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Original Research

Earthwork Volume Estimation for the Construction of Forest Roads that Would Account for an Ecological Criterion

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Abstract

Technical elements, such as forest road networks, are inseparable parts of forest ecosystems. The current approach to the layout of a forest road network is largely based on technical and economic solutions and does not include an approach related to the forest ecosystem itself, which should be taken into account in the form of an ecological criterion. The aim of this work was to find out whether inclusion of the ecological criterion in the current method for the layout of a forest road network will affect the construction of forest roads and its economy. The inclusion of the ecological criterion is based on respecting forest stands with a high value of the real potential of forest functions within the accessed area so that these stands would be disrupted as little as possible and the real potential of forest functions would not be reduced considerably in consequence of the construction and use of the forest road network. The forest road network is therefore designed in the stands with a low value of the real potential. Specifically, we examined the changes in parameters of earthwork amount and we analyzed if the changes were statistically significant, and whether the spatial design of the forest road cross profile would change and how this change would be manifested in the construction of forest roads. The results showed that inclusion of the ecological criterion in the construction of forest roads causes only a slight increase in the level of the evaluated parameters of earthwork and thus also economic costs.

Keywords: forest road network, forest road, forest ecosystem, ecological criterion

Introduction

Management in a forest environment is significantly affected by the density and layout of the forest road network. Ghaffarian and Sobhani [1] as well as Rafiei et al. [2] calculated the forest road density on the basis of minimization of economic costs. Sessions and Boston, and Ghaffariyan et al. [3, 4] are more focused on the parameter of optimal road spacing instead of optimal road density, as this parameter better expresses the distribution of forest roads in the area. Pryimachuk [5] emphasizes that forest access must be part of long-term forest management planning, and use of GIS is essential. Pentek et al. [6] created the process for analyzing a forest road network using instruments easily obtained with GIS, based on technical parameters, such as forest road density and skidding distances. Hayati et al. [7] highlighted that each transportation network has to be assessed and optimized to minimize the total costs of road construction and its environmental impact and claimed to use GIS also for the evaluation of forest road networks. Inclusion of ecological requirements in today's design forest road network approach is attempted in e.g. Pentek et. al. [8, 9]. According to Coulter et al. [10, 11], there are often various criteria for designing a forest road

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network, especially requirements concerning the environment. Hosseini and Solaymani [12] produced and analyzed digital maps to plan a forest road network from the ecological point of view using ArcGIS software techniques in their work. In contrast with GIS, Pelikan and Slezingr [13] used AutoCAD to explore the possible ways to use the program for terrain shape and forest road density establishment. A different approach to the forest access road layout is presented by Demir [14]. He emphasizes that each step has to be taken with respect to functional planning of forest roads. Another good example of the environmental impact approach was published by Gumus et al., Ezzati and Hosseini [15-17]. Potocnik et al. [18] also tackle the reduction of negative effects on the forest ecosystem, but mainly from a technical perspective as they deal with the width proportions of the road formation and the loss of the forest production area. Messingerova and Tajbos [19] searched for a different way to eliminate the consequences of extraction technologies for the environment using helicopter timber extraction.

However, all these solutions are based mostly on economic and technical principles and do not include the forest ecosystem, the forest stand itself, as a criterion for forest road network design.

The road formation has always represented a boundary within the terrain, which is why the technical criteria are designed to adapt the road formation to the current terrain so that it follows its shape in its entire length. A forest road constructed in a technical way should provide easy access to the surrounding forest stands and minimize the amount of earthwork during forest road construction. The construction of a forest road should cause minimum disturbance to forest stands as well. Inclusion of another criterion, e.g. an ecological one, which represents the biological part of forest ecosystem – forest stands – may change these technical demands.

Thus the aim of this work is to find out whether inclusion of the ecological criterion in the current forest access optimization design will change the parameters of forest roads, specifically the amount of earthwork, and whether the potential changes will affect the construction design of the forest roads. The monitoring of possible changes in the amount of earthwork will show potential changes in the amount of cut and fill work, cross moving, the area of new cut-and-fill slopes, and the take-up area.

