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TEACHING:
Introduction to Cartography
Topographic Cartography I
Topographic Cartography II
Thematic Cartography I
Visualization of Geodata I
Visualization of Geodata II
Historical Maps
Geodetic Seminar

PUBLICATIONS SINCE 1996:
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INVITED PRESENTATIONS:
Meng, L. 1997.05.15: Visualization in GIS (English) Seminar: Geographic Information Systems in Environmental and Public Health (Miljφmediicinska enheten), Stockholm
Meng, L. 1997.05.27: Introduktion och tillδmpningsomrεden av automatisk generalisering (Swedish) Joint seminar between University Gδvle and SWECO,

Stockholm
Meng, L. 1997.07.05: Aktuella forskningsteman fφr automatisk generalisering av geografiska databaser (Swedish) Autumn conference of ULI

(ULIs hφstmφte), Linkφping, Sweden
Meng, L. 1997.05.27: Varfφr automatisk Generalisering? (Swedish) Research seminar at the Royal Institute of Technology (KTH), Stockholm
Meng, L. 1997.06.02: Necessary and Sufficient Requirements for the Construction of a Geographic Information Web (English) SCANGIS, June 2.1997, Stockholm
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Meng, L. & Reichenbacher, T. 2003.03.12: Geodienste - Loaction Based Services - Geovisualisierungsdienste. 8. Mόnchner Fortbildungsseminar Geoinformationssysteme. 12. - 14.. Mδrz 2003, Technische Universitδt Mόnchen.

PROJECT:

Feasibility Study of Database Generalization and Cartographic Visualization of ATKIS
(finished in Feb. 2000)

INTERESTING LINKS:

International Cartographic Association
ICA Commission - Map Generalization
ICA Commission - Visualization and Virtual Environments
Geographisches Schallinformationssystem

VBB Viak

Table of Contents

"I find that such an outlook from a high mountain contributes extraordinarily much to the extension of concepts. All small things have vanished from sight, only the large ones retained their gestalt. Things run into one another, you do not perceive a set of small special objects, rather, an integral, colorful and shining picture, on which the eye stays with pleasure. As a result of much hard work and elaborate design, things that appear so large downhill disappear when you look at them on the top of the mountain".

Arthur Schopenhauer

1 Background

On request of Swedish Armed Forces, VBB Viak has conducted an in-depth investigation on the long-lasting problem of cartographic generalization in GIS. The project began in January 1997 and finished in May 1997.

The project contains an overview of worldwide generalization researches in academy and industry. Numerous generalization tools and data structures are introduced and analyzed. The objective of the project is to encourage and pave a way for intensive research activities in Sweden where geographic information has become a daily necessity not only for military commanders, but also for decision makers at all levels, system developers / practitioners, educators / researchers, data providers / receivers, and general public. Facing the situation that an increasing number of GIS users need a generalization component to release themselves from the heavy burden of spatial/temporal data access and facilitate purpose-oriented application of geographic information, this report is also intended to serve as a fundamental material for Ph.D. researches in Sweden.

Stockholm 1997-05-13
Liqiu Meng
Project leader

2 Summary

Since decades, researchers in the field of cartography and GIS have been aware of the fact: A safe, flexible and economical manipulation of tremendous data amount can only be realized, when a user-oriented and/or purpose-oriented data set from source dada model could be created automatically by means of generalization. Automatic generalization might be a narrow or even strange topic for general public, but it acts as an essential bridge linking the original source data with the wide spectrum of GIS applications.

Following an introduction in Chapter 3, concept, necessity and benefits of generalization for map users and an even wider spectrum of GIS actors are explained. New constraints on generalization problem in information society are outlined, which is followed by an analysis of strategic division of

cartographic generalization into model generalization and map generalization.

The state of the art of generalization research worldwide are summarized in Chapter 4. On-going research initiatives and major contributions of representative organizations from USA, Switzerland, United Kingdom, Germany, France, Finland and China are highlighted in a comparative way in order to give an overview of the worldwide research agenda and good examples on automatic cartographic generalization. So far the corresponding research activities in Sweden are embarrassingly humble in both scope and depth when compared with other European countries and other Nordic countries -- Finland, Norway and Denmark. There is a lack of awareness among national mapping agencies and other spatial information providers/receivers. A number of commercially available generalization systems or functions from ESRI, Intergraph, Siemens, Zeiss and prototype systems from some national research agencies are evaluated. Drawbacks of existing generalization methods such as cumbersome interactivity, inconsistent performance on different part of the same feature, low flexibility etc. are analyzed and reasoned. A series of acute bottleneck problems are pointed out, followed by suggestions of feasible strategies to their solutions. Quality issues of generalization methods and generalized data are handled in detail. Practical strategies of knowledge acquisition and knowledge representation are introduced and extensively discussed because knowledge engineering plays a significant role in the development of intelligent automatic generalization systems.

Chapter 5 introduced a selected set of popular generalization methods including those for automatic detection of graphic conflicts based on vector data, or raster based, or hybrid data. The importance of meta-method which defines above all the application scope of these methods are stressed with the intention of making reasonable use of available methods and avoiding redundant research. In addition, this report treats the design of intellectual data structures as an inseparable part of generalization task, especially for the applications that demand real-time generalization functions (e.g. military actions in modern war situation, vehicle navigation, decision making in case of emergency and disaster). Some essential principles on the design of intellectual data structures are explained with examples.

3 Necessity of automatic cartographic generalization

Under the slogan ”mapping for the new millennium”, many European countries have recently completed or will soon complete the establishment of digital geographic databases that correspond to the largest-scale in the national official map series. The largest scale in such national official map series varies from country to country, depending upon the size of territory, economic concerns, technical and political issues. For example, Switzerland, Northern Ireland and Finland start their landscape modeling from 1:5, 000, the Netherlands, Belgium, United Kingdom, Norway, Denmark and Sweden from 1:10,000, Germany, France and Spain from 1:25,000. At the same time, the need for pan-national and global database coverage is increasing. CERCO (Comité Européen des Responsables de la Cartographie Officielle) began five years ago the planning of pan-European topographic databases at the scales of 1:250,000 and 1:100,000, the pilot project MEGRIN of CERCO has constructed European administrative boundaries which can reach a precision level of 1:50,000 (Illert, 1995). USGS (United States Geological Survey) finished the Digital Chart of the World (DCW) 1:1,000,000 in 1993 and distributed DCW on CD-ROM worldwide. Besides the updating in almost continuous fashion, the DCW at larger scale as well as more and more national-level datasets will be available in the nearest future not only on CD-ROM, but also on Internet with value-added data processing functions. Today, ”*many satellite imaging processes exceed resolutions of 1-meter, and private and public sector retailers are able to collect and process terabytes of image data every day. As a consequence, data is increasingly available, from a greater number of national and international outlets, and at higher spatial and temporal resolutions*” (Buttenfield & Tsou, 1997). By the year 2000, the core data sets for Europe at a level of abstraction of 1:1,000,000-1:500,000 scale or similar will be accessed by general public free of intellectual property rights.

