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Possible Applications of Spatial Analyses in Designing the Agricultural Road Network with Particular Consideration of the Environmental and Landscape Aspects

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Abstract. The development of the agricultural road network is a complex activity based on a broad range of criteria necessary to be taken into account during analyses and desk studies. The analyses and design solutions cannot be unilateral, considering only technical and economic aspects. Elements of environmental protection and management of agricultural landscape, as well as solutions in the scope of protection of soils and waters are necessary in this type of design works, and result from solutions accepted for implementation in reference to the rural areas of all Member States of the European Union. Such a multi-aspect process requires the use of tools in an environment which technologically permits the development of multi-variant solutions to a given problem, and selection of a single, most appropriate proposal. Geographic Information Systems (GIS) currently constitute such an environment. Their undeniable advantages include their analytical possibilities which can be formalised in the form of developed models of spatial analyses – creating sets of new, ready to use tools supporting the decision making process in the scope of determination of the optimal course of agricultural roads. Additional advantages are the possibility of integration of data obtained from various sources, and presentation to stakeholders (e.g. residents, farmers, local authorities, entrepreneurs, and investors) of the obtained solutions in the form of maps, almost in real time, as well as possibility of making optimum decisions with their active participation. Easier access to GIS technology and systematically growing level of awareness regarding measurable benefits from the application of this type of solutions should also be emphasised. The article presents examples of spatial analyses allowing for relatively fast obtaining of spatial information necessary for efficient design-related decision making for the purpose of improvement of the system of agricultural roads with particular consideration of environmental and landscape aspects.

Keywords: spatial analyses, agricultural road network, environmental protection.

Conference topic: Technologies of Geodesy and Cadastre.

Introduction

Transport is commonly known to play an important role in rural areas. Together with the development of modern means of transport, machines, and tools, its role is becoming increasingly significant. Such development must be accompanied by the modernisation and transformation in rural areas of the road network, the poor technical state of which makes it difficult, and sometimes impossible to efficiently use means of transport used by particular agricultural farms. Striving for the maximisation of technical and economic effects is important, but not sufficient for the proper development of the agricultural road network. Elements of nature protection and agricultural landscape development, as well as solutions in the scope of soil and water protection are equally important, and result from the principle of sustainable development of rural areas. Therefore, the location, functionality, and accessibility of agricultural roads should constitute a resultant of several factors (Krupowicz 2016):

a) of technical and economic character:
- longitudinal inclination of the road,
- soil and water conditions of the substrate of the road surface structure,
- type of road surface,
- development of the agricultural production space,
- location of agricultural road in land relief,
- urgency of paving of ground-surface agricultural roads.

b) with environmental and landscape character:
- legal forms of nature and landscape protection,
- resistance of soils to pollution from traffic,
- protection of soils,

– threat of soil erosion by surface waters,
– areas of direct protection of surface and groundwater intakes,
– areas of inland surface waters,
– areas of direct flood threat,
– strengthening of the agricultural-forest boundary,
– aesthetic and landscape values.

The criteria presented above illustrate a broad range of issues necessary to implement during analyses and desk studies in the scope of location and design of agricultural roads. With such a high number of various criteria in the scope of road engineering, surveying, and environmental protection, it is necessary to use tools in an environment which makes it technologically possible to develop multidimensional solutions to a given problem and selection of a single, the most approperiate proposal minimising the negative effect of the investment on the surrounding space. Geographic information systems currently constitute such an environment (Demirel *et al.* 2008; Longley *et al.* 2005; Malczewski 2004).

The basic functions of GIS include the collection, gathering, processing, analysing, disclosure, and visualisation of data on the actual world (space). From the point of view of development of agricultural roads, one of the most important functions of GIS are spatial analyses performed through the application in the scope of the GIS system of analytical operations (statistical, mathematic) with different degrees of complexity on spatial data of different forms referred to objects of one or many information layers (Chmiel 2013). Information obtained as a result of analyses can be presented in the form of legible thematic maps, which undoubtedly supports the decision making process and is an important and efficient opinion-forming tool allowing for a broader outlook exceeding individual interests.

