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GIS BASED METHODS FOR COMPUTING THE MEAN EXTRACTION DISTANCE AND ITS CORRECTION FACTORS IN ROMANIAN MOUNTAIN FORESTS

PRIMJENA RAZLIČITIH METODA PODRŽANIH GIS-OM PRI ODREĐIVANJU SREDNJE UDALJENOSTI PRIVLAČENJA DRVA I PRIPADAJUĆIH FAKTORA KOREKCIJE U PLANINSKIM ŠUMAMA RUMUNJSKE

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Summary

Extraction distance is an important factor used for locating new forest roads. Correction factors should be used for adapting theoretical models to real life situations. The aim of this study was to show how extraction distance and the correction factors can be computed and used for assessing forest road options in a more efficient and effective manner using process automation in GIS. The study was located in a mountain forest in the South Central Carpathians of Romania. For determining the mean extraction distance, 71.5 km of skid trails were tracked in the field and mapped in GIS. Four computing methods were defined: raster method, grid point method, buffer strips method and centre of gravity method. For testing and validating the methods, four infrastructure scenarios were defined: one was describing the existing forest infrastructure and three others were proposing new road options. Statistical analyses were performed for testing the accuracy and the possible differences between methods. The paired samples t-tests revealed significant differences between scenarios proposing new forest roads and the current infrastructure conditions. The raster method, the grid point method and the buffer strip method reported high accuracy for computing the mean extraction distance. This study reported an extraction correction factor (ks) value of 1.50 and a total correction factor (kt) value of 3.40 which can be used for rough calculations in practice. The automation models developed in GIS improved the efficiency of computations. The correction factors determined in this study were comparable with those reported in literature, highlighting the reliability of the analysed methods.

KEY WORDS: mean extraction distance, forest roads, road network planning, model, process automation, GIS.

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INTRODUCTION
UVOD

Skidder extraction is the most commonly used method for timber extraction in Romania. This is mainly due to the poorly developed forest road network, which hinders the efficient utilization of cable yarders and forwarders. Enhancement of forest infrastructure is prerequisite for the entire wood value added chain and should consider *a priori* a thorough qualitative and quantitative assessment of the existing road networks. But planning new roads should also consider the most suitable harvesting systems for local conditions (Kühmaier and Stampfer 2010). An important phase in this process is the calculation of the real mean extraction distance (Pentek et al. 2005). Since one of the most important parameters for the optimization of forest road networks is the minimization of the total costs of timber extraction (Ghaffariyan et al. 2010), the mean extraction distance can be used for determining the necessary length of new forest roads and their possible layout. For this purpose, an accurate determination of the extraction distance is required. Several studies highlight the necessity of using correction factors for adapting theoretical models to real life situations. Mathews (1942) first established the theoretical framework of forest openness. Segebaden (1964) addressed the relationship between the mean extraction distance and the road network density, introducing two factors for adjusting the ideal geometric model to the specific local conditions: the *road network correction factor* (V-corr or k_n) and the *extraction correction factor* (T-corr or k_s). Addressing several theoretical models of road networks, Lünzmann (1968) defined the coefficient of opening-up (k_t) also known as the *total correction factor*, highlighting the factors which influence its determination. Amzica (1967; 1971) stressed the necessity of accurate determination of k_s and k_n.

The importance of one sided versus two sided opening of forest areas and the buffer zone concept for computing the coefficient of openness were introduced by Backmund (1966). Lünzmann (1968) demonstrated the applicability of these concepts based on a cost minimization approach. Hentschel (1999) and Janowsky (2001) showed GIS approaches for comparing different methods for calculating structure indices of road networks, focusing on the optimization of road networks with multiple uses. Lotfalian et al. (2011) described a basic method for determining the correction factor used in the computation of the real mean extraction distance. Contreras and Chung (2011) showed a model for generating optimal skid-trail networks. Krč and Beguš (2013) elaborated a GIS based model for determining the necessary density of forest roads, while Enache et al. (2013) presented a multiple criteria decision support tool for bench marking forest road scenarios.

The aim of this study was to show how computation of the mean extraction distance and of the correction factors can be done more efficient and effective using process automation in GIS and how extraction distance can be used in the evaluation of forest road options.

MATERIALS AND METHODS
MATERIJALI I METODE

Study area – *Područje istraživanja*

This study was conducted in a 903 ha private forest located in the South-Central Carpathians of Romania, in Brasov county. The most common forest types in this area are: mountain beech forests on shallow soils with mull flora and mixed fir-beech forests with mull flora of medium productivity. The geology is marly-flysch, sandstones and massive conglomerates. The hydrological network has permanent water streams with peak flows in spring. One fifth of the study area is located on gentle slopes (<20%) and about 10% is steep terrain (slopes >55%). The annual allowable cut is about 4310 $m^3$and timber harvesting is performed by local contractors with skidders and tractors. Forest traffic infrastructure consists of 11.7 km of forest roads and 71.5 km of skid trails. The skid trails were mapped in GIS on foot, using a GPS Garmin 60 CSx GPSMAP at recording intervals of five seconds.

Computation of mean extraction distance and other structure indices – *Izračun srednje udaljenosti privlačenja drva i ostalih pokazatelja učinkovitosti mreže primarnih šumskih prometnica*

The most important structure indices of the forest traffic infrastructure are: *road density* or *road network density index* (RDI), *road distance* (RD), *mean extraction distance* (SD) and *relative openness* (O_R). Road density is the ratio between the length of the forest road network and the area of the served forest (Bereziuc 1981), while road distance is expressed in meters as the ratio between surface of 1 ha (in m^2) and the road density (Dietz et al. 1984). Segebaden's (1964) definitions of *geometric extraction distance* (i.e. the shortest straight line distance from a given point to the nearest road) and of the *mean extraction distance* (i.e. arithmetical mean of the geometric extraction distances) were used in this study. Relative openness is determined by dividing the opened forest area for the real mean extraction distance to the total forest area analysed (Pentek et al. 2005). For computing these indices, classical analytical methods and GIS methods were used. For testing if there were significant differences between methods, the results were statistically analysed in PASW® Statistics 18 SPSS.

