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Methodology and Practice

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Generalization: state of the art and issues

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1.1 Introduction

This chapter intends to provoke discussions and reactions on a number of items relevant to GIS data visualization at multiple levels of scale (the ratio between the size of an object on the map and its real size on the ground) and resolution (the smallest object which can be represented on the map).

From a user point of view, visualization is the window of GIS and is essential for visual data exploration, interpretation and communication. Geographical processes are scale dependent and numerous applications in climate, water resources, agriculture, forestry, transportation, land and urban planning require changing degrees of detail and generalization when analysis and communication occur at the local or more global levels. Hence, there is a need for the modelling of geographic information at different levels of abstraction. Ideally, one should be able to view and analyse data at the level where geographical variance is maximized (Tobler and Mollering, 1972; Woodcock and Strahler, 1987) or where spatial processes are best understood.

From a data production point of view, the management and maintenance of spatial data are constrained by the requirements for accuracy, i.e. 'relationship between a measurement and the reality which it purports to represent' (Goodchild, 1991); precision, i.e. 'degree of detail in the reporting of a measurement' (Goodchild, 1991); and quality control. Requirements for the flexibility afforded by multiple scale production and update operations complicate the issues of accuracy, consistency and integrity.

The question, therefore, is not whether geographic information (in digital or analogue forms) should be made available at multiple levels of abstraction, but how it should be made available.

1.2 Pro- or contra-generalization?

Some authors argue that generalization — in the cartographic sense — is not a prerequisite to the delivery of geographic information at multiple levels of scale and resolution.

The ability of current GISs to zoom in and out of a given area, to break down a single multi-thematic layer into a series of mono-thematic layers, and concurrently to produce multiple windows of the corresponding zooming and layering operations, explains perhaps the historical lack of interest of the GIS community in cartographic generalization. Most GIS commercial firms have denied or ignored the cartographic generalization issue.

Other authors admit that generalization would be a useful tool in the GIS tool-kit but argue that automated generalization is either an 'NP-complete' problem (i.e. a computational solution cannot be devised) or the practical and economic benefits of a solution are dubious. The first view is strong among conventional cartographers. The latter view is shared by many national mapping agencies (NMAs) which store multiple scale versions of manually generalized data. In smaller countries like The Netherlands, where the size of the map series is rather limited, the inconvenience of storage overheads and duplication in updating efforts is perceived as a lesser evil compared to the potential processing cost of an automated generalization solution which has not yet arrived.

For larger countries like France, NMAs are still forced to store multiple scale versions, for a number of reasons: there is no production tool for generalization (on the market place) able to derive the required datasets; there is no tool to propagate updates through a series of derived datasets; the processes of regenerating datasets are expensive and require a long time (hence it is not profitable to carry those processes in an industrial context except once, which explains why the various datasets are maintained more or less separately). Finally, the smaller the scale, the shorter the update cycle. Hence, if a NMA wants to maintain only one scale version then it has to update it frequently, with the higher geometric accuracy, in order to respond to the update needs for all other smaller scale versions. This is a dilemma faced by NMAs which goes against the idea of one single database (the expression 'scaleless or scale-free database', which may lead to confusion, is purposefully avoided here; it seems that in the case of data coming from surveys or photogrammetry, it would be more appropriate to speak of precision, accuracy and resolution, not scale, since the notion of scale is meaningless in the absence of a mapping relation).

As a result, most research efforts to resolve the problem of automated generalization, whether in the context of GIS or for the production of paper maps, have been confined to academia. Some academics have argued that the storage of a finite series of multiple scale cartographic databases provides major impediments from both a scientific and management point of view. From a scientific view point because 'what if' and 'if–then' scenarios in GIS require the possibility of navigating dynamically and continuously from any scale to any other scale automatically. From a management point of view because one cannot afford the duplication of efforts that occur in map series updating as well as the inconsistencies which may arise through this process. Solutions to these impediments require moving beyond the paradigm of traditional paper map series, without sacrificing support for the production of paper maps. That is to say, the generation of digital products can no longer be driven by paper map production, as the needs for spatial data have become much broader and complex. Generalization facilities must be provided by GISs to support the use of geographic information at multiple scales for multiple purposes and tasks. Note that besides GIS electronic displays, paper maps will continue to exist; paper maps are permanent, transportable documents, and they also offer a far better accuracy and can represent more data than the screen of a CRT. Furthermore, maps, as visual communication means, are still the easiest and quickest to read media for communicating geographical information to the reader.

