AN ADAPTIVE METHODOLOGY FOR AUTOMATED RELIEF GENERALIZATION

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ABSTRACT

Digital Elevation Models (DEM) are used in a wide range of applications. Several institutions worldwide are now involved in the collection of DEM data. DEMs are generally compiled at large scales (e.g. 1:25,000) with high accuracy. However, users frequently require data at different scales and for differing purposes (e.g. analysis, display etc.). To derive models at reduced scales, a generalization process has to be applied.

This paper describes the development of an adaptive methodology for automated generalization of DEM data. The principal feature of this methodology is the adaptive selection of a suitable generalization method according to the scale of the resulting map and the characteristics of the given terrain: For smooth relief or minor scale reductions, a collection of filtering techniques (global and selective) is applied. For rougher terrain or larger scale reductions, a heuristic generalization procedure is used which works directly on the basis of structure lines.

INTRODUCTION

Digital Elevation Models (DEM) are increasingly becoming important as a source for geographical analysis and digital mapping. Possible application areas include terrain analysis (e.g. slope, aspect, visibility) for erosion studies, hydrology and various planning purposes, and the derivation of various display products (e.g. contour lines, shaded relief) within digital mapping systems (Burrough 1986). More and more institutions involved in the study and mapping of the earth's surface are collecting DEM data. The compilation generally takes place at a relatively large scale (e.g. 1:25,000) to achieve maximum resolution.

However, users frequently require data at various scales and for different purposes. If relief display is to take place on a smaller scale than the DEM was originally compiled, some of the details in the original data have to be eliminated: The original DEM has to be generalized. Since we are in an automated environment, this data reduction should be carried out automatically but in a cartographically consistent manner. This stands in contrast to the resampling processes used in data reduction for analysis purposes: Resampling for data reduction is guided by statistical criteria and not by visual effectiveness. The generalization procedure should take account of the purpose of the resulting data or map, and of the characteristics of the given terrain. Major scale reductions should be possible.

The development of a methodology for automated cartographic generalization of DEM data was aimed at, given the general frame that the procedures should

- run as automatically as possible, with a minimum of subsequent adjustements;
- perform a broad range of scale changes (from large to small scale);
- be adaptable to the given relief characteristics and to the purpose of the resulting data or map (selection of the best-suited method);
- provide the opportunity for feature displacement based on the recognition of the major topographic features and individual landforms (for major scale reductions);

- work directly on the basis of the DEM;
- enable an analysis of the results.

Several approaches already exist in the field of automated relief generalization, but even the most promising ones do not fulfill all the criteria stated above. Generalization of contour lines fails to address landforms individually and thus allows no major scale reductions. DEM filtering (Loon 1978, Zoraster 1984) applies a global filter operator which does not pay attention to local terrain characteristics and only smooths the data, which again allows only minor scale reductions. Information-oriented DEM filtering (Gottschalk 1972) is locally adaptive but is also restricted to simplification and elimination of details. Heuristic approaches which are based on a generalization of the terrain's structure lines (Wu 1982, Yoeli 1987) are promising for the treatment of rough relief or for major scale changes, but will be hard to operate in low or undulating relief without any clear structure lines; furthermore, they are still very much in an experimental stage and need to be refined.

It is clear that no single strategy can achieve all the above-stated requirements and can cover all scale ranges and all possible applications. The methodology we will describe in the following is therefore composed of a collection of generalization procedures, each one to be suited for a specific sub-area of relief generalization.

