Optimization of an existing forest road network using Network 2000

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Abstract – Nacrtak

Optimization of forest road network is an important part of logging planning. Matthews (1942) was the first to introduce a method for optimization of road spacing based on minimization of roading and skidding cost. The goal of this paper is to find the best road network for a district harvested by skidder. The skidding model developed by stepwise regression model was used to predict the cost of skidding per cubic meter for the 39 nodes, which were planned in the district map. The harvesting volume and roading cost per each node were computed. The data were entered into NETWORK 2000 and shortest path algorithm; simulated annealing and great deluge algorithms were run to find the best solution to optimize logging cost of the district. The results showed which roads can be eliminated from the existing forest road network.

Keywords*: road spacing, optimal road density, skidder, model of network analysis, Iran*

1. Introduction – *Uvod*

Forest road network planning is an important task of forest engineers. Matthews (1942) was the first to present a model for defining optimum road spacing based on minimization of skidding and roading costs from a landowner's point of view. Optimal road spacing can also be influenced by other factors having impact on optimal road network such as logging method, price of products, taxation policies, landing costs, overhead costs, equipment opportunity costs, road width and size of landing, skidding pattern, profit of logging contractor, slope and topography and soil disturbance (Segebaden 1964, Sundberg 1976, Peters 1978, Bryer 1983, Wenger 1984, Sessions 1986, Yeap and Sessions 1988, Thompson 1992, Liu and Corcoran 1993, Heinimann 1997, Thompson 1998, Akay and Sessions 2001, Sessions and Boston 2006).

A couple of studies on optimal road density (ORD) have been reported by several researchers. Pičman and Pentek (1998) calculated ORD of 14.7 m/ha for ground based skidding system using farm tractors in Croatia. In the Northern forests of Iran, the case studies on selection cuttings and skidding operations showed that optimal road density ranged from 9 to 28 m/ha for different areas (Mostafanejad 1995, Eghtesadi 2000, Lotfalian 2001, Naghdi 2004). Most of the above studies used minimization of total cost of roading and skidding. Optimal road spacing is only a value that provides a guide for locating roads and cost target but does not suggest where the roads should be actually placed (Tan 1999). In the past years, the mixed integer mathematical programming and heuristic algorithms such as: TIMBRI (Sullivan 1974), NETWORK (Sessions 1978), TRANSHIP (Kirbey et al. 1981), MINCOST (Wong 1981), NETCOST (Weintraub 1990) and NETWORK 2000 (Sessions and Chung 2003) have been used to find the appropriate solution for certain fixed and variable cost problem. Sessions (1992) introduced the method of using network analysis for road and harvesting planning, which is applied in this study. Gullison and Hardner (1993) described a rule-based simulation model designed to examine options for reducing the total length of forest roads. Clarck et al. 2000) also used a heuristic for access road development where roads are defined a priori. Akay et al. (2005) described commonly used modern heuristic techniques (Simulated Annealing, Genetic Algorithm, Tabu Search, and Shortest Path Algorithm). Simulated Annealing (SA) was used to guide the search for the best vertical alignment that minimizes the total costs of construction, transportation, and maintenance costs for a single forest road. Ichihara et al. (1996) proposed Genetic Algorithm (GA) model integrating two optimization techniques to optimize forest road profiles. Tabu Search and GA were compared to manually designed forest road profile by Aruga et al. (2005). Shortest path algorithms have been implemented by Sessions (1991) for secondary harvest transport. Anderson and Nelson (2004) used Dijkrstra's shortest path algorithm to project a road link that minimized the distance between a landing and the current road network.

Tan (1999) developed the spatial and heuristic procedure to locate forest roads. He reported that the improved procedure proved to be beneficial in helping forest road planning managers evaluate alternatives and hence select the optimal location for a road network.

Stueckelberger et al. (2006) considered roading cost, ecological effects and suitability for cable yarding landings in their automatic road-network planning using multi-objective optimization in Switzerland.

The current paper evaluates an existing forest road network in a district of research forest in Northern Iran using Network analysis. The goal is to find the best road network which minimizes total cost of skidding and roading in this district. The results of network procedure can show which road segments can be eliminated.

2. Method of study – *Metode istraživanja*

2.1 Site of study – *Mjesto istraživanja*

The study site is located in Northern forests of Iran in Nowshahr. The research was carried out on road network of Namkhaneh research district and training forest centre of Tehran University. The management method is mixed un-even aged high forest with single and group selective cutting regime. The district covers the area of 1,080.9 ha with the growing stock of 434 m^3/ha. The broadleaves stands mostly consist of *Fagus* sp., *Quercus* sp., *Carpinus* sp. The cutting volume of the district is 5,850 m^3 per year which means 5.41 m^3/ha. The slope ranges from 15 to 60%. The felling is done motor-manually using chainsaws. The felled trees are then delimbed and bucked to the assortments. The sawmill logs are skidded by wheeled cable skidders or tracked skidders to the roadside landings. The fuel woods are extracted by mules. Also, in steep terrain that can not be harvested by skidders, logs are processed to small lumber so as to be extracted by mules. Skidding group includes operator and chokerman.