Methods

To examine the effect of including an ecological criterion in forest road planning on the amount of forest roads earthwork we selected five transport areas called Smuch, Blatka, Rasnik, Kostkovica, and Spalena paseka. These five transport areas are under the administration of the Vysocina Region in the Czech Republic, Forest District Nove Mesto na Morave (Figs. 1 and 2).

The maps for the evaluation of the earthwork amount were created in ArcGIS. Raster data were obtained from the map server of the Forest Management Institute [20] to characterize the transport areas. This map was complemented with the altitude vector data from the Database of Geographical Data with contour lines with 1m interval (Fig. 3).

The situation of the current forest road network was processed using the data from a survey that was performed for the creation of Territorial Plans of Forest Development by the Forest Management Institute [20].

The design of forest road network optimization with the included ecological criterion respects the principle of the optimum density of forest roads based on the transport segment within the Territorial Plans of Forest Development [21] and all technical requirements [22].

The ecological criterion covers all functions of forest ecosystems. These functions are defined by Vyskot [23] as bio-productive, ecological stabilization, hydric, edaphic-soil protective, social recreation, and health and hygiene. The ability of different forests to fulfil these functions is highly differentiated; hence, forest functions can gain different values. Vyskot [23] presented the procedure for the calculation of these values and introduced the term real potential of functions. The values of real potentials can be calculated for forest stands across the forest ecosystems of the Czech Republic. The resulting value of the real potential of all functions is divided, based on the ability to fulfil the potential into six classes (I-VI), and each class is described from very low to outstanding.

Based on these real potentials, forest hauling roads were designed so that forest stands with a high value of total function potential were respected, which means these forest stands should be disturbed as little as possible, ensuring that no considerable decrease in the values of their function potential occurs in consequence of the forest access provision. The forest roads were designed in the forest stands with a low value of the total function potential as their potential value cannot be considerably decreased with the construction and the use of the roads. The layout of the optimized forest road network with the included ecological criterion was taken from the author's previous study [24].

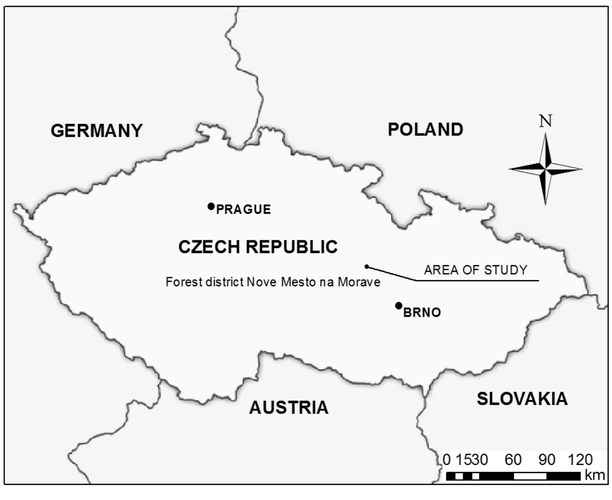


Fig. 1. Location of the study area.

Table 1. Classes of the real potential for all functions defined by Vyskot [23].

Functional value interval 0-100 %	Class of real potential	Description
1-30	I	very low
31-45	II	low
46-55	III	average
56-70	IV	high
71-90	V	very high
90+	VI	outstanding

Before the statistical assessment of the changes in earthwork amount, we formulated the null hypothesis that there is no statistically significant difference between the amount of earthwork in the forest hauling roads design based on technical and economic criteria only (represented by the current forest road network) and the ecological forest hauling roads design that accounts for the additional ecological criterion (comprehensively optimized forest road network). In other words, the hypothesis says that the earthwork amounts of the two evaluated design sets – the current and the comprehensively optimized design – do not differ.