GENERALIZATION PRINCIPLES AND OPERATIONS

Cartographic generalization is carried out by applying various generalization operations to the original map. We can identify four basic operations which are, however, not clearly separable (Fig. 1):

- eliminate (select)
- simplify
- combine
- displace

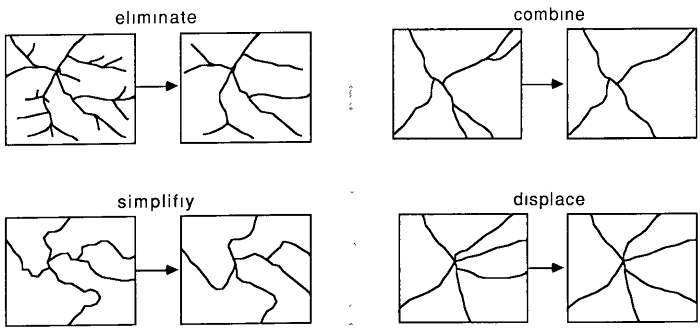

Fig. 1: Basic generalization operations

We do not want to come up with yet another definition of generalization operations or processes (cf. Steward 1974), but use this classification to clarify our understanding of the process of cartographic generalization:

"Eliminate" and "simplify" are conceptually and algorithmically relatively simple. They do not cause major locational changes of the features processed, and are therefore without severe impact on neighbouring elements. They always address features individually (in a clearly separable way) and can therefore be applied in a sequential manner. While they may remove details from the original data they do not create new features or structures.

"Combine" and "displace" are of higher complexity. They involve positional transformations which have an effect on neighbouring features. Because displacement of one element may cause a chain reaction of relocation of other features, they cannot address individual elements sequentially, but they rather do it in a parallel way.

They reorganize available space and build up new structures (e.g. combinations and placeholders). "Combine" and "displace" require a great deal of knowledge of the character and shape of individual features as well as processing strategies which record the spatial interrelationships of features and proceed in a synoptic manner.

The application of the specific generalization operations is determined by various criteria. The most important ones are: 1) scale reduction, 2) map or data complexity, and 3) generalization purpose.

Scale reduction: The smaller the scale of the resulting map or data, the less space is available for the individual map elements. Elimination and simplification does not solve this problem. A reorganization of map space has to take place, calling for combination and displacement.

Data complexity: The more complex the original map or data, the more likely will features interfere if scale is reduced. Here also feature combination and displacement has to be applied.

Purpose: In a digital environment, the purpose of generalization can take new form. In addition to just creating new maps from old ones, a user may want to transform a digital cartographic data base into a different yet generalized data base in order to save storage or processing time in subsequent manipulations, or for other processing purposes. In these cases the central issue is to diminuish the data contents while changing the geometry of the data as little as possible. It results in a mere data reduction, i.e. elimination and simplification. This process is equivalent to a generalization caused by minor scale changes.

Considering the above points, we can distinguish between two kinds of generalization procedures of digital data, according to the types of basic generalization operations applied:

- Filtering: Only elimination and simplification are used. Filtering may be applied only for minor scale changes and data of low graphical complexity. It is also used for controlled data reduction.
- Generalization (*): These procedures are oriented towards graphical output and involve all four basic generalization operations mentioned above. They are used for major scale reductions and/or data of high graphic complexity.

This range of requirements must be kept in mind when developing a strategy for automated generalization of any cartographic feature.

METHODOLOGY OUTLINE

We propose a methodology for automated relief generalization based on the observations stated in the previous section. We are currently implementing this methodology for gridded DEMs, but it could be modified to operate on other types of DEMs such as the TIN model (Triangulated Irregular Network).

This methodology provides for an adaptive selection of appropriate generalization procedures according to the conditions under which the generalization process takes place: scale reduction, relief characteristics, and generalization purpose. This is done by branching into one of two sub-processes, the fitering sub-process or the generalization sub-process (see Fig. 2 for methodology outline). The selection is made either by an operator who applies a priori knowledge, or by means of a selection procedure (i.e. global characterization of the relief type). The selection is guided by the perception of relief character through statistical measures (simple statistics of height distribution, local height changes, slope variation, fractal dimension, texture parameters).

For minor scale reductions and/or relatively smooth relief, a filtering procedure (either global or selective) is applied. For rougher topography or major scale changes, a heuristic generalization approach is taken. It works on the basis of the relief's structure lines (i.e. valleys, ridges, and other breaklines), assuming that these lines are geomorphologically meaningful. The various generalization operations are applied to the structure lines, and after this step the resulting gridded surface is reconstructed through interpolation.

