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Evaluation of Morphometric Terrain Parameters and Their Influence on Determining Optimal Density of Primary Forest Road Network

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Abstract

Planning forest truck roads network involves a lot of factors that directly affect their density and length. Depending on the purpose of the forest truck road network, this number is higher or lower. Our opinion was that these factors should be divided into invariable and variable. Common parameters, regardless of the purpose of the roads, are morphometric parameters because they can limit the length and density of the network of forest truck roads due to their variety of forms. For this reason, this paper deals exclusively with the morphometric characteristics of the terrain and their influence on the density of the network of forest truck roads. The DEM of the terrain was processed with GIS software based on the seven most important influencing factors. By standardizing the criteria, the obtained maps were reclassified, and then each of the seven selected parameters was weighted with the coefficients obtained by the AHP method.

In this way, a map of the suitability of the terrain for the construction and addition to the existing network of forest truck roads was obtained. The terrain is divided into 4 categories of suitability. Zero lines were drawn with GIS tools for road design. During the creation of the optimal road network, it was tested with absolute and relative openness.

As a final result, each of 26 Forest Economic Areas (FEA) was assigned to one of 4 categories of terrain suitability for the construction and density of the forest truck road network. For each category of terrain convenience, the optimal absolute and relative openness is shown. Based on this work, we suggest that the use of morphometric parameters should be considered as the first step of forest road planning in other regions.

Keywords: AHP, geomorphometry, GIS, forest roads, optimization

1. Introduction

An efficient road network has been the backbone of forestry, the design of which is based on fundamental principles. Those principles have been changing in time due to scientific advancements and due to the evolution in both off-road and on-road transportation technology (Heinimann 2017). Forest roads are planned, designed and built infrastructure facilities whose spatial and design solution depends on the shape of the terrain, purpose of the forest, and habitat and stand conditions of the forest ecosystem (Stefanović et al. 2016). Planning of forest accessibility includes the determination of optimal forest accessibility, which is expressed by an optimal density of forest roads or optimal road spacing. The optimal density of forest roads should ensure more rational, more complete and more successful forest management with minimal impact on the environment (Pentek et al. 2005). In previous research, one of the most common findings was that determining the optimal density of a road network is a demanding and complex problem influenced by a very large number of impact factors (Pičman 1994, Abdi et al. 2009, Pentek et al. 2011, Stojnić 2019) that act independently or in correlation with other relevant factors. Road density is the number of linear meters of road per hectare (m/ha). Many studies of forest openness were based on the FAO model (1998), which included only economic factors (wood volume, cost of road construction, felling volume). According to that model, the recommended density in hilly regions is 7 to 10 m/ha of forest truck roads and 15 to 25 m/ha in steep terrain. In Croatia, the minimum required current density of forest truck roads in lowland regions should be 7 m/ha, in hilly regions 12 m/ha and in mountain regions 15 m/ha (Pentek et al. 2011).

The subjectivity of experts had a great influence on such a classification because there were no clear qualitative indicators, especially for terrain roughness. Referring to the research of Košir (1982), Pičman (1994) divided the impact factors in their simplest form into invariable and variable ones. According to this author, the invariable factors are: slope, parent rock, soil properties, terrain configuration, erodibility, altitude, etc., whereas the variable ones are: forest openness toward forest roads, transport distance, stand shape, wood volume, increment, felling volume, type of cut, etc. Numerous previous studies on this issue emphasize the importance of terrain and its impact on the size of the optimal density of a road network (Ghaffarian and Sobhani 2007, Freitas et al. 2009, Danilović et al. 2013). Tičerić (1989) also recognized the configuration of the terrain as a relevant factor for determining the density of the road network, but at that time he stated that this factor could not have been directly expressed.

The notion of the optimal density of a forest road network is quite relative because it cannot be exactly determined so that the obtained result can be valid forever (Aćimovski 1997). Many domestic and foreign authors have dealt with the problem of optimizing the network of forest truck roads, and the slope is one of the main impact factors for the classification of terrain configuration and its impact on the density of a forest truck road network (Samani and Hosseiny 2010, Norizah and Mohd Kasmadi 2012). This work can help experts to know in advance how many more roads they need to build to reach the optimum in similar terrain morphometric characteristics.

The research objectives of this paper refer to the planning of the forest truck road network depending on the complexity of the terrain:

⇒ to show a more precise evaluation of the terrain concerning the previous traditional and rough geographical division of the terrain into lowlands, hills and mountains

⇒ based on the newly obtained division, to express the values of forest openness for each category of terrain suitability for the construction and optimization of the forest truck road network.

2. Materials and Methods

2.1 Research Area

The research was conducted in the territory of the Republic of Srpska, one of the two entities in Bosnia and Herzegovina (Fig. 1).

According to the Cadastre of Forests (PFE 2017), the total area of forests and forest land owned by the Republic of Srpska is 1,011,230.01 ha. Forests and forest land owned by the Republic of Srpska are managed by the Public Enterprise »Šume Republike Srpske« a.d. Sokolac, within 26 Forest Economic Areas (FEAs) without the Brčko District. We analyzed an area of 843,466.00 hectares. Other areas (National parks, кarst area) are not included in the analysis, because forests and forest land in this region have different purposes, which could have an impact on the results.