2.2 Data collection – *Prikupljanje podataka*

Jour Gholami (2005) studied cost production of TAF 1004P and Timberjack 450C skidders in this area. He used the continuous time study method in both production studies. A typical work cycle included: travel empty, releasing the winch, choker setting, winching, travel loaded, unhooking and dacking. During this time study technical, personal and operational delays were recorded. The same variables were used in both data collections. Variables included skidding distance, piece volume, load volume, number of pieces per turn and slope of trail. In this time study forty-four cycles for Timberjack 450C and forty-six for TAF 1004P were collected. Using the stepwise regression method, the time predicting model was developed for each cycle.

The system cost of the skidder was about 46.91 €/h (Jour Gholami 2005). The developed regression models to predict the time of skidding were used to study the road spacing.

The roading cost in this forestry centre included the costs of planning (384.6 €/km), construction of subbase (6,837.6 €/km), subgrade construction (11,794.8 €/km), culverts and ditches (4,273.5 €/km), and maintenance and repair cost as 15% of the roading cost in the 10 years period (349.3 €/km). The road the construction cost was 23,639.8 €/km or 23.64 Euro/m. The interest of investment would be 2.19 €/m considering 18.5% interest rate in Iran. If the life time of the forest road were 50 years, the deprecation cost would be 0.47 €/m. The total annual cost of roading includes the sum of the interest and deprecation costs of 2.66 €/m.

The mean harvesting volume of Namkhaneh district is about 5.41 m^3/ha/year. The existing road network has a density of 28.16 m/ha. The compartments 201, 202, 203, 204 and 205 are protected because of steep slopes (Fig. 1).

Network 2000 was developed to optimize large fixed and variable cost problems related to transportation. It provides three different algorithms: short path algorithm, simulated annealing (SA) and great deluge (GD). The first algorithm solves the network problem using a heuristic method that prorates the fixed costs in an iterative mode. The algorithm can solve very quickly a large fixed and variable cost problem related to transportation. However, the best solution found by this algorithm might not be optimal, but it is a »good« solution. If the solution is not optimal, it is possible to search for a better solution with continues iterations in this program.

To solve the problems of shortest path length, a Dutch computer scientist named Dijkstra, developed the shortest path algorithm in 1959. The basic premise of this algorithm is to find the length of the shortest path between the starting vertex and the first vertex; then the length of the shortest path between the staring vertex and the second vertex; continuing

