and Sobhani (2007) calculated the optimum road density by minimizing the sum of road construction and skidding costs. In another study, they developed a skidding model by stepwise regression to predict the cost of skidding per cubic meter for 39 nodes. The harvesting volume and road construction cost for each node were computed by using NETWORK 2000 and shortest path algorithm (Ghaffarian and Sobhani 2008). In this study, we used 12 nodes and 96 links to produce a graph for the optimization algorithm. The total skidding cost for a node decreased by decreasing the overall time spent for a skidding cycle and the number of trips for skidding all timber. Moreover, road cost increased with increasing length of links, longitudinal gradient of links, terrain slope and unit cost of link construction. Ghaffarian et al. (2010) used the same cost for yarding and road segment per node and links. Rees (2004) calculated the least–cost paths by applying Dijkstra's algorithm on a Digital Elevation Model. In this study, the total road construction cost was considered plus total skidding cost, as this factor was considered more important than other factors within the region.

A very big graph or network in the present algorithm is inefficient since a lot of calculations need to be repeated (Yongtaek and Hyunmyung 2005, Olsson 2007). In our study, links and nodes were routed in zigzag shape to access terminal depots without considering curve design. Therefore, it is necessary to develop a graph with the curvature design as used by Stückelberger et al. (2007). In this study, a weighted–graph algorithm consisting of nodes (depots) and links (roads) was used to optimize the haul network in the forest. Well–designed or optimal road network is a graph that includes the least–cost roads and skidding. The lower the cost, the greater is the chance that the link will get routed. Stückelberger et al. (2007) found that by considering various link patterns, road design elements and constraints, a designer can select cost–effective locations for road network in steep terrain on mountainous project areas. Liu and Sessions (1993) used an algorithm to find the least–cost road links by considering construction, maintenance and transport costs and various topographic conditions. Dahlin and Sallnas (1992) found the optimum road location by minimization of road transportation cost and road construction cost. They used a simulated annealing (SA) algorithm to optimize the road location. Locating roads within steep terrain can only be done if high node densities (30 nodes ha^{-1}) are used and obstacles are considered. In gentler terrain, node density can be reduced. Raster layers consist of a grid support accurate analysis of a graph (Dahlin and Sallnas 1992). Among 532 m of