The forest road data were collected using Garmin Oregon 600 GPS devices across the entire territory of state forests, managed by the Public Enterprise »Šume Republike Srpske«, and the recorded traces were compared and corrected by orthophoto snapshots with a 0.50 m resolution. The total length of forest truck roads is 7825.57 km. Assessment of the suitability of the terrain of Forest Economic Areas (FEAs) for the

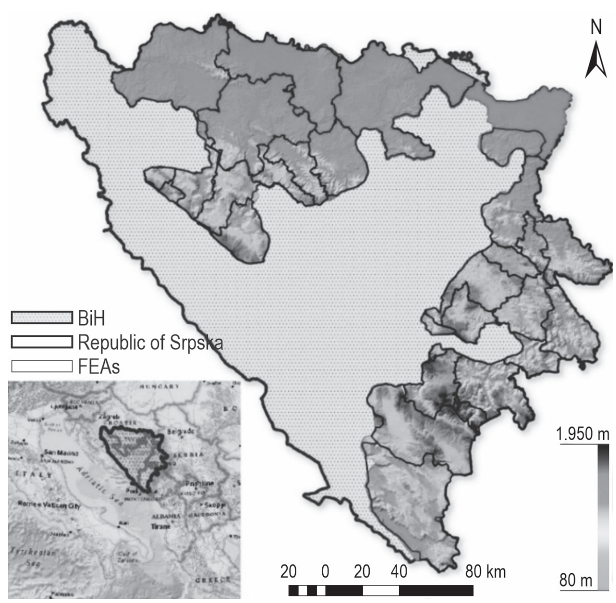

Fig. 1 A map of forest – economic areas in the Republic of Srpska

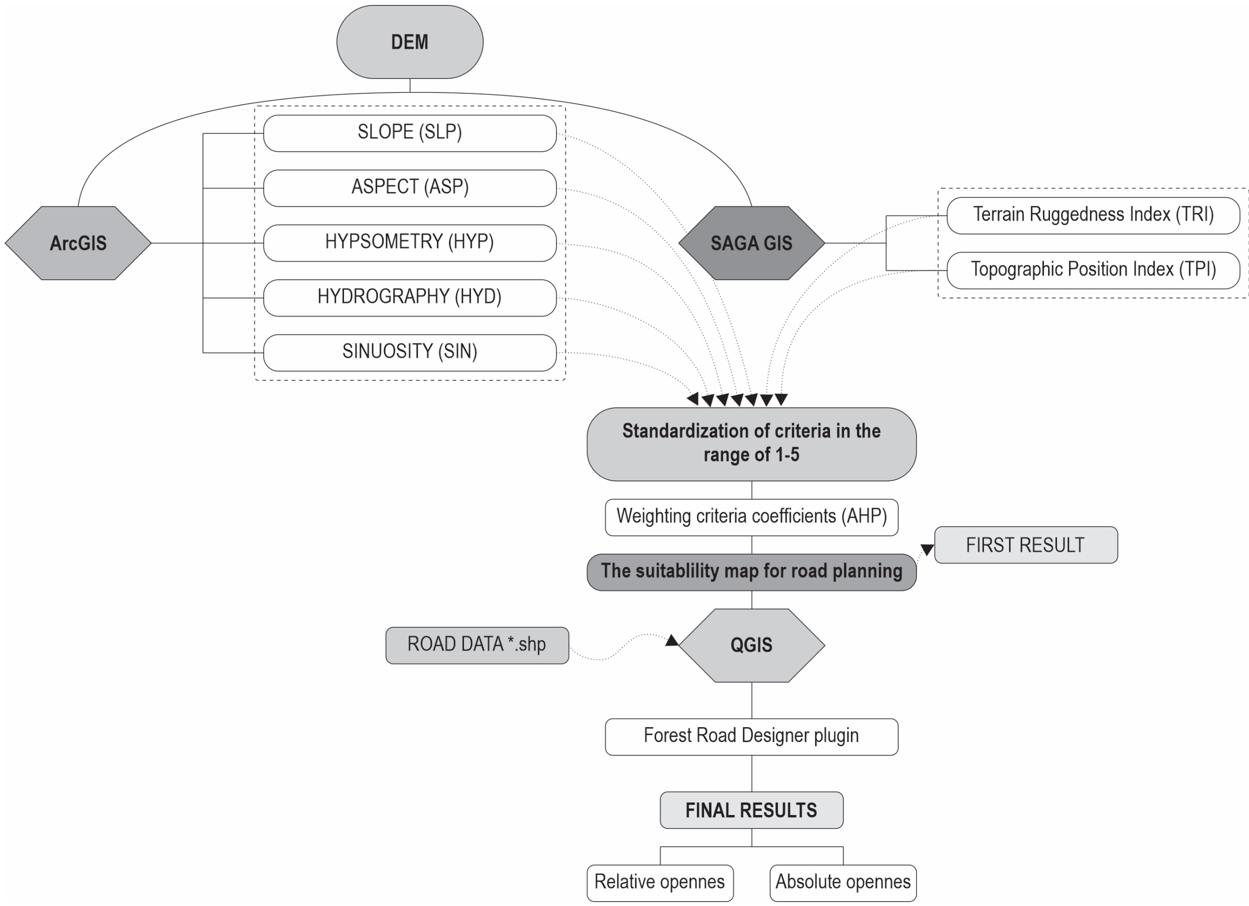

Fig. 2 Schematic representation of data process flowchart

construction of forest truck roads was performed using GIS software in combination with the analytical hierarchical process (AHP), as a method of multi-criteria decision making. A digital elevation model (DEM) with a resolution of 20x20 m in the SAGA GIS, ArcGIS and QGIS software environments was used for geoprocessing. The input parameters based on which the terrain was evaluated were: topographic position index (TPI), terrain ruggedness index (TRI), slope (SLP), hypsometry (HYP), hydrography (HYD), sinuosity (SIN) and aspect (ASP).

