CARTOGRAPHIC MODELLING OF TERRAIN RELIEF USING COMPUTATIONAL INTELLIGENCE METHODS

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Abstract

The discussed research works aimed at development of methodology of terrain relief modelling by means of DTM generalisation, using selected methods of computational intelligence (CI): artificial neural networks and fuzzy inference systems. This allowed to develop the knowledge base on cartographic methods of terrain relief generalisation, basing on two diversified approaches:

- Using methods of machine learning (*implicite* methods), which comprise gaining of examples of correct solutions in the field of terrain relief generalisation,
- Defining disclosed, however intentionally „fuzzy", rules of terrain relief generalisation (*explicite* methods).

Artificial neural networks are the example of the first approach – the *NEURO* method, and fuzzy inference systems – the *FUZZY* method, are the example of the second approach. Utilisation of both proposed approaches allowed for comparison of results. The proposed methodology also enabled to develop automatic generalisation of the Digital Terrain Model as a method of generalisation of terrain relief forms, and not as simplification of contours.

The author proposed two independent methods of generalisation of the Digital Terrain Model, using a regular GRID model and an irregular network of triangles, TIN, as the source of data. In both cases, the inference engine is the knowledge base, using methods of computational intelligence. Depending on a way of knowledge acquisition and on types of its formal presentation in the knowledge base, the computational system is based on utilisation of artificial neural networks (*implicite* given knowledge as a set of correct examples of solutions) or on fuzzy inference (*explicite* knowledge determined in the form of open fuzzy rules, using the, so-called, linguistic variables and membership functions). The duality of the proposed solution allows not only for diversification of a method of acquisition and representation of cartographic knowledge, which is required for automation of the generalisation process; it also allows for objective comparison of obtained results.

With respect to matrix data generalisation (the GRID model) the author proposes a non-linear variant of the global filtration, using the multi-feature *NEURO* or *FUZZY* knowledge base. Following the author's opinion, this solution allows for delineation and consideration of morphological in the modelling process, despite the lack of openly determined structural lines.

In order to generalise the irregular TIN model, an iterative, self-evaluating algorithm of elimination of model points, basing on the multi-criteria analysis of decision surfaces, was proposed. At the expense of computational time, this approach allows to check geometric errors, to maintain topology of structural lines of terrain relief and generalise geomorphological forms, according to the rules of cartography (Wilson, 2000).

Previous methods of generalisation of elevation data were mainly connected with the use of the, so-called, global filtration method (linear, e.g. Gauss filtration, or non-linear, e.g. median filtration) for the needs of generalisation of the Digital Terrain Model, stored in the regular GRID structure. The proposed solutions, based on computational intelligence algorithms, allow for generalisation of elevation data, which are specified both, in the GRID, as well as in the TIN structure (Gotlib, 2005; Kochman, 2005).

The author has also proposed a generalised, multi-parametric algorithm of iterative, local filtration of the TIN model, which allows for self-evaluation of obtained results. Performed research works also included the definition and maintenance, in the process of generalisation, of chains of spatial integrity between the structural elements of terrain relief and the idea of creation of a hierarchical TIN model. This model may have a mono-scale representation at a user defined reference level.

The obtained results prove that the proposed algorithms and computational systems (the knowledge base and the computational engine) allows to achieve the resultant model of terrain relief with the user defined geometric accuracy. This model is also correct from cartographic point of view. The geometric accuracy of the resultant model is considerably better that the DTM accuracy generated by means of conventional, global filtration methods.

The proposed methodology of cartographic modelling allows for automation of generalisation, with maintenance of its subjectivity.

1. Introduction

The objective of performed research works was to propose the methodology of cartographic modelling, which would allow for automation of the generalisation process with maintenance of its subjectivity. Performed works concern the issue of the multi-scale modelling of the terrain relief, however, they allow for formulating much wider hypotheses. At present, the elevation information is mainly recorded in spatial databases, in the form of the Digital Terrain Model (DTM) of the topological (TIN) or regular (GRID) structure (Butowtt, 2007; Li, 2005). Modification of information recording, resulting from the technological development, does not influence the methodology of cartographic modelling of the terrain relief at various levels of generalisation. The basic feature of generalisation of the terrain model should be the maintenance of its structure (the morphological skeleton). This allows for development of a model at the defined generalisation level, a model, which would be adequate with respect to information and semantic aspects, because cartography is a methodological science about modelling and visualisation of time and spatial information structures (Makowski, 2005). Therefore, development of the cartographic model may be equated with the generalisation process, understood as generalisation of geographic information, adequate for the objective and destination, which presents the essence of assumed goals.