Some mapping agencies and commercial firms are now investing resources to implement automated or semi-automated generalization facilities. Apart from the effect of individual leadership, this could mean that there is a growing belief among professionals that generalization could become an operational tool for the production of geographic information in the years to come. Professionals have also come to realize that the full potential of GIS can only be exploited if functions for automated generalization are available.

Assuming that the answer to the previous hypothesis is true — that is generalization in the context of GIS and automated map production is both desirable and feasible — we are now faced with the theoretical and practical issues of building systems for automated generalization. Some authors have used the term 'generalization machines' (e.g. João *et al.*, 1993) to describe such systems; the term has a strong mechanistic connotation, however, and we wonder whether we can use it in this context.

1.3 Generalization yes, but what are the issues?

We need to distinguish between the issues that are brought about by graphical representation from those which arise from modelling at different levels of spatial and semantic resolution. Generalization may be viewed as an interpretation process which leads to a higher level view of some phenomena — looking at them 'at a smaller scale'. This paradigm is always the first used in any generalization activity, whether spatial or statistical. Second, generalization can be viewed as a series of transformations in some graphic representation of spatial information, intended to improve data legibility and understanding, and performed with respect to the interpretation which defines the end-product. These two categories have motivated research mainly in two areas: model-oriented generalization, with focus on the first stage above-mentioned, and cartographic generalization, which deals with graphic representation.

Issues relevant to graphical representations are well known to conventional cartographers. In geographical circles, people usually think of generalization as part of cartographic compilation whose purpose is to resolve legibility problems. An operation such as feature displacement is typically cartographic. Should we go beyond this and consider generalization in contexts which are not necessarily representational? The distinction, for example, between cartographic and statistically controlled generalizations was made before (Brassel and Weibel, 1988). Modelling reliability on statistical surfaces by polygonal filtering (Herzog, 1989) is not necessarily directed towards visualization but helps to understand data by providing higher levels of abstraction. In this case, the motivation as well as the solutions to bring about the necessary transformations are not the same as for cartographic generalization. Generalization in the sense of modelling is a requirement for spatial analysis and the tools (e.g. spatial districting and aggregation of spatial enumeration units, image classification, trend surface analysis, surface filtering, and kriging) have already been developed (see, in particular, Tobler, 1966; Tobler and Moellering, 1972). Do we need to consider this category of generalization in our research agenda? Is it relevant to the producers of geoinformation? Is there a need for future research? Or should we close the book on statistically oriented generalization instead?

The first part of this position paper deals with data abstraction, i.e. a reduction of spatial as well as semantic resolution, whether motivated by data analysis or cartographic representation. We will coin this kind of activity under the general term 'model-oriented generalization'.

1.4 Model-oriented generalization

The difference between the model view and the cartographic view of generalization is the possibility for database manipulation in the former case, independent of cartographic representation. Spatial objects may need to have multiple digital representations in which internal representations (models) should be distinguished from visualization (cartographic) representations. One reason for generalization at the modelling level is to facilitate data access in GIS. This need becomes urgent in view of the design of GISs in which the user interacts with the geo-objects without knowledge of their internal representation. Also, model generalization may be driven by analytical queries (Where are the trends?, What is the spatial average?, Where are the new classes to appear at this level of variance?, etc.) whereas cartographic generalization is mainly driven by communication requirements (legibility, graphical clarity, and understandability). But the two types are not independent, and one (model-oriented) can be a precursor to the other (graphics-oriented). The question is how much and what kind of model-oriented generalization support is required for the accomplishment of routine tasks in cartographic generalization?