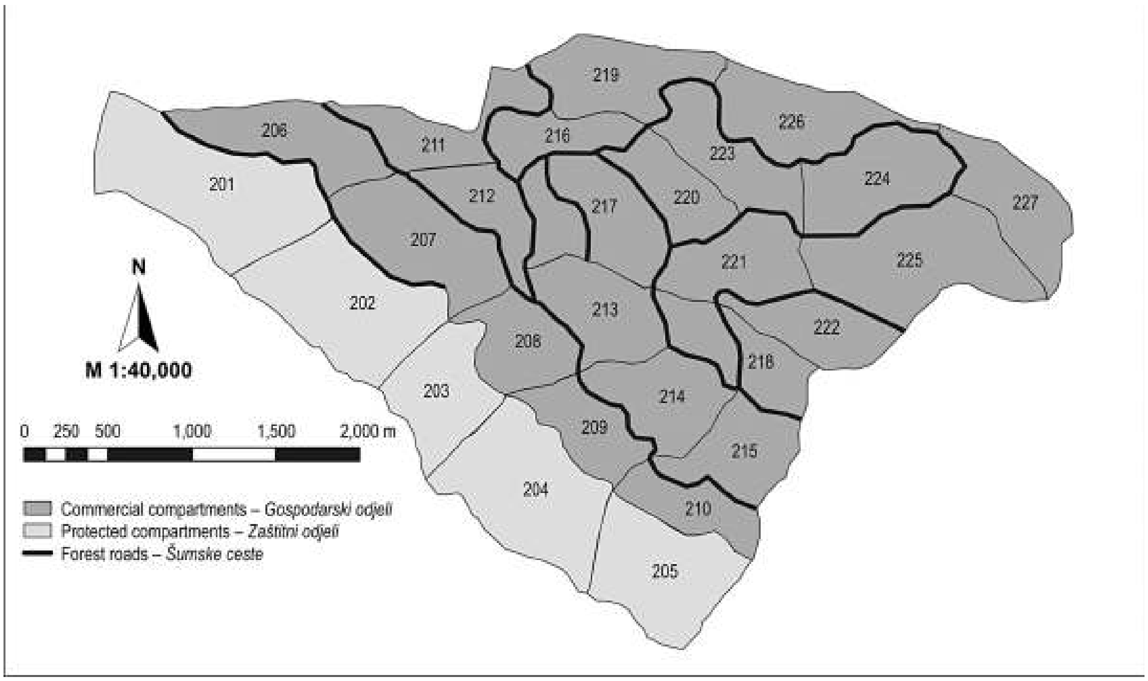

Fig. 1 Existing road network of Namkhaneh district

Slika 1. *Postojeća mreža šumskih cesta područja Namkhaneh*

until the length of the shortest path between the starting vertex and ending vertex is found.

Simulated annealing (SA) is a search technique which exploits an analogy between the way in which a metal cools and freezes into a minimum energy crystalline structure (the annealing process) and the search for a minimum in a more general system; it forms the basis of an optimization technique for combinatorial problems, etc. It was developed in 1983 to deal with highly nonlinear problems. SA's major advantage over other methods is an ability to avoid becoming trapped in local minima. The algorithm employs a random search, which not only accepts changes that decrease the objective function f (assuming a minimization problem), but also some changes that increase it.

The great deluge algorithm (GDA) is a recently developed variant of simulated annealing. It is similar to SA in that only a single change is considered as a »current« solution, the resulting temporary solution is evaluated, and a decision is made whether or not to convert the temporary solution to the current solution (Bettinger et al. 2002).

The GDA was introduced by Dueck (1993) and proved superior to similar Monte-Carlo based algorithms in solving a 442-city and 532-city Traveling Salesman Problem. The form of the GDA as presented by Dueck (1993) consisted of using a single parameter in the determining of whether or not to convert the temporary solution to the current solution (and perhaps change to an inferior solution). The use of one parameter rather than two, as in a simulated annealing algorithm, is believed to desensitize the algorithm thus leading to equally good results even when parameter estimation and formulation is poor.

In order to use Network 2000 program, the map of compartments was used including the existing forest road in the district (Fig. 1). Each compartment was used to define the nodes for the network approach. It was assumed that 2/3 of the logs in the compartments are skidded downhill and the rest are skidded uphill. Based on this assumption, the nodes were determined using Arc Map (Fig. 2). The area of the nodes was calculated, and then the logging volume for the nodes was determined based on its area and logging volume of the management area. The logs are transported from all the nodes to 3 mills which are marked in Fig. 2.

In each node the mean skidding distance was computed based on measuring 10 samples on the map. The skidding cost per cubic meter (Variable cost) was computed for each node using the mean skidding distance, hourly cost and time predicting model.

The road length for each node was measured on the map. The roading cost per node was computed by multiplying the road length and the roading cost per unit length. In Network 2000 program, the Link

