Planning and Assessment of Alternative Forest Road and Skidding Networks

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Abstract – Nacrtak

Road construction and harvesting operation have always been the two most expensive activities in forestry. The aim of this paper is to define a method to evaluate the forest road network variants. For this purpose,, the forest was sampled with the use of a systematic grid of 150 m by 200 m spacing by an inventory group. In each grid point the terrain conditions and stand data collected by the inventory group were analyzed using GIS. The forest was evaluated and maps of »Forest Potential for Road Construction« (FPRC) and »Forest Capacity for Harvesting« (FCH) were prepared, and then the first network was designed and costs were calculated. The skidding costs of each cross point were calculated for 3 types of extraction machines (two skidders and one farm tractor) and considering the results some better networks were designed. Finally a network was accepted in which not only the environmental impacts were decreased, but the costs of road network and skidding were minimized, so that the most suitable place for each skidder was determined and presented on a map using Linear Programming (LP).

Keywords: *forest road density, road network analysis, linear programming, road construction cost, skidding cost, Iranian forests*

1. Introduction and research problems – *Uvod i problematika istraživanja*

For decades forest engineers have tried to define methods for minimizing the sum of road costs (RC) and log extraction costs (LEC) because road construction and harvesting have always been the two most expensive activities in forestry. The planning of a road network to access timber harvest site is a difficult and time–consuming task (Murray 1998). Further more, the viability and profitability of operational forest management plans are very much influenced by road building and maintenance cost as well as the road network structure (Kirby et al. 1986).

Recent research has discussed the need for tools and techniques to assist in the development of road network systems in forest management, particularly within the context of accessing timber harvest site (Heinimann et al. 2003, Dean 1997, Newnham 1995, Lui and Sessions 1993). The basic problem is to build a road network in a forested region that provides access to identified harvesting site and minimizes overall road building (Kirby et al. 1986).

Computer and Linear Programming are the two means that help scientists to solve the problem and many researchers developed a variety of methods to determine the optimum forest road density. To reach this goal some heuristic methods have been developed (Akay and Sessions 2005, Tan 1999, Dahlin and Fredriksson 1995).

Optimization models for forest tactical planning problems are notoriously difficult to solve, hence various heuristic strategies and specialized solution procedures have been developed (Richards and Gunn 2000) and so some researchers have used a combination of a heuristic method and LP for optimum network development (Tan 1999, Dean 1997, Newnham 1995).

Some researchers have used DEM or systematic grids or both of them to identify feasible road segments. Liu and Sessions (1993) have evaluated the fixed and variable costs and the optimum set of road segments to be used, while others have enlarged the link pattern to 24 links, 8 to the nearest and 16 to the second nearest neighbour node.

Branch evaluation, a heuristic method developed by Dean (1997), is an automated method of developing a road network designed to access any number of potential harvesting sites while minimizing the overall cost of the network.

Both models by Liu and Sessions (1993) and Dean (1997) have the ability to solve multiple target access problems with designated targets and predefined cost matrix or link variables. In some cases, however, especially in developing skid trails or temporary access roads for timber harvest, the ending location of each road branch is not always fixed.

Anderson and Nelson (2004) have developed a computer algorithm to generate road networks under a variety of assumptions related to road design standards. This method does not create an optimized road network, but rather mimics the procedure a professional might use when projecting roads by hand.

Chung et al. (2001) described a methodology for optimizing cable logging layout using a digital terrain model (DTM). The methodology formulates a cable logging layout as a network problem. Each grid cell containing timber volume to be harvested is identified as an individual entry node of the network.

To calculate the network efficiency and total cost (road network and skidding cost), Pentek et al. (2005) considered an existing network. Then they measured the distance between the centre of each compartment and the network, and then they calculated the costs and applied a mathematical function to determine buffer and dead zone of the road network.

2. Aim of research – *Cilj istraživanja*

The aim of this study was to define a method to evaluate forest road network and related skid trails efficiency from the cost point of view.

We hypothesized that:

⇒ forest road networks could be evaluated by GIS and a dense grid field observation,

⇒ skidding cost is reduced using Linear Programming.

3. Study site – *Područje istraživanja*

The study site is located on 51°15′ E and 36°30′ N in the North of Iran. The study area was covered with hardwood of 14 forest types in approximately 2000 hectares. There were a large number of constraints (steep terrain, unstable area, environmental constraints, machines, etc.) for forest road network designing and construction in the area. There was a permanent stream flooding through the district and the banks of the stream were identified as landslides based on the studies done by geologists through field trips. And so, the construction costs and especially the maintenance costs increased noticeably in this area.

Field trips and soil studies showed that the southern parts with a surface of 1000 hectares contained shallow soil and hence decision was made to designate these parts as conservation areas.

There were two alternatives for choosing the network entry points, east and north. The forest network could be connected to a public road in East or to another district network in North. The logs were decked on the road banks and there was no place constructed for landing, so the landing construction cost would be zero. Ground skidding is the dominant method of harvesting and accounts for approximately 60% of the log volume in these mountainous uneven aged hardwood forests. The following extraction machines are used for primary transport: Timberjack 450C, HSM 904 and Zetor.