Modelling of geographic information, including cartographic modelling, may be performed in many ways, which differ with respect to the accepted methodology, as well as the level of automation of the modelling process itself. Thus, the challenge of contemporary cartography is to answer the question, how to reconcile the subjectivity of the cartographic modelling process with its automation.

Following the author's opinion, it is possible to find a compromise solution using the so-called, *computational intelligence* (CI) methods (Poole, 1998), and, in particular the *machine* *learning* (ML) (Winston, 1992) techniques and *data mining* (DM) Fayyad (1996). This solution comprises a specific „transfer" of subjective cartographic knowledge to a digital tool, which will determine the adequate method and its parameters, in the process of spatial data modelling at the given level of generalisation.

2. Methodology

The objective of performed research works is to develop the methodology of the terrain relief modelling by means of generalisation of the DTM, using selected methods of computational intelligence: the artificial neural networks and the fuzzy inference systems (Zadeh, 1965). This will allow for development of the knowledge base on cartographic methods of generalisation of the terrain model, basing on two different approaches:

- Using machine learning methods (**implicite methods**) comprising selection of examples of correct solutions in the field of the terrain relief generalisation,
- Using openly defining, however intentionally "fuzzy" rules of the terrain model generalisation (**explicite methods**).
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The examples of the first approach are artificial *neural networks* – the *NEURO* method, and examples of the second method are *fuzzy inference systems* – the *FUZZY* method. Utilisation of both proposed approaches will allow for comparing obtained results.

The author proposes two independent methods of generalisation of the terrain model, which utilise – as the data source – the regular GRID model and the irregular network of triangles, TIN. For both cases, the *inference engine* is the knowledge base, using the computational intelligence methods. Depending on the way of knowledge acquisition and types of its formal representations in the knowledge base, the computational system is based on utilisation of artificial neural networks (the *implicite* knowledge existing as a set of correct examples of solutions) or the fuzzy inference (the *explicite* knowledge determined in the form of disclosed fuzzy rules, which utilise the, so-called, linguistic variables and membership functions). The duality of the proposed solution allows not only for diversification of the method of acquisition and representation of cartographic knowledge, required for automating the generalisation process, but also for objective comparison of obtained results.

With respect to generalisation of matrix data (the GRID model) the author proposes the non-linear variant of global filtration, using the multi-feature *NEURO* or *FUZZY* knowledge base. According to the authors' opinion, this solution will allow for distinguishing and consideration of morphological forms in the process of modelling, although the disclosed structural lines are not explicite defined.

Thus, each of the proposed generalisation methods of the regular model (GRID) is a two-stage solution, which is based on the general model of generalisation of geographic information, proposed by Brassel and Weibel (1988) and Harrie and Weibel (2007). In the first stage of the process the structural information is analysed (by means of determination of the, so-called, spatial indexes or by determination of the, so-called, radial centres, for the *FUZZY* and *NEURO* methods, respectively). In the second stage this information is methodologically generalised using the previously developed knowledge base of the system.

An iterative, self-evaluating algorithm of elimination of model points basing on the analysis of the multi-criteria decision surface was proposed for generalisation of the irregular TIN model. At the cost of computational time, such approach allows for controlling geometric errors, maintaining topology of structural lines of the terrain relief and cartographically correct generalisation of geomorphological forms. This method requires the definition of methods used for:

- determination and maintaining topological relations in the process of generalisation,
- development of the system knowledge base, which facilitates the automated selection of the correct generalisation method and determination of its parameters,
- the objective method of evaluation of obtained results.

The important element of the generalisation process, connected with the irregular model, is also determination and maintaining of topological relations between structural elements of the terrain relief (skeleton lines and characteristic points) and other topographic elements, in particular hydrographic structures.

2.1. Generalisation of the TIN model

With respect to the generalised idea of the iterative generalisation of the TIN model Danovaro (1993), Olszewski (2005) proposed the method of creation of a hierarchic model, using the method of weighting the source model points basing on pre-defined structural lines of the terrain relief. Thus, that method utilises the *a priori* knowledge concerning the structural lines of the terrain relief. The proposed method of generalisation allows for obtaining the DTM representation in the form of an irregular networks of triangles at the arbitrary level of geometric accuracy El-Sheimy (2005). ch method of the terrain relief generalisation follows the idea of generalisation of spatial data, represented by the digital landscape model (DLM). It should be noticed that normalisation of particular factors has been assumed for the proposed methodology and the total of weights of those factors equals to 1. This allows for utilisation of the proposed idea for geomorphologically diversified areas.