The length of forest roads was calculated according to the following criteria. The entire length was taken into account for roads that pass through forest land.

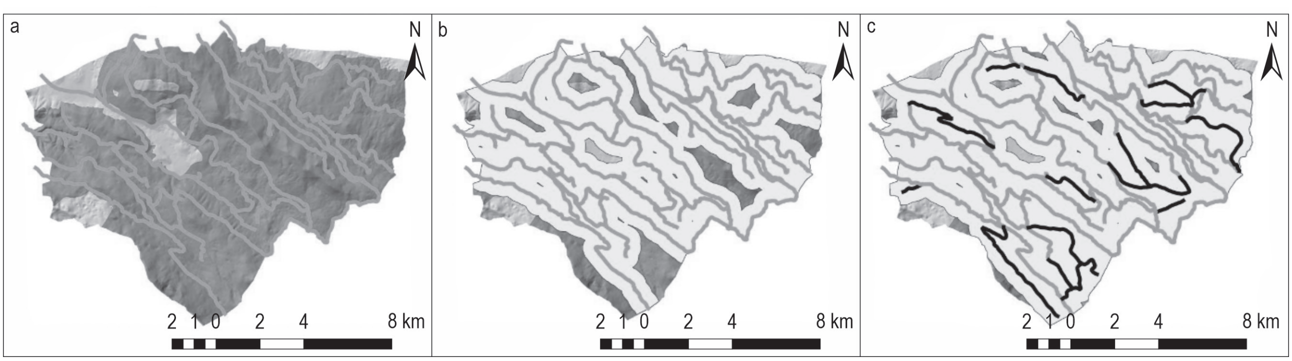

Fig. 3 (a) existing forest road network; (b) – existing forest road buffer zones; (c) – network of forest roads with buffer zones to full openness for one FEA

Half the length of the road was taken into account for roads that go to the edge of forest land or up to 300 m from the edge of forest land provided that they can be used for transport. In addition, roads coming perpendicular to the forest land were considered in the length of up to 500 m (Šikić et al. 1989). (Fig. 3a). The tool used to supplement the existing road network was the Forest Road Designer plugin in the QGIS environment. During the analysis, the spatial arrangement of forest truck roads included an average skidding 3D distance of 300 m and a 3D buffer zone of 600 m. The designed roads were also tested for relative openness to fill the unopened spaces in the most efficient way (Figure 3b). 3D distance is the length of a path along a 3D surface.

The absolute openness of the network of forest roads was calculated using the formula:

$$RD = \frac{L}{A} \tag{1}$$

Where:

RD density of the forest roads network, m/ha
L calculation length of forest roads
A area.

Relative openness shows the percentage share of the open area in the ratio to the total area of the analyzed economic area. Relative openness is calculated using the buffer zone method, which is at an average skidding 3D distance of 300 m and a 3D buffer zone of 600 m on both sides of the forest roads.

The relative openness of the forest road network was calculated using the formula:

$$R_0 = \frac{A_0}{A_t} \tag{2}$$

Where:

R_O relative openness, %
A_O opened area
A_t total area.

A Path Distance algorithm was used in the ArcMAP 10 software to determine the average skidding distance. This distance is the length of a path along a 3D surface.

The Euclidean distance tools describe each cell's relationship to a source or a set of sources based on the straight line distance. Path distance was calculated for each cell to the nearest road, while accounting for surface distance and horizontal and vertical factors (terrain slope).

To determine the density of a network of forest truck roads, the classification of FEAs according to a set of morphometric criteria was performed.

Given the size of the study area, this research did not include an analysis of the impact of economic, environmental and social factors on the assessment of the area suitability and establishment of the optimal density of a primary forest road network. The paper is based exclusively on the evaluation of terrain characteristics of the area to assess the terrain suitability for the construction and development of a network of forest truck roads. This paper aims to show how and