4. Materials and Methods – *Materijal i metode*

4.1 Designing of Forest Evaluation System – *Dizajniranje sustava procjene*

With the use of a systematic grid of 150 m by 200 m spacing, the forest was sampled by an inventory group (Fig. 1).

In each grid point the terrain conditions and stand data collected by the inventory group was analyzed using GIS (Fig. 2). The result was named »Evaluation Map« that showed land use of each land unit.

The »Map of unstable area« was created and improved through numerous field trips to avoid road construction in these areas. The Map of unstable area and the Evaluation Map were overlaid and this

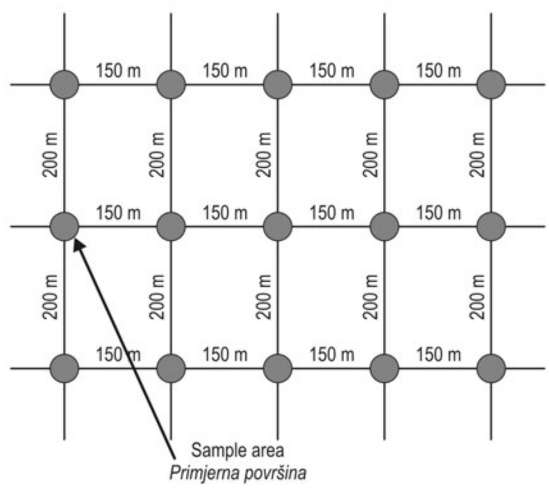

Fig. 1 Inventory grid
Slika 1. *Plan pokusa*

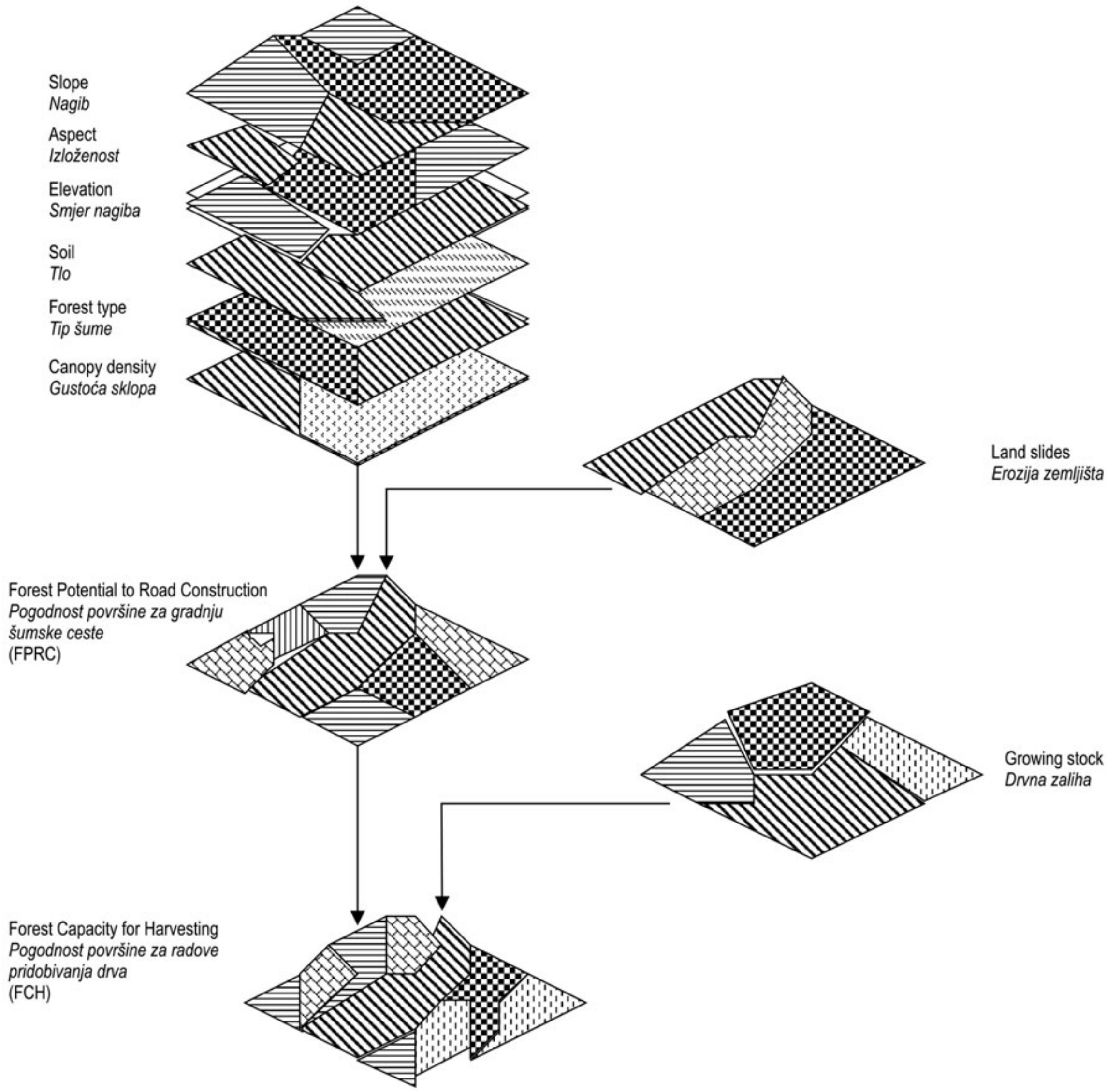

Fig. 2 GIS layers used in the designed forest evaluation system
Slika 2. *Sastavnice GIS-a primijenjenoga u procjeni dizajniranoga sustava procjene*