The proposed concept assumes iterative elimination of points of the source model, using the general algorithm of generalisation of the irregular topological TIN structure, proposed below:

- basing on analysis of the source data the, so-called, structural points (points located on skeleton lines), as well as the, so-called, mass points, are distinguished,
- coefficients of vertical and horizontal importance are determined for mass points,
- besides, coefficients of horizontal and vertical tortuosity are determined for structural points,
- values of all coefficients are normalised; the total of their weighs equals to 1,
- basing on normalised values of weighting coefficients of all model points the multi-dimensional decision surface is created (the multi-feature optimising function),
- at each step of calculations the global minimum of the decision function is found and one least important point of the model, is eliminated,
- elimination of the point results in re-calculation and normalisation of values of weighting coefficients of particular points and in the new determination of the global minimum of the assumed target function (the decision process),
- the process is performed until the defined condition is obtained: the elimination of a specified number of points or achievement of the required value of the mean/maximum error,

- in the process of generalisation relations of the spatial integrity are maintained – topological relations between structural elements of the terrain relief (Fig 1).

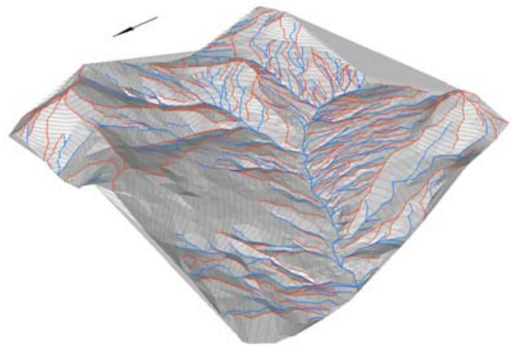
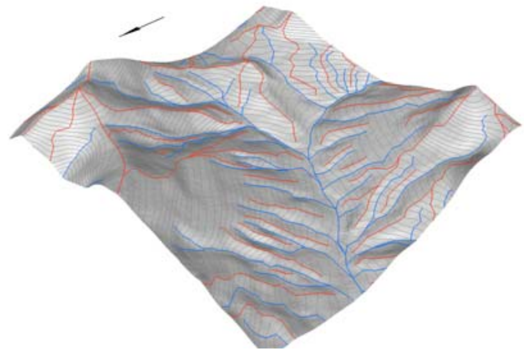
source TIN model	generalized TIN model
	

Fig. 1. Generalisation of the TIN model

For the functionality of the system, the method of determination of a multi-dimensional decision surface is of key importance. Construction of the decision function may be implemented in a linear way (the CRISP method), using the fuzzy logic (the FUZZY method) or using the artificial neural networks (the NEURO method). Both non-linear methods allow for adjustment of the inference engine of the computational system with the much higher accuracy, as well as for obtaining better results.

2.2. Generalisation of the GRID model

Simple methods of filtration of the regular model (linear filtration, one-parameter non-linear filtration, such as median filtration) lead to smoothing the resulting surface, what results, at the same time, in high flattening of the obtained results (Weibel, 1992). This flattening increases together with the increase of the number of iterations, the number of repetitions of the filtration process, as well as with the increase of the filter mask (the number of surrounding cells, which are considered in calculations of the resulting value). This procedure allows for averaging the values (the Gaussian filter) or for elimination of the outstanding values (the median filter), however, it does not consider structural information, which characterises the terrain relief. In order to maintain the cartographic correctness it is important to recognize and strengthen the main structural forms in the process of generalisation – important valleys and ridges and to eliminate secondary forms. Thus, this approach requires the utilisation of a priori knowledge, which determines the structure of morphological forms or determination of that structure in the course of research works.

2.2.1. The FUZZY Method

The author proposed the sequential algorithm for implementation of the two-stage procedure of the generalisation of the regular GRID model. At the first stage, the so-called, multi-feature spatial indexes, which characterise particular model points by means of analysis of their surrounding features, are calculated. Basing on obtained values, as well as on defined fuzzy rules the knowledge base of the inference system is developed. The extracted knowledge is used at the second stage of the generalisation process, allowing for semantically correct generalisation of the GRID model information level. The general algorithm of the *FUZZY-GRID* system operations is relatively simple:

- a set of data (the GRID regular model matrix) is read in the system,
- source data are analysed, the DTM derivative models are calculated for a given area: the digital model of slopes, curvature, standard deviations, relative heights. Then, those data are globally filtered in order to achieve the smooth decision surface,
- basing on specified decision attributes (spatial indexes) and defined fuzzy decision rules and highly non-linear membership functions, the knowledge base of the system is developed,
- source data are processed basing on the knowledge base rules, reports on maximum and mean errors are created, the level of generalisation of particular structural forms of the terrain relief is analysed,
- the resulting, generalised digital terrain model in the GRID format is developed (Fig.2).