The large scale geographic databases record in such a detailed, complete and accurate manner the location, attribute and spatial relations of geographic objects that they can be conceptually regarded as seamless and scaleless models of the reality. That is, the content of the database as a "window on the world" will be the user’s chosen window, rather than what happens to be convenient to the data suppliers. Although an ideal 1:1 model would never emerge, the scales implied in models are large enough to serve as starting point for all kinds of space related activities. One can arbitrarily extract a dataset from the models and use it as source material to produce thematic maps or derive small-scale geographic maps, or keep it as geographic information source for whatever spatial inquiry and analysis.

However, high density and high resolution of information do not always attract users because they do not always match the requirements of a special application. Problems arise when one tries to extract a relevant dataset from large data volumes or wish an abstract view of a data base on Internet. Users are complaining about current price policy on national data bases, partly because they are forced to purchase a complete data set over certain regions although their application only needs some aspects of the data set at certain detail levels. On the other hand, a quick distribution and retrieval of Internet databases is essentially impeded by current data distribution patterns and Internet traffic in addition to unsolved issues of quality assurance, data sharing and copyright. All these problems imply a strong need of cartographic generalization functions. *”The reason for performing generalization has frequently been ignored - or at least played down - in many GISs, which tend to treat data as though they were independent of scale or resolution”* (Robinson, 1993). However, as a matter of fact, *”numerous applications in climate, water resources, agriculture, forestry, transportation, land and urban planning require changing degrees of information detail when analysis and communication occur at the local or more global levels.*

From a data production point of view, the management and maintenance of spatial data are constrained by the requirements for accuracy (relationship between a measurement and the reality which it supports to represent), precision (degree of detail in the reporting of a measurement) 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 should be made available at multiple levels of abstraction, but how it should be made available" (Müller et al 1995). With the continuing rapid growth in the use of spatial information systems, *"there are many important potential applications of map generalization in which it will be essential that the cartographic processes are entirely embedded within a computer system. The full potential of GIS can only be exploited if functions for automated cartographic generalization are available"* (Jones et al, 1995). With the popularization of Internet service, not only automated, but also real-time or "on-the-fly"-generalization methods will become a necessity in order to distribute vast amount of data via network.

3.1 Concept of cartographic generalization

By cartographic generalization means a process of content and graphic adjustment with the purpose of improving the usability (e.g. cost efficiency) of geographic data and higher level visual perception of spatial/temporal entities as well as their relationships. The usability of geographic data is determined by applications and user groups, while visual perception of spatial information is mainly dependent on factors such as scale of a hardcopy map (the ratio between the size of an object on the map and its real size on the ground), resolution of a screen (the smallest object which can be represented on the map), and cognitive abilities of information receivers. The task of cartographic generalization is to *"prevent a representation of geographic data from a total collapse of information, if the allocated space becomes scarce, or if the complexity of the data creates confusion with the envisaged user group"* (Spiess, 1993), under the constraints that spatial accuracy, attribute accuracy, aesthetic accuracy and logical hierarchy of the information should be maintained (McMaster & Shea, 1989).

In a pre-digital age, map generalization was perceived as closer to art than to science. As a part of map compilation, generalization is performed manually by skillful cartographers either on the basis of hardcopy blueprint or screen graphics. In the context of digital cartography, generalization has become a necessary step of GIS construction and application. Two typical cases of map generalization can be identified:

3.1.1 Scale-driven generalization

This case usually concerns the derivation of a small scale general map from a next larger scale source map (Fig.3.1), where the scale ratio between the source map and the derived map lies usually from 2 to 5 in order to avoid abrupt changes or collapses. Source data of the base map are usually obtained from land survey, therefore, they have the highest accuracy and homogeneity in geometry. In order to fit map contents into the reduced space on a map at smaller scale or coarser resolution, operations such as selection, simplification, exaggeration, classification, symbolization, aggregation, typification, displacement etc. (Fig.3.2a-g) are applied to all feature categories by cartographers in an intuitive manner. Each of these operations needs a number of criteria and rules to define and guide the decision making.

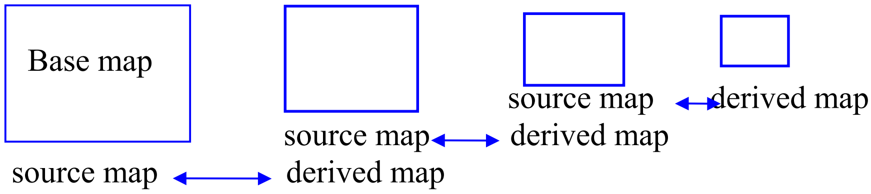


Fig.3.1 Step by step scale-driven cartographic generalization

Selection is usually applied to pick out map features based on their relative significance in the mapping area such as administrative meaning, traffic convenience, occurrence frequency, size etc.

Simplification is a combination of many operations including the elimination of small shapes of a map feature, reduction of points on a line or surface, smoothing a line or area boundary (adjusting the position of each point of a line according to the position of its surrounding points) in order to decrease the angularity and preservation of geometric characteristics such as fractal tendency of a coast line or the square corners of a building.

Exaggeration means the graphic enhancement of significant characteristics of map features such as enlargement of road width, dilation of a building (or part of building) that is of architectural interest, caricature a shape in a single pre-defined direction.