In model-oriented generalization, methods are currently being developed to support insertions, deletions, updates and geometric queries at an arbitrary location for an arbitrary scale (Becker *et al.*, 1991). A generalization index may be applied to point data which, in turn, defines their priority for access or rescaling operations. Storage structures for seamless, 'scaleless' geographic databases have also been proposed (Oosterom, 1989). Hierarchical data structures, including quad trees and strip trees, are often used to subdivide and merge data for generalization purposes (Jones and Abraham, 1986). The working hypothesis put forward by database experts is that spatial proximity information must be implicitly available in order to favour access to local information and neighbourliness relationships.

The basic categories of space found in the GIS literature, namely metric, topological, and structural categories, can be used to describe various levels of abstraction for spatial objects. The metric space describes distance relations and constitutes the lowest level of abstraction. The topological space, instead, deals with the existence of spatial relations between points in space. The highest level of abstraction is reached through the structural space which only deals with entities and relations (Sowa, 1984). Abstraction of a road network using hypergraphs and graph theoretic concepts is an example of structural representation (Titeux, 1989; Salge *et al.*, 1990). The question is whether we can invent protocols to propagate changes (say through updating) from one level of abstraction to all others. This would go a long way towards detecting inconsistencies between representations.

Other models for data abstraction and data structuring are also available, but are still in the laboratories. For instance, what are the potentials of abstraction mechanisms known from semantic modelling (Smith and Smith, 1977; Hull and King, 1987), including classification, generalization, aggregation and association, in formalizing relations between spatial objects? There has been much excitement about the introduction of object-oriented programming in GIS. Apart from the confusion surrounding the idea of object orientation, most GIS vendors use the concept for advertising purposes. The object-oriented environment, where procedures (methods) are bound to the object, objects communicate with each other and inherit attributes and methods from others, seems to offer great potentials for implementing generalization procedures. The concept of 'delegation between objects', in particular, could be used to perform updates concurrently across all map-scale layers in the database. As with semantic modelling, the proposed models are attractive but have no proven records yet in the field of generalization.

Temporal abstraction is another type of data modelling which expresses changes occurring in spatial objects (and their attributes) at different intervals of time (Langran, 1992). Representations can either be snapshots of the real world, or they can express an average state over a certain interval of time. The subject has become increasingly relevant among custodians of ephemerous spatial databases (particularly in meteorology, forestry and navigation) who require consideration of the problems of object identity and changes not only in the spatial and attribute domains, but also in the temporal domain. The addition of the time dimension raises new problems in data structuring (time is topologically unidimensional) and representation. The tools to analyse, generalize and visualize temporal information are still in their infancy.

Model-oriented generalization research has been somewhat neglected in comparison with the efforts invested in graphics-oriented generalization. The traditional view of generalization in support of surveying and mapping organizations for multi-scale map production is overwhelming and has been much more studied. Busy implementing algorithms to perform the analogue of cartographic generalization tasks such as simplification, exaggeration, elimination and displacement, we have forgotten the intimate relationship between generalization at the modelling level and generalization at the 'surface' (e.g. graphical representation). Cartographic generalization requires (1) inside information regarding a spatial object (including spatial, semantic and perhaps temporal aspects), and (2) outside information regarding the relationship among objects and their contextual relevance. The resolution of conflicts, for instance, typifies the problem of generalization on the 'surface', but requires both types of information for its solution. As mentioned earlier, the way the data model is organized and can be generalized is likely to influence the performance of cartographic generalization.

1.5 Cartographic generalization

The tools currently available for automated cartographic generalization resemble those of manual generalization. In this sense, efforts in the automatic domain are oriented towards the manual domain. Furthermore, the quality of computer-produced maps is often tested by comparing the results with manually produced ones. The question is whether we should use manually generalized maps as a criterion of good performance for automated generalization. Should automatically produced maps look like manual ones? This is perhaps a dubious goal and probably unrealistic. Some authors have argued for methods whose results mimic the way people generalize by looking at objects from a distance (Li and Openshaw, 1993). But the fact remains that no new paradigms have emerged under the hat of automated generalization.