Analytic methods – *Analitičke metode*

Computation of mean extraction distance – *Izračun srednje udaljenosti privlačenja drva*

The most commonly used definitions of the mean extraction distance are those proposed by Dietz et al. (1984): *theoretical mean extraction distance* (SD_0), *shortest mean extraction distance* (SD_s) and *real mean extraction distance* (SD_e), defining the *total correction factor* (k_t) as the product between the extraction correction factor and the network correction factor.

In Romania, Amzica (1967; 1971) highlighted the importance of considering the most suitable harvesting systems for local conditions for determining the optimum forest road density. Bereziuc (1980; 1981) approached the issue of forest road network optimization in correlation with the reduction of the mean extraction distance. Olteanu (1985) focused on the characteristics of the structure indices of the forest road networks in hilly regions of Romania, while Ciubotaru (1996) addressed the topic of extraction distance at the harvesting plot level. The following formulas gathered from literature were used inthis study, assuming that timber is extracted at the landing areas located at the road side, which is the most commonly used practice in Romanian forests:

(1) $SD_0 = \frac{RD}{4} = \frac{2500}{RDI}[m]$ (two side skidding – *dvostrano privlačenje*)

(2) $SD_0 = \frac{RD}{2} = \frac{5000}{RDI}[m]$ (one side skidding – *jednostrano privlačenje*)

(3) $SD_s = k_n \cdot SD_0 [m]$

(4) $SD_e = k_s \cdot SD_s [m]$

Ciubotaru (1996) and Pentek et al. (2005) used the *method of centre of gravity* for determining the real mean extraction distance ($\overline{SD_e}$), as a weighted arithmetical mean of the extraction distances from each centre of gravity of the forest management units to the closest forest road (SD_{ei}) and the allowable cut of timber (V_i) from each unit. Ciubotaru (1996) showed the role of sinuosity and elongation of skid trails for the accurate determination of real mean extraction distance, proposing the following formulas:

(5) $\mathrm{SD}_{0i} = \frac{SD_0}{\cos\alpha} \cdot k_{ss} \cdot k_{se} [\mathrm{m}]$

(6) $\mathrm{SD}_{ei} = k_t \cdot SD_{0i} [\mathrm{m}]$

(7) $\overline{\mathrm{SD}_e} = \frac{\sum (SD_{ei} \cdot V_i)}{\sum (V_i)} [\mathrm{m}]$

where: SD_{0i} – corrected extraction distance for management unit *i*, in *m*; SD_o – theoretical extraction distance measured on map, in *m*; α – average side slope in the management unit, in degrees; k_{ss} – coefficient of skid trail sinuosity; k_{se} – coefficient of skid trail path elongation; k_t – total correction factor.

Correction factors – *Faktori korekcije srednje udaljenosti privlačenja*

The network correction factor (k_n) reflects the adjustments owed to the geometry and unevenness of road layout, while the extraction correction factor (k_s) refers to the sinuosity and slope variation of the skid trail network (Segebaden 1964).

The influence of the skid trails layout on the determination of mean extraction distance is given by k_s, defined as the ratio between the real mean extraction distance and its orthogonal projection in the horizontal plane (Segebaden 1964; k_s=1.25–1.55). Amzica (1971) recommended k_s values of 1.30–1.75 for rough calculations depending on terrain topography.

The network correction factor (k_n) increases with the unevenness of the distribution of the roads and in theoretical models varies strongly with the geometric design of the road network (Segebaden 1964): 1.00 for ideal case (parallel roads with no intersections); 1.33 for road networks layouts in the shape of regular polygons; and 2.0 for random layouts of road networks. Segebaden (1964) recommended k_n values 1.60–1.70 for rough calculations, while Amzica (1971) reported values of k_n between 1.05 and 1.65.

The total correction factor k_t is given by the following formula (Lünzmann 1968):

(8) $k_t = k_n \cdot k_s = \frac{SD_e}{SD_0} = \frac{SD_e \cdot RDI}{2500}$

According to FAO (1974a), this factor ranges between: 1.6 –2.0 in flat areas, 2.0–2.8 in hilly areas, 2.8–3.6 in mountainous areas and above 3.6 for very steep mountain areas. In addition, FAO (1974b) introduced the *road efficiency factor* as the relationship between road density index (RDI) and the real mean extraction distance:

(9) $a = RDI \cdot SD_e$

where: a – *road efficiency factor* depending on terrain topography, with the following values: 4–5 for flat undulated terrain, 5–7 for hilly terrain, 7–9 for steep terrain and above 9 for very steep irregular terrain; SD_e – real mean extraction distance, in *km*.

GIS based methods for computing the mean extraction distance – *Metode izračuna srednje udaljenosti privlačenja utemeljene na GIS-u*

For computing the real mean extraction distance (SD_e) the *raster method* was defined. For determining the shortest mean extraction distance (SD_s) the *centres of gravity method*, the *grid point method* and the *buffer strips method* were defined. These methods were automated using *ESRI® ArcGIS Desktop 10* tools. Four traffic infrastructure scenarios were defined for the selected study area: scenario *Zero*, reflecting the current traffic infrastructure conditions; and scenarios