The article presents examples of spatial analyses allowing for relatively fast obtaining of spatial information necessary for efficient making of design decisions for the purpose of improvement of the layout of agricultural roads with particular consideration of environmental and landscape aspects.

Literature review

Results of analyses depend not only on the spatial location of objects, but also on the accuracy, credibility, completeness, and validity of data. Due to the complexity of the process of development of agricultural roads, a considerable number of various source data is collected regarding the land, objects forming rural space, and road network, such as: cadastral data base, data base of topographic objects, digital terrain model, orthophotomaps, road network maps, soil and agricultural maps, geological maps, maps of surface and groundwaters, maps of protected areas, maps of flood threat, planning documentation, photographic documentation from conducted inventory, and other data directly related to the analysed area. It is important for the data to have a logical structure and be subject to relevant verification and update to permit their integration, and then their comprehensive analysis and visualisation of results. It should be emphasised that proper visualisation of results of analyses is of high importance at the stage of spatial communication in the case of proposed changes in the transport system aimed at the facilitation of the daily functioning of agricultural farms.

The most important categories of spatial analyses performed in the GIS environment, useful in the process of development of the agricultural road network, include:

– simple spatial analyses based on overlapping, intersecting, and combining thematic layers, determining buffers zones based on the condition of distance or contiguity of the analysed objects, or search of objects through their selection in given areas, e.g. selection of agricultural plots with no access to a public road (e.g. Krupowicz 2016),
– analyses based on the application of data of the digital terrain model, e.g. precise adjustment of the course of the road to the land relief (e.g. Wawer 2004; Shrestha *et al.* 2014),
– multi-criteria comparative analyses involving the selection of the best variant of the course of the road among alternatives explicitly provided at the preliminary stage, in the context of coherence of the planned route with the existing structure of the land, minimisation of construction costs, or environmental impact (e.g. Geneletti 2005; Kalamaras *et al.* 2000; Vermote *et al.* 2013),
– multi-criteria analyses of land usefulness involving the determination of the optimal course of the road based on the assessment of the validity of criteria considered for such a purpose, sometimes mutually excluding (of technical, economic, legal, or environmental and landscape character) and preferences of the decision-making parties (e.g. Klungboonkrong, Taylor 1998; Krupowicz 2016),
– network analyses permitting the development of a map of temporal accessibility of the road network or determination of the shortest route of access from economic centres to agricultural roads (e.g. Bielecka, Filipczak 2010; Radziszewska, Jaroszewicz 2012),
– cost analyses concerning the determination of the optimal road connection (with the lowest cost) between a given surface object and existing road section, with the application of the raster model of data (e.g. Chmiel *et al.* 2013; Mahini, Abedian 2014).

Research methodology

The literature on the subject (e.g. Malczewski 1999; Malczewski, Rinner 2015) points to very high importance of multi-criteria spatial analyses in decision making processes in various areas of application. In considerable generalisation, spatial analyses considering a group of criteria in decision making can be understood as a process of combining and processing of source geographic data corresponding with the considered criteria in the resulting decision map. Such analyses permit the consideration of not only the values of particular criteria, but also preferences of the decision making party (or parties) concerning particular groups of criteria. This way, the obtained result depends not only on the spatial distribution of the values of the considered criteria, but also on the value of assessments incorporated into the decision making process. Therefore, the multi-criteria character of analyses finds broad application in the determination of optimum locations of road investments, where the key factor affecting the decision making process is the social factor and environmental solutions the characteristic feature of which are numerous correlations and mutual influences. The further part of the paper presents an example application of multi-criteria analysis of land usefulness in the GIS environment for the purposes of location of new roads, and taking a decision on the fate of the existing roads in the scope of the occurring environmental and landscape limitations dependent on the specificity of the study area. The procedure of the course of analysis was described in Table 1.