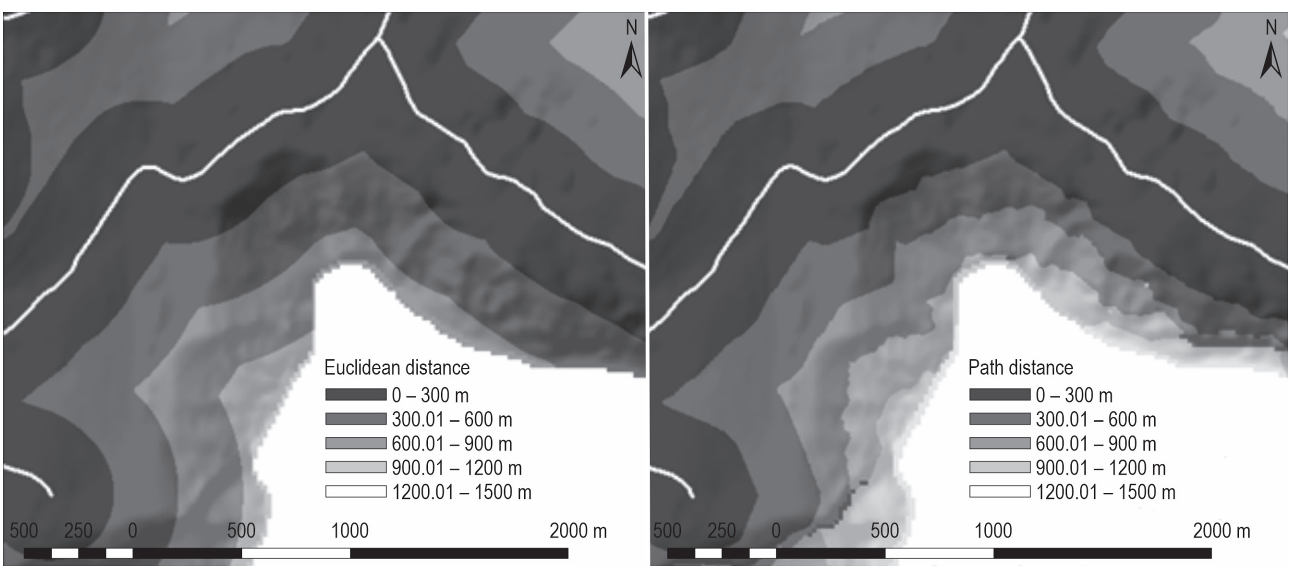

Fig. 4 Difference between Euclidean and Path distance

to what extent terrain configuration affects the density of a forest truck road network. In addition, unopened or insufficiently opened areas can be categorized according to similar terrain characteristics classified in this paper.

2.2 Morphometric Parameters

The field of science dealing with terrain forms and their classification is called geomorphology. Unlike morphography and morphogenesis, as an integral part of geomorphology, morphometry is a quantitative determination of general parameters: hypsometry, slope, terrain ruggedness (terrain energy), aspect, and specific parameters that imply isolated terrain forms (e.g. ridge, sinks, drainage network, etc.).

Geomorphology is a scientific discipline that deals with the study of the origin, evolution and dynamics of the Earth's relief (Pike et al. 2009). It is an analytical – cartographic approach to the study of topographic features of the Earth as well as an interdisciplinary field derived mostly from mathematics, natural sciences and informatics (Radoš et al. 2012).

Slope (SLP) is considered to be the most important morphometric parameter used for more efficient terrain analysis and description (Šiljeg 2013). The classification of space is divided into three categories: 0–40%, 40–70%, and over 70% slope. When planning the development of forest roads, the importance of slope is huge, since it directly affects the scope of earthworks and the size and stability of cut slopes and embankments, and thus the cost of construction and maintenance of forest roads.

The Topographic Position Index (TPI) is a terrain classification algorithm developed by Andrew Weiss (2001) and later supplemented and programmed by Jeff Jennes (2006, 2013) as a computer extension for ArcGIS. TPI is the difference between the altitude (elevation) of a cell (pixel) and the average altitude of the cells in the neighborhood. It is desirable to develop a network of roads in all possible directions. This classification of terrain differentiates the areas that limit road network development.

Terrain Ruggedness Index (TRI), or ruggedness – roughness or terrain energy, is a term used to describe how »irregular« an area is. It is used to model natural threats, e.g. avalanches (Margreth and Funk 1999), rockiness (Dorren and Heuvelink 2004), and floods (Govers et al. 2000). In the past, Terrain Ruggedness Index was mostly used for ecological monitoring and not for the planning of operations in timber harvesting (Đuka et al. 2015). TRI is a morphometric terrain parameter that represents the difference in height between the lowest and highest points in the observed area (Lozić 1996). In this paper, TRI is calculated for each cell in the DMT network by calculating the sum of height changes between the central cell of the network and the mean of the 8 adjacent cells (Riley et al. 1999). TRI shows the space through which the road network may or may not develop in the longitudinal sense, in the form of large height differences in a small space, resulting in the design of serpentines on roads and road network extension.

Sinuosity (SIN) is a parameter that can help evaluate the morphometric characteristics of terrain based on the existing digitized network of forest truck roads. Since forest truck roads are designed by applying the principle of the lowest construction costs and integration into space, without significantly disturbing the landscape, they almost as a rule follow the terrain configuration and adapt to terrain shapes. This algorithm shows how much the existing path is longer than the straight line from starting point A to endpoint B and is expressed as a percentage. This python code was generated by ArcMAP Field Calculator.

!Shape.Length!/(math.sqrt(math.pow((float(!Shape.FirstPoint.X!)–float(!Shape.LastPoint.X!)),2)+math.pow((float(!Shape.FirstPoint.Y!)–float(!Shape.LastPoint.Y!)),2))). This assumes using a Projected Coordinate System where the length and coordinates are in the same unit type (meters, feet, etc.).

Hypsometric distribution (HYP) is a numerical parameter and refers to the amount of area of a certain space or the entire territory of a country or region, which belongs to a certain height category (Fazlić 1983). The terrains are classified as follows: below 400 m, 400–600 m, 600–800 m, 800–1000 m, and >1000 m above sea level. At higher altitudes, air temperature is much lower in winter, and the period with cold days is much longer compared to areas with lower altitudes. This implies significant exposure of the space, and thus also infrastructure facilities to low temperatures, which requires special conditions of construction and maintenance to preserve the functionality and durability of the built facilities.