resulted in the »Forest Potential for Road Construction Map« (FPRC).

To overcome the above shortcoming, the map of »volume per hectare« was created and overlaid on the FPRC map and this resulted in the »Forest Capacity for Harvesting Map« (FCH) – Fig. 3. The map was used as a guide in network designing.

4.2 Road Network Designing and Evaluation – *Planiranje mreže šumskih cesta i procjena kakvoće*

Evaluation is necessary to compute road costs (RC) and log extraction costs (LEC) and these data are analyzed so as to find the network which contains the minimum sum of RC and LEC. The procedure of calculating RC and LEC will be demonstrated below.

4.2.1 Road costs (RC) – *Troškovi povezani sa šumskim cestama*

Calculating the benefits of forest roads, where a number of factors must be considered, is a complicated operation (Dahlin and Fredriksson 1995) However, RC generally consists of three elements:

⇒ depreciation costs,

⇒ maintenance costs,

⇒ lost productive area costs.

In Iran roads are constructed by constructors and experience shows that they estimate the road

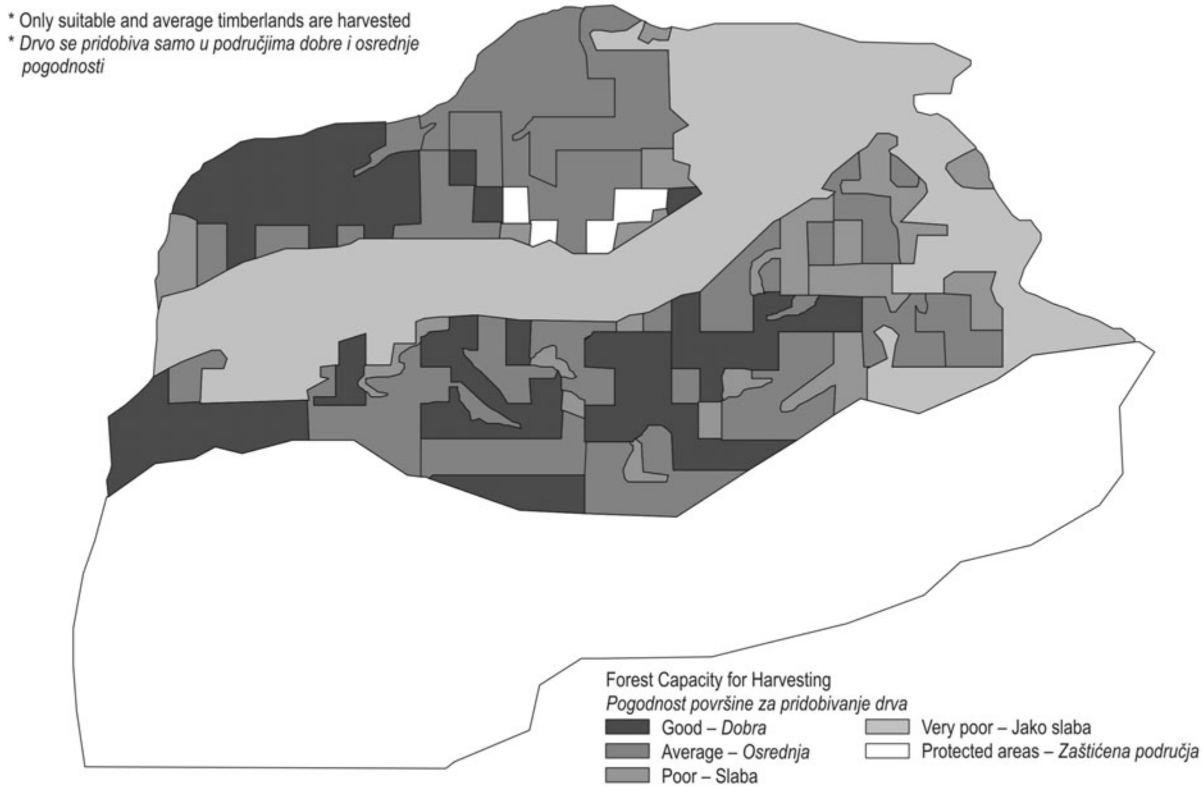

Fig. 3 Forest Capacity for Harvesting Map (FCH)*
Slika 3. *Potencijal istraživanoga područja za pridobivanje drva**