2.2.2. The NEURO Method

The above idea of the GRID model generalisation, is based on the utilisation of the explicite method, which openly defines the rules of the fuzzy inference system. From the methodological point of view, definition of the knowledge base of the generalisation system, which utilises artificial neural networks, is also interesting. This approach, being the example of utilisation of the implicite method, is connected with the defined set of examples of solutions, which will be used by the ANN (Fausett,1994) to extract the generalised model. It is the two-stage method, since it requires independent definition of a set of examples being the source of knowledge for the artificial neural network and the training and utilisation of a regression network of a given type. The objective of performed experiments was to achieve the full automation of not only the second stage of the defined generalisation process (regression training of the ANN and its utilisation), but also of the initial stage of selection of training data, representative for the given type of the terrain relief, which are the source of knowledge for the ANN.

In the course of performed research works, the author utilised the general model of geographic information generalisation, proposed by Brassel and Weibel (1988). The essence of this approach is to consider the stage of analysis of the source data structure in the assumed strategy of the DTM generalisation. Therefore, the proposed procedures of generalisation should allow for recognition of the terrain relief structure. That process is performed by determination of a series of locally specified spatial indexes, such as slope, differences of heights, standard deviations, profile curvature etc. In the process of unsupervised classification, performed with the use of the neural Kohonen network, the determined coefficients allow for determination of point objects, which are characteristic for particular forms the terrain relief (Kohonen, 1982). Elevation DTM attributes, specified at those points, are the source of knowledge for the ANN regression training at the second phase of the process.
Thus, it may be stated that the automated DTM generalisation (understood as the DLM model generalisation) should be interpreted as the process which consists of the following stages:

1.selection of characteristic points from the source model, performed by means of the classification network (the Kohonen network),
2.non-linear re-composition of the secondary model, basing on the regression network of the given type.

It should be noticed that the majority of research works, performed in the field of generalisation of elevation data, are focused on the issue of representative selection of characteristic points from the source model, assuming that interpolation of the secondary model is based on linear algorithms. In the course of performed works, an attempt of non-linear interpolation of the terrain characteristic points was made and obtained results were compared with the conventional global filtration of raster data. For the proposed approach to automated generalisation of the DTM the natural ability of the artificial neural networks of generalisation of information supplied by the ANN in the process of „training" was utilised.

With respect to the generalisation of the DTM, performed basing on fuzzy inference systems, the algorithm of the generalisation system is characterised by the higher level of complexity:

- the data set (the GRID regular model matrix) is read in the system,
- Stage I – selection of examples for regression training the ANN using the Kohonen network:
  - Source data are analysed, DTM derivative models are calculated: the digital model of slopes, relative elevations within the specified area etc.,
  - The self-organising Kohonen network is created with the specified number of neurons. Basing on processed input data, radial centres are determined – the characteristic points of geomorphological forms,
  - Values of the method parameters are calculated for determined points,
- Stage II – regression training the ANN and creation of the knowledge base of the system:
  - Teaching the GRNN, RBF or MLP networks basing on example data extracted during the Stage I (radial centres),
  - Basing on decision attributes, the knowledge base of the system is formalised,
  - Source data are processed by the trained regression network, reports on maximum and mean errors are created, the level of generalisation of particular structural forms of the terrain relief is analysed,
- The resulting, generalised numerical terrain model in the GRID format is developed (Fig.2).

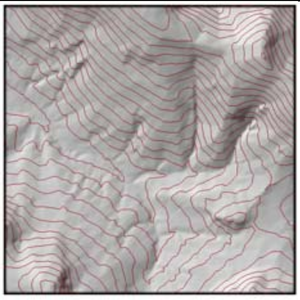
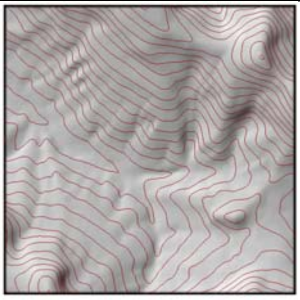
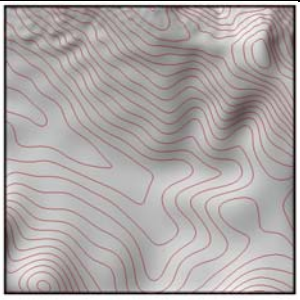
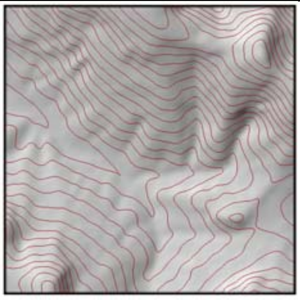
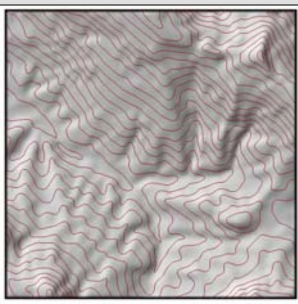
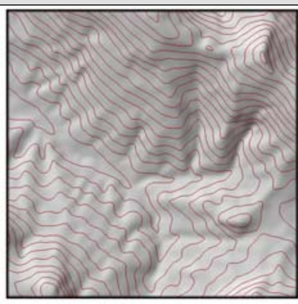
source GRID model	generalized GRID model: reference DTED2 base
	