Table 1. Stages of multi-criteria implementation of the analysis of usefulness in GIS environment

SOURCE DATA 1 MAPS OF CRITERIA	– collection and processing of source data, – development of maps of criteria, – standardisation (normalisation) of values of criteria, – development of maps of normalised values of criteria.
MAPS OF CRITERIA 2 MAPS OF GROUPS OF CRITERIA	– combining criteria in the mixed approach (WLC – Weighted Linear Combination method), – development of maps of land usefulness for particular groups of criteria.
MAPS OF GROUPS OF CRITERIA 3 PRIMARY GOAL	– development of a map of land usefulness for the primary goal.
PRIMARY GOAL 4 SOLUTION - MAP OF RECOMMENDATIONS	– development of a map of recommendations presenting the classification of land by degree of its usefulness for the purposes of the construction and transformation of the agricultural road network.

In the spatial approach to the multi-criteria analysis, criteria related to geographic objects and correlations between them can be represented in the form of raster maps. In such a situation, each criterion constitutes a separate class of objects (layer) in the GIS data base. A class of objects (layer) constituting a response to the data of the criterion is called a map of the criterion. Two basic types of maps of criteria are distinguished, namely barriers and factors. A barriers map of criterion represents limitations imposed on decision making variables. Barriers exclude specific surfaces of objects from the area subject to the decision making problem (e.g. surface waters) which are unacceptable for the implementation of the specified goal. Barriers have a character of "sharp" criteria, i.e. they have binary solutions – "0" (false) or "1" (true). A factors map of criterion constitutes a single GIS layer representing values of an attribute distributed in the geographic space. It results from the geoprocessing of source data and their analysis in GIS. Data are collected in the GIS spatial data base, and then subject to processing in order to obtain information concerning a specified criterion. Such criteria are of "fuzzy" character – the degree to which the basic goal can be achieved changes in a continuous way in a given interval.

Maps of criteria can have values of attributes expressed in various measurement scales (quantitative, ordinal, or qualitative) and in different units. At the second stage of the analysis of the map of criteria, the resulting maps are combined. Such an operation is not possible if the compared (combined) values are variable, e.g.: distances expressed in meters changing in different scopes, types of agricultural land expressed in the classification (qualitative) scale, etc. The introduction of variable data to a common analysis requires the stage of their standardisation (normalisation) to interval [0;1] based on relevant classification rules. The reclassification of values of rasters should reflect weights of particular criteria. At this stage, values of weights for "fuzzy" criteria (factors) should be used.

The most common methods of determination of weights of criteria include (Malczewski 1999): the method of sum of ranks, methods of inversion of ranks, methods of awarding points, method of estimation of factors, or method of paired comparison developed by Thomas L. Saaty (Saaty 1994). In the simple approach, weights can be determined based on the knowledge and experience of the person performing the analysis, or based on the preferences of the decision making parties.

After the preparation of maps for each elementary criterion, they should be appropriately combined for the purpose of obtaining the resulting maps of land usefulness for particular groups of criteria. Combining "fuzzy" (with continuous scale of usefulness in interval [0;1]) and "sharp" criteria (constituting images with values of pixels of 0 or 1) involves the application of the WLC method. The final effect of the second stage of the analysis are raster maps corresponding to the number of defined groups of criteria with values of pixels equal to the sum of products of values of criteria and weights introduced to the analysis, and values of "sharp" criteria (barriers).

At the third stage, source data are raster maps of usefulness of land for particular groups of criteria. The resulting map includes values determined as a sum of products of values from source maps of particular groups of criteria and the ascribed weights.

The result of the analysis is a raster image presenting degrees of usefulness and limitations and exclusions of land for the purposes of location of new elements of the road network in rural areas and corrections of the course of its existing elements.