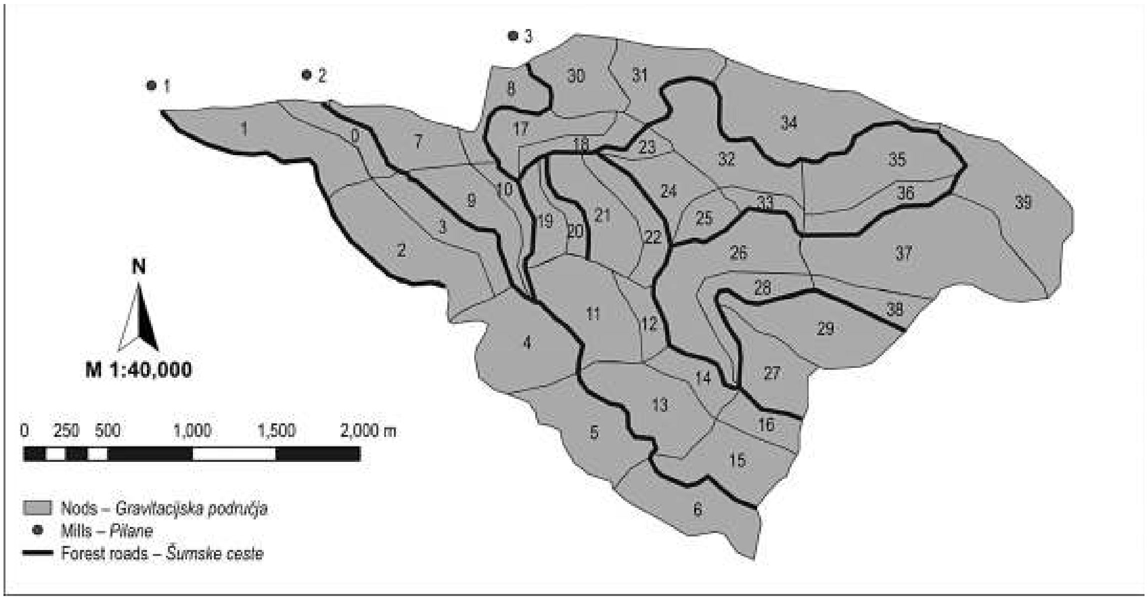

Fig. 2 Nodes and mills of network analysis

Slika 2. *Čvorišta i pilane u mrežnoj analizi*

file provides the variable cost and upper and lower volume bounds from node to node.

The Sale file includes entry nodes, destination node, harvesting volume, harvest year and discount rate.

The objective is to minimize skidding and roading cost. The network model can be expressed mathematically as:

$$\text{Minimize} \quad z = \sum_{i=0}^{i=39} Sc_i V_i + \sum_{i=0}^{i=39} Rc_i V_i$$

Subject to: $V_i > 0$

where:

Sc_i – Skidding cost per node per m^3

Rc_i – Roading cost per segment

V_i – Harvesting volume per node

$0 < i < 120$.

3. Results – *Rezultati*

3.1 Production – *Proizvodnost*

The time study resulted in a net production rate of 8.22 m^3/h (based on free delay hours). The gross production was 8.88 m^3/h (including delay times). The skidding cost based on the net production rate was 5.69 €/m^3 (Jour Gholami 2005).

3.2 Time predicting model for skidding – *Model procjene vremena privlačenja*

Jour Gholami (2005) used stepwise regression method using variables such as skidding distance, piece volume, load volume, number of pieces per turn and slope of the skid trail. The model was developed by SPSS.

$$t = 4.142 + 1.988 \times N + 0.0176 \times L +$$
$$+ 1.093 \times V \ (R^2 = 0.786, n = 43)$$

where:

t – skidding time, min/cycle

N – number of pieces per cycle

L – skidding distance, m

V – volume of load, m^3/cycle

The effect of each variable on skidding time was studied by changing one variable while holding the other variables constant at their mean value. Figures 3, 4 and 5 show the effect of skidding distance, number of pieces per turn and load volume on skidding time, respectively.

Increasing skidding distance, number of pieces per turn and load volume will increase skidding time.

3.3 Optimum road network – *Optimalna mreža prometnica*

The variable cost (skidding cost per m^3) and fixed cost (road construction cost per segment) were entered for all the nodes in the Link file. For the Sale file, the entry node, destination node and harvesting volume per node were entered. The same harvest year was assumed for all nodes.

Shortest path algorithm was run based on the data and the best solution was found at 45 iteration