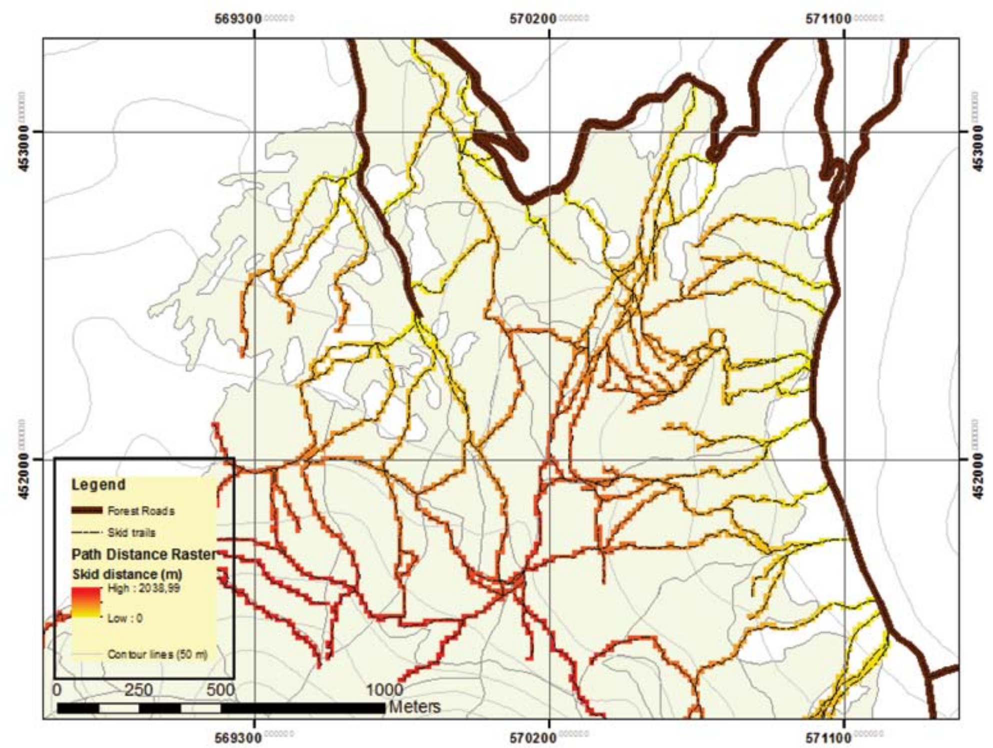

Figure 1 Skid trails raster with path distance allocation in scenario Zero

Slika 1. Udaljenost privlačenja drva za mrežu traktorskih putova u rasterskom obliku – scenarij nula

FR1, FR2 and *FR3* which propose new forest road options. The new forest roads were mapped in GIS considering the longitudinal gradient of the road, the terrain steepness, and the positive and negative cardinal points identified in the field survey, based on contour lines derived from a DEM with accuracy of 20 m.

Raster method – *Rasterska metoda*

This method assumes that all harvested timber is located on the skid trails. The skid trails were first converted from vector to raster format. The skid trail raster (with 12.5 m sized cells) was updated with altitudinal information obtained from the DEM. Using *Spatial Analyst Tools*™ in ESRI® ArcGIS, the least accumulative path distance for each cell of the skid trail raster to the nearest forest road were calculated (Figure 1), considering horizontal and vertical constraints (Equations 10 and 11). Each cell of the skid trail raster contains the slope distance to the nearest forest road, adjusted with the elongation occurred due to the sinuosity of the trail. The path distance from cell *a* to the adjacent cell *b* and the accumulative path distance from cell *a* to cell *c* were computed as follows (ESRI ArcGIS Resources 2013):

$$(10)\quad Cost_{distance} = \left(\frac{\left(Cost_{Surface(a)} \cdot Horizontal_{factor(a)}\right) + \left(Cost_{surface(b)} \cdot Horizontal_{factor(b)}\right)}{2}\right) \cdot Surface_{distance(ab)} \cdot Vertical_{factor(ab)}$$

$$(11)\quad Accum_{cost_{distance}} = a_1 + \left(\frac{\left(Cost_{Surface(b)} \cdot Horizontal_{factor(b)}\right) + \left(Cost_{surface(c)} \cdot Horizontal_{factor(c)}\right)}{2}\right) Surface_{distance(bc)} \cdot Vertical_{factor(bc)}$$

In case the movement from one cell to the adjacent cell was diagonal, *Equation (10)* was multiplied with $\sqrt{2}$. In *Equation (11)*, a_1 represents the path distance between the adjacent cells *a* and *b,* calculated with *Equation (10)*. The real mean extraction distance (SD_e) of the study area is given by the arithmetical mean of the values contained by each cell of the skid trail raster. Similarly, the minimum and maximum real extraction distances for all infrastructure scenarios were determined.

The automation of work flow processes was performed in *Model Builder*™, an extension of ESRI® ArcGIS which allows workflows to be combined in interactively linked sequences using DEMs, GIS datasets and results of previous calculations making calculations faster and easier (Allen 2011). Automation models were developed for all methods presented below.

Centres of gravity (*CGR*) method – *Težišna metoda (CGR)*

This method assumes that harvested timber is concentrated in the centres of gravity of each forest management unit (Ciubotaru 1996; Pentek et al. 2005). The extraction distance was calculated from these irregular located points to the nearest forest roads using *Analysis Tools*™ in ESRI® ArcGIS. The shortest mean extraction distance (SD_s) is the arithmetical mean of the values obtained for each forest management unit. The SD_s derived with this method was dependent on the extracted volume of timber and hence it was weighted with the volumes of the allowable cut from each forest stand.

Grid point method – *Metoda pravilne mreže točaka*

Segebaden (1964) introduced the concept of regular system of points for calculating the SD_s of a given area as the arithmetical mean of the shortest distances from each point of the grid system to the nearest forest road. The accuracy of this method depends on: the accuracy of measuring these distances, the number of points in the grid system and the size of the area. In this study, the project area is the same for all scenarios and the accuracy of distance measurement is extremely high due to vector format computations in GIS. Hence, the only factor influencing the accuracy is the number of points from each grid point set.

The SD_s was computed using five different sets of regular grid points for each infrastructure scenario, in order to determine which grid point set provides the most reliable results. The grid point sets were defined using *Data Management Tools*™ in ESRI® ArcGIS (Figure 2) and described rectangular cells of: 10x10 m (method *G10*), 50x50 m (*G50*), 100x100 m (*G100*), 500x500 m (*G500*), and 1000x1000 m (*G1000*), respectively. The shortest distances from each point of the grid to the closest forest road were calculated.

Automation of the grid point method focused on establishing the grid point sets and calculating simultaneously the SD_s for each scenario and grid point set. The model was created and executed using multiple inputs in *Batch processing* tool of Model Builder™. This tool allows choosing more input files or parameter values in order to create multiple outputs (Allen 2011). A list of the input datasets (e.g. traffic infrastructure scenarios) was compiled and used as a batch variable in the model for iterating through scenarios.