The assessed parameters of earthwork were the cubature units of cuts, fills and cross moving, and the size of areas of cut sloping, fill sloping, and the take-up area. In total, six parameters of earthwork amount were assessed.

The earthwork amount was examined in five transport areas: Smuch, Blatka, Rasnik, Kostkovica, and Spalena paseka. Transport areas Blatka, Rasnik, Kostkovica and Spalena paseka are adjacent; while Smuch is separated by a terrain saddle.

Due to this fact, the current as well as the comprehensively optimized forest road networks of the five transport areas were considered the basic set for statistical processing. The five areas were analyzed altogether and the analysis involved 27,903 m of the current forest road network and 28,993 m of the comprehensively designed optimized forest road network.

With respect to the total length of both compared forest road networks, a sample section was selected in each transport area for the terrain survey of the assessed parameters, both in the current and the comprehensively optimized forest road networks. The selection of sample sections was based on the calculation of the longitudinal gradient: the sample section with the average longitudinal slope was chosen for field measuring of each of the evaluated road networks (Fig. 3). In total, 10 sample sections were selected: five in the current and five in the comprehensively optimized forest road network. Each transport area includes one

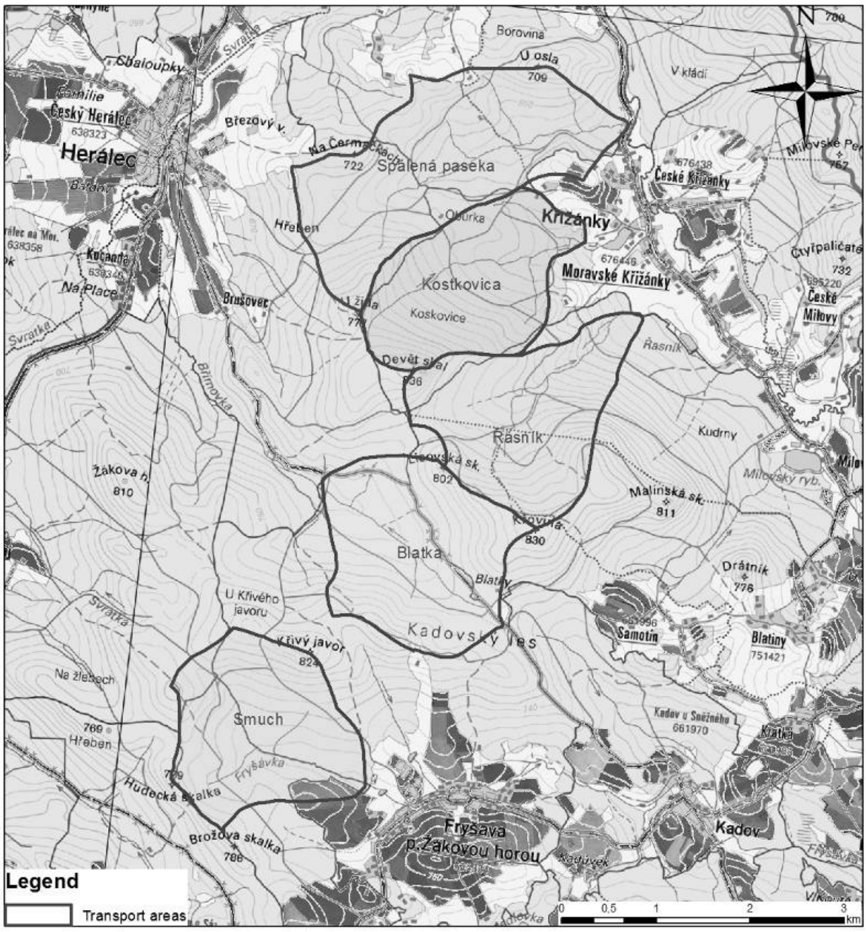


Fig. 2. Selected transport areas.