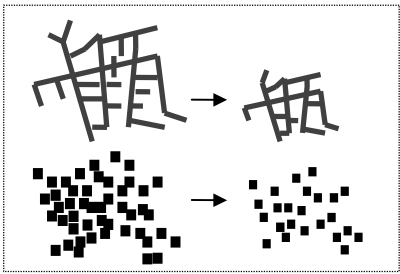
Classification means that many individual objects are grouped into a class representing their common attributes or dominant coverage. In case of dominant coverage, the original nature of small objects will be changed. This operation of changing nature is also defined as a kind of amalgamation (Ruas, 1995a).

Symbolization often implies a change of geometric dimension, i.e. collapse from area to line, area to point etc.

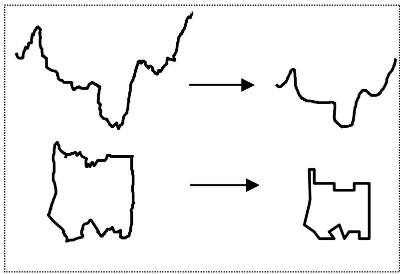
Aggregation means the fusion of adjacently located objects of the same class into a single one, or the amalgamation of closely located objects (e.g. public buildings) into a bigger one.

Typification means that a large number of discrete objects with similar forms are represented by a small number of object that has the same and typified form. The typified objects have to preserve the initial distribution characteristics.

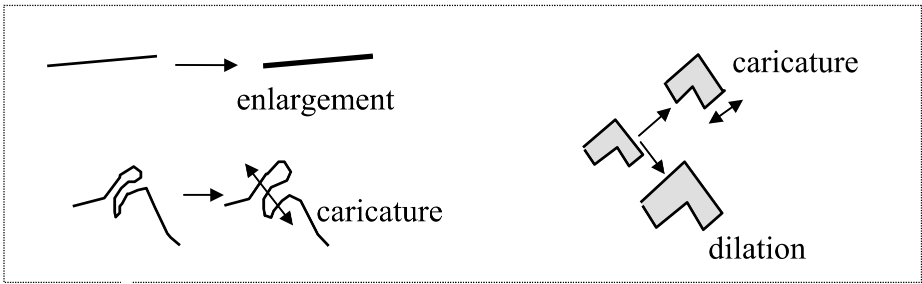
Anamorphose is a local transformation of a set of objects in order to solve proximity conflicts. Anamorphoses are composed of displacements and local deformations with propagation (Ruas, 1995a).



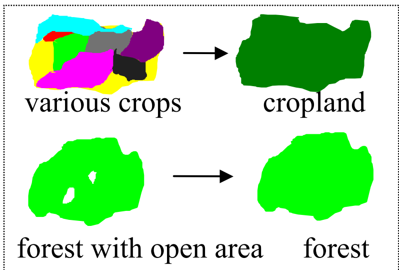
a) Selection



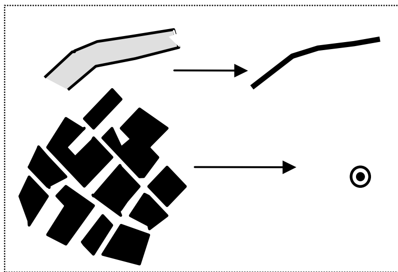
b) Simplification



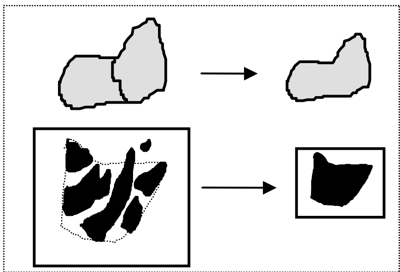
c) Exaggeration (see Ruas, 1995a)



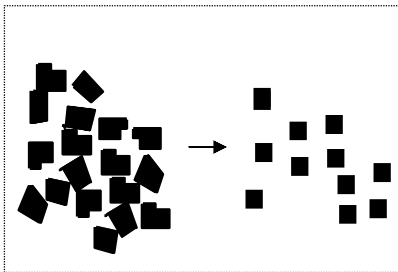
d) Classification



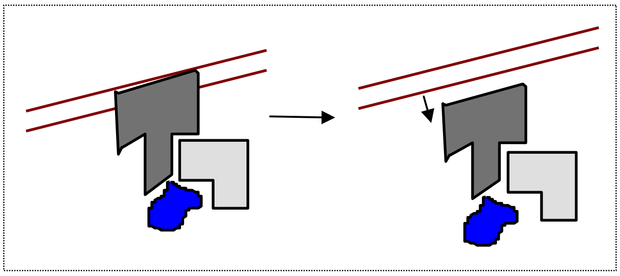
e) Symbolization



f) Aggregation



g) Typification



h) Anamorphose

Fig.3.2 Generalization operations in traditional map compilation

Generalization degree is determined by scale constraints, therefore, relative stable numerical thresholds can be worked out for predefined scale range. The manual generalization process, no matter if it is performed on the base of a hardcopy map or a screen map, is to a great extent subjective. But well-educated and experienced cartographers are able to preserve and highlight the major characteristics of map features, their semantic and topological relationships. Many national mapping agencies have so far digitized the manually generalized official map series at different scales and therefore created so-called multiple representations of the data. This way of regenerating databases is expensive and time-consuming. In addition, without information on connections between different scale versions of databases for the same objects, it is impossible to propagate the updates of one version to another.

3.1.2 Application-driven generalization

This case usually concerns the derivation of a thematic map from a single digital database or analog base map which contains detailed and multi-layered spatial/temporal-related information (Fig.3.3). In order to fit the map content to the requirements of a specific application or reader group, cartographers should not only try to satisfy the basic requirements on graphic clarity and legibility, but also analyze the relevance of map features including their geometric and semantic attributes, thus apply the generalization operations in Fig.3.2 to a selected set of features from selected layers. As generalization degree for different feature categories or the same feature category at different locations is determined by both scale and application constraints, stable numerical thresholds can hardly be defined, hence more subjectivity in the resulting map.

No matter whether the map generalization is primarily scale-driven or application-driven, cartographers always face with the traditional dilemma: how to insert the maximum amount of relevant information into a given map without either making it unintelligible to the reader or increasing its physical size to an unmanageable level. The final map -- despite the best efforts of the cartographer -- must always represent an uneasy compromise between the conflicting goals of maximization of information content and ease of visual extraction of that information.