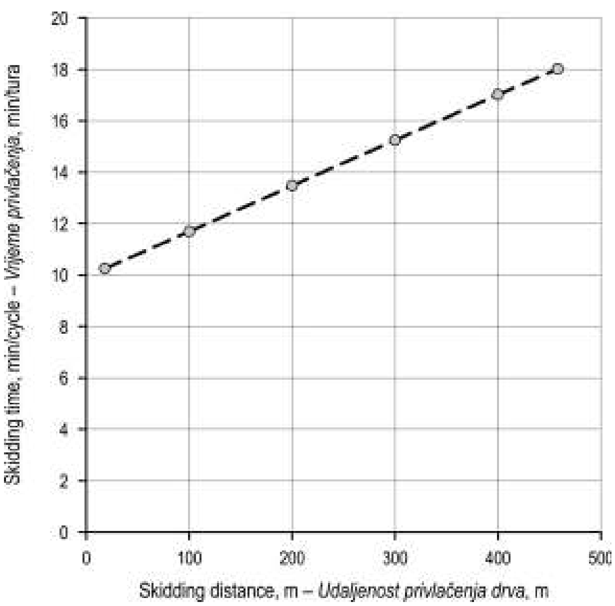

Fig. 3 Cycle time vs. skidding distance

Slika 3. *Ovisnost vremena turnusa o udaljenosti privlačenja*

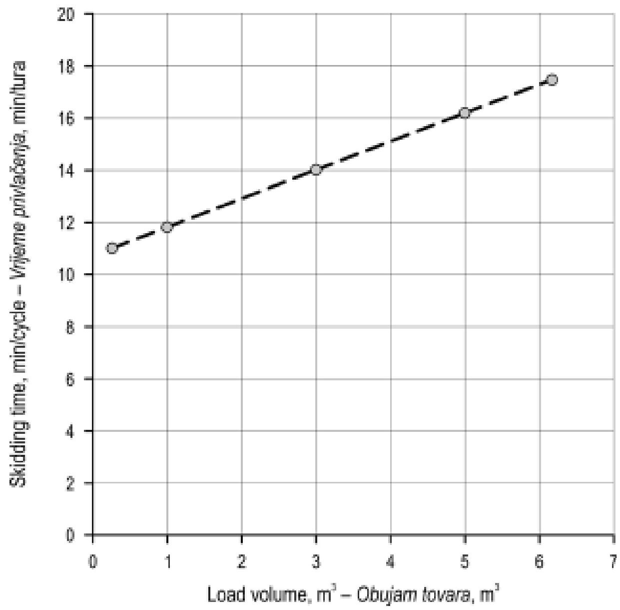

Fig. 5 Cycle time vs. load volume

Slika 5. *Ovisnost vremena turnusa o obujmu tovara*

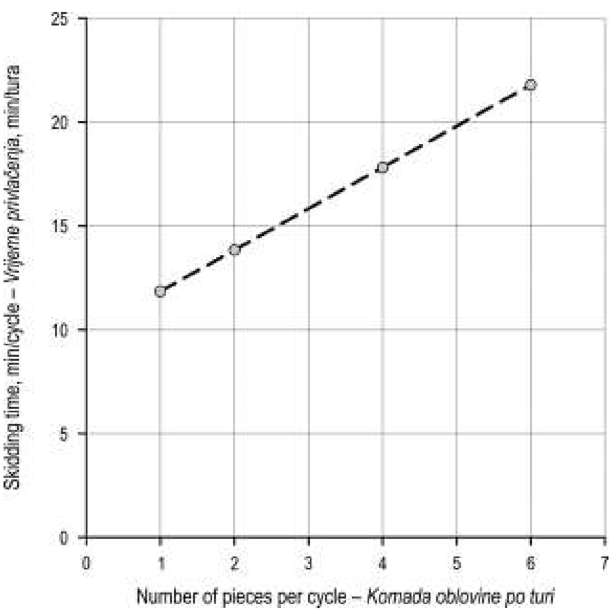

Fig. 4 Cycle time vs. number of pieces per turn

Slika 4. *Ovisnost vremena turnusa o broju komada u tovaru*

of the shortest path algorithm. Figure 6 shows the links to be used based on the result of running the algorithm. Using these results, the proposed links were marked on the map and the best solution was obtained as shown in Figure 7.

Total variable cost, fixed cost and sum of variable and fixed cost was 8.30 €/m^3, 18.89 €/m^3 and 27.19 €/m^3, respectively. SA and GDA were also run to see if they can find better solution, but these algorithms could not find better solution than the shortest path algorithm.

The network analysis suggested eliminating the road from node 1 to 2 and the road from compartment 28 to 38.

4. Discussion – *Rasprava*

The results of work and time study indicated that the variables such as number of pieces per turn, load volume and skidding distance have significant effect on RMS of the model. If these variables increase, the cycle time and cost of skidding will increase.

The solution found by running the shortest path algorithm helps logging planners decide which road segments can be used and which segments should be eliminated to achieve the minimum total cost of roading and skidding.

The solution suggested eliminating the road segments of nodes 1, 2, 28 and 38. If these roads are closed, the forest company not only can avoid their maintenance cost but can also decrease total cost of skidding and roading of the district. The logs in nodes 1 and 2 can be extracted to nodes 0 and 3 using the longer skidding distance. The felled trees in nodes 28, 29 and 38 should be skidded to node 16 and 27.