Buffer strips method – *Metoda omeđenih površina*

This method relies on the approach of Backmund (1966) and the method presented by Hentschel (1999). Buffer strips with a width of 100 m around the forest roads were established using automation models in GIS (Figure 3). The SD_s of a buffer strip was given by the distance from its me-

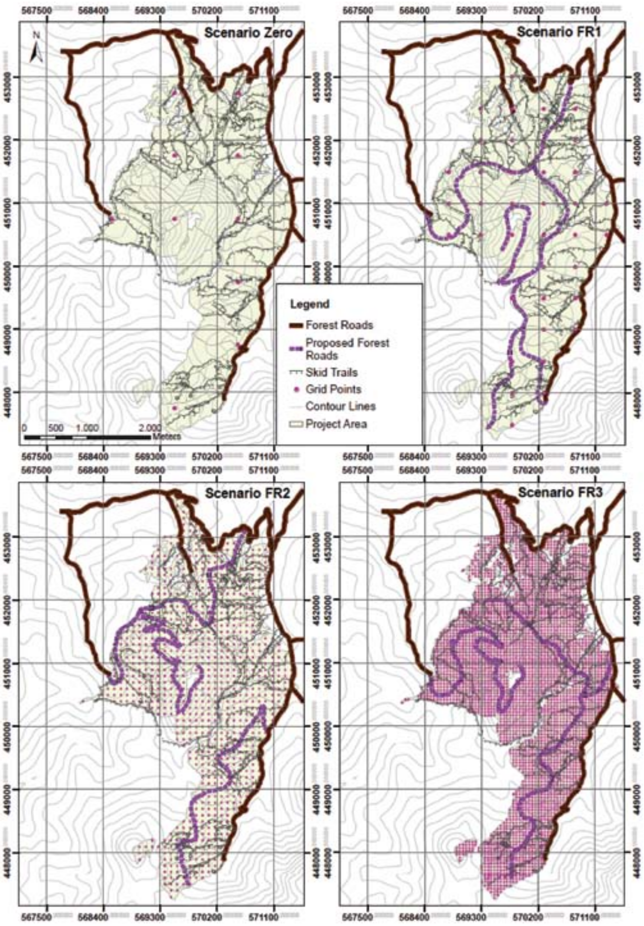

Figure 2 Examples of established grids of points

Slika 2. Primjeri uspostavljanja pravilne mreže točaka

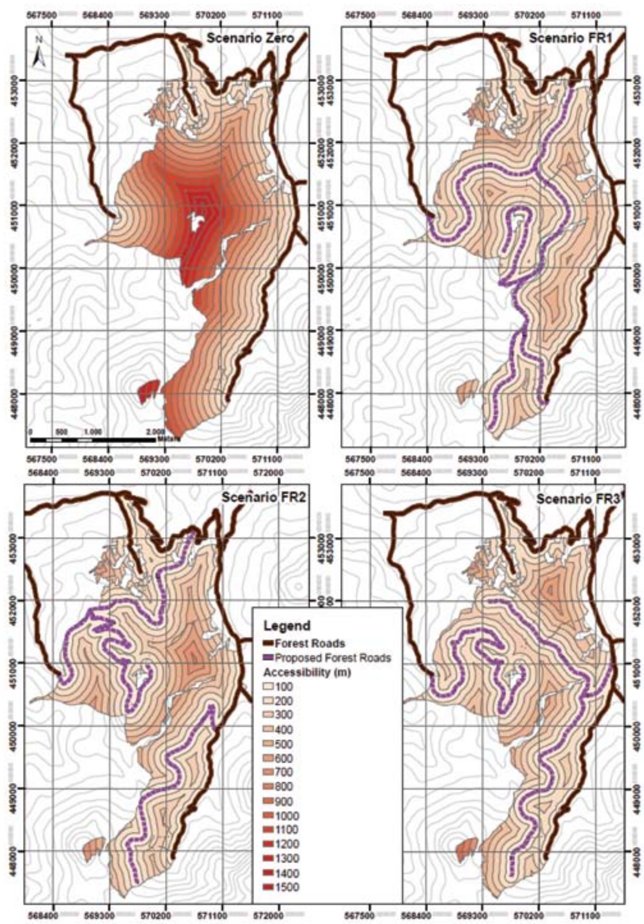

Figure 3 Example of buffer strips used for computing SD_s

Slika 3. Primjeri metode omeđenih površina pri izračunu geometrijske srednje udaljenosti privlačenja dian line to the nearest forest road. The mean SD_s of the study area is given by the sum of weighted SD_s of each buffer strip area. The following formula was used:

$$(12)\quad SD_{s\_buffer} = \sum_{i=1}^{n}\left(\left(W_{bs}\cdot(i-1)+\frac{W_{bs}}{2}\right)\cdot\frac{A_i}{A_t}\right)[m]$$

where: SD_{s_buffer} – shortest mean extraction distance of the study area, computed with the buffer method, in *m*; *i* – current buffer strip number; *n* – total number of buffer strips used in computations; W_{bs} – width of the buffer strip, in *m;* A_i – area covered by buffer strip *i*, in *ha*; A_t – total surface of the study area, in *ha*.

Computing correction factors – *Izračun faktora korekcije*

The *extraction correction factor* (k_s) was calculated as the ratio between SD_e determined with raster method and SD_s computed with the spatial methods. The *road network correction factor* (k_n) was computed separately for the assumptions of one sided and two sided timber extraction to forest roads. The following formulas were used:

$$(13)\quad a)\ k_s=\frac{SD_e}{SD_s}=\frac{\overline{Sd_{raster}}}{\overline{Sd_{grid}}};\quad b)\ k_s=\frac{\overline{Sd_{raster}}}{\overline{Sd_{gravity}}};\quad c)\ k_s=\frac{\overline{Sd_{raster}}}{\overline{Sd_{buffer}}}$$

$$(14)\quad a)\ k_n=\frac{SD_s}{SD_0}=\frac{\overline{Sd_{grid}}}{SD_0};\quad b)\ k_n=\frac{\overline{Sd_{gravity}}}{SD_0};\quad c)\ k_n=\frac{\overline{Sd_{buffer}}}{SD_0}$$

where: $\overline{Sd_{raster}}$ – is the SD_e computed with the raster method, in *m*; $\overline{Sd_{grid}}$ – is the SD_s computed with the grid point methods, in *m*; $\overline{Sd_{gravity}}$ – is the SD_s computed with CGR method, in *m*; $\overline{Sd_{buffer}}$ – is the SD_s computed with the buffer method, in *m*; SD_0– is the theoretical mean extraction distance, computed with the analytical method, in *m*.