A prior attempt towards automated cartographic generalization was to provide a theoretical foundation by answering questions such as what, why, when, and how should we generalize, and providing a framework of objectives to attain, including philosophical, application, and computational ones (McMaster and Shea, 1988). A second step was to make an inventory of the tools available in order to attain those objectives. The list and the definition of those tools vary among generalization specialists, mainly because they fail to differentiate between the transformation applied to an object and the operators used to perform this transformation (Ruas *et al.*, 1993). For example, in the process of simplification, we can list various operators, including select-and-delete, aggregation, compression, smoothing, caricaturization, and collapse. Nevertheless, such inventories were useful since they were used as 'cahier des charges' by commercial firms to set up their development agenda. For instance, a partial catalogue of generalization operators has been already implemented or is intended to be developed by INTERGRAPH, including selection/elimination, simplification, typification, aggregation, collapse, classification, symbolization, exaggeration, displacement, and aesthetic refinement (Lee, 1993). A third attempt was to model the generalization process by suggesting sequential and recursive scheduling scenarios of the generalization steps involving different operators. Those could be different depending on the map subject (Lichtner, 1979; Müller, 1991; Lee, 1992; Müller and Wang, 1992).

One can essentially distinguish between two approaches for the implementation of the working tools in automated generalization. One is batch while the other is interactive.

1.6 Batch generalization

At the most basic level, we have a batch approach where individual algorithms are used to execute various tasks (elimination, simplification, etc.) applied to various kinds of objects. Line generalization has been the most thoroughly studied subject in academic circles (for over 20 years). As with map projections, new algorithms for line generalization keep popping up in the literature. This is no coincidence. Eighty per cent of the cartographic objects are perceived to be lines (in fact, many of them are polygons). Furthermore, single lines viewed in isolation are easier to handle than complex objects like a building or a polygon nesting. Can we now claim that we have reached the state of the art in line generalization? Probably not, especially in view of a lack of theory as to which algorithm is the most appropriate for which line object (river, contour, road, census boundary). Perhaps we need to concentrate more on the application of existing algorithms than on the invention of new ones (Weibel, 1991b). Besides line simplification, we now dispose of algorithms to aggregate and simplify polygons, to exaggerate object size, to collapse complex objects into simpler ones, and to classify and to symbolize cartographic features. But we need an inventory of the performance and the applicability of the different algorithms currently available at universities, national mapping agencies or in private industry. Nobody has a really clear view of what is exploitable. In the generalization tool-kit, however, displacement is not well represented. This is without doubt the most difficult operator to implement, and although some solutions are available (Lichtner, 1979; Nickerson, 1988; Jäger, 1990), they are not comprehensive enough to cover the entire range of possible conflicts. Displacement has become a priority item on the research agenda.

Going one step further, individual batch solutions may be bundled into one 'total' comprehensive batch solution that can be applied for the generalization of an entire map composed of many different objects. Issues such as scheduling management and object interaction have then to be resolved.

A program such as CHANGE, developed at the University of Hannover, is a combination of procedural steps which comes close to the idea of a 'total' solution (Powitz and Schmidt, 1992; Gruenreich, 1993). To develop effectively such a program, one has to define clear objectives. In the case of CHANGE, for instance, the goal was to provide the automated generalization of some feature classes of German topographic maps for a limited range of scales, going from 1:5 000 to 1:25 000. Even in this case, however, the program is suboptimal in the sense that it performs only 50 or 60 per cent of the work. At the end, the user is still required to intervene to perform the necessary quality control and corrections required by operations that could not be entirely automated, such as displacement of conflicting objects in complicated surroundings. As a further example, Nickerson (1988) developed a system for automated generalization of topologically structured cartographic line data. The system is capable of handling feature elimination, feature simplification, and interference detection and resolution. The system is implemented in Fortran, but uses English-like rules for the user to specify generalization options. The intended scale range is 1:24 000 to 1:250 000.