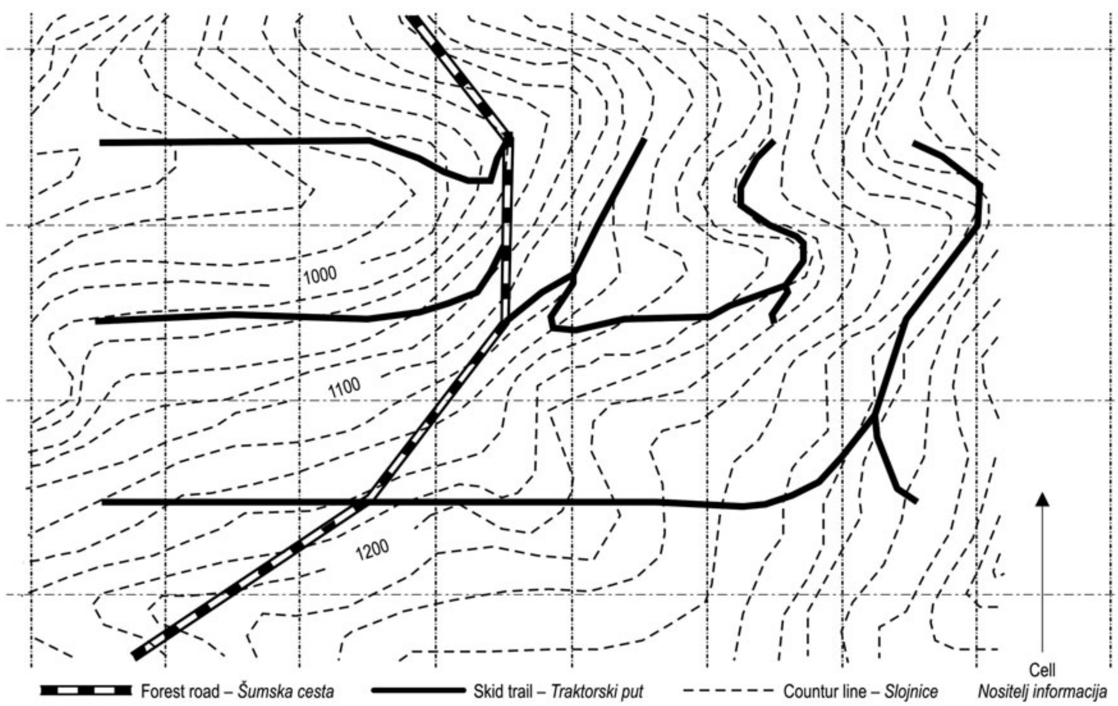

Fig. 4 A schematic map of forest road, skid trails and cells
Slika 4. *Shematski prikaz obilježbe šumskih cesta, traktorskih putova i vlaka te nositelja informacija*

construction and maintenance costs according to the average conditions of the forest and hence depreciation and maintenance costs per unit are unchanged within a specific planning area.

The stock growth of the surface allocated to the road construction is called the growth of lost productive area. This method calculates the growth value of lost productive area (m^3/ha) in each cell, where the road segment may be located.

Road costs are calculated as follows: RC = annual depreciation + annual maintenance + value of growth of lost productive area.

RC is converted to $/$m^3$ for comparison with skidding costs and so RC per m^3 = RC / total annual allowable cut.

4.2.2 Log Extraction Costs (LEC) – *Troškovi privlačenja drva*

Centre of all cells were accessible by skid trail and more cells were connected to a skid trail.

There are three costs involved in the calculation of LEC:

⇒ landing costs,

⇒ skid trail construction costs,

⇒ skidding costs.

The maximum allowable gradient in every access spur is 25%, which is limited based on erosion hazards. If skid trails are constructed on slopes of more than 25%, the costs are estimated as construction costs, and if skid trails are cleared by skidder, the costs are considered as skidding cost.

The Division of Forest Techniques of the Austrian Federal Forest Research Centre of the Federal Ministry of Agriculture Forestry Environment and Water Management (FBVA 2000) used to determine the skidding costs, depending on the annual utilization.

Time study of HSM 904 has been done and production per hour has been calculated by some authors because the related data were not available.

Evaluation of skidders shows that the skidding time is a function of many independent variables such as total volume of logs (m^3) in each travel, skid trail gradient, skidding distance, etc. These variables are estimated in each cross point of the grid, using

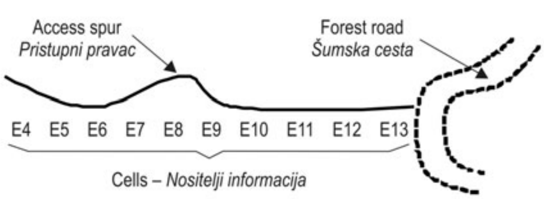

Fig. 5 Access spur
Slika 5. *Pristupni pravac (traktorski put)*

GIS and inventory data and the related skidding costs in each cell and trail are calculated. For example, Fig. 5 shows ten cells (E4 … E13) which are connected by skid trail with a slope gradient of more than 25%, so an access spur should be constructed. The skidding distance between E4 and the road was measured on the access spur.