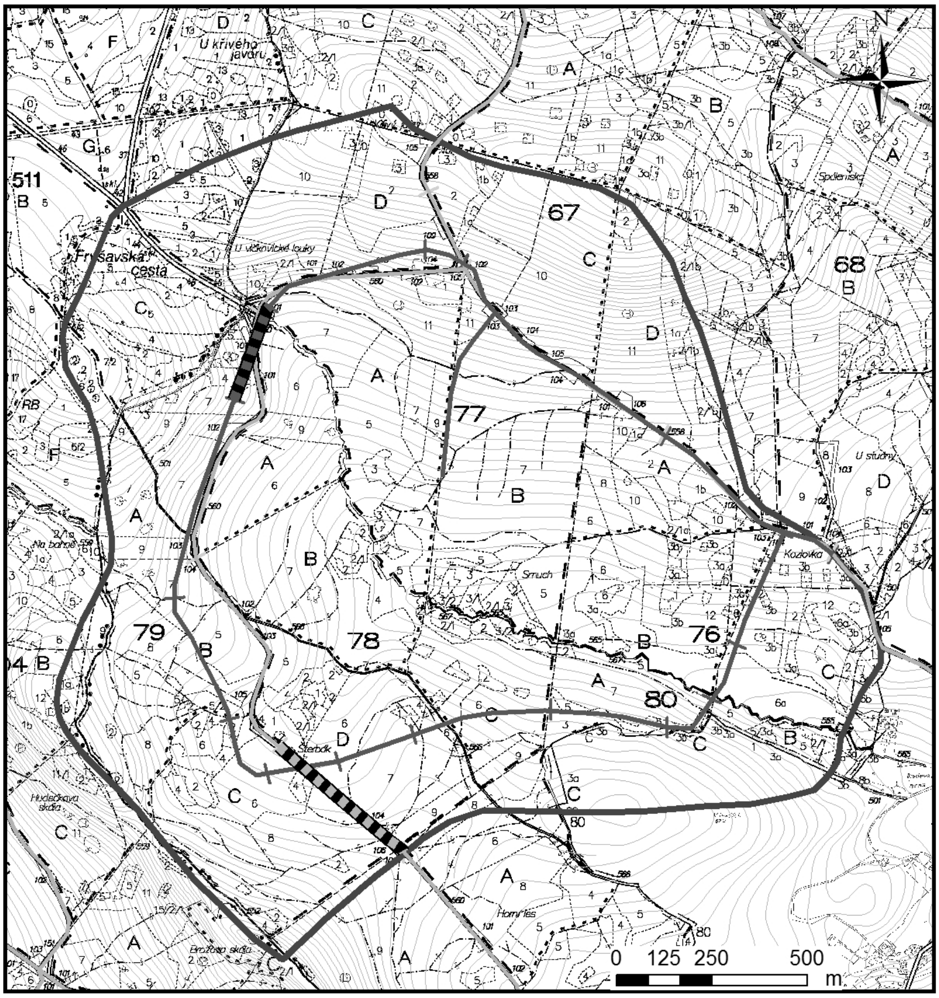
sample section from the current network and one sample section from the optimized network. Each of the representative sections were identified in the terrain and 10 cross profiles in 20 m distances were surveyed using geodetic tools (i.e. each of the sample sections was 180 m in length).

Afterward, the results of the field measurements were processed in AutoCAD. For the current forest road network, cross-sections of the terrain together with cross-sections of the road formation in the measured points were drawn.

Due to the fact that the comprehensively optimized forest road network is only a proposal and has not been constructed, it was necessary to draw the shape of the road formation on the surveyed terrain. It also was necessary to proceed as when a new forest hauling road is designed, including the elevations, i.e. the creation of the longitudinal profile of the terrain and design of the elevation of a future road. This was plotted in the entire length of the designed forest road where the representative section appeared according to the Czech standard [22].

The created cross profiles of forest roads were used to perform the calculations of earthwork amount in Excel. The values of individual parameters were calculated for the five sample sections of the current forest road network and the five sample sections of the comprehensively optimized network.

