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## An Attempt at the Automation of the Routing of Mountain Forest Roads with the Use of GIS Spatial Analyses<sup>3</sup>

**Abstract:** The routing of road corridors in the project of a forest road network in the mountains, along with defining the functions of these roads, is the most important activity in the entire task. It must be preceded by a detailed inventory consisting of many factors characterising the analysed transport area, including economic, technical or environmental factors. This study presents an attempt at the semi-automatic routing of road corridors with the use of GIS technology. The original multi-stage methodology proposed by the present authors is based on raster analyses of the Digital Terrain Model at a resolution of 1 m. The initial stage consists in a preliminary outline of the road network being designed, which is performed by an experienced designer on a contour map. Due to the complicated terrain in mountain areas, the pre-determined road sections are divided into sections for which a generalised direction in the form of a straight line can be indicated. On the basis of the azimuths of these particular direction lines, “targeted” terrain inclinations are calculated for each section separately, which help in decisions concerning the location of the planned road sections. The results obtained indicate the key role of the initial concept of the designed road network, as outlined by the expert, and based on the expert’s professional experience. The problem lies in strongly varied terrain, which forces the designer to use short sections of corridors. This, in turn, significantly increases the amount of work. Good effects of road routing automation can be obtained in areas where land relief is complicated. The designed locations of road sections must be finally verified in terms of terrain inclination along the designated lines, which is essential for the possibility of subsequent detailed design, construction and use of road sections.

**Keywords:** mountain forest roads, raster analyses, GIS, automation of forest road routing

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## 1. Introduction

Making forest accessible should be understood as actions aimed at facilitating access to its specific parts in order to perform certain economic, protective or cognitive activities, as well as for the purposes of tourism and recreation. Such actions (making forest accessible) include the design and construction of traffic routes and technical infrastructure facilities where traffic will be adapted to the functions of these traffic routes and to the purposes of forest accessibility.

The first stage of road network planning in mountain forests consists of making an inventory of economic, natural and technical factors as well as the recognition of the degree of fire hazard, ownership relations and the possibility of connecting the forest road network in the transport area in question with public roads with adequate load-bearing capacity of the surface. While standard methods of data inventory are based on forestry-specific instructions [1], new satellite data [2], open for general use, as well as laser-scanning data [3, 4] may constitute promising sources of information. Making an inventory of the remaining factors is based on analyses of the content of thematic layers of the Digital Forest Map (DFM) [5].

The information obtained during inventory making and decisions on the density of the optimised network, including the future wood extraction technology, allow for the determination of the outline of the optimised road network and the functions of individual road sections [6]. This results in indicating the location of road corridors on the map (in the form of lines), along which, in a separate design process, specific road sections will be designed. It is important that each road corridor is designated in such a way that it is possible to make a detailed road design whose parameters are in accordance with the applicable technical standard, mainly concerning the possibility of maintaining the inclination of the gradeline within the permissible limits.

Proper planning of a road network that would make the forest accessible may be aided by analyses based on the standard contents of the Digital Forest Map (DFM) and the Digital Terrain Model (DTM) using GIS technology [7]. Support of this type of spatial decisions in GIS can be divided into: a) support implemented “manually” by the designer, mainly through interpretation and visualisation of the collected digital spatial data, and b) support aided, to a greater or lesser extent, by automated algorithms, including derivative maps, up to the total automation of the process.

The interpretation method is a simple analogy to the classic design methods, where the use of paper maps allowed an experienced designer to first plot a constant inclination line. This auxiliary line suggests the future course of a route, determining the selected longitudinal inclination (smaller than the one admissible for a given type of road in the technical standard). On its basis, the designer decides on the final arrangement of straight sections of the route and the parameters of horizontal curves at points of route direction change. The constant inclination line fulfills its auxiliary role if the route is not too far to the sides of this line and if it does not