The *total correction factor* (k_t) was computed with the following formula:

$$(15)\quad k_t=\frac{\overline{Sd_{raster}}}{SD_0}$$

Statistical and empiric analyses of the computation methods – *Statistička i empirijska analiza metoda izračuna srednje udaljenosti privlačenja*

For testing the possible differences between infrastructure scenarios in respect of SD_s values computed with the grid point methods, Student's *t*-test (Bühl 2010) was performed. The standard error (SE) for computing SD_s was determined and then compared to the preferred SE (which was set at 5%) in order to identify the accurate grid point methods. The minimum number of points required for a statistically sound determination of the SD_s was computed for a confidence interval (CI) of ±10% and precision of 5%, with the following formula:

$$(16)\quad n_p=\left(\frac{S_x}{\overline{S_x}}\right)^2=\left(t\cdot\frac{s_x}{CI}\right)^2$$

where: s_x – standard deviation of the SD_s; $\overline{S_x}$ – standard error of the SD_s; CI – confidence interval of the determination of SD_s; t – *t-value* distribution for α=5%.

Post-hoc analyses were performed in order to test if there were any significant differences between SD_s values computed with these methods. For homogenous variances Bonferroni's and Duncan's tests were carried out, while for non-homogenous variance the Tamhane-T2 test was performed (Backhaus et al.2011; Bühl 2010). For all tests, the significance level was set to 5%. Empiric analyses were performed between the grid point methods, the centre of gravity method and the buffer strips method. The necessary computation time for running the models was also determined. In this way the reliable computation methods were identified.

3 RESEARCH RESULTS
REZULTATI ISTRAŽIVANJA

Analytic methods – *Analitičke metode*

Table 1 reveals the structure indices computed with classical methods. A considerable reduction of the theoretical and real mean extraction distances as well as of the maximum extraction distance was reported in scenarios proposing new roads (FR1-FR3) compared to scenario ZERO.

GIS based methods – *Metode izračuna utemeljene na GIS-u*

The SD_s values are presented in Table 2 by computation method and analyzed scenario**.** The paired samples Student's *t*-tests revealed that SD_s in scenario Zero is significantly higher than scenarios FR1-FR3 due to the low road density (Table 3). Significant differences were reported between SD_s values in scenarios FR1 and FR3, respectively between scenarios FR2 and FR3. The extraction distance is one of the factors which influence the efficiency of forest operations. The economic, the environmental and the social aspects of timber harvesting depend on the extraction distance. Longer extraction distances generally lead to lower productivity, higher costs, higher energy input and higher strain on the machine operators (e.g. exposure to vibrations; Rottensteiner 2014).

Methods G100, G50 and G10 reported the highest accuracy in computing SD_s (Figure 4). Table 4 shows the minimum required number of points for computing SD_s varies between 151 and 245 (SE of 5%), respectively between 38 and 61 (SE of 10%), depending on scenario and grid point.

Table 1 Structure indices of the forest road network (analytic methods)
Tablica 1 Pokazatelji učinkovitosti primarne mreže šumskih prometnica (analitičke metode)

Structural indices – *Pokazatelji učinkovitosti*	Scenario – *Scenarij*			
	ZERO	FR1	FR2	FR3
Length of road network (m) *Duljina primarnih šumskih prometnica (m)*	11719	25795	25327	24501
Road density (m/ha) *Gustoća primarnih šumskih prometnica (m/ha)*	13.0	28.6	28.1	27.2
Road distance (m) *Razmak između primarnih šumskih prometnica (m)*	770.3	349.9	356.4	368.4
Theoretical mean extraction distance – SD_0 (m) (two sided opening) *Teorijska srednja udaljenost privlačenja – SD_0 (m) (dvostrano privlačenje)*	192.6	87.5	89.1	92.1
Theoretical mean extraction distance – SD_0 (m) (one sided opening) *Teorijska srednja udaljenost privlačenja – SD_0 (m) (jednostrano privlačenje)*	385.1	175.0	178.2	184.2
Real mean extraction distance – SD_e (m) (raster method) *Stvarna srednja udaljenost privlačenja – SD_e (m) (rasterska metoda)*	651.9	264.6	342.8	309.6
Maximum extraction distance – SD_{max}(m) (raster method) *Najveća udaljenost privlačenja – SD_{max}(m) (rasterska metoda)*	2039.0	1011.3	1481.5	1232.7
Road efficiency factor (a) *Faktor učinkovitosti mreže primarnih šumskih prometnica (a)*	8.04	8.10	7.05	6.34

Table 2 Values of SD_s by method and infrastructure scenario
Tablica 2. Vrijednosti geometrijske srednje udaljenosti privlačenja za različite metode i scenarije

Methods *Metode*		N *Broj*	Shortest mean extraction distance (SD_s), m *Geometrijska srednja udaljenost privlačenja, m*			
			ZERO	FR1	FR2	FR3
Grid point method *Metoda pravilne mreže točaka*	G1000	10	484.81	144.44	158.82	172.06
	G500	39	559.99	170.61	179.70	170.95
	G100	903	577.96	169.43	191.59	178.87
	G50	3601	579.02	169.87	191.80	178.97
	G10	90284	578.21	170.03	191.72	178.98
Buffer strips *Metoda omeđenih površina*		–	579.06	172.81	194.92	182.23
Centers of gravity *Težišna metoda*		81	571.02	193.61	174.99	167.88

Table 3 Paired samples t-test between scenarios in respect to SD_s
Tablica 3. T-test parova između različitih scenarija primarnog otvaranja šuma s obzirom na geometrijsku srednju udaljenost privlačenja

Pairs of scenarios *Parovi scenarija*	Paired Differences *Razlike između parova*			t	df	Sig. (2-tailed)
	Mean *Srednja vrijednost*	SD	SE			
ZERO – FR1	333.68	18.85	8.43	39.589	4	.000
ZERO – FR2	353.12	27.05	12.10	29.188	4	.000
ZERO – FR3	320.92	22.47	10.05	31.931	4	.000
FR1 – FR2	19.44	17.18	7.68	2.530	4	.065
FR1 – FR3	–12.76	6.56	2.93	–4.351	4	.012
FR2 – FR3	–32.20	11.38	5.09	–6.329	4	.003

SD_s – shortest mean extraction distance – *geometrijska srednja udaljenost privlačenja*
SD – standard deviation – *standardna devijacija*
SE – Std. Error Mean – *standardna pogreška*
Sig. (2-tailed) – *dvosmjerni test*