Hydrography (HYD) of a certain area has a significant impact on the shape of the terrain. Pronounced slopes of the riverbed and basin slopes, the presence of erosion processes, frequent occurrence of flood waves that occur quickly and have a pronounced destructive effect (Ristić and Malošević 2011). The density of watercourses is taken into account to find an efficient numerical attribute that would link the presence/absence of a watercourse network with geomorphology (Melelli et al. 2017). The density of watercourses is the ratio of the length of watercourses and

Table 1 Assessment of terrain suitability for the construction of forest truck roads

	Terrain ruggedness index TRI	Topographic position Index TPI	Slope SLP	Sinuosity SIN	Hydrography HYD	Hypsometry HYP	Aspect ASP
Rating	According to dissection	Share of areas of plateaus and open slopes	Share of slope areas from 0 – 40%	Shortening of the existing road distance to the straight line from point A to point B of the road	The average length of watercourses on an area of 1 ha	Suitability of terrain according to the share of areas with certain altitudes	According to aspect of suitability
5	Nearly level	>50%	>80%	>75%	0–5 m/ha	<400 m	South
4	Slightly rugged	45–50%	70–80%	70–75%	5–10 m/ha	400–600 m	Southeast–South-west
3	Intermediately rugged	35–40%	60–70%	65–70%	10–15 m/ha	600–800 m	East–West
2	Moderately rugged	30–35%	50–60%	60–65%	15–20 m/ha	800–1000 m	Northeast–Northwest
1	Highly rugged	<30%	<50%	<60%	>20 m/ha	>1000 m	North

the area, and it ranges from 6–20.8 m/ha Jurík (1984) according to Pičman (1994). Digitized layers of permanent and ephemeral watercourses were used for the classification.

Aspect (ASP) represents the orientation of the highest slope line for the observed point (Borisov et al. 2011). Aspect suitability in terms of roads implies that sunny aspects are considered more suitable for forest truck roads because of faster drying of roads after precipitation, while northern aspects are unsuitable, because on such forest truck roads moisture and snow cover last longer, which directly affects their durability and increases maintenance costs.

2.3 AHP Method

AHP – the Analytic Hierarchy Process is one of the best known and most commonly used methods in predecision making an evaluation, in case the decision depends on many attributes used as criteria (Samani and Hosseiny 2010, Norizah and Mohd Kasmadi 2012, Pellegrini et al. 2013, Chabuk et al. 2017), etc. This method is »analytical« and »hierarchical« because the decision-maker breaks down the complex decision-making problem into several decision-making elements and establishes a hierarchy among them. A model for the evaluation of morphometric parameters based on the AHP method Saaty (1980) was used in this paper. The choice of criteria was made by the author and coauthors by experience. This combination of morphometric parameters was not used in earlier research (Table 1 and 2).

Each area was reclassified with values from 1–5 depending on the morphometric parameter and the classification is shown in Table 2.

Table 2 Standardization of criteria in the range of 1–5

FEAs	TRI	TPI	SLP	SIN	HYD	HYP	ASP
Istočnodrvarsko	5	5	5	4	5	1	5
Petrovačko	4	5	5	5	5	2	1
Romanijsko	5	5	5	5	4	2	5
Hanpjesačko	5	5	5	5	4	1	5
Dobojsko-derventsko	5	3	4	5	1	5	4
Donjevrbasko	4	4	4	5	2	4	4
Jahorinsko	3	4	4	4	3	2	4
Kozaračko	4	3	4	5	1	5	4
Mrkonjićko	4	5	4	3	5	2	4
Nevesinjsko-gatačko	4	5	4	4	3	2	4
Posavsko	5	4	4	5	1	5	4
Ribničko	3	5	5	3	5	2	2
Srednjevrbasko	4	4	4	2	4	2	4
Čemerničko	3	4	3	4	4	2	5
Vlaseničko	3	3	3	2	2	3	2
Kalinovičko	3	2	3	3	2	2	3
Majevičko	4	2	3	5	1	4	2
Milićko	2	3	2	1	3	3	1
Rogatičko	2	3	3	4	4	2	5
Trnovsko	2	2	3	3	3	2	2
Višegradsko	1	1	1	3	3	3	5
Gornjedrinsko	1	1	2	2	3	2	5
Donjedrinsko	1	1	2	2	2	4	3
Kotorvaroško	1	1	1	4	1	3	3
Usorsko-ukrinsko	2	1	2	4	1	4	4
Čajničko	1	1	2	2	3	2	3

Table 3 Weighting criteria coefficients (AHP)

Parameters	TRI	TPI	HYP	SLP	SIN	HYD	ASP	*w*	*b*	*b/w*
TRI	1	2	7	1	3	3	7	0.2584	1.9498	7.5454
TPI	1/2	1	7	1	3	3	7	0.2089	1.6117	7.7162
HYP	1/7	1/7	1	1/7	1/5	1/5	1	0.0280	0.2016	7.2050
SLP	1	1	7	1	5	5	7	0.2717	2.1534	7.9247
SIN	1/3	1/3	5	1/5	1	1	7	0.1109	0.8390	7.5668
HYD	1/3	1/3	5	1/5	1	1	7	0.0954	0.6882	7.2171
ASP	1/7	1/7	1	1/7	1/7	1/7	1	0.0268	0.1898	7.0891
							Σ	1.0000		

λ_{max} = 7.4663, CI = 0.078, RI = 1.32, CR = 0.0589 < 0.10 = OK

The obtained values were weighted with the coefficients obtained through the AHP method.