run beside this line along long sections. Otherwise, in the subsequent design stages in mountainous terrain, this would generate large problems with maintaining the correct inclination of the gradeline and result in large volumes of earthworks such as excavations and embankments, and in the resulting large transport of soil during the implementation of the investment (costs). The longitudinal profile of the terrain, made along a properly designed route, will not contain "difficult places" for the proper design of the gradeline. Obviously, it must be understood that a mountain area is sometimes so complex that (in certain sections) the designer is unable to design a route while respecting all of the relevant principles. In such situations, after choosing the least complicated variant, the designer will try to reduce the problem in the gradeline design by means of larger excavations or embankments or even a locally exceeded longitudinal inclination. Taking into consideration the terrain, as well as the mutual location of the constant inclination line and the route on the contour line map, an experienced designer is able to minimise future earthworks by deciding on the arrangement of the gradeline under specific conditions. All these activities are determined above all by the applicable technical standards and the minimisation of investment costs [8], but it is very important (for natural and social as well as technical reasons) to minimise the interference of the construction with the local environmental system. For example: if we design and build a road in a deep trench in the flysch area with a complicated hydrological system, we will face serious technical and environmental problems. The environmental problem will consist in disrupting the local hydrological relations (drainage of the surrounding area, significant acceleration of the water cycle, increasing the water level dynamics in the stream draining the valley) and in very likely initiation of slope erosion in the form of landslides. The technical problem will concern unsuitable ground underlying the roadbed (difficult to stabilise and compact properly, with a possibility of landslides) and the need to use an advanced drainage system for the road body and surface.

The application of the Digital Forest Map standard in the State Forests has made it possible to work on digital data in the appropriate CAD and GIS software. This has given designers more options for varied data visualisation, dynamic scale adjustment, easy design of many variant solutions with the possibility of their immediate confrontation with combinations of any selected features of terrain and stands. This is facilitated by increasingly easier application of the growing resources of digital thematic maps.

Under the conditions of mountain forests with their complicated terrain, interpretative and semi-automatic methods are generally used, where the designer outlines the designed objects manually and in many variants, using the available digital maps and auxiliary analytical operations, by obtaining derivative maps and with the complementary use of different thematic layers of the GIS database [5, 9, 10]. In the iterative cycle, with the use of available GIS tools (QGIS Help), the designer controls the design process by assessing the effects of forest stand availability, fire protection, utilisation of available forest road network connections with

public roads and inclinations of the gradeline, as well as by means of quantitative and qualitative comparisons of objects encountered along the route. On this basis, it is possible to verify the initial tasks and to correct the course of one of the variants or eliminate it.

Under large-scale conditions, the initial concept of junctions can to a greater extent be supported by automatic methods, where on the basis of given boundary conditions the optimal paths or corridors are determined between the indicated objects or regions [11]. A new approach consists of taking advantage of large databases obtained from users (by tracking the routes of their movements), which facilitates the analysis of the functioning of the transport network and learning the algorithm of traffic connection optimisation [12]. In view of forest road design as a different philosophy, whose main goal is to make stands accessible, as compared to public road design, where the primary goal is to connect specific locations, it seems that the application of this group of methods – even in lowland forests, with regular area division – is limited only to indicating the course of roads with specific functions in the existing road network, e.g. strategic roads (major timber transport routes connecting neighboring forest districts) or fire escape routes.

The basis of algorithms implemented in GIS, where one of the main problems is the calculation of the shortest (cheapest, fastest, etc.) path, is graph theory. The most common algorithm that fulfils this task is Dijkstra's algorithm, which finds its application in GIS in network analyses carried out on a vector representation of spatial data (ArcGIS Help), but also in car navigation. Swarm intelligence, i.e. the ant colony optimization algorithm developed by Dorigo [13], is used experimentally. In GIS, in the case of raster representation of spatial data, friction maps are defined whose values correspond to connections between the vertices of a graph. The number of connections from a single cell and the method of virtual graph generation from raster data depends on the neighborhood pattern: "castle", "queen" and "knight" [14], whose names derive from the movements of chess pieces. The most common pattern used in the GIS software is the "queen" (ILWIS Help, Idrisi Help), less often the "knight" (GRASS Help). In the case of ArcGIS, the neighborhood pattern applied is not specified. There are also solutions that are not based on graph theory, such as the Idrisi Pushbroom algorithm [15]. Often, in practical applications, various available path algorithms are tested in raster analysis in order to select the right one for the given issue [16]. Cost analyses are most often of an isotropic character (equivalent to an undirected graph) in which the friction associated with moving over cells is independent of the direction. There are also anisotropic analysis algorithms (an equivalent of a directed graph with a double number of edges), in which local information about the direction and power of friction is additionally introduced, although particular solutions differ depending on the software [14]. The application of the concept of cost maps, with support in the form of a weighted linear combination, is used in issues of the routing of forest roads [17, 18].