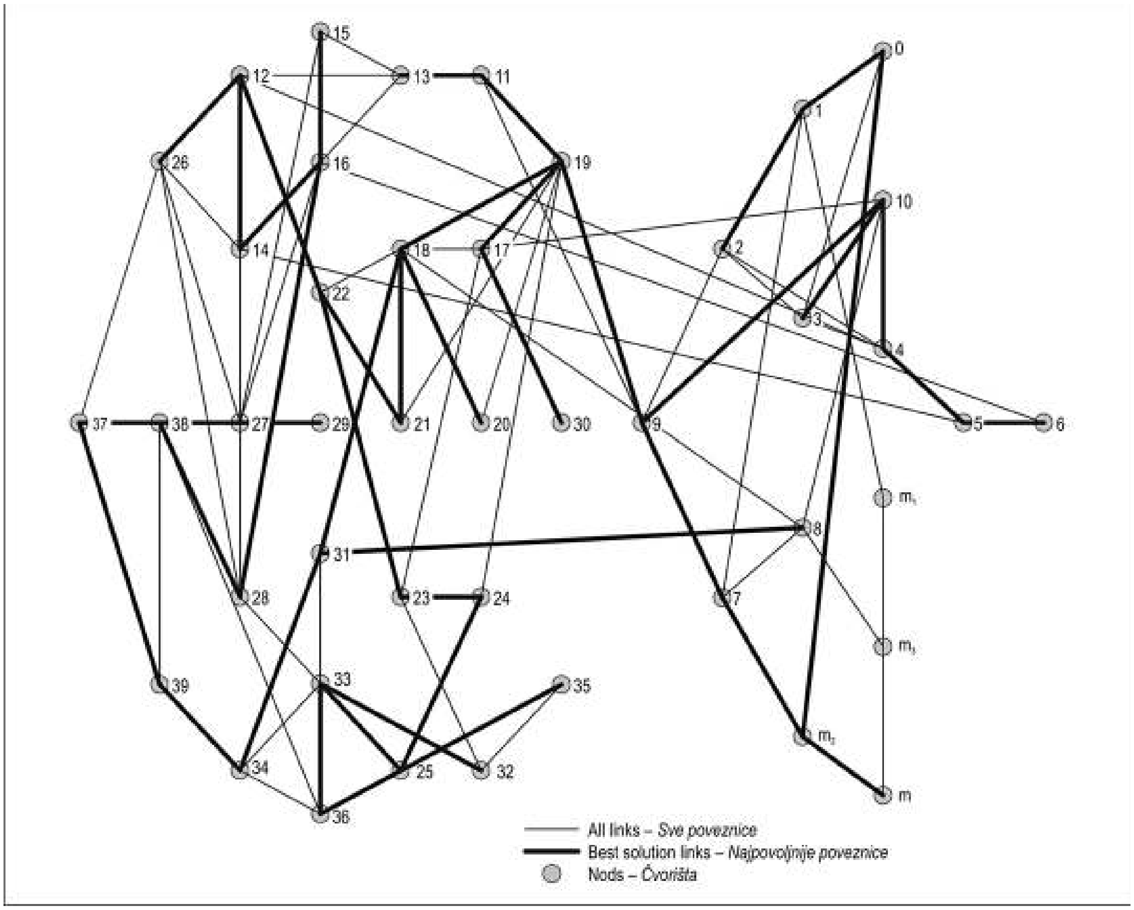

Fig. 6 Links in network analysis

Slika 6. *Poveznice u mrežnoj analizi*

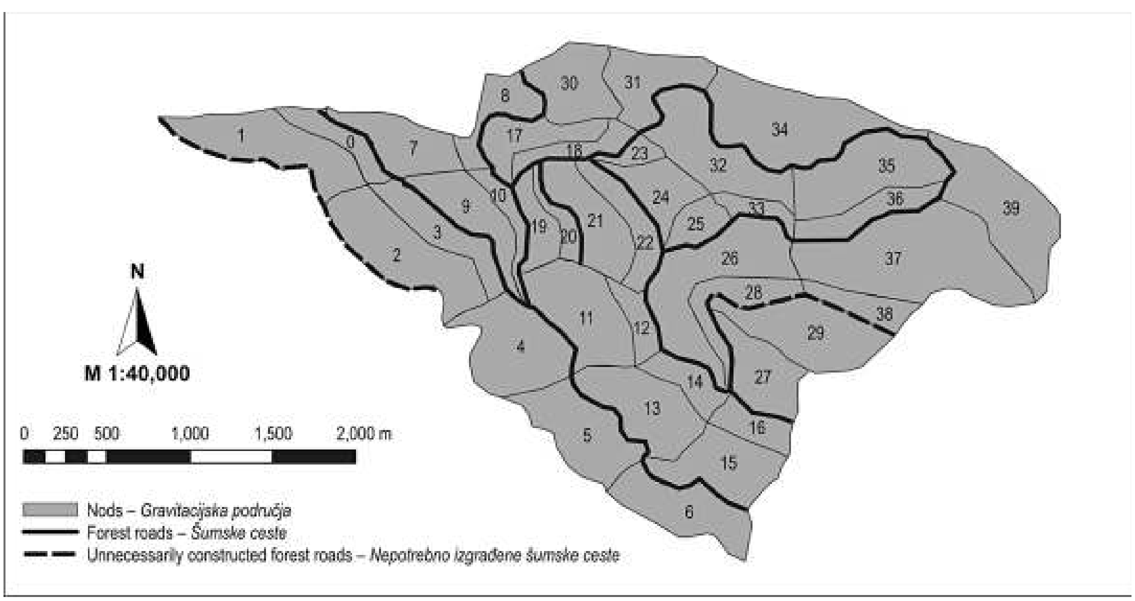

Fig. 7 Best solution of Network Analysis for the road network of Namkhaneh district

Slika 7. *Najpovoljnije rješenje mreže šumskih cesta u području Namkhaneh dobiveno mrežnom analizom*

5. Conclusions – *Zaključci*

The results of time study and the model developed for predicting skidding time give the forest engineers a tool for logging planning.