The final values are shown in Table 4. Each FEA was ranked by assigned place and the convenience of the terrain suitability for the construction and optimization of the forest truck road network The displayed values are sorted by ranges of 1–2, 2–3, 3–4 and 4–5. The minimum total value can be 1, and the maximum

Table 4 Weighting criteria values

EAs	TRI	TPI	SLP	SIN	HYD	HYP	ASP	TOTAL	Rating
Romanijsko	1.292	1.044	1.359	0.555	0.382	0.056	0.134	4.82	1
Hanpjesačko	1.292	1.044	1.359	0.555	0.382	0.028	0.134	4.79	1
Istočnodrvarsko	1.292	1.044	1.359	0.444	0.477	0.028	0.134	4.78	1
Petrovačko	1.034	1.044	1.359	0.555	0.477	0.056	0.027	4.55	1
Mrkonjićko	1.034	1.044	1.087	0.333	0.477	0.056	0.107	4.14	1
Posavsko	1.292	0.836	1.087	0.555	0.095	0.14	0.107	4.11	1
Ribničko	0.775	1.044	1.359	0.333	0.477	0.056	0.054	4.10	1
Nevesinjsko-gatačko	1.034	1.044	1.087	0.444	0.286	0.056	0.107	4.06	1
Donjevrbasko	1.034	0.836	1.087	0.555	0.191	0.112	0.107	3.92	2
Dobojsko-derventsko	1.292	0.627	1.087	0.555	0.095	0.14	0.107	3.90	2
Srednjevrbasko	1.034	0.836	1.087	0.222	0.382	0.056	0.107	3.72	2
Kozaračko	1.034	0.627	1.087	0.555	0.095	0.14	0.107	3.64	2
Jahorinsko	0.775	0.836	1.087	0.444	0.286	0.056	0.107	3.59	2
Čemerničko	0.775	0.836	0.815	0.444	0.382	0.056	0.134	3.44	2
Majevičko	1.034	0.418	0.815	0.555	0.095	0.112	0.054	3.08	2
Rogatičko	0.517	0.627	0.815	0.444	0.382	0.056	0.134	2.97	3
Vlaseničko	0.775	0.627	0.815	0.222	0.191	0.084	0.054	2.77	3
Kalinovičko	0.775	0.418	0.815	0.333	0.191	0.056	0.08	2.67	3
Trnovsko	0.517	0.418	0.815	0.333	0.286	0.056	0.054	2.48	3
Milićko	0.517	0.627	0.543	0.111	0.286	0.084	0.027	2.19	3
Usorsko-ukrinsko	0.517	0.209	0.543	0.444	0.095	0.112	0.107	2.03	3
Gornjedrinsko	0.258	0.209	0.543	0.222	0.286	0.056	0.134	1.71	4
Čajničko	0.258	0.209	0.543	0.222	0.286	0.056	0.08	1.65	4
Donjedrinsko	0.258	0.209	0.543	0.222	0.191	0.112	0.08	1.62	4
Višegradsko	0.258	0.209	0.272	0.333	0.286	0.084	0.134	1.58	4
Kotorvaroško	0.258	0.209	0.272	0.444	0.095	0.084	0.08	1.44	4

can be 5. The most suitable areas took the number 1 place, while the most unsuitable areas took the number 4 place.

3. Results

3.1 Morphometric Analysis

The classification of FEAs according to the suitability for the construction of forest truck roads was obtained through morphometric analysis of areas covered only by forests and forest land. By overlapping seven thematic maps, the final map of terrain suitability for each FEA was obtained (Fig. 5).

The terrain of the Republic of Srpska is very heterogeneous. Among the impact factors, a slope of 27.17% has a leading significance over the other six parameters. The Terrain Ruggedness Index (TRI) is closely related to the slope, which amounts to 25.84%.