Study results and discussion

The procedure of the multi-criteria analysis of usefulness in the scope of development of the agricultural road network was implemented based on the example of the Harta village located in the southern part of Poland. The Harta village is characterised by diverse land relief, intensive soil erosion processes, dense network of access roads to fields, and excessive fragmentation of arable land. Due to the correlations and interactions between the aforementioned elements, the development of the road network in the study area is a difficult process, and it should occur in multiple dimensions based on the multi-criteria analysis. For this purpose, relevant criteria were selected concerning:

A. Technical and economic conditions:
- A1. Longitudinal inclination of the road.
- A2. Soil and water conditions of the substrate of the road surface structure.
- A3. Type of surface.
- A4. Location of agricultural roads in land relief.

B. Environmental and landscape conditions:
- B1. Soil quality.
- B2. Resistance of soils to pollution from traffic.
- B3. Threat of surface water erosion of soils.
- B4. Distance from the boundary of forest complexes.

The group of criteria also includes a group of barriers resulting from the provisions of common and local law, i.e.: forests, protected soils, land occupied by trees and shrubs on arable land, areas of direct protection of surface and groundwater intakes, areas of inland surface waters, landslides and areas threatened with mass movements, minerals, objects of protection of cultural and historical protection, built-up and urbanised land.

As a result of processing of data and their analysis in ArcGIS software, each elementary criterion was presented in the form of a raster map. Eight maps of values of "fuzzy" criteria (factors) were obtained, as well as nine maps of values of "sharp" criteria (barriers). Then, standardisation (normalisation) of values of "fuzzy" criteria was performed to interval [0;1] with the application of relevant rules of reclassification (Reclassify tool in ArcGIS software). The results of the reclassification process were presented in Fig. 1.

Combining of "fuzzy" and "sharp" criteria was performed in accordance with the WLC formula with the application of map algebra (Raster Calculator tool in ArcGIS software). As a result, two raster maps were obtained (Fig. 2) with values of pixels corresponding to the sum of products of values of criteria respectively from groups of technical and economic character and of environmental and landscape character and weights introduced to the analysis, as well as values of barriers.

The final effect is the map of usefulness of land for the primary goal with values determined as a sum of products of values from source maps of particular groups of criteria and the ascribed weights (Fig. 3).