## 2. Aim and Scope of the Study

The subject of the present study is the application of modern information technology in the design of forest road networks in mountain areas.

The aim is to present the possibilities and the desirability of using GIS tools in forestry design projects (tested in the conditions of the Beskid Wyspowy Mts), in particular in designing a road network in forests at the stage of decisions concerning the location of new road sections – in initial routing. The scope of the present study was limited to the stage of determining the course of road corridors (routing) following previous design stages, i.e. making an inventory of stands and of the existing road network as well as preparing an environmental and ground inventory of the transport area and technological classification of stands. Taking into consideration the literature data, terrain specificity and preliminary test results, the application of automatic routing methods by means of raster GIS tools was abandoned for the sake of semi-automatic routing.

The following software was used to carry out the analyses planned: QGIS 2.18.6 Las Palmas; ILWIS 3.4 Open.

## 3. Characteristics of the Research Area

The analyses were performed for the “Łopień” forest complex (Fig. 1), based on the information contained in the Digital Forest Map of Limanowa Forest District and the DTM with a pixel of 1 m. The area was treated as a single transport area due to the possibility of connecting the forest road network of this complex with public roads.

Łopień is the triple peak of the Beskid Wyspowy Mts; the height of the main peak reaches 951 m above sea level, and the lowest part of the analysed forest complex lies at 460 m above sea level. Steep and very steep slopes are dominant, although in areas near the ridges the inclination is very small: the average fall exceeds 17° (31%).

The climate of the region in which the studied transport area is located is pluvio-nival, shaped by the influence of the continental climate. The average annual air temperature ranges from 2.8°C in high mountains, to 7.4°C in the city of Limanowa and submontane areas. In accordance with Suliński's formula [19], the average precipitation in the analysed forest complex, with the peak coordinates N: 49°42', E: 20°16', ranges from 840 to 1089 mm depending on altitude. Precipitation reaches its maximum in the summer months and the minimum in the winter months. Snow cover is present from 85 to 140 days. The length of the growing season varies from 160 to 210 days [20–22]. Geologically, the area belongs to the Magurian nappe, which developed from Tertiary sandstones, shales and marls, and, to a lesser extent, chalk shales and sandstones [23].

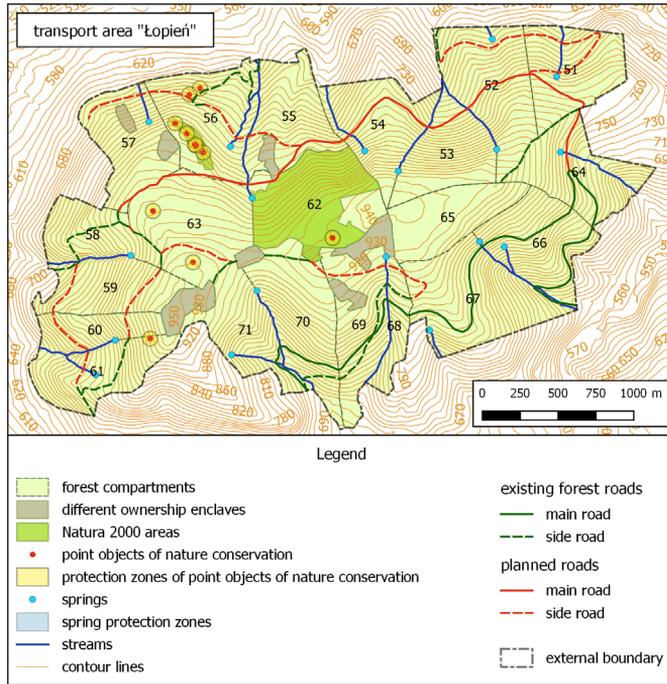


Fig. 1. Inventory of terrain factors important in the process of forest road routing

The described system of factors determines the conditions for the construction and use of roads in the area, modifying the physical characteristics of the local flysch soil. The influence of climatic and terrain factors is manifested in the need to use (or not use) more advanced construction and drainage technologies, appropriate machines, erosion protection, materials (exchange of loose soil, geosynthetics), as well as in the possibility of locating intersections and exits, or applying normative radii of horizontal and vertical arcs, and gradeline inclinations.