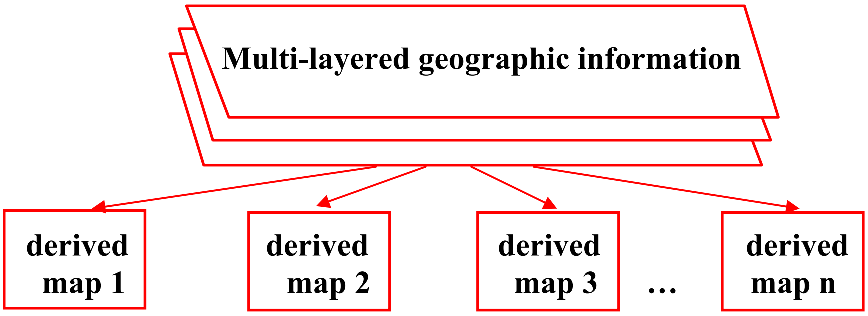


Fig.3.3 Application-driven generalization

Due to the great flexibility of human intelligence, map makers have been undertaking manual generalization since centuries following some general principles. Although no two map makers can produce exactly the same generalized map (in fact, even the same map maker may produce different maps at different times), the discrepancies between these results are well-accepted as long as they do not violate the constraints of cartographic convention. In this sense, there is no need in manual generalization to ask individual map makers what kind of thinking procedure they follow for a particular generalization task and whether or not the procedure can be repeated without deviation. These questions were not seriously taken until 60ties when automation process in map production began to tackle generalization problems. Without automatic generalization systems, maps can not be produced and distributed at accelerating speed required by increasing users.

Today, after thirty years research (sporadically or intensively) and countless experiments, a variety of automated subprocesses in generalization procedure have reached their commercial maturity, yet generalization problems are still far from being completely solved. More serious phenomena in information society which deserve attention are that 1) maps are no longer a working tool only for a small group of politicians, high military commanders, scientists, educators or adventurers, rather, a daily necessity for general public; and 2) paper maps are no longer the dominant form for the communication of spatial/temporal information. This does not mean that the necessity of generalization will fade away with time, on the contrary, new constraints such as those concerned with access speed, multiple presentations of the same database (with varying scales or themes), temporal interpolations, ad-hoc solutions etc. have been posed on generalization function.

Due to its enormous complexity, interdisciplinary as well as multi-disciplinary involvement and extremely diverse user requirements, the topic of automatic generalization has been placed on the top of research agenda in geographic information (GI) area worldwide since 80ties.

3.2 Distinction between model generalization and map generalization

Generalization component (primitive or advanced) built in current GISs can be usually split into a number of more or less self-closed automatic operations that are then chained sequentially and/or recursively by human operators in an interactive way. In order to set optimal parameters to each operation and find out a reasonable calling order of the operations, human operators must have a comprehensive insight into the behavior of individual generalization operations, in addition to cartographic knowledge. As a consequence, such working tools do not necessarily take less time than purely manual methods to complete a generalization task, and not so many operators would be qualified for the demanding interactive job without extensive training because *"spatial modeling process can be simulated only by strategies based on understanding and not by a mere sequence of operational processing steps"* (Brassel & Weibel, 1988). This situation obviously blockades the communication channel between information providers and mass users. Neither is it wise to wait for the emergence of intelligent generalization systems, if any.

As a strategic remedy, a distinction can be made between model and map generalization in digital working environment. That is, data manipulation of geographic objects may need to have multiple digital representations in which implicit model representations are independent of explicit visual representations. This distinction has its realistic meaning in view of the wide spectrum of GI applications where the users are either mainly interested in analytical queries (e.g. calculation of spatial/temporal trends, mode, average, variances etc.), without need to have a clean view of the data, or they will mainly interact with the geographic objects in the easiest possible way (e.g. geographic location of the objects, distribution pattern, spatial relationships between neighboring objects), without need to know the details of data structure and digital coding. *"Distinction between model and graphics brings about the issue of database for multi-purpose applications. Can a single database be used for producing maps at different scales? And if so can we speak of scaleless or scale-free database? The concept of scale would only come in when a relationship between object and representation (in some kind of output medium) would be established"* (Müller et al, 1995). The minimum thresholds for a clear view of graphic details depend on the resolution capacity of the output as well as on the human perception and differentiation capacities (Spiess 95).

3.2.1 Model generalization

As indicated in Fig.3.4, model generalization aims at deriving one or many secondary object models of lower resolutions from a primary object model of higher resolution. The derived models in turn can be treated as primary models for creation of secondary object models of even lower resolutions. The primary object model at the paramount level represents the reality with the highest resolution allowed by the latest techniques (Meng & Grünreich, 1994). The lower the resolution of a secondary model, the higher its abstraction level. Therefore, model generalization is, in essence, a process of data abstraction dealing with the identities of objects and their semantic relationships. A part of generalization operations such as selection, classification and aggregation are used as abstraction mechanisms as they afford considerable flexibility in reducing data densities and can be manipulated to provide application-oriented contextual emphases in the spatial, thematic and/or temporal domain.

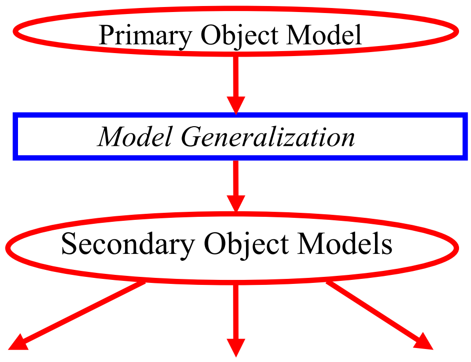


Fig.3.4 Model generalization

As compared to other generalization operations, abstraction mechanisms are well defined, therefore, it is relatively easy to computerize them. However, constructing a Digital Object Model (DOM) is not merely an abstraction process from reality to primary model, or from primary model to secondary models and so on, if DOM is considered to be an integral of a spatial reference, i.e. Digital Landscape Model (DLM), and digital thematic models of all disciplines as suggested by Grünreich (1995). Homogenization of accuracy and resolution of objects through data integration or data fusion, for example, is one of the most difficult issues which should be better handled as separate research area. This report will concentrate discussions on the derivation of DLMs at multiple levels of accuracy and resolution and inheritance of object attributes that fit the derived DLMs. The concept of model generalization will, therefore, be applied to a *"subproblem of cartographic generalization, detection and elimination of errors in continuous data and continuously changing data, and the modeling of uncertainty"* (Bruegger & Müller, 1992; Weibel, 1995). Results of model generalization can be delivered either as final product to various GIS users or as intermediate product to cartographers for further treatment in map production (Fig.3.5). Since automation of model generalization will facilitate the data access and understanding of the reality without introducing artifacts like symbolization, displacements and exaggerations, the communication impediment between the mapping reality and the majority of GIS users thus becomes less serious. On the other hand, *"much of the success in cartographic generalization will require geographical modeling in order to support the characterization of geographic space. In this sense, the implications of the generalization results go far beyond the notion of map production. This is why research in cartographic generalization remains at the top of the research agenda in GIS"* (Mackaness, 1997a).