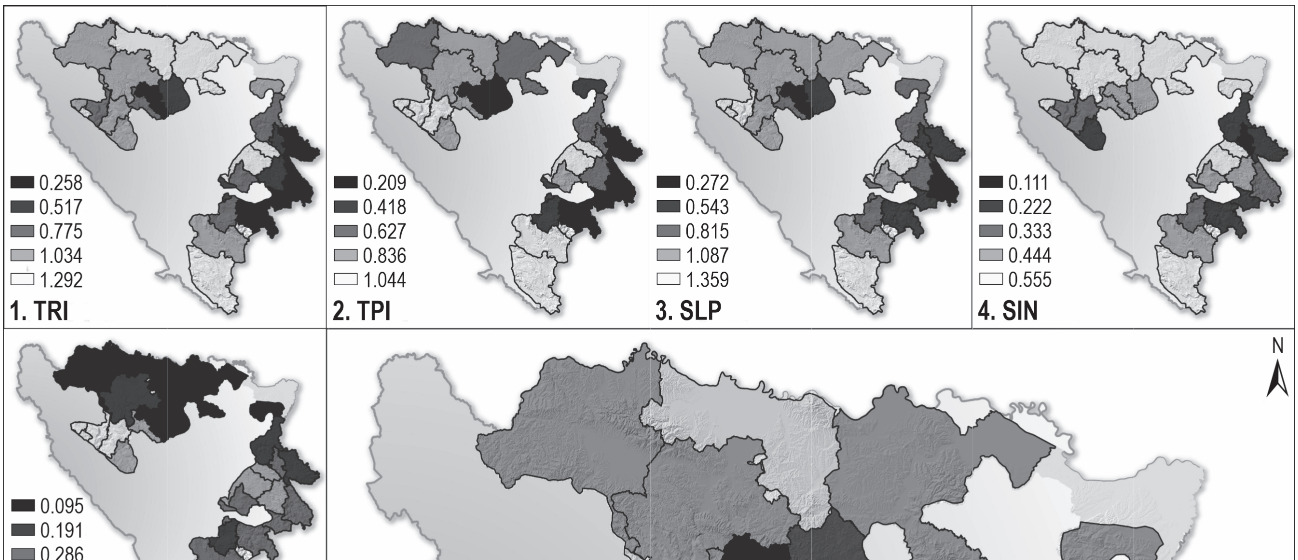

Fig. 5 Final morphometric classification of the terrain by FEAs

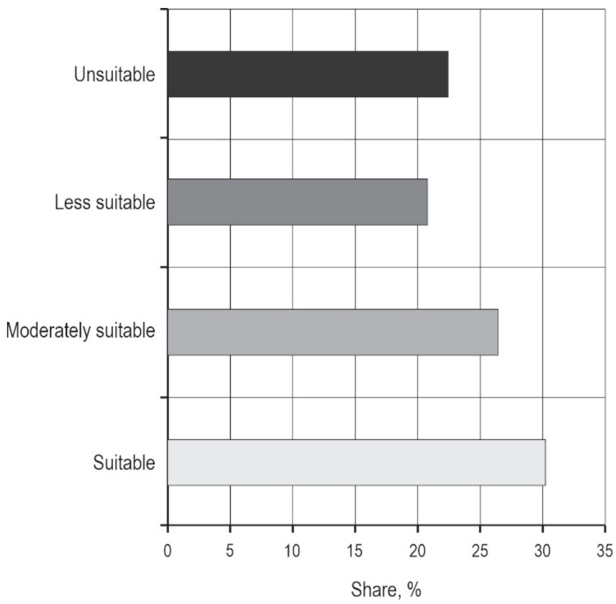

Fig. 6 Percentage shares of areas by terrain suitability categories

The impact of the Topographic Position Index (TPI) accounts for 20.89%, sinuosity (SIN) for 11.09%, and Hydrography for (HYD) 9.54%. Hypsometry (HYP) with 2.80% and Aspect (ASP) with 2.68% have the lowest impact in terms of terrain assessment.

Based on the results of the morphometric evaluation, areas were selected according to their suitability for the construction of forest truck roads. The shares of areas belonging to certain categories of terrain suitability are the following (Fig. 6): very suitable category accounts for 30.30% of the area of forests and forest land in the Republic of Srpska, moderately suitable areas for 26.44%, less suitable for 20.85% and 22.41% is unsuitable for the construction of forest truck roads. The research conducted in the area of forests and forest land owned by the Republic of Srpska showed that, according to a morphometric classification of the terrain, 22.41% of the area, or 189,020.73 ha belongs to the category of unsuitable areas for the construction of a primary forest road network. In some parts of this area, the construction of forest truck roads is not possible or could be many times more expensive compared to the cost in other categories of terrain. Each FEA has between 5 and 11% of areas that are completely unsuitable for laying out a forest truck road network. Different logging systems should be used on these surfaces as an alternative. Traditional steep slope logging operations involve manual tree falling and cable rigging operations in difficult terrain.

3.2 Optimal Density of Forest Truck Road Network

According to the obtained results, the classification of FEAs was performed based on the classification of terrain suitability for the construction of forest truck roads. The results are shown in Fig. 5.

A total of 8 FEAs were distinguished with very suitable terrain for the construction and development of a network of forest truck roads, with an absolute openness of 16.2 m/ha. A total of 7 FEAs belong to

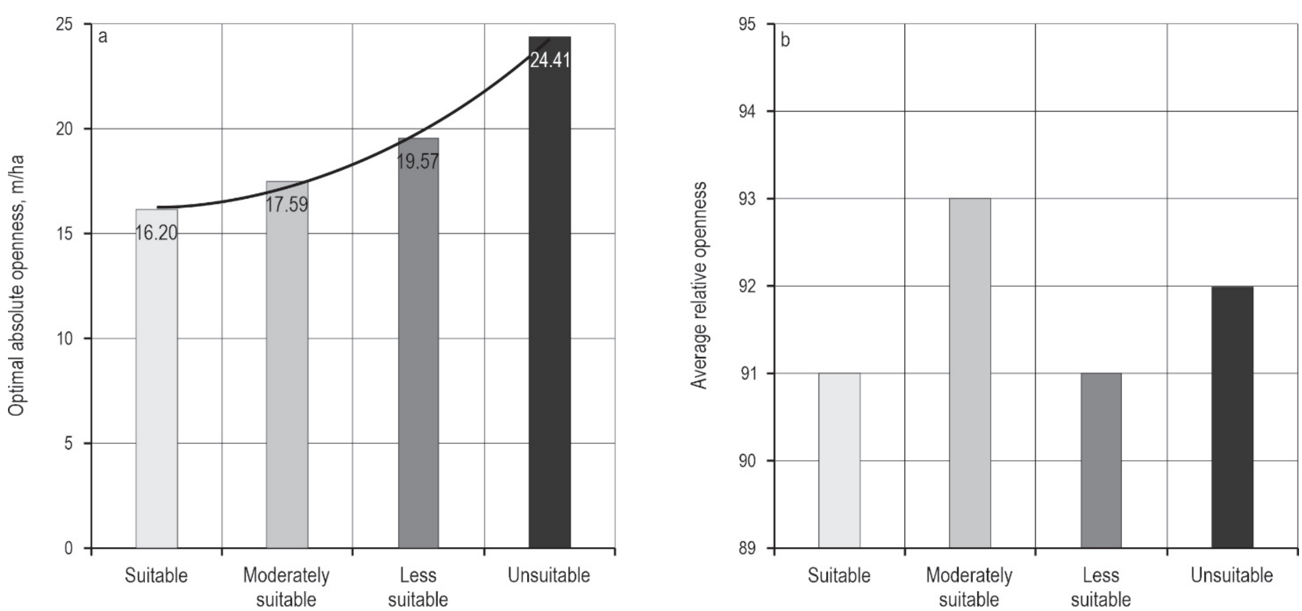

Fig. 7 Final absolute and relative openness: (a) Optimal absolute openness, (b) Average relative openness

moderately suitable areas with 17.59 m/ha, 6 are less suitable with 19.57 m/ha and 5 FEAs belong to unsuitable terrains with an absolute openness of 24.41 m/ha. The best rated FEAs are located on plateaus, and Istočnodrvarsko, Petrovačko, Hanpjesačko and Romanijsko FEAs stand out among them. On the other hand, the lowest rating was scored by the Gornjedrinsko, Kotorvaroško, and Čajničko FEAs.