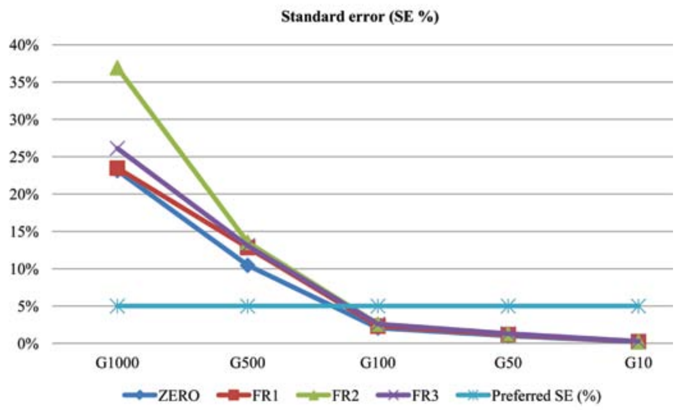

Figure 4 Standard error of computing the SD_s, by grid point method and scenario
Slika 4. Standardna pogreška izračuna srednje teorijske udaljenosti privlačenja za različite inačice metode pravilne mreže točaka i različite scenarije

Methods G1000 and G500 used less points than the minimum required, which means they are not accurate for computing SD_s in forest areas below 1000 ha. They can be used with precision results (SE 5%) for computing SD_s in forest areas of above 4500 ha.

The SD_s computed with methods G100, G50 and G10 homogenously clustered in only one subset (Table 5), which means these methods provide similar results. Method G100 is recommended for use in practice in forest areas of about 1000 ha, since it requires less computation time than methods G50 and G10.

Table 4 Required *Vs.* used number of points, by method and standard error (SE, %)

Tablica 4. Usporedba potrebnog i korištenog broja točaka izmjere pri određivanju teorijske srednje udaljenosti privlačenja za različite metode i standardnu pogrešku (SE, %)

Scenario *Scenarij*	Required N°. of points by method and preferred accuracy *Potreban broj točaka izmjere za različite metode rada i traženu točnost*										
	Method *Metoda*	G1000		G500		G100		G50		G10	
	SE (%)	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%
ZERO	–	214	54	171	43	153	38	151	38	152	38
FR1	–	220	55	257	64	195	49	197	49	198	49
FR2	–	546	136	286	72	243	61	244	61	245	61
FR3	–	273	68	267	67	242	61	243	61	244	61
Used N° of points *Korišteni broj točaka*		10		39		903		3601		90284	

Table 5 Duncan's test between the most accurate grid point methods

Tablica 5. Duncan-ov test između najtočnijih inačica metode pravilne mreže točaka

	Grid point method variants *Inačice metode pravilne mreže točaka*	N *Broj točaka*	Subsets by infrastructure scenario *Podskupovi prema scenarijima primarnog otvaranja*			
			ZERO	FR1	FR2	FR3
			1	1	1	1
Duncan[a,b]	G100	903	577.96	169.43	191.59	178.87
	G50	3601	579.01	169.87	191.80	178.97
	G10	90284	578.21	170.03	191.72	178.98
	Sig.		0.928	0.877	0.966	0.981

a. Uses Harmonic Mean Sample Size = 2148.695 b. Alpha = 0.05.

a. Uz korištenje harmonijske srednje veličine uzorka = 2148,695 *b. Alfa vrijednost = 0,05*

Table 6 reveals that buffer strips method has a general tendency of slightly over estimating the SD_s values reported by the grid point methods, while the CGR method has a tendency of under estimating these values. The buffer strip method is more accurate than the CGR method and hence is recommended for use in practice.

Correction factors – *Faktori korekcije*

The extraction coefficient (k_s) is a good qualitative indicator of the skid trail network. When k_s values are closer to 1 (ideal case), the skid trails are straighter and have lower gradients. This study reported k_s values between 1.13 and 2.16 (Table 7). Considering that methods G100, G50 and G10 are within the established accuracy threshold, the statistically sound values of k_s vary between 1.13 and 1.79 and an average value of 1.50 is recommended for use in practice. This is similar to previous literature findings (Amzica 1971; Bereziuc1981) regarding mountain forests in Romania (Table 9).

In respect to the *network correction factor* (k_n), in the hypothesis of a two sided opening of the studied forest area (Table 8), the values reported by scenario Zero vary between 2.52 and 3.01. These values are considerably higher than those reported in literature (Table 9). This situation reflects the current uneven distribution of the roads in the studied forest area. In scenarios proposing new roads (FR1 to FR3), k_n values are lower (from 1.65 to 2.15). This means an improvement of the location and spatial distribution of the roads within the new forest road network. The hypothesis of one sided opening of forests seems to better explain the current infrastructure conditions (scenario Zero), k_n values ranging between 1.26 and 1.50 (Table 8). This explains the current practices in the study area where all harvested timber is extracted downhill to the existing valley roads located at the edge of the forest area. Scenarios FR1, FR2 and FR3 are closer to the ideal model for one sided timber extraction, with values of k_n between 0.97 and 1.08 (methods G100, G50 and G10). This situation can be interpreted as close to optimum located forest roads in the ideal theoreti-

Table 6 Difference in percentage between SD_s values computed with buffer strips method and CGR method, versus grid point methods

Tablica 6. Postotne razlike između geometrijske srednje udaljenosti privlačenja određene metodom omeđenih površina i težišnom metodom u odnosu na različite inačice metode pravilne mreže točaka

Infrastructure Scenario *Scenarij primarnog otvaranja šuma*	Buffer strips method Vs. … *Metoda omeđenih površina u usporedbi s …*			CGR method Vs. … *Težišna metoda u usporedbi s …*		
	G100	G50	G10	G100	G50	G10
ZERO	0.2%	0.0%	0.1%	–1.2%	–1.4%	–1.2%
FR1	2.0%	1.7%	1.6%	14.3%	14.0%	13.9%
FR2	1.7%	1.6%	1.7%	–8.7%	–8.8%	–8.7%
FR3	1.9%	1.8%	1.8%	–6.1%	–6.2%	–6.2%

Table 7 Values of extraction correction factor (k_s) by method and scenario

Tablica 7. Vrijednosti korekcijskog faktora privlačenja (k_s) prema metodi izračuna teorijske srednje udaljenosti privlačenja i scenariju primarnog otvaranja