(*) The term "generalization", in this particular case, is to be understood as a subset of the entire process of cartographic generalization. "Filtering" is another subset.

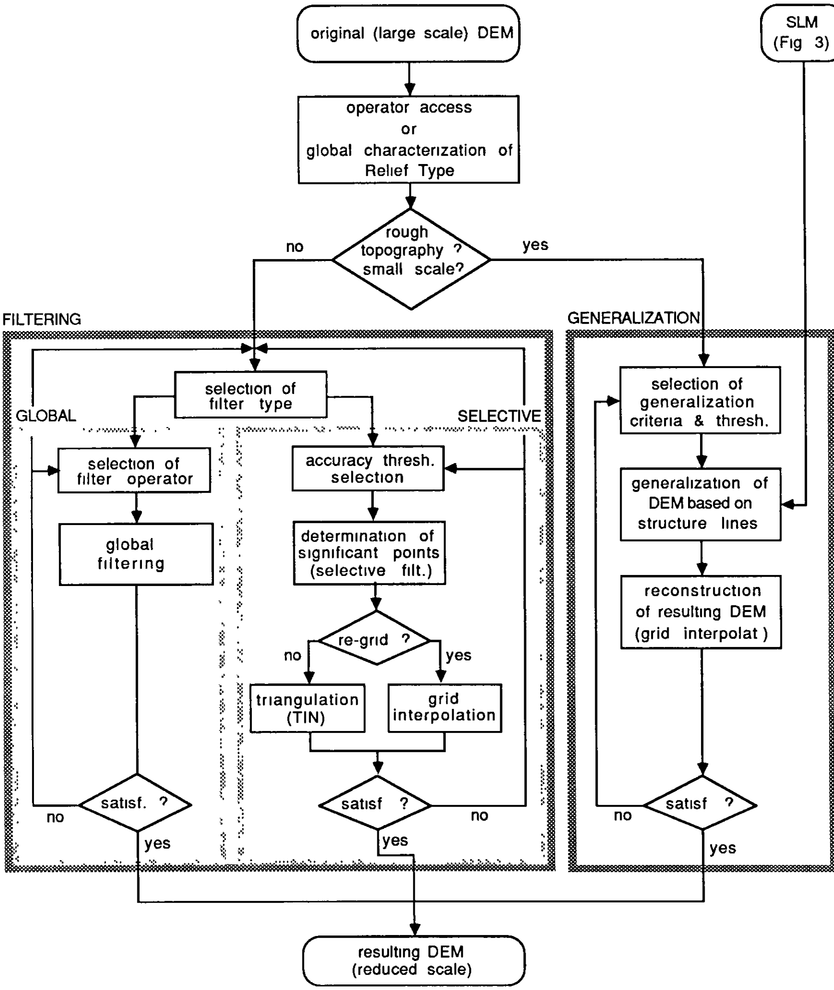

Fig. 2: Outline of generalization methodology

FILTERING SUB-PROCESS

Filtering procedures can be applied to automated relief generalization if scale reduction is modest and/or if the given terrain is relatively smooth.
Two filter types are used in our methodology: 1) global filtering, and 2) selective filtering. The choice between the two alternatives is made under operator control.

Global Filtering

Basics: This filter process operates globally; it does not adapt to local relief features. However, it can be applied if scale reduction is only minor (depending on relief complexity). Global filtering is computationally the least expensive of all generalization procedures in our methodology. It is equivalent to position invariant two-dimensional filters in image processing. Global filtering can take place in the spatial or in the frequency domain.
Operation: For the time being, the selection of a suitable filter operator is guided by an operating person but it would also be possible to control it via the previously made global characterization of relief type. A selection among several filter operators is given. It is also possible to concatenate low and high pass filters for edge enhancement.
The resulting filtered DEM can be viewed through shaded relief display. If the result is not satisfactory, action can be resumed to re-select another filter type or filter operator.