The question is whether a 100 per cent batch solution in generalization will ever be attainable (or desirable). Performance in batch solutions is more likely to follow the economics of 'diminishing returns'. The landscape of geographical features portrayed on topographic maps, for example, can vary almost to infinity. This great variation creates generalization problems which cannot all be foreseen and the research required to cover all cases is so complex and so demanding that it would not be economical. The situation may improve in the future, however, when our methods will be derived from the 'deep' structure (semantic and topology) rather than from the surface level (form and size), and, therefore, will be less sensitive to the variation of individual objects.

1.7 Interactive generalization

The difficulties of providing a batch solution and the disappointment over the progress of the formalization of generalization knowledge (see below) have led some researchers to put their efforts towards the exploitation of interactive techniques. In this case, low-level tasks are performed by the software, but high-levels tasks, such as the choice of an object to be generalized or a particular routine or parameter, are performed or controlled by humans. In other words, the computer implements some tasks (usually execution) which it is good at solving but relies on the user for control and knowledge. Such an approach was suggested by Weibel (1991a) and was termed the 'amplified intelligence approach'. Furthermore, batch technology reflects a line of thought more appropriate to the 60s and 70s than to the 90s. The present trend is to use the interactive environment made available through work stations, PCs and powerful interfaces. So one might say that the dichotomy between batch and interactive generalization is rather artificial and will vanish in the future.

Interactive solutions are based on a user-friendly interface (including multi-window displays, pull-down menus, tool palettes, and menu shortcuts) which allows the user to navigate easily through the system's options and select the objects to be generalized as well as the tools used for generalization. Weibel (1991a, 1991b) gives a detailed list of components required for an 'amplified intelligence' system (mentioned above). Among these are facilities that support the user in making correct generalization decisions (e.g. measures giving data statistics or indicating object complexity; query and highlight functions, etc.) as well as functions for logging of interactions and scripting facilities required. For an interaction approach to be successful, it is essential that it does not just replace the cartographer's pen, but really enables the user to make decisions about generalization on a high level, that is, the system must be capable of amplifying human intelligence. The approach of interactive systems could also be regarded as an equivalent to decision support systems which are frequently used in business and planning applications (Sprague and Carlson, 1982).

The system MGE Map Generalizer produced by INTERGRAPH provides a first step in that direction (Lee, 1993). In a sense, it is comparable to 'electronic' hand generalization, providing more powerful legs to run and a better opportunity to think. The emphasis is on graphic output supervised by human judgment rather than on database or model-oriented generalization. Hence, the approach follows the manual cartographic tradition. Such an approach is more flexible and versatile than a batch program (e.g. allowing reductions along a wider scale range for a greater variety of map types) but the question is whether it is practical in large production environments. The provision of logging and script capabilities which can 'remember' the values of the parameter used and the scenarios that were adopted for similar map situations may give a partial answer.

Interactive systems offer a good potential for the supervised testing and assessment of generalization algorithms and methods. Also, due to mechanisms for interaction logging, they provide an opportunity for the recording audit trails of expert users with the system and thus offer a potential avenue to the formalization of knowledge about generalization processes. Interactive systems have thus also been proposed as a workbench for generalization research. The testing, according to production criteria, of existing batch and interactive methods, or methods which are a mix of these two approaches, must be a priority on our research agenda.

A further degree of sophistication could be reached if we were able to create programs intelligent enough to mimic human thoughts. Cartographic generalization being essentially a creative process (Robinson *et al.*, 1984), it is clear that the batch and interactive solutions need to be combined with some intelligence if we ever want to attain a performance close to a human expert. This explains the growing interest in building rule-based or knowledge-based systems for generalization.

1.8 Generalization and knowledge-based approaches

The introduction of artificial intelligence (AI) in automated generalization is essentially a problem of knowledge acquisition, representation and implementation. The programming languages (Prolog, Lisp) and tools (expert system shells) to manipulate that knowledge and infer generalization decisions already exist. Recursive programming and backtracking techniques, searching strategies and reasoning strategies are part of the problem-solving tool-kit available in any AI software. The fundamental issue is whether we can represent generalization knowledge with 'if–then' production rules that can feed an AI-based system.

Generalization knowledge can be acquired from three different sources: (1) written information available in textbooks and mapping agency guidelines, (2) existing map series, and (3) human cartographic experts.