Infrastructure Scenario *Scenarij primarnog otvaranja šuma*	Extraction correction factor (k_s) *Korekcijski faktor privlačenja (k_s)*						
	CGR *Težišna metoda*	Grid point method (variants) *Metoda pravilne mreže točaka (inačice)*					Buffer method *Metoda omeđenih površina*
		G1000	G500	G100	G50	G10	
ZERO	1.14	1.34	1.16	1.13	1.13	1.13	1.13
FR1	1.37	1.83	1.55	1.56	1.56	1.56	1.53
FR2	1.96	2.16	1.91	1.79	1.79	1.79	1.76
FR3	1.84	1.80	1.81	1.73	1.73	1.73	1.70

Table 8 Values of k_n and k_t, by computation method and infrastructure scenario
Tablica 8. Vrijednosti mrežnog korekcijskog faktora (k_n) i ukupnog korekcijskog faktora (k_t) prema metodi izračuna teorijske srednje udaljenosti privlačenja i scenariju primarnog otvaranja

Infrastructure Scenario *Scenarij primarnog otvaranja šuma*		k_t	k_n by method *k_n prema metodi izračuna*						
		Raster method *Rasterska metoda*	CGR *Težišna metoda*	Grid point method (variants) *Metoda pravilne mreže točaka (inačice)*					Buffer method *Metoda omeđenih površina*
				G1000	G500	G100	G50	G10	
ZERO	Two sided opening *Dvostrano privlačenje*	3.39	2.97	2.52	2.91	3.00	3.01	3.00	3.01
FR1		3.02	2.21	1.65	1.95	1.94	1.94	1.94	1.98
FR2		3.85	1.96	1.78	2.02	2.15	2.15	2.15	2.19
FR3		3.36	1.82	1.87	1.86	1.94	1.94	1.94	1.98
ZERO	One sided opening *Jednostrano privlačenje*	1.69	1.48	1.26	1.45	1.50	1.50	1.50	1.50
FR1		1.51	1.11	0.83	0.98	0.97	0.97	0.97	0.99
FR2		1.92	0.98	0.89	1.01	1.08	1.08	1.08	1.09
FR3		1.68	0.91	0.93	0.93	0.97	0.97	0.97	0.99

Table 9 Comparison of computed correction factors, a literature review
Tablica 9. Usporedba izračunatih faktora korekcije srednje udaljenosti privlačenja i literaturnih podataka

Correction factors *Korekcijski faktori*	Computed values *Izračunate vrijednosti*	Segebaden (1964)	Lünzmann (1968)	Amzica (1971)	FAO (1974)	Olteanu (1985)
k_s *Korekcijski faktor privlačenja*	1.13–1.79	1.00–1.83	–	1.30–1.75	–	–
k_n *Mrežni korekcijski faktor*	1.94–3.01	1.24–2.14	0.98–2.00	1.05–1.65	–	–
k_t *Ukupni korekcijski faktor*	3.02–3.85	–	–	–	2.8–3.6**	3.61–4.84*
a *Faktor učinkovitosti mreže primarnih šumskih prometnica*	6.34–8.10	–	–	–	5–7*; 7–9**	–

* hilly region – *brdsko područje*,
** mountainous regions and steep terrain – *planinsko područje i strmi tereni*.

cal case and in the hypothesis of downhill timber extraction to the closest forest road and no uphill extraction.

This study reported k_t values between 3.02 and 3.85 (Table 8), recommending k_t is 3.40 for rough calculations. These values are similar to those reported by FAO (1974a) for hilly and mountainous regions (Table 9). In turn, they differ from the findings of Olteanu (1985) which reported higher values of k_t (from 3.61 to 4.84) for forests located in hilly regions. This can be explained by the fact that when determining the k_t, Olteanu (1985) also considered the fragmentation degree of the forest stands. This is the specific case of Romanian forests from hilly regions; due to the high degree of forest fragmentation, in order to serve more stands, forest roads are in general located outside the forest areas. The values of *road efficiency factor „a"* ranged between 6.34 (scenario FR3) and 8.10 (scenario FR1), similar to what FAO (1974b) reported for hilly areas and steep terrain (Table 9). Since in this study k_t was determined based on SD_e values computed with the raster method, it can be concluded that the *raster method* can be used for a sound determination of the real mean extraction distance.

4 DISCUSSIONS AND CONCLUSIONS
RASPRAVA I ZAKLJUČCI

This study presented several methods for computing the mean extraction distance using spatial analyses and process automation in GIS. The correction factors (k_s, k_n and k_t) for adjusting the theoretical models to the real cases were determined. They were comparable with the values reported in literature and they can be used by practitioners in forest areas similar to this study. This could be the case of forest areas where skidding and forwarding are most commonly used in timber extraction. The raster method is recommended for the computation of SD_e, while the grid point method G100 and the buffer strip method are recommended for computation of SD_s in forest areas of up to 1000 ha. For larger areas, grid point methods G500 or G1000 are recommended.

This study also showed that both buffer strip method and grid point methods can be efficiently used in computing SD_s with high accuracy, which is similar to the empirical results of Janowsky (2001) and opposite to what Hentschel (1999) found, which suggested a buffer method is more proper in this respect than Segebaden's (1964) grid point approach. DEMs and DTMs derived with state of the art remote sensing techniques (e.g. LIDAR) should be used for accurately mapping skid trails and forest roads (White et al. 2010). The data can be used in conjunction with GIS based tools, such as the methods presented in this study, for a more efficient and reliable assessment of primary and secondary forest traffic infrastructure.

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Sažetak

U Rumunjskoj se, zbog loše razvijene mreže primarne šumske prometne infrastrukture (šumskih cesta i onih javnih cesta, pretežno nižih kategorija, koje se mogu koristiti pri radovima u šumarstvu), u fazi privlačenja drva najčešće koriste skideri. Zbog male je gustoće primarnih šumskih prometnica primjena forvrdera za privlačenje drva izvoženjem, odnosno šumskih žičara za privlačenje drva iznošenjem, vrlo rijetka. Smanjivanjem udaljenosti privlačenja drva, što je jedna od važnijih zadaća novo planiranih, projektiranih i izgrađenih šumskih cesta, smanjuju se i troškovi privlačenja drva.