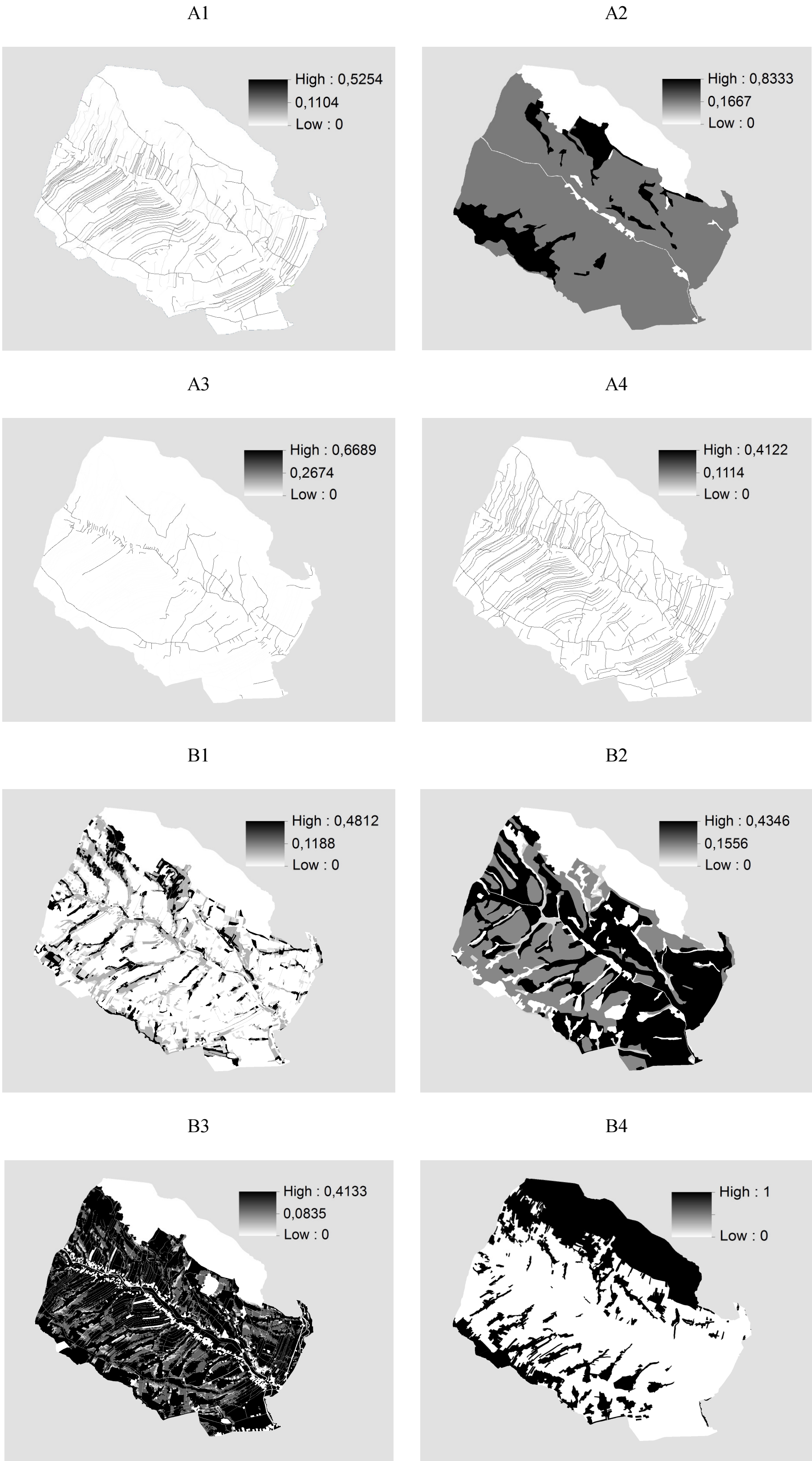


Fig. 1. Maps of normalised values of criteria of technical and economic character (A1, A2, A3, A4) and of environmental and landscape character (B1, B2, B3, B4)

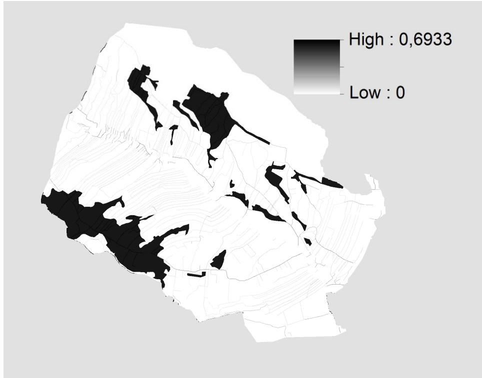
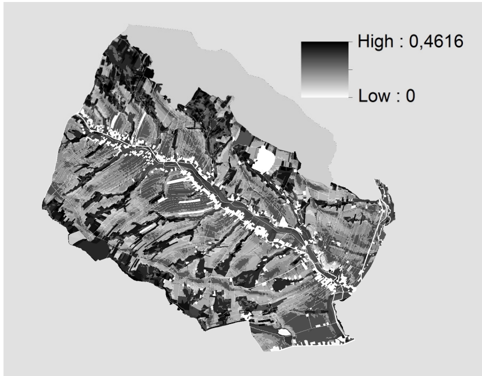
Equation	Result
A = (A1*0.0420) + (A2*0.5683) + (A3*0.1446) + (A4*0.2450) + barriers	
B = (B1*0.2066) + (B2*0.0517) + (B3*0.6578) + (B4*0.0839) + barriers	