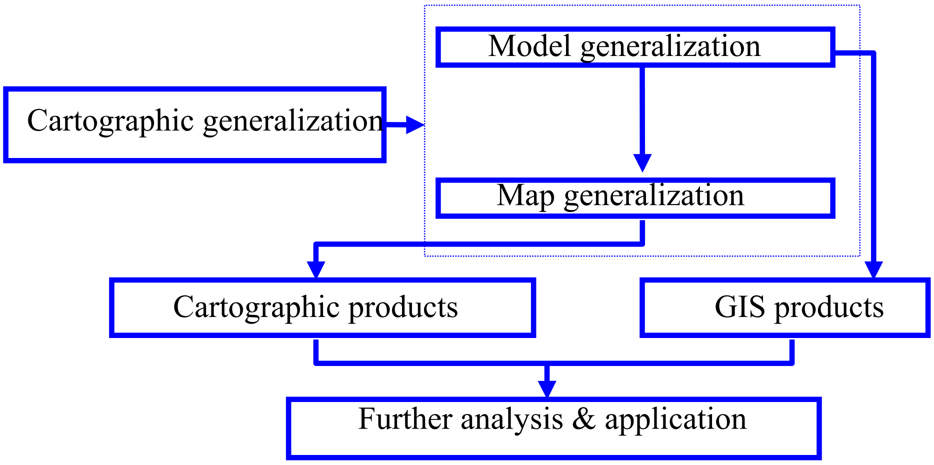


Fig.3.5 Relationship between model and graphic generalization

3.2.2 Map generalization

Fig.3.5 implies that model generalization can be a precursor to map generalization. While model generalization strives for the creation of a geometrically and semantically correct object model, map generalization aims at deriving a collection of topologically reasonable map symbols with pleasant look, no matter how they are stored.

Map generalization process will be inevitable, whenever the database has not been purposely structured for the production of maps, as is the case with digital object modeling for GIS applications. The production of up-to-data multiple scale versions of general maps and the multiple representations of thematic information for a variety of special user groups on the bases of scaleless object models, with one single maintenance procedure (Fig.3.6), would require a *"high, well-conceived and consistent system of efficient generalization facilities. This is by no means a straightforward undertaking for an automated system. Different minimal dimensions are used and intricacy of detail varies considerably"* (Spiess, 1993). It is this long lasting struggle for the maximum of information content and minimum of visual loading on the shrinking map space that has troubled the system developers most. As symbol configurations to represent real phenomena are infinite, it proves difficult to strike a balance automatically between objectivity required by the functional characteristics of an analog map as scientific document and subjectivity required by aesthetic aspects of map symbols as work of art. Not only the individual generalization operations have to be computerized such as adjustment of selection and classification after model generalization, graphic simplification, exaggeration, symbolization, aggregation and displacement, but also the strategies controlling these operations and database structures. Only when both methods and meta-methods are automatically implemented can the corresponding systems be regarded as more efficient than human cartographers.

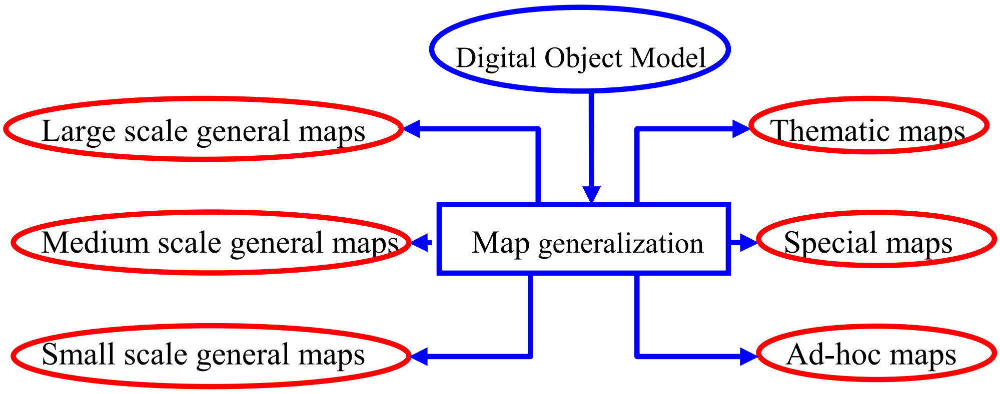


Fig.3.6 Products of map generalization

3.2.3 Benefits of automatic cartographic generalization

Based on above introduction, major benefits of automatic cartographic generalization comprise following aspects:

1. Description of reality with varying degrees of abstraction in different models or even within the same model, concentrating on the essential information for each group of users or particular purposes

2. Modeling of uncertainty, error and trends in databases, particularly those continuous and continuously changing datasets

3. Filtering of noise in an image or map and enhancement of the essential parts, thus render relevant and optimal amount of information legible at a given scale or format

4. Effective distribution and access of mass spatial/temporal information via Internet

4 State of the art

Automation of cartographic generalization is not a new research topic, but it is constantly obtaining new research contents. Since the problem was raised for the first time in the middle of 60ties, research activities have experienced a major cycle of upswing (e.g. 1965-1980), euphoria & suspicion (e.g. 1980-1990), and stagnation (e.g. 1990-1995) followed by possibly a new upswing (since 1995 --) . Research progresses have been made at an uneven pace. The derivation of cartographic products from a digital object model is so far manually done with help of human-machine dialogue. In spite of the fact that *"a vast range of research topics have attempted to address the issue of automated map design where generalization constitutes an essential part - fractals, neural nets, cognitive ergonomics, models of communication, protocol analysis, expert systems, etc., all we have are a dozen generalization algorithms or so"* (Mackaness, 1996). Many generalization operations such as graphic simplification, classification, elimination and aggregation already exist in commercial GISs, even more complicated operations such as feature displacement can be partly resolved by using buffer and snap commands in systems like ArcInfo and MapInfo, however, none of these GISs can perform generalization in the sense of assembly and adaptive work. The available individual generalization functions are therefore not able to play more significant role than graphic editing and statistical calculation. This means, the lack of entirely automated tools is still standing in the way leading to the development of true flexible GISs.