The number and volume of logs in each cycle are also estimated using the inventory data. All independent variables that affect the skidders' productivity are explicitly calculated by use of skidding distance, as explained above.

Then the skidding time in each cell is calculated and converted to skidding costs based on the cubic meter considering the skidders' hour productivity cost. For instance the mathematical model of productivity for Timberjack 450C calculated by time study was:

$$T = 4.61 + (0.073 \cdot V) + (1.152 \cdot N) + (0.0162 \cdot D) \quad (1)$$

where:

T time of travel to extract all harvested timbers from cell E4, min
V total volume of logs in each travel, m^3
N number of log in each travel
D skidding distance, m

If the calculated skidding time for total harvested timber in E4 is 114.07 minutes and its hour cost is $36.37, the total skidding cost will be $69.14 and if the annual allowable cut in E4 is 7.7 m^3 per cell, the skidding cost based on cubic meters will be $8.98.

As mentioned above the access spur should be constructed between E4 and E10. The distance between E9 and E10 to be constructed is 80 meters through which the logs of 6 cells are carried and if the construction costs of the access spur per kilometre is $341, this cost in E9 will be $4.55.

The total distance between E4 and E9 is 790 m but only 200 m of it should be constructed, so the share of E4 considering the above mentioned method will be 49.33 m and the access spur construction cost in E4 is $16.82

The construction cost of the access spur based on cubic meter is $2.18.

The landing construction cost is zero, and the log extraction cost (LEC) will be $11.16.

The sum of LEC of all cells divided by the sum of annual allowable cut will result in the LEC based on cubic meter.

4.2.3 Machines Allocation – *Planiranje rada šumskih traktora*

Although RC and LEC are calculated in each cell and can be compared in a Forest district, dividing a district based on 3 ha cells does not seem to be practical because a very complicated procedure is needed to manage them. To solve the problem, the costs are calculated and compared in skid trails.

Productive machine hours (PMH) of various skidders in an identical skid trail were not the same because of the difference among the engine powers of skidders and, as the time allocated to each skidder by the company were limited, we were not able to allocate a skidder an unlimited working time in an area, that is we had to apply a combination of skidders in the district.

We used LP to show how much log each skidder in each skid trail should extract to minimize the total skidding costs.

The model could be described as:

$$\mathrm{Min}\sum_{i\in I}\sum_{j\in J} C_{ij} X_{ij} \qquad (2)$$

$$\sum_{i\in I}\sum_{j\in J} X_{ij} = \sum_{i\in I} V_i \;;\forall_{ij} \qquad (3)$$

$$\sum_{j\in J}\sum_{i\in I} t_{ji} X_{ij} \leq \sum_{j\in J} T_j \;;\forall_{ij} \qquad (4)$$

where:

- I number of trails,
- J number of skidders,
- V_i total annual allowed cut on the trail (i), m^3
- C_{ij} skidding costs on the trail (i) extracted by skidder (j), $\$/m^3$
- X_{ij} volume of logs extracted by skidder (j) on the trail (i), m^3
- t_{ji} log extraction time of skidder (j) on the trail (i), min/m^3
- $\sum_{j\in J} T_j$ time allocated for skidder (j) by the company, hour

The first constraint shows that the total allowable cut is equal to the sum of allowable cuts of all cells. The second constraint emphasizes that total skidding time of each machine cannot be more than total allowed time. Total time is determined by the forest manager with regard to their facilities. T_{ji} is estimated according to PMH of the machines and some other independent variables such as distance to road, trail gradient, etc. in each cell of the trail.

Now LEC and RC can be summed and the sum can be compared with other districts' costs because they are both calculated based on cubic meter. When each network is designed, these elements are also calculated and compared. The costs of each road segment and skid trail and their effects on the total costs were evaluated separately and the results were used to design the next network. In this way the best network was designed with the minimum sum of LEC and RC.

5. Research results and discussion – *Rezultati istraživanja i rasprava*

5.1 Road network »A« – *Mreža šumskih cesta »A«*

A major segment of the road network »A«, designed by the Forest Company, is located in unstable area so the forest damage, erosion and annual maintenance costs would certainly be much higher than the average. The segment is close to a permanent stream and the erosion caused by unstable road will have negative impact on the stream ecosystem. The network can neither be acceptable from the economical point of view, because of high annual maintenance costs. To evaluate the road network, the annual allowable cut was determined according to FCH map (low volume and sensitive areas were eliminated). Table 1 shows the results.