The data from the five sample sections of the current forest road network were put together to create one dataset and the data from the five sample sections of the comprehensively optimized network was put together to create a second dataset for the statistical testing of individual parameters of the earthwork amount calculation: cuts, fills, cross moving, cut sloping, fill sloping and take-up area. Thus the five sample sections from the current network and another five from the comprehensively optimized network formed two datasets for statistical processing. Since these are two different road networks – the current and the comprehensively optimized, designed by different routes – we can say that these datasets are independent of each other.



Legend

Transport area Smuch

Representative section of comprehensively optimized forest road network with the average longitudial gradient

Representative section of current forest road network with the average longitudial gradient

Complexy optimized forest road network

Current forest road network

Fig. 3. An example of forest road network representative sections in the Smuch transport area.

Statistical assessment of the earthwork parameters should confirm or reject the null hypothesis that there is no statistically significant difference in the earthwork amount between the current forest road network and the comprehensively optimized forest road network.

For each of the evaluated parameters of earthwork the original data of two datasets were used and basic characteristics of the datasets were calculated: arithmetic mean, modus, median, standard deviation, variance, skewness and kurtosis, and confidence interval at significance level $\alpha=0.05$.

Furthermore, the normal distribution test was conducted for each parameter using the Shapiro-Wilk test to verify the assumption that the selection set comes from a basic set with a normal distribution and to select the following procedure of testing, i.e. whether to use parametric or non-parametric analysis of variance to test the null hypothesis. As not all the conditions for the usage of parametric analysis of variance were met (the normal distribution of values in the sets), we used the non-parametric analysis of variance, which compares two independent selections – the Mann-Whitney (Wilcoxon) test. The results of the non-parametric analysis were calculated in software Statistica 8.

Results

The resulting values of particular parameters were always calculated for the two cross profiles of the two analyzed designs and are thus presented for 20 m of the forest road length.

The average size of the cuts parameter of the two cross profiles of the current network and the optimized network was 21.18 m^3 and 20.94 m^3, respectively; these values are nearly equal, while the value of the optimized forest road network is slightly lower, the same was observed for the confidence intervals with values 13.98-28.40 m^3 and 13.82-28.09 m^3 for the current and the optimized networks, respectively. The confidence intervals of the cuts parameter overlap – we can assume that the compared mean values of the two sets are equal (Fig. 4). This assumption was confirmed by the non-parametric analysis of variance – the Mann-Whitney test. The resulting p value of the test reached 0.9839, meaning that the null hypothesis about the equality of the selection datasets can be accepted and that the difference of cuts values in the two sets of the parameter is not statistically significant.

The average size of the parameter "cross moving" was 2.74 m^3 and 3.89 m^3 for the current network and the optimized network, respectively. This indicates an increase in the earthwork in the optimized forest road network by nearly a third. The confidence intervals reached values of 1.87-3.62 m^3 and 2.86-4.91 m^3 for the current and the optimized networks respectively, which mean that the values still overlap (Fig. 5). We can assume that the compared values of the sample section sets are statistically the same. The assumption was confirmed by the Mann-Whitney non-parametric test. Based on its results (p=0.09807), we can again confirm the null hypothesis about the equality of the sample section sets of the current and comprehensively optimized forest road networks.

The average values of fills were 7.79 m^3 and 22.32 m^3 per cross profile in the current and the optimized forest road networks, respectively. These values show three times the

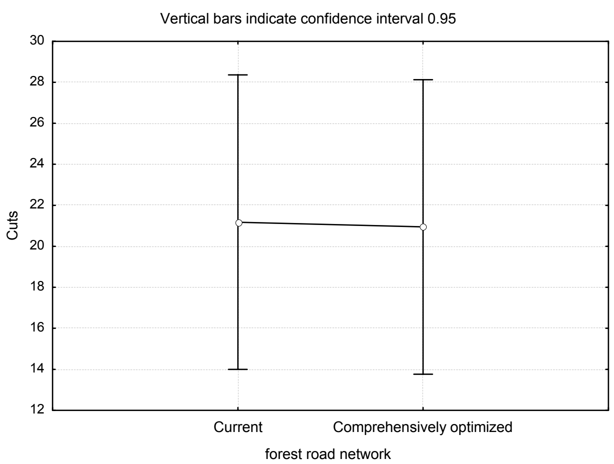


Fig. 4. Confidence intervals for the average size of cuts of the two 20 m cross profiles.