Forest truck road network on unsuitable terrains is almost 1.5 times longer than on suitable terrains. Average relative openness represents the openness of each category of suitability. Fig. 6b shows that this openness is variable and does not have a clear correlation and explanation of the results obtained. This information depends on each case, that is, on the surface shape of the analyzed area, its homogeneity and heterogeneity of the terrain.

4. Discussion

The evaluation of different terrain units is very important because it has an impact on the final length, density, and shape of the network of forest truck roads. The optimization of the network of forest roads should inevitably be accompanied by the assessment of terrain morphometry. Considering the economic and sociological criteria, in terms of density of the network of forest truck roads, desired and required, the terrain characteristics should be observed as a reality, i.e. something that is almost unchangeable in our lifetime. Given this fact, the roads must be adapted to the realistic possibilities offered by the terrain of the open space.

The impact of certain morphometric parameters of the terrain on the development of a forest road network has so far been dealt with by a relatively small number of researchers, who paid most of their attention to the slope and exposure of the terrain (Abdi et al. 2009, Samani et al. 2010, Naghdi et al. 2012, Caliskan 2013, Motazeh et al. 2013). According to Samani and Hosseiny (2010), slope is the most important parameter for the construction of forest roads (21.2%), followed by hydrography (21.1%), parent rock (19.5%), and soil type (15.1%), while the shares of other factors are significantly lower. Stojnić (2019) argues that slope is the most important for the construction of forest roads in forests of high protection value of Fruška Gora NP 21.6%, followed by hydrological network 21.1%, parent rock 19.5%, and soil type 15.1%. Norizah and Mohd Kasmadi (2012) estimate four factors in terms of their impact on forest exploitation, the slope accounting for 55.8%. Different combinations and values of impact factors can be found in previous research, depending on the need and type of analysis that the authors dealt with. The optimal density of the forest road network was processed by many researchers, and the results they obtained varied depending on the case. Žàček and Klč (2008) state in the Report on Forests and Forestry of the Czech Republic for 2005 that the recommended optimal density of the network of forest roads should be 15 m/ha for lowland areas, 22.5 m/ha for hilly areas and 27.5 m/ha for mountain areas. Beneš (1986) gave recommendations for optimal density and average skidding distance depending on terrain characteristics. For flat terrain with a slope of up to 15%, he recommended a density of 15 m/ha and an average geometric mean skidding distance of 170 m, for hilly conditions 22 m/ha and an average geometric skidding distance distance of 150 m, for mountain conditions with uniform relief 19 m/ha and an average skidding distance of 170 m and in mountainous conditions with uneven relief 24 m/ha and an average geometric skidding distance of 160 m. Hodić and Jurišić (2011) state that in the lowland and foothill areas of Croatia, which can be characterized as the areas included in this study, the minimum required density of the forest road network is 10 and 13 m/ha, and that the density to be aimed for under these conditions is 13 and 20 m/ha.

Different results of forest openness through previous research has forced the need for a new way to determine the openness of forests with roads. Each area is unique in terms of its morphometric parameters, so openness values cannot be unique, but must be calculated. It is difficult to make a comparison with previous research because the results were obtained with different input parameters. The results obtained in this paper are close to the earlier results. For suitable terrains, similar results were obtained in the lowland category, whereas they differed for unsuitable terrains in the mountain category.

The advantage of this approach is that a large area, as well as a large number of variants and iterations, can be analyzed fairly quickly. Also, it is much easier, faster and more precise to get results using GIS technologies. The main contribution of this research is the determination of the density of the network of forest truck roads based on the influence of the morphometric characteristics of the terrain. The Analytic Hierarchy Process (AHP) in the geospatial environment and GIS technologies should be the first step in optimizing the forest truck road network

5. Conclusion

According to the obtained results, in case of a quality assessment of the terrain morphometry and spatial arrangement of roads, and the average skidding distance of approximately 300 m, the above are the values of density of forest truck road network allowed by the specific terrain and space. If other factors important for forest opening are included, the efficiency of the forest truck road network and the damage that a denser road network may do in the long run should be taken into consideration. A denser road network also means permanent removal of a productive layer of land, which is very important for silviculture, utilization, and protection of forest resources. In terms of relative openness, no area could be opened up to a relative openness of 100%. Most often, these are terrains completely unsuitable for management, or a large number of small forest areas scattered in the form of islands. In terms of absolute openness, more complex terrains require a higher density of the forest truck road network. The slope is the most important morphometric parameter, but not the only one. There is a noticeable trend of increasing road density depending on terrain suitability, which is not linear. The results and this method can be useful to researchers interested in studying the benefits of morphometric conditions in forest construction, forest-silvicultural works, forest utilization, differentiation of ecological – vegetation belts, hydrology, agriculture, and recreational tourism. The study itself should not be linked to a specific area but viewed as a methodological procedure for the analysis of any area in the production of suitability maps for forestry.

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