Stoga je srednja udaljenost privlačenja drva jedan od temeljnih parametar procjene kvalitete i kvantitete postojeće mreže primarnih šumskih prometnica ali i parametar koji se koristi pri daljnjem razvoju i optimizaciji primarnog šumskog transportnog sustava, odnosno na osnovu kojega se, uz ostale dodatne kriterije (parametre), obavlja odabir između više inačica primarnog otvaranja šuma (mreže šumskih cesta) ili pojedinih idejnih trasa šumskih cesta te odabiru najbolje.

Srednja se udaljenost privlačenja drva može odrediti različitim metodama rada, a u novije se vrijeme velika većina suvremenih metoda bazira na primjeni GIS tehnologija. Dietz i dr. (1984.) daju najčešće korištene definicije srednje udaljenosti privlačenja drva i definiraju tri inačice srednje udaljenosti privlačenja drva: teorijsku, geometrijsku i stvarnu udaljenost privlačenja drva, te sveukupni korekcijski faktor, koji u sebi objedinjuje mrežni korekcijski faktor i korekcijski faktor privlačenja drva (prethodno definirane po Segebaden-u (1964.)), a služi za izravnu pretvorbu teorijske u stvarnu srednju udaljenost privlačenja drva.

Osnovni je cilj istraživanja dokazati kako se parametar srednje udaljenosti privlačenja, uz primjenu suvremenih tehnologija rada (GIS) te poznatih i novo razvijenih metoda i postupaka, ali i uz automatizaciju kompletnog postupka, može vrlo učinkovito koristiti pri ocjeni različitih inačica unapređenja postojeće mreže primarnih šumskih prometnica u postupku njene optimizacije, te pri određivanju prije navedenih korekcijskih faktora srednje udaljenosti privlačenja drva.

Istraživanje je provedeno u rumunjskim privatnim šumama smještenima u jugo-centralnim Karpatima regije Braşov, na površini od 903 ha. Radi se o bukovim planinskim šumama srednjega boniteta na plitkome tlu i nagnutim terenima. Godišnji je etat oko 4310 m^3, a privlačenje drva se obavlja skiderima i adaptiranim poljoprivrednim traktorima. Oko 20 % površine istraživanog područja ima blagi nagib terena (<20%), a oko 10 % se nalazi na vrlo strmom terenu (>55%). Mreža stalnih vodotoka je vrlo razvijena. Šumska se prometna infrastruktura sastoji od 11,7 km šumskih cesta te 71,5 km traktorskih putova (koji su snimljeni GPS uređajem Garmin 60 CSx GPSMAP te je, uz postojeći katastar primarnih, formiran katastar sekundarnih šumskih prometnica).

Za određivanje teorijske, geometrijske i stvarne srednje udaljenosti privlačenja su korištene četiri metode rada podržane GIS-om: rasterska metoda, metoda pravilne mreže točaka (sa pet veličina otvora mreže predstavljene inačicama: G10, G50, G100, G500 i G1000, gdje svaki broj iza slova G predstavlja razmak između točaka iskazan u metrima), metoda omeđenih površina i težišna metoda (CGR). Za testiranje, međusobnu usporedbu i ocjenu korištenih metoda izrađena su četiri scenarija optimizacije mreže primarnih šumskih prometnica. Prvi scenarij (*Zero*) predstavlja postojeće stanje, a ostala tri scenarija (*FR1, FR2 i FR3*) unapređenje postojeće primarne šumske prometne infrastrukture sa ciljem njihove optimizacije. Uz srednju udaljenost privlačenja drva, za svaki su scenarij određene najveća i najmanja udaljenost privlačenja te razmak između šumskih cesta.

Automatizacija postupka izračuna je izrađena u aplikaciji *Model Builder*™ *(ESRI® ArcGIS)* uz uporabu digitalnog modela terena (*DTM*). Alat *„Batch processing“* iz aplikacije *Model Builder*™ je korišten za odabir većeg broja ulaznih datoteka i kreiranja višestrukih rezultata. Provedena je statistička analiza između četiri metode rada korištene pri određivanju parametra srednje udaljenosti privlačenja drva. T-test parova ukazuje na statistički značajnu razliku između triju predloženih inačica optimizacije primarnog šumskog transportnog sustava i postojećeg stanja primarne šumske prometne infrastrukture.

Rasterska metoda, metoda pravilne mreže točaka i metoda omeđenih površina su visoko točne metode za određivanje srednje udaljenosti privlačenja drva. Inačice metode pravilne mreže točaka G100, G50 i G10 su najtočnije metode za izračun korekcijskog faktora privlačenja drva (k_s) (koji se koristi pri pretvorbi geometrijske u stvarnu srednju udaljenost privlačenja drva). Metoda pravilne mreže točaka G100 se preporuča za operativnu primjenu u šumskim kompleksima od oko 1000 ha i većima. Rasterska se metoda izračuna sugerira za određivanje stvarne inačice srednje udaljenosti privlačenja drva (SD_e).

Na istraživanom je području određena vrijednost korekcijskog faktora privlačenja drva u rasponu od 1,13 do 1,79, sa srednjom vrijednošću od 1,50 koja se predlaže za uporabu u operativnom šumarstvu. Mrežni korekcijski faktor istraživanog područja (k_n) poprima vrijednosti u intervalu 1,65 – 2,15, uz pretpostavku da se scenarijima unapređenja postojeće mreže primarnih šumskih prometnica planiraju šumske ceste koje će čitavom svojom duljinom šumu otvarati obostrano. Sveukupni korekcijski faktor (k_t) na području istraživanja poprima vrijednosti između 3,02 i 3,85, a šumari u praktičnom šumarstvu se upućuju na vrijednost od 3,40.

Automatizirani model razvijen u GIS-u, a korišten pri izračunu srednje udaljenosti privlačenja drva, pripadajućih korekcijskih faktora i različitih inačica unapređenja postojeće mreže primarnih šumskih prometnica, doprinosi povećanju učinkovitost i točnosti dosadašnjih izračuna navedenih parametara. Vrijednosti korekcijskih faktora srednje udaljenosti privlačenja drva su vrlo slične literaturnim vrijednostima korekcijskih faktora dobivenim dosadašnjim istraživanjima u usporedivim reljefnim područjima. To ukazuje na moguću i preporučljivu primjenjivost rezultata istraživanja u operativnome šumarstvu.

KLJUČNE RIJEČI: srednja udaljenost privlačenja drva, šumske ceste, planiranje mreže šumskih cesta, model, automatizacija procesa, GIS