4.1 History of development

Most of the initial progress in 1960's and 70's were concentrated on the development of geometric measures and algorithmic solutions, such as fractal dimension of map features, numerical constraints on symbols (e.g. scale dependent minimal size, angle, length, and area) and relations between symbols (e.g. minimal distances between neighboring symbols), selection of discrete features based on Töpfer's Radical Law or its modifications, vector data filtering with Douglas-Peucker or its variants, low-pass and/or high-pass filtering of elevation raster data based on image processing techniques, spline functions for line smoothing, edge enhancement of raster areas, and algorithms for displacement. Countless articles reported the usage of algorithms (either developed or borrowed) on more or less contrived test data. *"Many of the available algorithms were developed for the purpose of line simplification, and to a much lesser extent, area and surface simplification. Very much less research effort was devoted to solving the map generalization problem in a holistic manner that takes account of cartographic constraints on the relationships between multiple map objects and of the interactions resulting from the application of individual object generalization operators"* (Jones, et al. 1995).

From 1980 to 1990, the direction was turned to the higher level processes in generalization that should be less mechanistic and more human-like. At the same time that more individual and separate algorithms were built in GISs, people became aware of the necessity to acquire meta-knowledge, for example, what is meant with a special term such as line simplification (Is it data reduction, or data reduction plus adjustment, or data reduction plus smoothing based on interpolation or spline functions?), which techniques should be applied in which context, in which sequence should the techniques be applied and with which parameters or tolerance values). Rule-based systems were prevailing techniques to gather the knowledge that is partly available in text books or handbooks of cartographic convention. Cartographic specialists were interviewed in various ways. Behaviors of system operators or users on well-defined cases were traced. Relative stable expert knowledge was translated into "goal-condition" clauses of logical programming languages such as Prolog and LISP, or "IF- THEN"-statements in procedural languages like FORTRAN and C. However, the euphoria with artificial intelligence soon was overwhelmed by strong suspicions among cartographers against the possibility of a one hundred percent batch solution or multi-purpose expert system as attempts with rule-bases did not make the generalization results smarter. Numerous studies revealed that knowledge beyond the declarative level such as common sense, cartographers' capability of thinking in graphics and parallel handling of generalization operations was difficult, if not impossible, to be explicitly formulated in computer languages. It seemed by the beginning of 1990's that the only reasonable choice was to develop interactive generalization systems.

Generalization researches in academy and industry suffered a stagnation period from 1990 to 1995 due to the fact that neither the refinement of algorithmic solutions nor the increasing size of rule bases was able to bring about a break-through, and the cost/benefit aspects of interactive systems proved not particularly encouraging. Yet, the stagnation period was also marked with very intensive brainstorming. A series of international forums such as EGIS, ICA and OEEPE made it possible for specialists to exchange their opinions on the subject of generalization and identify the bottleneck problems. Suggestions were made to *"create test-scenarios and push the operationality of existing software to their limits"* (Müller et al 1995). Sporadic attempts were made to evaluate and validate the existing tools, instead of re-inventing the wheel. It was suggested that quality control be exercised at the model level. as well as the graphical level. That means, distinctive quantitative and qualitative specifications concerned with metric, topological and semantic accuracy of models and map products should be developed. Delaunay triangles and Voronoi diagrams found their extensive applications in detecting topological changes incurred by objects displacements and semantic/context relationships among objects that are not necessarily from the same feature category and spatially near to one other. Meanwhile, techniques of parallel distributed processing or neural nets were tried to simulate cognitive aspects of generalization process that can hardly be verbally formulated in programming languages.

Since 1995, popularization of World Wide Web communication has brought about new challenges to generalization researches. In addition to the requirements on more comprehensive generalization solutions for increasing GIS applications, the speed of generalization performance has become one of the essential factors that decide the acceptance degree of a system. Examples of these applications include the provision of maps for navigation and the display of information relating to urban and regional planning, tourist facilities, mineral exploitation, and emergency response. Interactive solutions can no longer satisfy real-time demand. Professionals have realized the influence of different data structures on the efficiency of a generalization system. Regarding the design of data structure as part of generalization task, numerous proposals on so-called intellectual data structures have been tested that can considerably accelerate access of data with required resolutions. The object-oriented environment, where methods are bound to the object, objects communicate with each other and inherit attributes and methods from others seems to offer great flexibility for implementing generalization procedures and updating datasets. Many GISs with generalization component are being built upon object-oriented environment. Many existing generalization tools have been evaluated on non-contrived geographic datasets and inserted into method banks. Efforts with meta-knowledge acquisition are continuing based on neural nets and new approaches such as the modeling of temporal information that provides additional dimension to interpret image and detect semantic as well as graphic conflicts. In addition, people have begun to realize the significance of cognitive factors for the development of more local solutions of map generalization, because the global methods of generalization fail to reproduce the subtleties that even a naive human map interpreter can find in maps. *"Early attempts to tackle the cognitive problem from a computing perspective underestimated the difficulties involved in attempting to reproduce such a complex human capability"* (Edwards, 1997). As a summary, *"recent research in cartographic generalization has focused on many issues, including: (1) more robust data structures for supporting the process, (2) continued work in algorithmic development, (3) semantic support for the generalization process, and (4) the modeling of geometric features"* (McMaster, 1996).

4.2 Representative research organizations

4.2.1 United States

Generalization activities are quite concentrated at NCGIA (**N**ational **C**enter for **G**eographic **I**nformation and **A**nalysis) where scholars worldwide have been doing Ph.D. degrees or intensive GIS researches that are divided into a series of initiatives. Two of NCGIA initiatives led by Buttenfield are devoted to generalization: (1) Multiple representations (1990-1991), and (2) Formalizing cartographic knowledge (began in 1993).