Table 1 Road costs (RC), Log extraction costs (LEC) and Total costs for different alternatives of forest road networks

Tablica 1. *Troškovi povezani sa šumskim cestama, troškovi privlačenja drva te ukupni troškovi pridobivanja drva za različite inačice dizajniranih mreža šumskih cesta*

Road network variant *Inačica mreže šumskih cesta*	Log Extraction Costs – *Troškovi privlačenja drva*				Road Costs *Troškovi povezani sa šumskim cestama*	Total Costs *Ukupni troškovi pridobivanja drva*
	Zetor	Timberjack 450C	HSM 904	LP Solution *Inačica dobivena linearnim programiranjem*		
	$\$/m^3$					
A	**3.83**	2.60	4.01	-	**3.87**	8.32
B	**1.90**	4.12	6.98	-	**6.42**	7.70
C	**2.00**	2.67	4.74	-	**4.74**	6.74
D	2.95	3.44	5.55	**2.94**	**3.25**	6.19

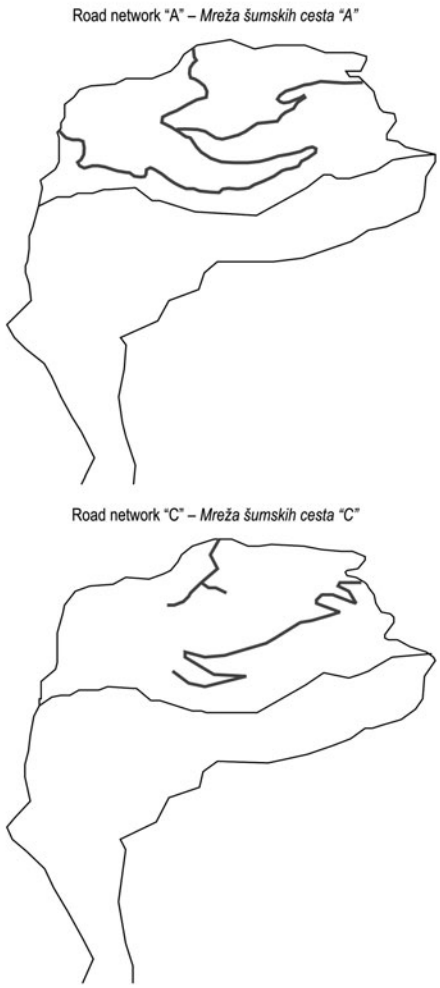

Fig. 6 Designed alternatives of forest road network
Slika 6. *Dizajnirane inačice mreže šumskih cesta*

5.2 Road network »B« – *Mreža šumskih cesta »B«*

Road network »B« was the first road network designed in this research (Fig. 6). Our objective was to avoid unstable areas and to access high stock land based on quality and quantity investigations. Evaluations showed that total costs were decreased but it could not be a candidate for the best road network. There was not any road segment on the north part of the forest, so it could not be acceptable regarding other goals of forest management such as forest protection. On the other hand log extraction from the north part required the design and construction of many skid trails, which had to cut the stream in many places and could be harmful for the fish.

5.3 Road network »C« – *Mreža šumskih cesta »C«*

The stream and the unstable area were located in the middle of the district and divided it into two parts and constructing a road to connect the two parts of the district was impossible so, two segments were added to network »B«. The end part of the south segment was eliminated to prevent RC increment and a new road network called network »C« was created. The new segments were connected to the road network of the northern neighbouring district (Fig. 6). Results (Table 1) showed that total costs were decreased.

5.4 Road network »D« – *Mreža šumskih cesta »D«*

The eastern segment of the north road and a small ending part of the south road were eliminated (Fig. 6) and the changed network (i.e. »D«) was evaluated. The result showed that total RC and LEC in the new road network were lower than in others. This network was also unacceptable regarding environmental and forest management aspects.