Fig. 2. Maps of values of groups of criteria of technical and economic character (A) and of environmental and landscape character (B)

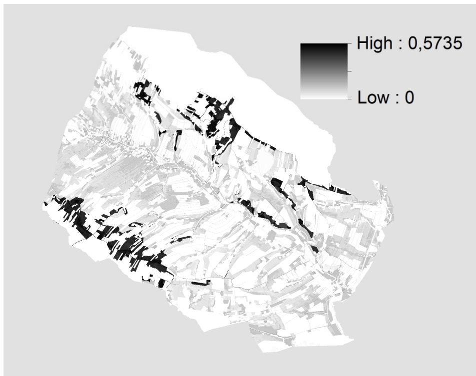
Equation	Result
Primary goal = (A*0.7500) + (B*0.2500)	

Fig. 3. Map of usefulness of land for the primary goal

The result of the analysis is a map of recommendations (Fig. 4) prepared based on the map of usefulness of land for the primary goal. The map of recommendations shows degrees of usefulness as well as limitations and exclusions of land for the purposes of development of the road network in rural areas in accordance with the following classification:

- degree 1 – land useful with no limitations, change of location of the existing roads not required;
- degree 2 – moderately useful land, change of location of the existing roads moderately urgent, recommended paving of dirt roads and strengthening of surface drainage facilities;
- degree 3 – weakly useful land, change of location of the existing roads recommended, urgent need to pave dirt roads and strengthen surface drainage facilities;
- degree 4 – useless land, change of location of the existing roads very urgent.

The intervals (classes) defining particular degrees of usefulness were determined based on the analysis of distribution of the analysed variable. For this purpose, the Naturale breaks classification method was applied (ArcGIS software) which permitted the determination of thresholds of classes allowing for grouping similar values and maximisation of differences between classes. Pixels of the raster were grouped in classes, the thresholds of which were determined where relatively high differences exist between their values.

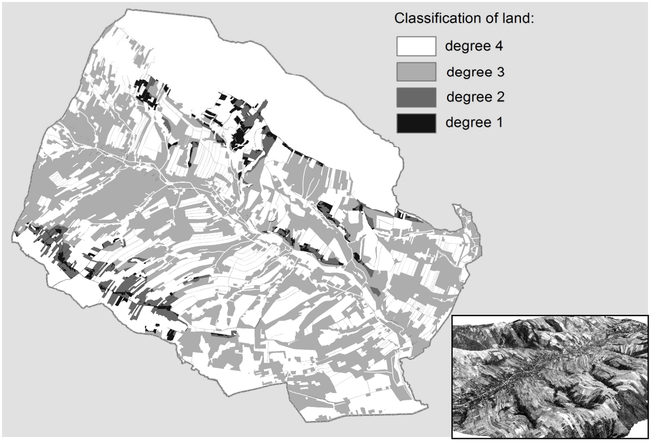


Fig. 4. Resulting map of recommendations

Conclusions

The efficient making of design decisions in the scope of improvement of the layout of agricultural roads is particularly facilitated by spatial analyses, including multi-criteria analyses, as confirmed by the results of the performed research. Through the appropriate analysis based on accurately selected data, spatial information necessary for efficient management of the road network was obtained relatively fast (in one calculation process). Such a determination of land useful for the construction of new road sections, and useless, where sections of the existing roads are the most prone to degradation, contributes to proper management of financial resources and their allocation where they can generate sufficiently significant and permanent effect. Therefore, the process of development of the agricultural road network in the GIS software becomes faster, more accurate, and more efficient than the traditional design method. It also considers the requirements of sustainable development of rural areas. Moreover, it provides the possibilities of visualisation of the obtained solutions in the form of maps, and possibilities of making final decisions with active participation of stakeholders.

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