#### 4. Methodology

To achieve the intended goal, a sequence of analytical activities carried out within the transport area was determined (the "Łopień" forest complex, Fig. 1):

1. The creation of a vector layer containing objects in which no road routing will be carried out (different ownership enclaves, nature reserves, Natura 2000 areas, protection zones of nature protection facilities, stream springs and stream spring buffers, and landslide areas).
2. The creation of a vector layer containing the initial concept of an optimised road network (based on the contour system) including the determination of road functions and categories.

3. The creation of a vector layer with designed road network junctions. This process is based on the preliminary concept of a new road network, including restrictions in the course of roads (cf. point 1 of Methodology) and a contour map analysis. The arrangement of junctions should be adapted to the terrain because, apart from the connections of road sections, they will also indicate places where a road must significantly change its direction. Hereafter, sections will be understood as road fragments between designated junctions.
4. The creation of a vector layer containing direction lines between neighboring junctions, providing the azimuths of all lines (the direction of a line is consistent with the direction of wood transport). The lines should bear numbers in accordance with the numbers of the relevant road sections (Fig. 2).
5. Calculation, based on the DTM, of the altitude gradient, followed by the terrain inclination along the X axis. This is a single calculation, used in all further analyses (for each section) (Fig. 3).
6. Calculation, based on the DTM, of the altitude gradient, followed by the terrain inclination along the Y axis. This is a single calculation, used in all further analyses (for each section).
7. Calculation of "directed inclination" (i.e. in the direction determined by the azimuth of the direction line of a selected road section); on the basis of the inclinations determined along the X axis and the Y axis, according to one of the following formulas, depending on the quarter of the system in which the azimuth of the direction line is included: (1), (2), (3) or (4). The result is a raster layer containing the average inclination, weighted by the azimuth of the direction line  $A_k$ , as follows:

- for the azimuth  $[\circ]$  from the 1<sup>st</sup> quarter of the system:

$$iK(nr) = \frac{iY \text{ mod} \cdot (90 - A_k) + iX \text{ mod} \cdot A_k}{90} \quad (1)$$

- for the azimuth  $[\circ]$  from the 2<sup>nd</sup> quarter of the system:

$$iK(nr) = \frac{iY \text{ mod} \cdot (A_k - 90) + iX \text{ mod} \cdot (180 - A_k)}{90} \quad (2)$$

- for the azimuth  $[\circ]$  from the 3<sup>rd</sup> quarter of the system:

$$iK(nr) = \frac{iY \text{ mod} \cdot (270 - A_k) + iX \text{ mod} \cdot (A_k - 180)}{90} \quad (3)$$

- for the azimuth  $[\circ]$  from the 4<sup>th</sup> quarter of the system:

$$iK(nr) = \frac{iY \text{ mod} \cdot (A_k - 270) + iX \text{ mod} \cdot (360 - A_k)}{90} \quad (4)$$

8. The creation of a vector layer ultimately containing the routes of road corridors of all road sections (Fig. 4). The basis for the design of each corridor is constituted by an analysis of previously prepared layers containing: road network junctions (cf. point 3 of Methodology), design constraints (cf. point 1 of Methodology), topographic features in the form of contour lines (drawn on the basis of the DTM) and a specific layer containing a directed inclination, included separately when designing a specific road section (cf. point 7 of Methodology). The initial concept of an optimised road network can also be helpful (cf. point 2 of Methodology).
9. The creation of the longitudinal profile of the area for each designed road section corridor in order to check whether the obtained longitudinal inclinations remain within the limits of permissible inclinations as defined in the technical standard for roads of the planned category (Fig. 5).

### 5. Analysis of Results

The results of the individual steps of the methodology are provided below (Figs. 2–5). Due to the size of the present paper, maps related to specific sections of routed corridors are limited to two examples, numbered 1 and 6 (the remaining analyses: [24]). The contents of some of the maps have been combined.