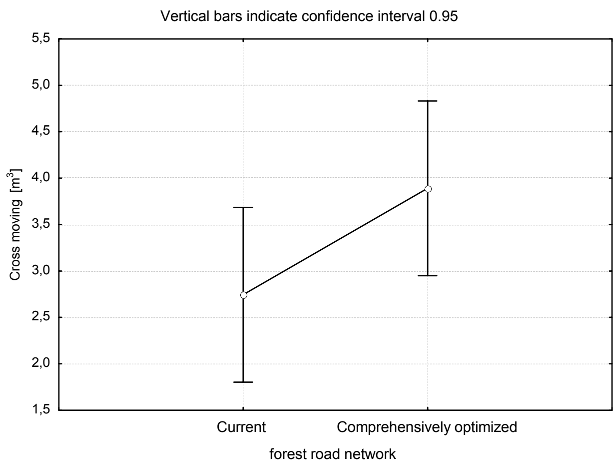


Fig. 5. Confidence intervals for the average size of cross moving of the two 20 m cross profiles.

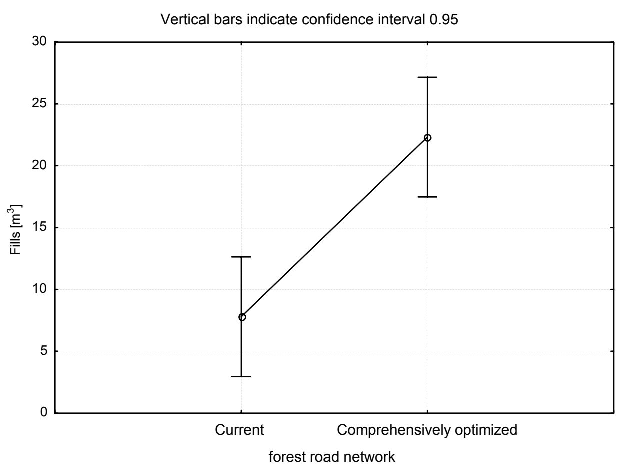


Fig. 6. Confidence intervals for the average size of fills of the two 20 m cross profiles.

amount of fills in the optimized forest road network than in the current network, which is also reflected in the final result of the Mann-Whitney non-parametric test. The confidence intervals of the average fills were 2.79-12.71 m^3 for the current forest road network and 15.92-28.92 m^3 for the optimized forest road network (Fig. 6). We can assume that the two sets are different – their confidence interval limits with the significance level $\alpha=0.05$ do not overlap. Based on the resulting value $p=0.00125$, we reject the null hypothesis about the equality of the sample section sets and we conclude that if the road layout is optimized using the ecological criterion (comprehensively optimized forest road network), the changes in the volume of fills are statistically significant.

The average values of the cut sloping parameter were 33.2 m^2 and 36.71 m^2 per a cross profile for the current and the optimized forest road networks, respectively. The confidence intervals with values 28.92-37.42 m^2 for the current network and 32.58-41.00 m^2 for the optimized network overlap (Fig. 7), i.e. we can assume that the two compared datasets are statistically equal. This assumption was confirmed by the Mann-Whitney test with p value equal to 0.22921, confirming the null hypothesis about the equality of the sample section sets.