generalized GRID model: RBF ANN	**generalized GRID model: GRNN ANN**
	
generalized GRID model: FIS 1	**generalized GRID model: FIS 2**
	

Fig. 2. Generalisation of the GRID model

3. Conclusions

The following conclusions may be formulated basing on performed investigations:

- utilisation of the computational intelligence methods allows for automation of the generalisation process, with simultaneous maintenance of its subjective features,
- the proposed algorithms of the TIN model generalisation allow for maintenance and stressing topological relations between structural elements of the terrain relief,
- the proposed algorithm of the TIN model generalisation has the self-evaluating characteristics and it allows for maintenance of the specified geometric accuracy by determination of the maximum and/or the mean error at every stage of calculations,

- the proposed algorithm of the GRID model generalisation – the combined nonlinear filtration allow for stressing important structural forms with simultaneous scumbling of forms of secondary importance,
- for the needs of the GRID model generalisation the artificial neural networks allow for obtaining much better results than the fuzzy concluding systems. It results from the fact that thousands of source examples were chosen to determine the knowledge base of the artificial neural networks (ANN) and only six simple rules and two input variables were chosen to formalise the knowledge base of the fuzzy inference systems (FIS). This disadvantage is partially compensated by the simplicity of the FIS system, as well as by speed of its creation and operations. And not only the time of computations (the speed of operations) is important, but, first of all the simplicity of acquisition and representation of knowledge (the speed of the system creation) should be considered. In order to create the FIS knowledge base only several rules and membership functions must be determined; development of the ANN knowledge base requires acquisition of hundreds of examples and two-stage processing of those examples,
- the fuzzy inference systems produce slightly better results than the artificial neural networks for generalisation of the TIN model. This results from the fact that not the physical, three dimensional space, described by XYH co-ordinates is the object of consideration, but the abstractive decision space, described by four co-ordinates: the horizontal and vertical importance and horizontal and vertical tortuosity. Therefore, the object of optimization is relatively simple, but non-linear decision space, and not the topographic surface, arbitrarily diversified with respect to geomorphology.

In both cases of utilisation of computational intelligence algorithms results obtained depend on the subjective selection of parameters of a method; however the developed bases of the generalisation process precisely determines the scheme of operations. Without any loss of the generality of concluding it may be stated that obtained results of generalisation of the regular terrain relief model (GRID) or the topological (TIN) model will contribute to development of the complex methodology of generalisation of geographic information by means of computational intelligence methods.

The proposed approach also integrates the apparently conflicting features of the geographic information generalisation process – it allows for automation of this process, maintaining, at the same time, its subjectivity. Utilisation of other techniques of formulating the knowledge base of the system and the process of control of the multi-scale modelling – basing on openly determined rules of the FIS system (the explicite method) or on the set of correct examples (the implicite method), allows for determination of the proposed method as the universal method. Performed experiments were connected with the process of the terrain relief model generalisation, however, it may be stated, without losing the generality of concluding, that the proposed methodology allows for generalisation of an arbitrarily determined data set, defined in the spatial information domain.

Thus, in the author’s opinion, the correct examples of cartographic utilisation of the CI methods allow for answering the question concerning the scope of the usefulness of the computational intelligence methods in cartography. Practical implementation of research tasks in the field of generalisation will allow for defining the general guidelines of development of the knowledge base, which facilitates the process of automation in cartography and in derivative fields.

It should be stressed that the objective of research performed by the author, was not to optimise the computational efficiency, or to chose the „optimum" set of parameters of particular algorithms. The objective of research was to propose the methodological concept, which would create the bases for automation of the terrain relief generalisation, basing on expert systems, using the computational intelligence methods.

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