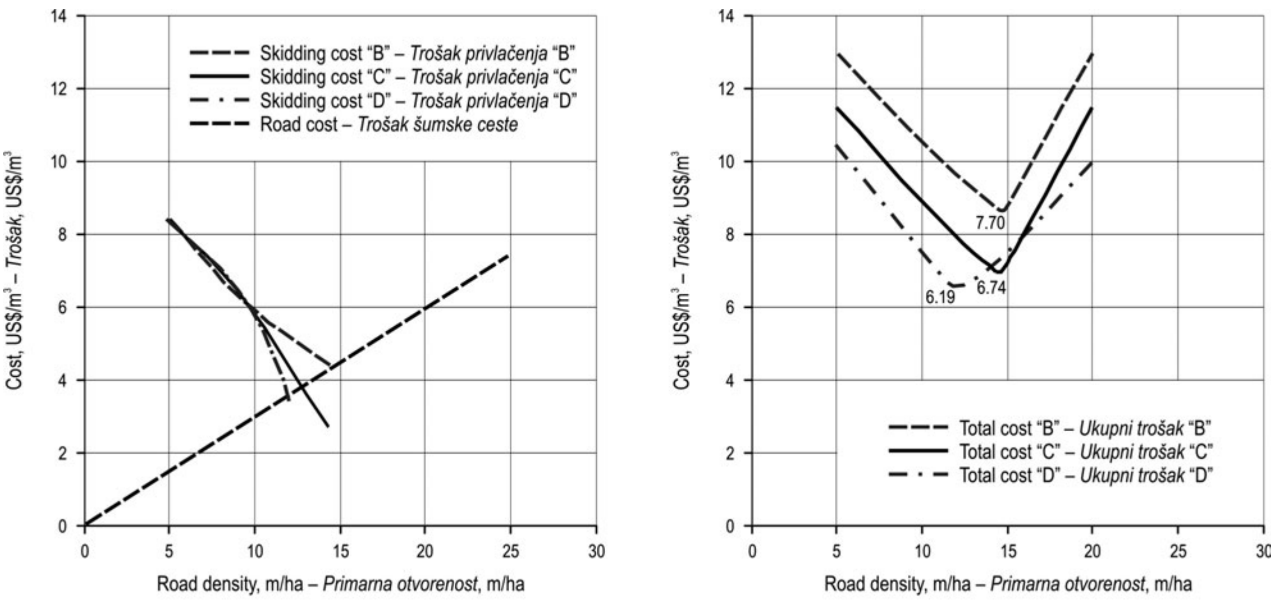

Fig. 7 Range of Road costs (RC), Log Extraction Costs (LEC) and total costs for different alternatives of forest road networks

Slika 7. *Prikaz troškova povezanih sa šumskim cestama, troškova privlačenja drva te ukupnih troškova pridobivanja drva za različite inačice dizajniranih mreža šumskih cesta*

Fig. 8 Extraction machine operations area

Slika 8. *Područje rada pojedinoga stroja pri privlačenju drva*

The next step was to design new road networks by adding some feasible segments or omitting some other segments to determine the lowest total costs (results not shown). These issues were considered in the network »D« after their evaluations (Fig. 7) and it was determined to be the best road network.

Figure 7 shows that factors such as road density or road network efficiency cannot determine the optimum road network density in the mountainous uneven age forests and factors such as stock distribution, slope and unstable area are more important and effective and they can be measured by the method developed by this research. This method can evaluate the road networks easily, precisely and in detail. Many LEC lines (Fig. 7) can be drawn for a single road density and the gradient of LEC depends not only on road density but also on road distribution.

As the inventory groups in Iran gathered most of the above data, they incurred no additional costs. Doing the same study in other forests with different conditions can be beneficial for a better evaluation of this study.

Regarding the limitation of skidders power, allowable cut, budget and skidder availability LP was used to increase the work productivity and to decrease the skidding costs and also to determine the skidders spatial allocation. Then a valuable and applicable map was created which showed where and how long each skidder must work (Fig. 8).

In the current research not only the road network costs and linkage costs are considered but also the skidding and distribution costs. We developed a method to design the network and its related skid trails manually and – using LP and GIS – have investigated transportation (road network and skid trail) efficiency and total costs. We used a grid point which was overlaid on the forest and our judgment was based on the real data in details.

As in this method the forest has been divided into 3 hectare mosaics, data analysis was done in a more explicit manner and also it became possible to calculate the cost of each skid trail or each segment separately. Next skid trail networks were systematically designed and not randomly, so that each network was more complete than the previous network and also closer to the objective of the research. In this way the procedure to reach the best skid trail network has been enhanced, providing the possibility to this method to be applied in vast areas as it saves a lot of time in designing networks.

Furthermore data analysis and machine allocation became possible in each skid trail. Machine allocation in each skid trail leads to an optimum combination of skidders.

This method can also be used in forests where there are already some built transportation networks (road and skid trail network). This method analysis enables us to add or eliminate some parts of skid trails or roads.

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Sažetak

Planiranje i procjena kakvoće različitih inačica mreže šumskih prometnica

Troškovi povezani sa šumskim cestama (RC) te troškovi pridobivanja drva (LEC) oduvijek su, poglavito zbog izgradnje i održavanja mreže šumskih cesta te privlačenja drva, imali značajan udio u ukupnoj strukturi troškova radova u šumarstvu.

Planiranje dobre mreže šumskih cesta radi omogućavanja pristupa šumskomu radilištu (sječini) i smanjivanja srednje udaljenosti privlačenja drva zahtjevan je i vremenski dugotrajan posao (Murray 1998). Održivost i isplativost cjelokupnoga operativnoga šumarskoga planiranja i gospodarenja šumom pod snažnim je utjecajem troškova izgradnje i održavanja mreže šumskih cesta te ovisi o količini i kategoriji šumskih cesta (Kirby i dr. 1986).

Najnovija istraživanja raspravljaju o potrebi primjene novih alata i metoda koji će pomoći unaprjeđenju postojeće mreže šumskih cesta radi boljega i učinkovitijega obavljanja šumskih radova uz poseban naglasak na radove pridobivanja drva (Dean 1997, Newnham 1995, Liu i Sessions 1993). Temeljni je problem kako uz što manje ukupne cestovne troškove izgraditi dovoljno dobru mrežu šumskih cesta koja će osigurati pristup svim, u fazi planiranja determiniranim kao ključnim, šumskim radilištima.