Network analysis using the shortest path algorithm, GD or SA, is a useful method to optimize transportation problems. The results of running Network 2000 based on an existing forest road network harvested by cable skidder, showed that the best solution (Fig. 7) can be found with the total cost of 27.19 €/m^3. The solution showed which links can be used to achieve the lowest cost of skidding and roading (Fig. 6). Using the proposed links, it was established which road segments can be eliminated.

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Sažetak

Optimizacija postojeće mreže šumskih cesta aplikacijom Network 2000

Planiranje mreže šumskih cesta, odnosno njihova optimizacija jedan je od vrlo važnih zadataka inženjera šumarstva. Mathews je (1942) prvi autor koji je predstavio model optimizacije mreže šumskih cesta (optimalnoga razmaka između šumskih cesta) zasnovan na najmanjim ukupnim troškovima (s jedne strane troškova privlačenja drva, a s druge strane svih troškova povezanih s uspostavom šumskih cesta na terenu).

Mnogi su autori (Sundberg 1976, Peters 1978, Bryer 1983, Wenger 1984, Sessions 1986, Yeap i Sessions 1988, Thompson 1992, Liu i Corcoran 1993, Segebaden 1964, Heinimann 1997, Thompson 1998, Akay i Sessions 2001, Sessions i Boston 2006) odredili osnovne čimbenike koji utječu na optimalan razmak šumskih cesta. To su: metoda sječe i izradbe, tehnologija pridobivanja drva, cijena drvnih proizvoda, politika oporezivanja, troškovi skladištenja trupaca, opći troškovi, oblik sekundarne mreže šumskih prometnica, dobit izvoditelja radova pridobivanja drva, širina tijela šumskih cesta, veličina stovarišta, nagib terena, konfiguracija terena i moguća oštećenja tla.

U prebornim je šumama sjevernoga Irana, u različitim reljefnim područjima, izrađeno više studija (Mostafanejad 1995, Eghtesadi 2000, Lotfalian 2001, Naghdi 2004) kojima je utvrđena optimalna gustoća mreže šumskih cesta u rasponu od 9 do 28 m/ha. Pri tome je primijenjena metoda najmanjih ukupnih troškova pridobivanja drva.

Optimalan razmak između šumskih cesta, s jedne strane, predstavlja brojčanu vrijednost koja je putokaz i vodilja šumarskim stručnjacima pri provedbi primarnoga otvaranja šuma, ali s druge strane ne kazuje ništa o stvarnim trasama šumskih cesta na terenu (Tan 1999). Radi optimizacije mreže šumskih cesta i određivanja optimalnoga položaja svake pojedine trase šumske ceste razvijen je veći broj matematičkih programa i algoritama: TIMBRI – Sullivan 1974, TRANSHIP – Kirbey i dr. 1981, MINCOST – Wong 1981, NETCOST – Weintraub 1990, NETWORK – Sessions 1978 te NETWORK 2000 – Sessions i Chung 2003.

U ovom je radu, za mrežnu analizu postojećega primarnoga sustava šumskih cesta, primijenjen računalni programski paket NETWORK 2000 koji je dizajniran radi optimizacije fiksnih i varijabilnih troškova koji se javljaju pri transportu drva, a sastoji se od triju različitih algoritama. Definiran je i cilj istraživanja – pronaći, u okviru postojeće primarne šumske prometne infrastrukture, najbolju mrežu šumskih cesta sa stajališta najmanjih ukupnih troškova pridobivanja drva (troškova privlačenja drva i troškova povezanih sa šumskim cestama).

Područje istraživanja – gospodarska jedinica Namkhaneh (1080,90 ha) smještena je u mješovitim prebornim šumama sjevernoga Irana. To je nastavno-pokusni šumski objekt Sveučilišta u Teheranu. Prosječna drvna zaliha iznosi 434 m^3/ha, a godišnji je etat 5,41 m^3/ha (oko 5850 m^3 na čitavom istraživanom području). Sječa i izradba obavlja su motornim pilama lančanicama uz primjenu. Pilanska se oblovina privlači do pomoćnih stovarišta kotačnim i gusjeničnim skiderima. Jednometarsko ogrjevno drvo iznosi se mulama kao i sve izrađeno drvo na strmim terenima koji su nedostupni skiderima (tada se od pilanske oblovine na mjestu sječe izrađuju piljenice). Nagibi se terena kreću od 15 do 60 %. Postojeća primarna otvorenost šuma iznosi 28,16 m/ha uz napomenu da su odjeli 201, 202, 203, 204 i 205 zaštitni zbog velikoga nagiba terena te nisu obuhvaćeni daljnjim analizama.