Three categories of knowledge have been suggested to implement a rule-based system: geometrical knowledge (size, form, distance, etc.), structural knowledge (underlying generating processes which give rise to a cartographic object), and procedural knowledge (operations and sequencing of operations necessary for generalization) (Armstrong, 1991; Müller, 1991).

Partial attempts at gathering information from human experts have been reported (Richardson, 1989). Some knowledge has already been compiled in mapping agency guidelines (e.g. USGS, 1964). A method of 'reverse engineering' is presently being experimented with at NCGIA Buffalo (Leitner, 1993) and the University of Zurich, where existing map series displaying information at different scales are systematically analysed, in order to gather knowledge about generalization.

Observation of map series shows that changes in the graphic representation of an object are sometimes rather abrupt (Ratajski, 1967). In extracting procedural knowledge we have paid too little attention to those 'catastrophic' levels where a change between two successive scales in map series may cause large variations in the representation of the objects (where the polygon envelope of a church turns into a cross symbol, for example). Furthermore, sequencing of operations are usually predefined in already existing batch generalization software (ASTRA, 1986; CHANGE, 1992). But sequencing can also be determined by the user in case the software is interactive (MGE/MG, 1993). In principle, the interactive approach to automated generalization offers more flexibility; it allows the application of procedural knowledge closer to the needs of the user. Its drawback could be that it may require a long period of interactive operations.

The difference between a straightforward verbal account of generalization events and rules is that in the latter case an attempt is made at formalizing the knowledge in some kind of structure which is machine interpretable. The lowest level of formal representation is a look-up table. Imhof's suggested relationship between settlement size, map scale and settlement representation is perhaps the oldest attempt at constructing a look-up table for generalization (Imhof, 1937). But Imhof's table may be also translated into predicate calculus statements, a formal representation of 'if–then' rule statements. Most of the rules available in mapping guidelines can be rewritten in this way. This type of representation leads naturally to programming in logic (e.g. Prolog) at the implementation stage. Another useful representation is the semantic network where the nodes correspond to facts or concepts and the arcs are relations or associations between concepts. One popular application of semantic networks are the hypergraph database structures (HDBS) which describe relations between complex objects and classes (Bouillé, 1984). Similar representations could be used for scheduling and controlling the generalization process.

There is unfortunately little which can be said about the implementation of rules in automated generalization. Except perhaps for name placement (Cook and Jones, 1989; Freeman and Doerschler, 1992), and some experiments to combine procedural and logical programming for the generalization of specific cartographic features (Nickerson, 1988; Müller, 1990; Zhao, 1990; Graeme and João, 1992; Lee and Robinson, 1993; Wang and Müller, 1993) there is no rule-based comprehensive generalization system ready for operation. There is, in fact, no proof that such a system can be constructed. Previous attempts by various NMAs at formalizing cartographic knowledge in the form of a huge collection of rules are rather deceiving. The difficulty comes from the way generalization knowledge presents itself. Most of the guidelines are a collection of common sense statements, addressed to specific cases, such as 'IF windmills appear in large numbers THEN do not show them all' or 'IF contour forms small island THEN do not show'. Those refer to what one might call superficial knowledge (Nijholt and Steels, 1986). But to become operational, a rule-based system cannot rely on superficial knowledge alone. Like a human cartographer, the system should be able to reach deeper knowledge to add to the superficial knowledge when needed. Deeper knowledge refers to more complex reasoning and the ability to make inferences based on geographical context, priority, pattern, map purpose, etc. The real challenge in future research will be the acquisition and formalization of this deeper layer of knowledge which is not in the guidelines but in the mind of the practitioner. Practitioners admit themselves that they find it difficult to rationalize their decisions into a set of formalized rules. Some suggest that deeper knowledge might be extracted through statistical studies of called sequences of procedures and statistical frequency study of calls for each procedure stored in a log-file during the execution of a particular generalization software. It is further hoped that even more specific relationships can be determined using this approach, such as the context in which individual generalization operators may be used. One requirement for research in this direction is the availability of user-friendly interfaces which enable the user to interact comfortably and dynamically with the cartographic software, as if she/he were in a real production situation.