Cilj je ovoga istraživanja razviti metodu pomoću koje će biti moguće optimizirati mrežu šumskih prometnica (šumskih cesta i traktorskih putova) s troškovnoga gledišta. Istraživanje je temeljeno na dvjema pretpostavkama (hipotezama):

⇒ *optimizacija se mreže šumskih prometnica može postići modeliranjem cestovnih troškova i troškova pridobivanja drva*

⇒ *najbolji se raspored strojeva za privlačenje drva na istraživanom području može odrediti pomoću linearnoga programiranja (LP).*

Istraživanje je provedeno na površini od oko 2000 ha u 14 različitih tipova šuma tvrdih listača. Terenski su uvjeti, s gledišta planiranja, projektiranja i izgradnje najbolje moguće mreže šumskih prometnica, bili vrlo zahtjevni. Nagibi su terena vrlo veliki, tlo je nestabilno (klizišta) i slabo nosivo, vodotok koji prolazi istraživanim područjem je poplavio, a na samim je obalama potoka zemljište klizilo (utvrđeno geološkim studijama). Zbog navedenoga troškovi su izgradnje i održavanja šumskih prometnica na istraživanom području vrlo visoki. U ovim se prebornim planinskim šumama drvo najčešće privlači po tlu (60 % drva privuče se na taj način), a pri tome su korištena dva zgobna traktora: Timberjack 450C i HSM 904 te jedan prilagođeni poljoprivredni traktor Zetor.

Na terenu je postavljena mreža pravilnih četverokutnih nositelja informacija dimenzija 150 x 200 m (slika 1). Izrađen je GIS istraživanoga područja čije su sastavnice vidljive na slici 2. Dizajnirane su dvije temeljne karte: karta pogodnosti (potencijala) pojedinoga nositelja informacija za prolazak šumske ceste (FPRC) i karta pogodnosti (potencijala) pojedinoga nositelja informacija za radove na pridobivanju drva (FCH – slika 3) koja prikazuje sječnu gustoću u m^3/ha.

Planiranje mreže šumskih cesta i procjena kakvoće pojedine inačice (izrađene su četiri inačice: A, B, C i D) temelji se na minimaliziranju ukupnih troškova povezanih sa šumskim cestama (RC) i troškova pridobivanja drva (LEC). Cestovni se troškovi dijele u tri skupine: trošak amortizacije, trošak održavanja i trošak gubitka proizvodne šumske površine. Jedinični trošak povezan sa šumskim cestama izračunava se pomoću formule 1.

Troškovi se pridobivanja drva sastoje od: troška izgradnje pomoćnih stovarišta, troška izgradnje traktorskih putova i troška privlačenja drva. Pri izračunu troškova privlačenja drva za različite strojeve koji se za navedene radove koriste preuzete su kalkulacije Austrijskoga državnoga šumarskoga istraživačkoga centra pri Ministarstvu poljoprivrede, šumarstva i vodnoga gospodarstva Austrije (FBVA 2000). Zbroj svih troškova privlačenja drva (po svim nositeljima informacija) podijeljen je ukupnim godišnjim etatom i tako je dobiven jedinični trošak privlačenja drva po kubnom metru. Kako organizacija rada, ponajprije planiranje strojeva za privlačenje drva, nije praktična (zbog kompliciranoga upravljanja) na tako malim površinama, godišnji je etat razdijeljen na traktorske putove (drvo koje gravitira pojedinomu traktorskomu putu) te je za svaki stroj izračunat trošak privlačenja i pronađeno najbolje (najjeftinije) rješenje.

Dizajniranjem više inačica mreže šumskih cesta (slika 6), s tim da su se svakom novom inačicom nastojali ukloniti prethodno uočeni nedostaci (čime se iz inačice u inačicu postizao viši stupanj kakvoće mreže šumskih cesta) ostvarilo se optimalno rješenje s inačicom D mreže šumskih cesta (slika 7 i tablica 1). Zbog raznolikosti terena, količine i strukture etata te raspoloživosti skidera pomoću linearnoga programiranja (LP) nastojao se povećati učinak (PMH) i ujedno smanjiti troškovi privlačenja. Kreirana je i karta kojom je utvrđen prostorni raspored i područje rada pojedinoga stroja, odnosno kombinacije strojeva (slika 8).

Planiranje šumskih prometnica (šumskih cesta i traktorskih vlaka) opisanom metodom uz primjenu GIS-a dobro je rješenje pri otvaranju neotvorenih ili slabo otvorenih šumskih područja gdje je, radi postizanja optimalne otvorenosti, potrebno izgraditi veću količinu šumskih prometnica. Metoda je također primjenjiva u onim šumskim područjima u kojima već postoji mreža šumske prometne infrastrukture, ali njezin prostorni razmještaj nije zadovoljavajući pa određene sastavnice mreže treba ukloniti, a nove izgraditi. Linearnim se programiranjem osigurava rasporedom strojeva za privlačenje drva bolja organizacija posla i učinkovitost strojeva.

Ključne riječi: *gustoća mreže šumskih cesta, raščlamba mreže šumskih prometnica, linearno programiranje, cestovni, troškovi pridobivanja drva, iranske šume*

Received (*Primljeno*): February 12, 2007
Accepted (*Prihvaćeno*): April 8, 2008

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