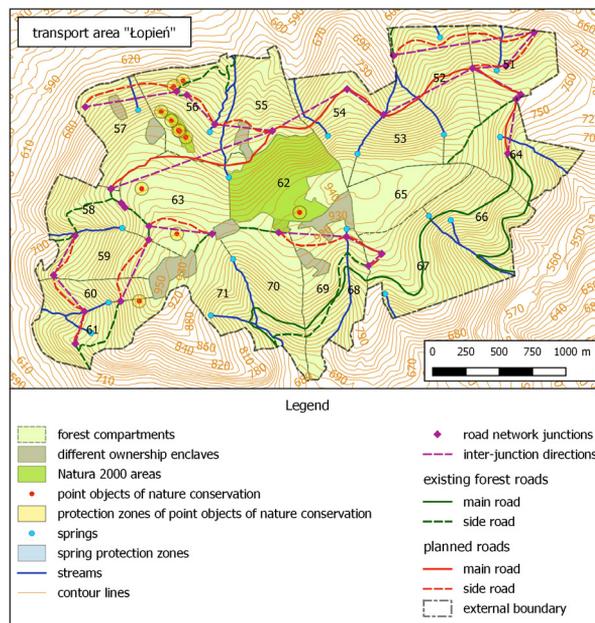
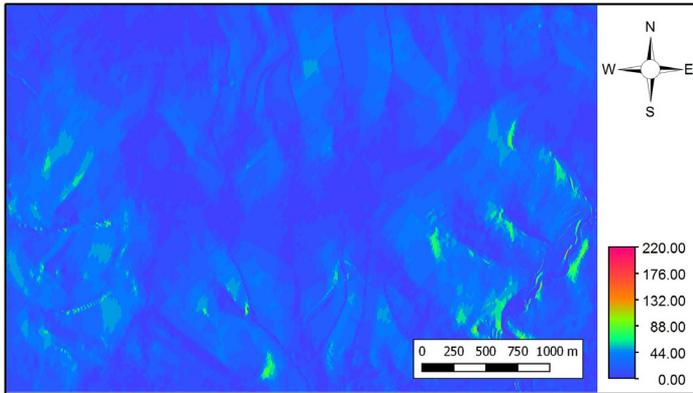
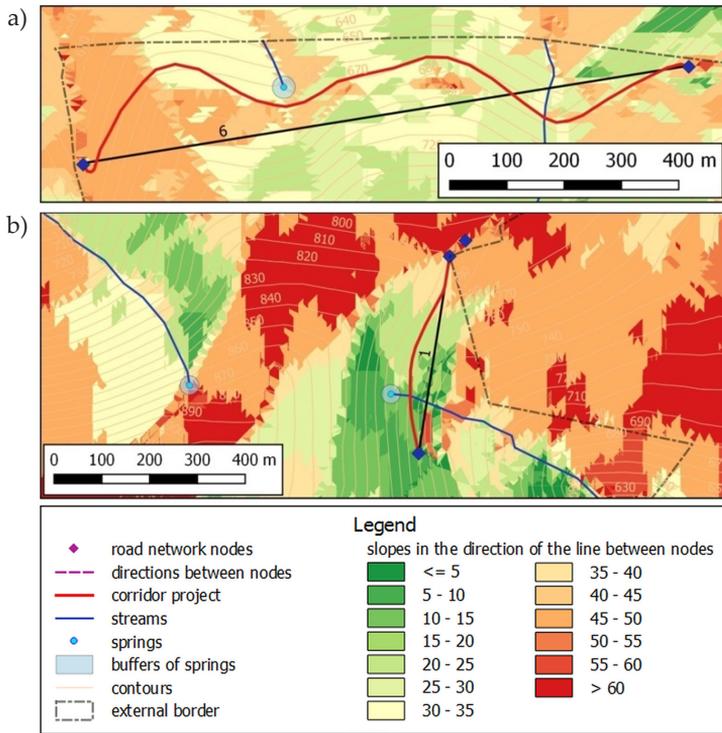


Fig. 2. Boundary conditions of the designed transport network (as a result of Methodology steps: 1, 2, 3 and 4). Performed using QGIS software

The azimuths obtained for all inter-junction directions, following from  $A_1$  to  $A_{22'}$ , amount to:  $188.9^\circ, 225.2^\circ, 118.6^\circ, 265.6^\circ, 220.2^\circ, 80.7^\circ, 62.3^\circ, 125.4^\circ, 60.7^\circ, 96.6^\circ, 136.4^\circ, 80.3^\circ, 70.1^\circ, 320.4^\circ, 96.9^\circ, 24.5^\circ, 15.9^\circ, 319.9^\circ, 28.2^\circ, 93.7^\circ, 115.6^\circ, 227.8^\circ$ .