1.9 Generalization and data quality

An almost forgotten consideration in generalization research is data quality. It is obvious that generalization will influence some of the components of data quality, including location accuracy, attribute accuracy, consistency and completeness (Müller, 1991). Displacement will lead to lower local accuracy; completeness will be affected by selection and merging operations; some attributes may be lost through reclassification; consistency may be affected by uneven applications of spatial or temporal abstractions. Note that positional accuracy (i.e. the ability to get access to correct position) is a different issue to shape accuracy (the ability to recognize the 'true' shape of the object). In the former case, the generalized paper map is obviously a poor surrogate to the original database and one might claim that measurements of this sort should be conducted with a GIS, not a map. In the latter case, however, the map remains an indispensable tool. Quality also relates to the specification of the generalized dataset. What was the purpose of the generalization process and how do the results compare to this purpose? Here we need to distinguish between quality in the context of model-oriented generalization and quality in the context of cartographic generalization. Although both objectives are obviously related, they are driven by different purposes. Ultimately, quality is related to fitness with respect to some use: is the data product suitable for the intended use, or conversely what are the possible uses of it?

Generalization may have unpredictable effects on the metrics, topological and semantic accuracies of map products. In a recent study, João *et al.* (1993) showed that the length of a feature usually decreases, but may also increase, with scale reduction. Furthermore, João *et al.* showed that those changes (lateral shift, angular distortion, etc.) may critically affect GIS analysis involving map overlay at different scales. The question here is whether the results introduced by cartographic generalization, a visual-oriented process, could be used in GIS for modelling! On the other hand, model-oriented generalization may have a purpose in GIS analysis. Again the two issues, i.e. cartographic generalization versus generalization for modelling purposes, should not be confused when referring to data quality. Nevertheless, there is an urgent need for a systematic analysis of the effects of model-oriented generalization and the potential dangers of using graphically generalized documents on GIS operations.

1.10 Present and future development: critical thoughts

The following is a critical discussion (at times deliberately provocative and polemic) of what we believe to be the state of the art in automated generalization, with some hypotheses about why we have got so far and yet have accomplished so little, and some postulates regarding possible developments in the future. This section is intended to provide food for thought and provoke further argumentative discussions.

1.10.1 Critical hypotheses

- Most people in cartography and GIS now realize that there is a problem with generalization. Nobody, however, has a clear perspective of what the objectives of generalization should be, and what scale ranges, feature classes, or methods we should concentrate on.
- Nobody in the field has a clear vision of what generalization should be able to accomplish in a digital context. While many researchers argue that generalization should be performed with a different view in the digital domain, most people still resort to cartographic generalization when they claim to be busy developing methods for non-graphic generalization (i.e. model generalization).
- As a result, many researchers confuse the objectives and characteristics of model-oriented versus cartographic generalization.
- In particular, the issue of data quality in the context of GIS and model-oriented generalization is often confused with the objectives of cartographic generalization.
- Most of the research (80–90 per cent) in generalization has focused on rather secondary issues (such as single cartographic line generalization), instead of attacking the burning, more complex issues (such as object-oriented, purpose-dependent generalization processes and database requirements).
- Formalization of knowledge is stagnant because there is too little interaction between the computer experts and expert cartographers. Those who are working on the automation of generalization do not know how to generalize, and those who would know how to generalize are not really being asked (at least not being asked the right questions).
- The data models and data structures which are being used for today's automated solutions are archaic and not capable of supporting any comprehensive approaches involving context-dependent generalization operations (e.g. merging or displacement).
- Limited topological data models (e.g. the commonly used arc–node structure) require on-the-fly geometrical computations for conflict detection. These solutions will never be capable of solving the problem of merging and displacement satisfactorily.
- Achieved research projects in generalization are deliverable in the form of dispersed, incompatible modules developed independently at various places. Hence, a holistic view integrating various generalization processes for a particular scale range and a clear purpose is missing.
- As a result, the few generalization tools which have been implemented in GIS software (like line simplification) have distorted or oversimplified the generalization issue.
- Most research has concentrated on the development of new tools, but little research has been done on evaluation and validation of what already exists. Hence, there is a tendency to reinvent the wheel.
- Academic research has a tendency to turn towards the easiest and most publishable issues that are on the agenda at a given time — rather than turning towards the most relevant and urgent issues (because those might be more complex). One example is the recent interest in user-interface research, which is of little relevance to the generalization problem in its entirety, but in which it is relatively easy to achieve visible results thanks to the prototyping capabilities of hypermedia software (e.g. HyperCard).