Selective Filtering

Basics: Selective filtering is more sensitive to local variations of terrain in that it is guided by the information content of the individual data points (i.e. it is position variant). The basic idea is to select data points with high significance and to drop the ones with low information content. The approach is related to Gottschalk's filtering of TINs (Gottschalk 1972); however, his solution was computationally inefficient. In our methodology it is also applied to gridded DEM. Because it is sensitive to local relief features, selective filtering can cover a wider scale range and rougher relief than global filtering. Moreover, because it seeks to eliminate only insignificant or redundant points, it can be used as a means for controlled data reduction (e.g. grid-to-TIN conversion).
Operation: After an accuracy threshold has been selected, the set of points is triangulated and each point in turn is temporarily deleted, and an estimated elevation value is interpolated at its position. This action is iteratively applied to all points, and after each iteration, the point with the least difference between actual and estimated elevation value is definitely eliminated. This is done until all points with a difference less than the selected threshold have been eliminated. The amount of accuracy in the resulting data (i.e. the information content) can hereby be controlled.
This procedure can only work acceptably fast, if the re-triangulation caused by point elimination and the interpolation of estimated elevations can be computed locally (i.e. only among neighbouring points). Algorithmically, this task is complex. Development of a differential algorithm for local adjustment of triangulation is now under way at our institution (Heller 1986a). To test our methodology, we are using a pragmatic approach at the moment. It identifies points along structure lines and subsequently selects further points based on their difference to neighbouring cells.
After the set of significant points has been determined, the operator selects the further processing steps. If he desires data reduction only, he will choose a TIN structure as the resulting DEM; if he wants the original DEM to be generalized by selective filtering, the resulting generalized grid is reconstructed through interpolation of significant points. In either case, control returns if the shaded relief display shows no satisfactory result.

GENERALIZATION SUB-PROCESS

If substantial scale reductions and complex topography have to be handled, mere feature elimination and simplification processes are not sufficient; we have to combine and displace relief features and reorganize available space (e.g. smaller landforms have to be combined into larger landforms). These new structures have to reflect the original character of the topography (Imhof 1982).
Structure lines (i.e. valleys, ridges, and other surface-specific edges) build the structural skeleton of the relief. In manual cartography, they are used to support the generalization process. For small scale generalization and in rough topography, we therefore rely on the structure lines.

The flow of the generalization sub-process is as follows (Fig. 2): The structure line model (SLM) serves as the basis for the heuristic generalization procedure. It holds the geometry, topology, and feature attributes of the structure lines of a particular DEM. After setting up this model (which needs to be done only once in an initialization step), the structure lines are subjected to generalization processes (elimination, simplification, combination, displacement), and the new skeleton serves as input to the reconstruction of the resulting gridded DEM at a reduced scale. As in the filtering sub-process, the result can be visualized through shaded relief display. If it is not satisfactory, the generalization can be re-started with different generalization criteria.

Generation of SLM

The structure line model (SLM) is generated by the extraction of the geometry of the structure lines, their concatenation to form network topology, and a subsequent classification of the landforms (see Fig. 3).

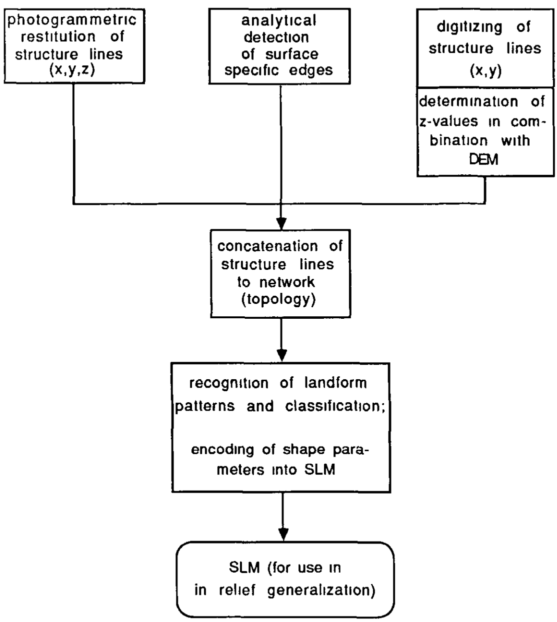

Fig. 3: Generation of structure line model (SLM)

Geometry and topology of structure lines: The aim of the SLM is not only to record valley and ridge lines (which are the main features of fluvial relief), but also other prominent edges (e.g. edge lines of glacially eroded valleys). The sources for geometry are: 1) photogrammetric restitution (Makarovic 1976); 2) digitization (and subsequent z-value interpolation); and 3) automated or analytical detection. The quality of the structure lines influences the subsequent generalization process.