**Fig. 3.** Calculation, based on the DTM, of terrain inclination along the X axis (as a result of Methodology step 5). Performed using ILWIS software



**Fig. 4.** Determination of the designed corridors (as a result of Methodology step 8). The results obtained for the section: a) No. 6; b) No. 1. Performed using QGIS software

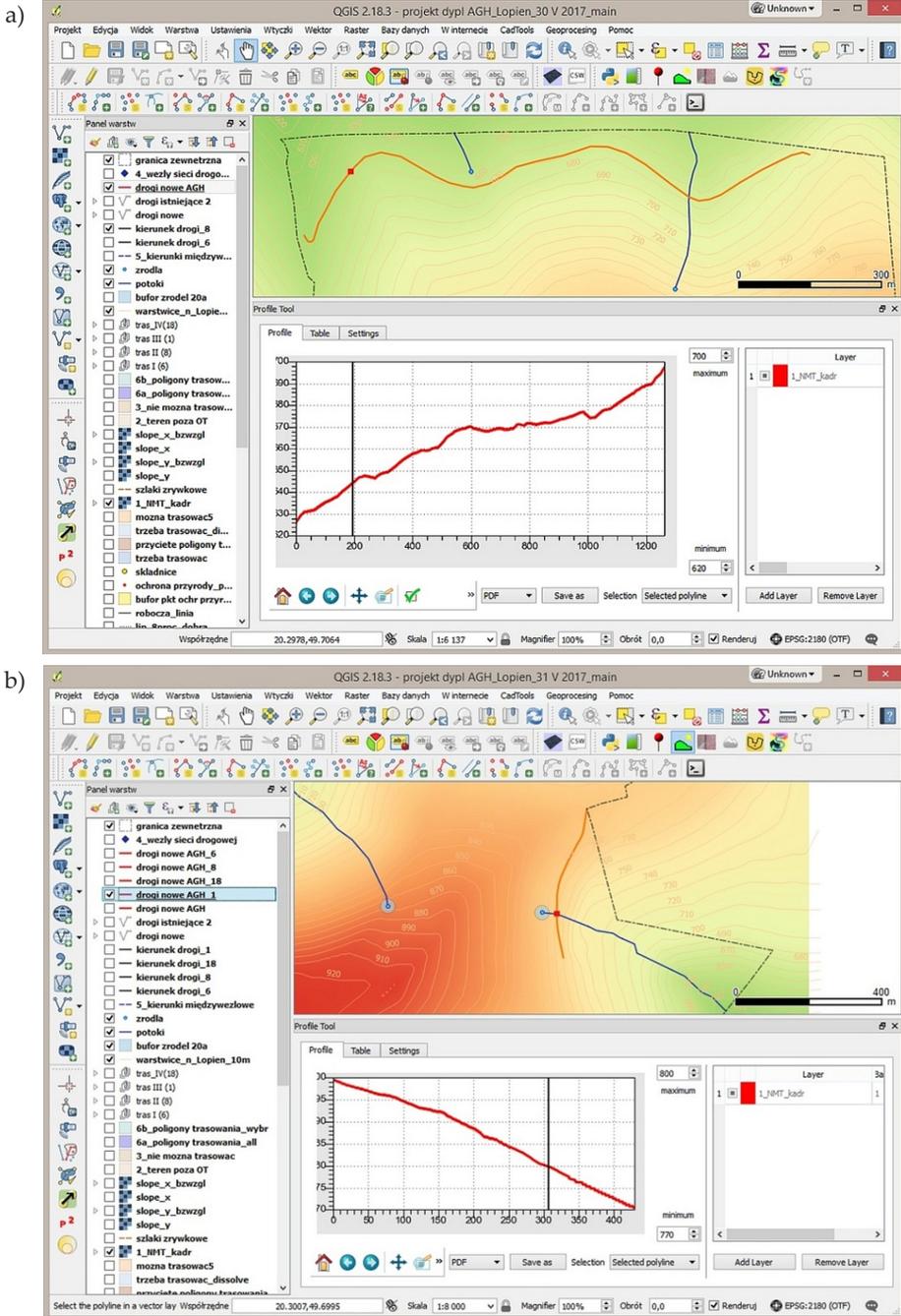


Fig. 5. The longitudinal profile of the terrain along the corridor (as a result of Methodology step 9): a) for corridor No. 6:  $i_{mean}$  12.13%,  $i_{max}$  48.95%,  $i_{min}$  0,09%; b) for corridor No. 1  $i_{mean}$  9.90%,  $i_{max}$  46.46%,  $i_{min}$  0.12%. Performed using QGIS software (the "Profile tool" plugin)

## 6. Summary and Conclusions

During the initial analyses based on the available literature [25–30], the application of a raster data model was considered for the purpose of obtaining the automatic determination of optimal “paths” by means of multi-criteria analysis and cost analysis and, ultimately, a forest road network. However, the experiments performed did not provide results that would justify the effective application of those methods in the selected research area. The main reason is the degree of engineering detail in the conducted analysis, which is in contradiction with the main application of the automatic designation of corridors meant to support the designer at the stage of preliminary, conceptual and multivariant tasks, usually carried out over a large area, taking into account a number of different factors, not only technical ones [10, 11]. At the design stage, at such a level of detail, the already determined plans of road courses are re-evaluated with the help of automatic GIS algorithms [17, 18].

Another reason should be identified, namely the unique nature of the forest road network. An experienced designer, guided by specific principles, may accord preferences to specific ground or hydrological conditions during an automation attempt by diversifying resistance values in such places, and even introduce a barrier, e.g. in protected areas. However, the terrain is usually the key factor in road routing. Such problems have been encountered, for example, in determining potential corridors of the course of railway lines, where authors have decided to base their cost analysis on the contour map and achieved the intended result [11]. Such an action makes sense in the design of roads at the conceptual stage, in the design of roads with a small permissible inclination and in the design of