1.10.2 Directions for future research

General issues

- Identify the objectives of generalization in the digital context. Identify why and when it is needed (e.g. are there cases where generalization can be or must be avoided, thanks to zooming, multi-window displays, or because of GIS modelling requirements?).
- Develop a specific suite of methods for data abstraction and data reduction (i.e. model generalization) and discriminate clearly between issues of data reduction and quality and issues related to cartographic representation.

Generalization operators

- Identify what are the operations that may be automated in graphical generalization (and which ones cannot), which techniques may be used for that purpose, how and how far can we automate the process, etc.
- Strive for the development of the most complete palette of generalization operators for all types of cartographic features (point, line, area, and surface) and feature classes (transportation, hydrography, etc.).
- Make wiser use of tools that are already in place and assess the applicability (scale range, feature classes, etc.) of existing operators.
- Create test scenarios for existing software and push the operationality of the tools to their limits. Write a set of quantitative and qualitative evaluation specifications in relation to production needs. The question is not what is right, but what is good enough for the purpose at hand (a heuristic question).
- Take a step towards more complex and burning issues. Focus on methods for conflict resolution and feature displacement and for the treatment of point and area features, rather than concentrating on line simplification problems alone.
- Experiment with new approaches, such as neural nets and genetic algorithms.

Generalization and data quality

- Clarify the expectations in terms of data quality both for model-oriented generalization and cartographic generalization. Identify the substantive issues that arise from the application of data-quality criteria as we know them from surveying and GIS in the context of generalized datasets.
- Analyse the potential errors introduced by using digitized generalized maps in a GIS.

Human–computer interaction

- Implement more intuitive ways to interact with generalization operators. For example, provide visual feedback on the consequences of parameter selection; inform the user about possible actions that should be taken; suggest to the user various scenarios for sequential actions and select the one most appropriate for the purpose at hand (Should aggregation follow displacement or vice versa? Should a parameter be involved repetitively, like selection and reselection?). In other words, implement a cooperative behaviour between user and software.
- Provide a pre-generalization report indicating potential conflict areas and designating features which are 'softer' and may be more generalized than others.
- Provide functions that constrain the user in order to avoid actions which do not comply with generalization 'rules'.

- Implement all generalization methods, including batch-oriented ones, in an interactive environment for optimal user control.

Data models and data structures

- Make data richer in terms of the feature attributes they are capable of carrying (concerns data production stage).
- Employ data structures that are capable of explicitly representing spatial proximity and spatial relations for points, lines, and polygons (e.g. Delaunay triangulation, Voronoi diagram).
- Develop methods for the dynamic maintenance of data structures to support changes of feature relations during generalization.
- What kind of data model and data structure are best suited for model-oriented generalization?

Knowledge formalization

- Exploit all available methods for knowledge acquisition (knowledge elicitation, reverse engineering, machine learning, scripting techniques in amplified intelligence systems, etc.) involving both computer and cartographic experts.
- Research cooperation between national mapping agencies (NMAs) and academic research should be intensified. NMAs should state their requirements with respect to generalization functions more clearly, and academic research should take up these issues.
- Likewise, the third player in R & D, software vendors, should be in close contact with developments taking place at NMAs, and sponsor research at academic institutions.

Structural knowledge (structure recognition)

- Methods for the definition and extraction of structural knowledge (structure recognition) are urgently needed.
- This requires a range of supporting functions which are able to express the complexity, distribution, and spatial relationships of cartographic features, and improve the selection and control of generalization operators.

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