The objectives with multiple representation is to organize multiple topological and metrical versions of the same data for efficient access, and the implementation of linkages between multiple representations. The research scope covered the areas: data models; linkages between multiple representations; maintenance of graphic views; spatial modeling issues; generalization issues; and problems posed by multi-agency, multi-scale demands for and of data. Investigations were made on the establishment of rules that ensure consistency and accuracy in cartographic generalization.

Digital cartographic representation requires robust algorithms and a suitable data model. Since many geographic features vary their appearance with scale, it is difficult to encapsulate all possible details for all scales within a single data model. Buttenfield proposed in 1995 an object-oriented solution to multi-scale data modeling based upon the Digital Line Graph (DLG-E) data model developed at the US Geological Survey. With help of encapsulation in object-oriented programming (combination of data record with procedures) and polymorphism (parts and subparts of a complex object share a procedure but apply it with differing results), this solution extended the DLG-E model to accomplish a link from a single geographic database to its multiple cartographic representations. At the same time, Buttenfield pointed out that major impediments to implementation of this solution beyond the prototype level included formalizing knowledge about what are the appropriate ranges of scale for each graphical scheme.

The objectives with formalizing cartographic knowledge are to develop methods for the acquisition of cartographic knowledge in the procedure of spatial modeling, map production and map use, and to represent acquired cartographic terms, strategies of map design, measures (cartometric, semantic and cognitive) of map evaluation and interpretation into forms that can be recognized and automatically processed by machines. Some knowledge was directly taken from industrial mapping specifications (e.g. guidelines of mapping agency like USGS). A method of "reverse engineering" was experimented with at NCGIS Buffalo and the University of Zurich where existing map series displaying information at different scales are systematically analyzed. ”Reverse engineering” is a suitable technique that can keep track of cartographic knowledge applied in generalization by detecting and explaining changes from one scale of representation to another as well as cultural influences. Partial attempts were made to gather information from human experts. Issues of structuring/modeling knowledge and meta-knowledge, data structures for efficient update, cartographic data exchange and data compression were also tackled.

Being encouraged by the fact that many difficult generalization procedures can be now formally described and parameterized, Buttenfield and Tsou made attempts to send formalized generalization methods across the Internet to very large data archives to perform data reduction and other data modeling tasks, and return subsets of the original archives encapsulated with the parameters used in the generalization tasks. This concept of bringing processes to data instead of data to process is unique (Buttenfield &Tsou, 1997).

In addition to research initiatives at NCGIS, extensive studies on the evaluation of generalization quality, knowledge acquisition and representation have been made also in other institutions in USA. In 1989, Shea & McMaster approached systematically a number of mathematical/geometric measures that can help describe or estimate gestalt pattern of map feature classes, individual features in the same class and characteristic parts of a single feature. For example: Object clusters are described by density and distribution measures or evaluated by more abstract measures such as homogeneity, neighborliness, symmetry, repetition, recurrence, and complexity; Line features are described by length, sinuosity and angularity; Area features are described by more or less fuzzy shape measures such as elongation, roundness etc.; The structural kinship between the reality and its cartographic representation is estimated by distance and gestalt measures such as closure, continuation, proximity, similarity, figure ground and so on. Meanwhile, Shea & McMaster established a theoretical framework that indicates why to generalize (identification of objectives and constraints), when to generalize (assessment of the conflict situations which provoke semantic or geometric changes), where to generalize (which part of the information should be generalized first), what to generalize (which objects, what are the available operations to solve a conflict), how to control the effect of an algorithm and propagate the effect in order to maintain consistencies, and finally who to generalize (the system, an expert user or an user). A platform named MGS was implemented in 1991 at University of Minnesota for knowledge acquisition by testing existing generalization algorithms.

McMaster also studied the behavior of manual digitization, trying to find out how the characteristics of a line influence the data capture process, such as the spacing of digitized points along the line and the speed with which the cursor is moved. The acquired knowledge of data encoding in turn might assist in the generalization of digital line (McMaster, 1995).

Based on their experiences with line simplification, Buttenfield and McMaster were among the first who put forward the ideas of splitting a line into "homogeneous" sections for certain scales, assigning to each of such sections the best-suited generalization methods and parameter values in accordance with the geometric nature. These initial ideas were further converted into decision making steps by a number of French researchers (see section 4.2.5). For example, division between building boundary and road according to angularity, subdivision of road according to sinuosity, assigning appropriate algorithm to simplify road sections with different sinuosity degrees.

In order to help users understand and evaluate the result of the available methods (e.g. simplification, smoothing, enhancement and displacement of vector data, pixel-to-area transformation, spatial filtering, classification of digital images, gap bridge, smoothing and aggregation of raster data), McMaster & Comenetz established in 1996 a comprehensive conceptual framework for generalization measurement that included both procedural measures and quality assessment measures. In 1997, McMaster further developed a visualization framework. In case of vector-based generalization, various visual variables such as hue, saturation and value of a color are applied to indicate generalization operator, the number of iterations, and tolerance value of parameters (Fig.4.1). In raster mode, resolution change is displayed by superimposing a set of original grid lines on a modified image (Fig.4.2). A saturation mask is used to highlight the pixels based on their modification degree.

hue (red, green, blue …)	generalization operator
saturation (pure red, less pure red …)	number of iterations
value (bright red, dark red)	tolerance value of parameters

Fig.4.1 Visualization of vector-based generalization

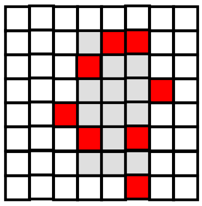


Fig.4.2 Superimposition of raster image before and after generalization

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4.2.2 Switzerland

Brassel and Weibel at the University of Zurich proposed in 1988 a conceptual framework for cartographic generalization which has been well-adopted as theoretical reference for generalization researches in Europe and America. The framework is composed of five steps: structure recognition, process recognition, process modeling, process execution and display (Fig.4.3). According to this framework, a successful cartographic generalization is largely dependent on the understanding of structures in original databases and generalization processes involved in a particular task. The useful processes are contained in a library and may consist of rules, constraints and algorithms. Through process modeling, a calling sequence of the processes will be formed that is adaptive to purposes of the generalization task. This framework has twofold meaning: it stressed the importance of context information to decision making for a reasonable integration of individual operative modules; it brought the necessary distinction between model generalization and map generalization to light.