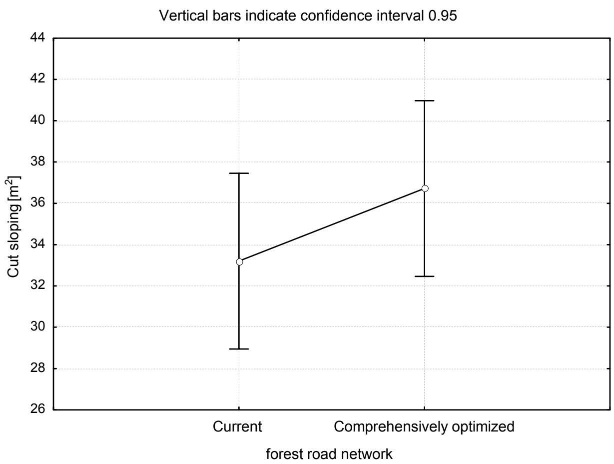


Fig. 7. Confidence intervals for the average size of cut sloping of the two 20 m cross profiles.

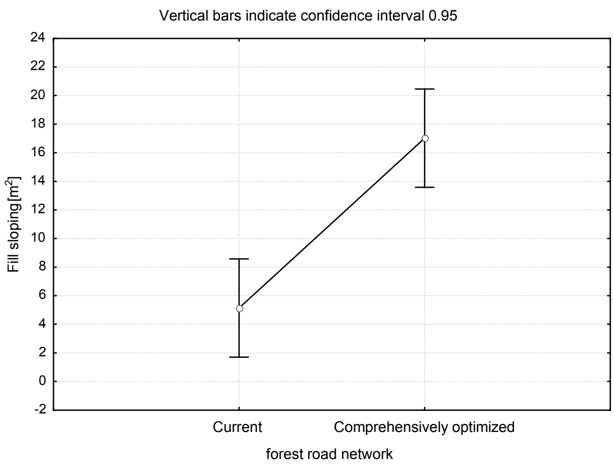


Fig. 8. Confidence intervals for the average size of fill sloping of the two 20 m cross profiles.

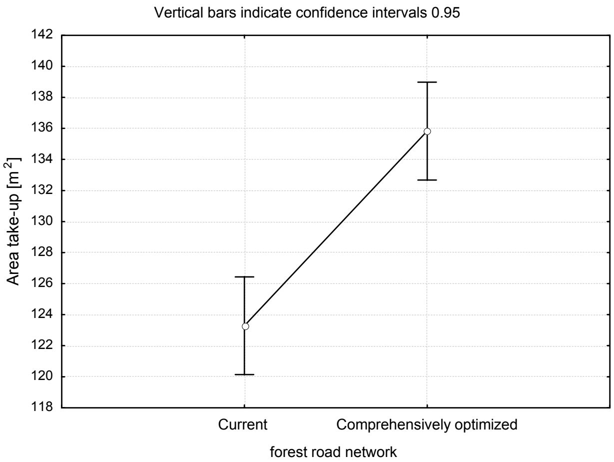


Fig. 9. Confidence intervals for the average size of area take-up of the two 20 m cross profiles.

The average values of the fill sloping parameter are 5.14 m^2 for the current and 17.02 m^2 for the optimized road networks. The values of the confidence interval are 1.85-8.46 m^2 and 13.53-20.58 m^2, respectively. The confidence intervals do not overlap (Fig. 8), and the results of the compared datasets that are statistically different were confirmed by the Mann-Whitney test – the resulting p value achieved 0.00032 and the null hypothesis was thus rejected. The fill sloping parameter of the optimized forest road network designed with regard to the included ecological criterion is significantly higher than that of the current forest road network.

The last tested parameter was the take-up area, which does not reflect the earthwork amount directly but indicates the size of the take-up of the forest stand area and is important from the perspective of the preparation of the construction site. The average value of the area take-up in a cross profile is 123.29 m^2 in the current forest road network and 139 m^2 in the optimized network. The confidence intervals do not overlap (Fig. 9), since the interval in the current forest road network is 120.13-126.44 m^2 and in the optimized network it is 132.54-139.05 m^2. The results of the compared datasets are statistically different, as was confirmed by the Mann-Whitney test – the resulting p value was 0.000001 and the null hypothesis was thus rejected. The difference in the take-up area has been proven statistically.