railway routes. However, the roads designed in the present study on forest slopes, in accordance with their specificity [8], have to fulfil the function of making stands accessible over the entire slope (rather than just connecting two points in the area at the least costs) and therefore they cut through entire slopes from valley bottom zones to mountain ridges. The technical standard that is in force in designing the roads of these categories recommends the maximum gradeline reduction of 9% (in exceptional cases and short sections: 12%), but this is also related to the functions of a particular road section in the network and the type of traffic. Unfortunately, these factors could not be taken into account in the tested friction maps. Therefore, the analyses performed were based mainly on inclinations and the terrain, with semi-automatic GIS support.

The analysis of the obtained results of road routing highlights the key role of one of the first steps of this activity, namely the creation of the initial concept of an optimised road network, preceded by in-depth research into the ownership, stand, environmental, hydrological and ground conditions as well as the terrain. It is this concept that constitutes the basis of the selection of junctions and the determination of inter-junction directions and their azimuths. It should be added here that the local

terrain has a very strong influence on the final results of analyses via decisions on the location of junctions: varied land relief thickens their arrangement (e.g. directions 21 and 22, Fig. 2), which significantly increases the amount of work, while reducing the number of junctions (rare distribution, e.g. directions 6 and 13, Fig. 2) excessively generalises inter-junction directions and thus strongly limits the use of subsequent raster analyses. This observation is confirmed by the situation presented in Figure 4a (junction direction 6), where the large distance between the junctions, accompanied by varied land relief, enforces the routing of the corridor of this section along a course that is completely different from the one indicated by the inter-junction direction. In this case, the role of the main factor determining the arrangement of the corridor route is taken over by the layout of contour lines, because inclinations along the inter-junction direction reach unacceptable values for this road category ( $i_{\text{mean}} = 18.5\%$ ,  $i_{\text{max}} = 55.4\%$ ). This undermines the desirability of performing the assumed analyses.