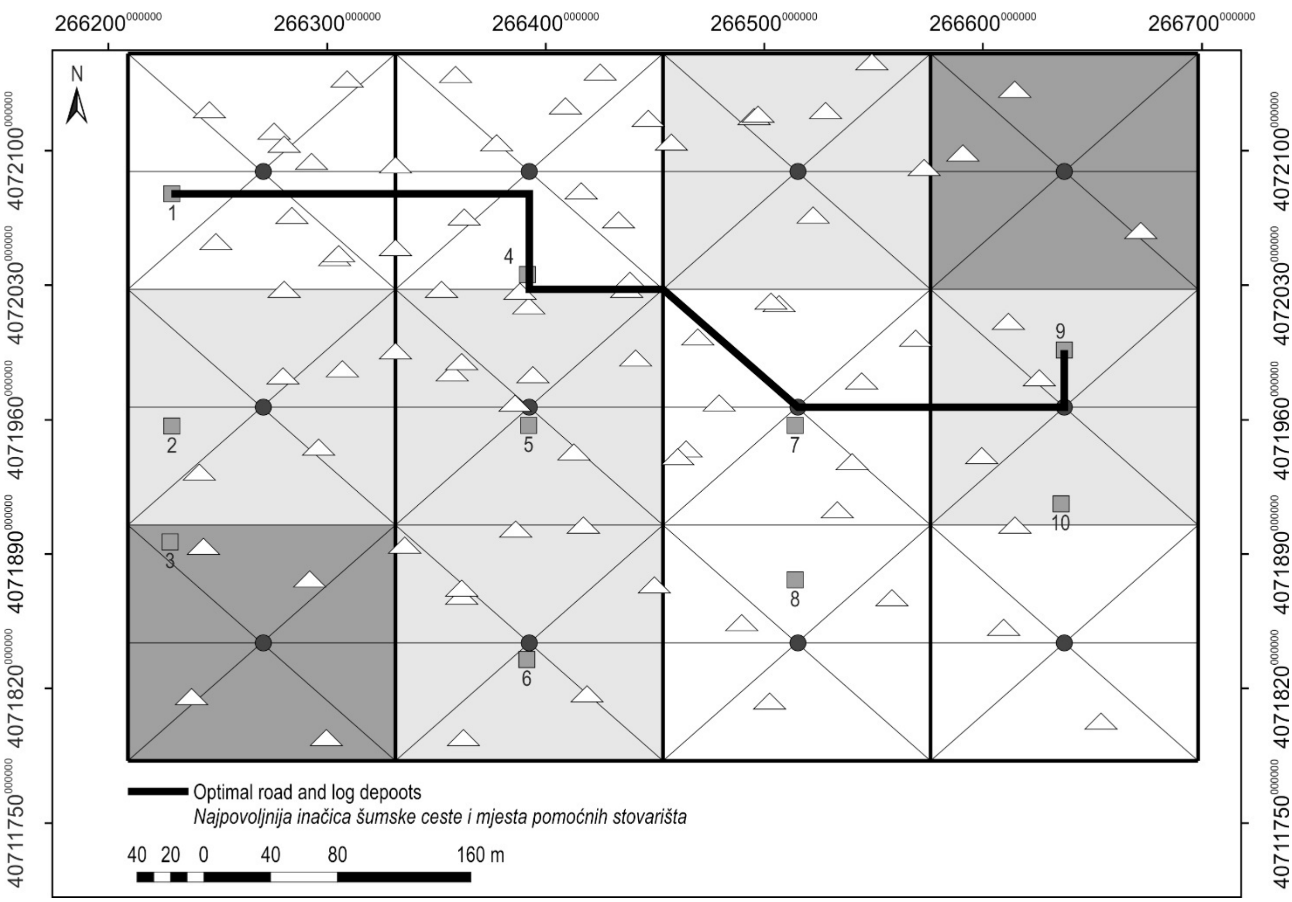

Fig. 5 Least–cost road selected as optimal variant in weighted–graph algorithm

Slika 5. *Inačica šumske ceste s najmanjim troškovima odabrana kao optimalna varijanta dobivena ponderiranim grafičkim algoritmom*

roads optimized by the weighted–graph algorithm in the study area, 432 m of roads were located within the slope terrain of 0–5% and 100 m within 5–10%. Our findings show that the optimization algorithm provides equal distribution of roads over the study area using short road length. The algorithm used in this research could provide engineers with good candidate choices for a forest road network plan.

In the present study, a weighted–graph algorithm has been developed to find the least–cost road network and log depots in harvesting units. The advantage of the model is that it can consider a wide range of data including skidding distance, number of logs and skidding turns, winching distance, skidder cost, log length, side slope, road gradient and road length, which may affect the total cost of skidding and road construction. The economic analysis carried out in this paper clearly illustrates the adequacy of application of the methodology used for opening of the forest area. Weighted–graph optimization algorithm requires many input parameters to determine the desired location of the road network and log depots. Therefore, other parameters can be added to the model in individual harvest units with their unique physiographic and vegetative conditions. The results of the analysis based on the weighted–graph on raster cells do not provide the understanding of nature, but this approach offers simplicity in implementation. Additional research needs to be done on refining links geometry in order to accurately evaluate longitudinal gradient and vehicle speed and to improve estimates of construction quantities. Moreover, algorithms such as Dijkstra should be integrated in weighted–graphs to produce better networks at lower cost.

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Sažetak

Određivanje najpovoljnijih mjesta pomoćnih stovarišta i najpovoljnijega pružanja šumske ceste ponderiranim grafičkim algoritmom optimizacije

Održivo i ekonomski isplativo gospodarenje šumskim ekosustavima može se postići isključivo u slučaju uspostave optimalne šumske transportne mreže na terenu pri kojem su troškovi izgradnje i održavanja primarne i sekundarne šumske prometne infrastrukture svedeni na minimum. U ovom istraživanju korišten je ponderirani grafički algoritam koji je pomoću čvorova (prijedlog mjesta pomoćnih stovarišta) i veza (inačica šumske ceste) optimizirao šumski transportni sustav. Vrijednosti svakoga čvora i veze izračunavane su za svih 36 inačica šumskih cesta u istraživanoj sječini. Analizirajući vrijednosti čvorova (mjesta pomoćnih stovarišta) ustanovljeno je kako ukupni troškovi privlačenja variraju u ovisnosti o vrijednostima duljine privitlavanja i privlačenja te o broju privučenih trupaca. Ukupni troškovi privlačenja izračunati za svaki čvor omogućili su određivanje mjesta pomoćnih stovarišta kod kojih su troškovi privlačenja najniži te nadalje određivanje veza koje će poslije služiti pri odlučivanju o optimalnom horizontalnom pružanju šumske ceste. Troškovi vezani uz šumsku cestu ovise o duljini i uzdužnom nagibu veza, poprečnom nagibu terena i jediničnim troškovima izgradnje pojedine veze. Općenito se može reći da troškovi izgradnje svake veze rastu povećanjem duljine veze, poprečnoga nagiba terena i uzdužnoga nagiba. Rezultati ovoga istraživanja pokazuju da su čvorovi i veze konstruirani na padinama blažih nagiba najjefitinije, a ujedno i ekonomski najopravdanije inačice. Rezultati dobiveni ovim istraživanjem uvelike doprinose razumijevanju svih pogodnosti koje, na GIS-u temeljen, ponderirani grafički algoritam pruža pri određivanju optimalnoga šumskoga transportnoga sustava. Ukupni troškovi privlačenja manji su na pomoćnim stovarištima u čijem gravitacijskom području postoji veća doznačena masa odnosno više doznačenih stabala. Dakle, ako je broj doznačenih stabala u blizini mjesta pomoćnih stovarišta veći, a udaljenost do pomoćnoga stovarišta manja, ukupni troškovi privlačenja promatranoga pomoćnoga stovarišta postaju manji.

Ključne riječi: ponderirani grafikon, šumska cesta, pomoćno stovarište, minimalni troškovi, optimizacija, GIS

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