U ovom istraživanju korišteni su rezultati prijašnjih istraživanja. Jour Gholami (2005) došao je do ovih rezultata: učinak zglobnoga traktora Timberjack 450C iznosi 8,22 m^3/h, trošak strojnoga rada 46,91 EUR/h, a jedinični trošak 5,69 EUR/m^3. Isti je autor razvio i regresijski model za određivanje utroška vremena pojedinoga turnusa privlačenja drva, čiji su ulazni parametri: udaljenost privlačenja, nagib traktorskoga puta (vlake), obujam pojedi-

noga trupca, obujam tovara i broj komada trupaca u tovaru. Utjecaj udaljenosti privlačenja, broja komada trupaca u tovaru i obujma tovara na trajanje turnusa privlačenja drva prikazan je na slikama 3, 4 i 5. Smanjenje srednje udaljenosti privlačenja, manji broj komada trupaca u tovaru i manji obujam tovara utječu na smanjenje turnusa privlačenja drva.

Troškovi povezani sa šumskim cestama uključuju: projektiranje (384,6 EUR/km), izgradnju donjega stroja (6837,6 EUR/km), izvedbu gornjega stroja (11 794,8 EUR/km), izradu objekata odvodnje – cijevnih propusta i odvodnih jaraka (4273,5 EUR/km) i održavanje (349,3 EUR/km). Ukupni je trošak povezan sa šumskim cestama i iznosi 23 639,8 EUR/km. Uz razdoblje amortizacije od 50 godina i važeće financijske pokazatelje u Iranu godišnji je trošak povezan sa šumskim cestama 2,66 EUR/m.

Svaki odjel istraživane gospodarske jedinice razdijeljen je, pomoću programa ArcMap, na određeni broj gravitacijskih područja, uz pretpostavku privlačenja 2/3 etata smjerom nizbrdo te 1/3 smjerom uzbrdo. Težište pojedinoga gravitacijskoga područja predstavljalo je čvor (nod) mreže, poslije korišten pri mrežnoj analizi.

Sva je izrađena pilanska oblovina transportirana do jedne od triju pilana čiji je položaj označen na slici 2. Srednja je udaljenost privlačenja određena izmjerom na digitalnom zemljovidu. Na zemljovidu je određena i duljina šumskih cesta pojedinoga čvora. Prema navedenim modelima i cijenama izračunati su, primjenom matematičkoga oblika mrežnoga modela, troškovi privlačenja drva i troškovi povezani sa šumskim cestama. Cilj je minimalizirati ukupne troškove pridobivanja drva.

Unosom i obradom podataka za svaki čvor te pokretanjem algoritma za traženje najkraćega puta (shortest path algorithm) dobivena je najbolja povezanost prikazana na slici 6. Korištenjem navedenoga rješenja preporučena je optimalna mreža primarnih šumskih prometnica (slika 7).

Ukupni su varijabilni troškovi (troškovi privlačenja drva) 8,30 EUR/m^3, varijabilni troškovi (troškovi povezani sa šumskim cestama) 18,89 EUR/m^3, odnosno ukupni troškovi pridobivanja drva 27,19 EUR/m^3. Radi provjere dobivenih rezultata pokrenuti su i algoritmi SA (simulated annealing algorithm) i GDA (great deluge algorithm) u okviru programskoga paketa NETWORK 2000, ali oni nisu pronašli bolje rješenje za primarno otvaranje šuma od onoga koje je ponudio algoritam za traženje najkraćega puta.

Mrežnom analizom sugerirana je eliminacija šumskih cesta od čvora 1 do čvora 2 te od čvora 28 do čvora 38. Privlačenje izrađenih trupaca iz čvora 1 i čvora 2 treba obavljati prema pomoćnim stovarištima u čvorovima 0 i 3, dok trupce iz čvorova 28 i 29 treba privlačiti prema stovarištima u čvorovima 16 i 27. Na taj su način ukupni troškovi pridobivanja drva za istraživano područje minimalizirani.

Ključne riječi: *raspored šumskih cesta, optimalna gustoća šumskih prometnica, skider, model mrežne analize, Iran*

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