If structure lines are to be found analytically, the procedure used is a combination of heuristic approaches (for valleys and ridges) and image processing algorithms (for other egdes). If certain edges are already known (e.g. from photogrammetry), they are no longer searched for. Edge detection is followed by a vectorization step to concatenate the surface-specific points into connected line systems. This task is not trivial especially if edges are not clearly pronounced. Analytical detection still needs some subsequent interactive editing.

If the geometry is determined through photogrammetry or digitizing, the individual structure lines can be topologically connected through operator interaction or through a topology building process.
Landform classification: To guide the generalization of the structure lines, some information on the importance of these local structures is required. The individual structure lines must therefore be classified according to their prominence. Possible parameters are: edge length; stream order (for valleys); average height (for ridges); volume of pertinent land orm (ridges); ratio volume / area of landform (ridges). This information can be used to form a generalization hierarchy.
Again, if the edges are determined through photogrammetry or digitizing, the operator can assist in that he visually sets an attribute of relative and absolute importance for each edge.
SLM formation: For each structure line, its geometry (x,y,z), network topology, and landform parameters (as attributes) are stored. The SLM data are pertinent to the original data and as such are permanent. The SLM generation needs to be done only once.

Generalization Operations

The generalization of the structure lines can be exemplified by the above-mentioned basic generalization operations:

Eliminate: Based on previously selected thresholds and on attribute information of the SLM. This operation is applied first.
Simplify: Second operation. Simplification of the course of the remaining structure lines according to selected criteria by means of known line simplification algorithms (see Zoraster 1984 for a discussion).
Combine and displace: The simplified edges are now subjected to combination and displacement, controlled by the landform information of the SLM. Algorithms to be developed can profit of experience with automated feature displacement in name placement and line generalization (Zoraster 1984 for further references).

Only a few general guidelines for the application of the individual generalization operations are known from manual practice (Imhof 1982, Zoraster 1984). Our aim is to gradually and iteratively develop heuristic rules that could control generalization. This would also give further insight into formalization of fuzzy cartographic knowledge.

Relief Reconstruction

After the network of structure lines has been modified by generalization, the resulting gridded DEM can be reconstructed through interpolation. The interpolation procedure should generate smooth slopes between the edges, but it should not destroy the breaks. An interpolation base on triangulation and bivariate quintic interpolation is used in our case (Heller 1986b).

CONCLUSION

We have proposed an adaptive and comprehensive methodology for automated relief generalization which combines different approaches. It serves as a comprehensive framework for testing of existing procedures and for the development of new ones. We have shown that it is most important to adapt automated procedures to the degree of scale reduction to be made, to the complexity of the given terrain, and to the purpose for which the generalization is applied. To meet these requirements, we have set up two alternative strategies: A filtering sub-process and a generalization sub-process. For most of the filtering procedures and for some of the generalization procedures, tentative solutions have been implemented. These algorithms can now be tested and refined, and the knowledge for control structures (e.g. thresholds, generalization rules etc.) can be developed. Future research has to address the following points:

- development of hard criteria to select either filtering or generalization procedures, based on statistical relief characterization and on the amount of scale reduction;
- improvement of analytical detection of structure lines;
- develoment of adequate measures for local landform classification;
- formalization of knowledge from manual generalization practice;
- development of appropriate feature displacement algorithms.

ACKNOWLEDGEMENTS

The work for this paper was supported by a grant of the Swiss National Science Foundation. The author wishes to thank Prof. Kurt Brassel, PD Dr. Haruko Kishimoto, and especially Mr. Martin Heller for valuable discussions and for reviewing the manuscript.

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