A certain pattern becomes visible: the obtained large intersection angle of an inter-junction direction with contour lines generates large land inclinations along this line and the need for a significant departure of the road section being routed from the general direction.

Therefore, it is necessary to control the inclinations in the longitudinal profile of the corridors being routed, so that the road sections designed on their basis (detailed designs) can run in accordance with these corridors, while preserving parameters within the limits allowed by the technical standard. Exceeding those inclinations only slightly and locally can be solved in a detailed design by a slightly different route arrangement in a given place or compensated by suitable earthworks (excavations and embankments), while finding too large inclinations over long distances usually requires immediate re-routing of a given corridor, followed by verification.

In particular, it is believed that:

- Automation of road routing in mountain areas with distinct land relief encounters a number of general difficulties (e.g. the quality and validity of data contained in the DFM as well as DTM resolution) and specific problems (e.g. frequent changes of the route of roads on forest slopes, the need to provide access to entire slopes, or exclusion from the area intended for routing an entire range of areas exempted from engineering activities).
- The basic stage of the routing of the corridors of forest slope roads consists in preparing a preliminary concept of a road network, based on the contour system.
- The location of road network junctions, without adjusting the distribution of these points to the terrain and at excessively large distances, may result in little (or even no) usefulness of raster analyses performed in subsequent stages of the procedure. On the other hand, excessively dense distribution of road network junctions generates too great an amount of work and its low efficiency.

- A small intersection angle between an inter-junction direction and contour lines yields remarkable results (line no. 1, Fig. 2) and facilitates route location decisions, but under such hardly complicated terrain conditions that the use of an extensive, multi-stage raster analysis (e.g. analysis of anisotropic costs) is ineffective.
- It is necessary to control the terrain inclination along road corridors being routed and to conduct ongoing correction of their course if the admissible inclinations are exceeded.

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## Próba automatyzacji trasowania leśnych dróg górskich z wykorzystaniem analiz przestrzennych GIS

**Streszczenie:** Trasowanie korytarzy drogowych w projekcie sieci dróg leśnych w górach, z określeniem funkcji tych dróg, jest najważniejszą czynnością w całym projekcie. Musi ono być poprzedzone szczegółową inwentaryzacją bardzo wielu czynników charakteryzujących opracowywany obszar transportowy, w tym: gospodarczych, technicznych czy przyrodniczych. W pracy pokazano próbę półautomatycznego trasowania korytarzy przy wykorzystaniu technologii GIS. Zaproponowana autorska, wieloetapowa metoda opiera się na analizach rastrowych numerycznego modelu terenu o rozdzielczości 1 m. Etapem

wyjściowym jest wstępny zarys projektowanej sieci wykonany przez doświadczonego projektanta na mapie warstwicowej. Ze względu na skomplikowaną rzeźbę terenów górskich wstępnie wyznaczone odcinki dróg dzieli się na fragmenty, dla których można wskazać uogólniony kierunek w postaci linii prostej. Na podstawie azymutów tych właśnie linii kierunkowych wyliczane są (dla każdego odcinka osobno) „ukierunkowane” spadki terenu (wzdłuż tych linii), które pomagają w decyzjach lokalizacyjnych projektowanych odcinków dróg. Uzyskane efekty wskazują na kluczową rolę wstępnej koncepcji projektowanej sieci, zarysowanej przez eksperta. Problemem jest silnie urozmaicona rzeźba terenu, która zmusza projektanta do stosowania krótkich odcinków korytarzy, przez co znacznie zwiększa się ilość pracy (niska efektywność procedury). Dobre efekty automatyzacji trasowania można uzyskać w terenach o mało skomplikowanym reliefie. Zaprojektowane lokalizacje odcinków dróg muszą być jeszcze ostatecznie sprawdzone pod względem spadku terenu wzdłuż wyznaczonych linii, co ma zasadnicze znaczenie dla możliwości późniejszego szczegółowego zaprojektowania, wybudowania i użytkowania odcinków dróg – spadki niwelety muszą się mieścić w granicach dopuszczonych normatywem technicznym dla tych kategorii dróg.

**Słowa**

**kluczowe:** górskie drogi leśne, analizy rastrowe, GIS, automatyzacja trasowania