Discussion

The most ecosystem friendly ways of designing forest road networks and especially the location of forest roads have been tackled by several authors, e.g. Pentek et al., Hayati et al. and Gumus [6, 7, 14]. Their studies concentrate on recommendations on how to design a forest road network as a whole and where to locate it within the forest environment so that it harms the forest ecosystem to the smallest possible extent. However, their research does not include reflections of how these solutions will affect the construction of the forest road itself.

Just a few authors have dealt with the issue of the effect of accounting for environmental factors in forest road network design on the construction parameters of the forest roads. For example, Ezzati et al. [17] explore the influence of such a solution on the longitudinal slope of forest hauling roads. Therefore, this perspective is still needed.

The presented study investigated the question of what the effects of all functions produced by the forest ecosystem established as an ecological criterion would have on the amount of earthwork during the construction of forest roads, while meeting the current standards for construction.

The analysis of the effect of adding the ecological criterion on the amount of earthwork showed that the earthwork amount of the construction of an optimized forest road network would not increase in each of the investigated parameters. The first parameter – cuts – would hardly change or may even decrease, although by a mere 1%. Concerning the other parameters, the differences gradually increase with an included ecological criterion, i.e. the comprehensively optimized forest road network. The change was not statistically proved for the two parameters (cross moving and cut sloping). The change of cut sloping was 3% higher in the optimized forest road network than in the current solution. The change of cross moving reached over a third of the earthwork amount (41%), but was still not significant due to the non-parametric Mann-Whitney test. With respect to the percentage of the change in the earthwork amount, we can explain the non-significance with a small volume of cubature ground with a wide interval of occurrence of parameter with 95% probability, which was affected by the cross moving (Fig. 5). Cuts are always the first technological step within the construction of forest roads, followed by cross moving. Significant changes only occur after the technological stage of road formation construction referred to as longitudinal movement of the ground.

Statistically significant changes and an increase in earthwork amount would occur in these parameters − fills, fill sloping and take-up area. The fills parameter increased by nearly 186% in the comprehensively optimized forest road network. Although the size of fills would triple, the total costs of the construction would not increase dramatically. According to Hanak [25], costs of earthwork make about 20% of the total costs of forest road construction, depending on the characteristics of the terrain. The highest portion of costs is taken by reinforcement when a typical road surface is used – 70% – and the remaining 10% are the costs for drainage structures.

Due to the fact that the formation of fills and their sloping are closely related, an increase of the volume of fill formation will naturally lead to an increase in the area of its sloping. The change here is threefold and when expressed in percentage, it is 231% higher.

Similarly, there is a relationship to the statistically significant change in the parameter of take-up area as it is affected by the size of fills. However, in contrast to the fills and their sloping, this change is not so dramatic. This can be explained by the fact that the changes in the other evaluated parameters as cuts, cross moving, and cut sloping are not statistically significant and the take-up area is thus only increased by the parameters of fills. An inclusion of the ecological criterion in the current way of forest road network optimization would cause a slight increase of 10% in the take-up of the stand area when compared to the current situation.

The results show that a solution that accounts for the functions of the forest stand as the ecological criterion does not always mean a better economical technical solution and in this case the amount of earthwork during the construction of forest roads would increase.

Conclusion

In the future, forest road networks will have to be designed with respect to all ecosystem functions of forests. They will have to be applied in the current concept of forest constructions, which is predominantly based on technical and economic parameters so that forest accessing will cover technical-economic-ecological attributes. Considering all the effects related to implementation of forest access, the long-term aim of forest road network construction needs to be a harmonization of technical, economic, and ecological requirements together with a minimization of negative impacts on the forest ecosystem.

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