Based on the framework, Weibel experimented with computer assisted terrain generalization that is adaptive to different terrain types, map objective, scale, graphic limits and the quality of data (Weibel, 1992). By combining various approaches that cover many aspects of terrain generalization such as global filtering of DTM, determination of significant data points and structure lines on DTM, iterative filtering of triangulated DTMs (Weibel & Heller, 1990), and heuristic generalization of DTM based on structure lines, the experiment resulted in an interactive, flexible and open-ended system. The adaptive character of such a system is said to be a kind of Amplified Intelligence – a term widely circulated among specialists of computer-assisted generalization. A system with Amplified Intelligence can be tailored to undertake specialized tasks by adding the knowledge about purpose-dependent parameter settings and calling sequences of operational steps.

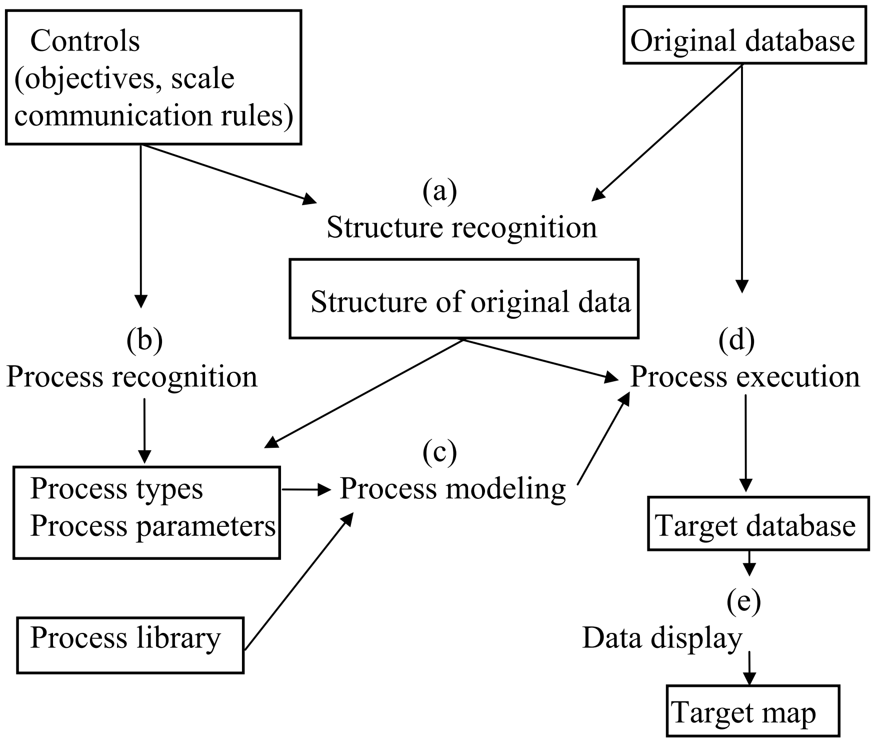

Fig. 4.3 Framework of generalization (Brassel &Weibel, 1988)

In order to extract the steering knowledge of software users, Weibel suggested that a log-file be built in a generalization software that can record the calling sequences and frequency of procedures for particular tasks. A platform was developed for knowledge acquisition on top of Arc/Info.

In addition to the efforts on acquisition and formalization of cartographic generalization in collaboration with NCGIA, the University of Zurich has also made considerable progresses in polygon map generalization (Bader & Weibel, 1997) that include issues such as data structure for efficient updating, definition and modeling of constraints relating to size and proximity for irregular shapes, development of special treatment for narrow parts of polygons, detection and resolution of conflicts based on Constrained Delaunay Triangulation (CDT) (see Chapter 5) and polygon data structure.

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4.2.3 United Kingdom

The University of Glamorgan has made major contributions to automatic cartographic generalization based on their innovative techniques for identifying spatial conflicts and modeling solving mechanisms. As early as 1986, Jones and Abraham conducted comprehensive studies on vector coded line features with particular concern to the merits of hierarchical data structures, for individual storage of lines and their spatial decomposition. They established a line generalization tree and developed a technique for its storage within a set of scale-dependent levels, each of which may be independently segmented by a quadtree adapted for storing internal line points. They were among the first who realized the fact that the design of intellectual data structures is an important part of generalization procedure.

In 1992, the line generalization tree was extended to a strategy of database design which integrates multi-scale storage of point, line and polygonal features, with a multi-scale surface model based on the Delaunay pyramid (Ware & Jones, 1992). The constituent vertices of topologically-structured geographical features are distributed between the triangulated levels of a Delaunay pyramid in which triangle edges are constrained to follow those features at differing degrees of generalization. This multi-resolution data structure provided a means of retrieving geographical features from a database at levels of detail which are adaptable to different scales of representation (see Chapter 5).

In 1994, the multi-resolution data structure began to have an object-oriented nature which represents geographical phenomena derived from different sources and scales. The relations between real world objects and their geometric representations at different scales are maintained using an object directory. Maintenance, update and retrieval of the multi-scale data are governed largely by deductive process and rule bases (Jones, 1994).

The University of Glamorgan made its sensational progress in 1995 when various generalization operations were tested on the data structure called Simplicial Data Structure (SDS) and the prototype system Map Authoring and Generalization Expert (MAGE) that integrates the advantages of SDS and context frames was implemented in Kappa on a Sun workstation. Kappa is an object-oriented tool from Intellicorp that allows deterministic procedures to be implemented using C++ and non-deterministic procedures and rules to be expressed in a language called ProTalk (Bundy et al, 1995).

SDS is based on simplexes of Constrained Delaunay Triangles (CDT), i.e. the smallest geometric objects of a given dimension -- a vertex, a line with two vertices, and a triangle. Each triangle in CDT belongs either to a discrete object or to free or unattributed space, if there is any in the map (Fig.4.4). The representation is very similar to a triangulated irregular network (TIN), but Jones introduced a change in terminology to disassociate the data structure from the use of TINs in GIS for representing terrain surfaces. That is, the SDS is used for representing points, lines and areas solely in two dimensions, though this does not preclude its future use in a three-dimensional context.

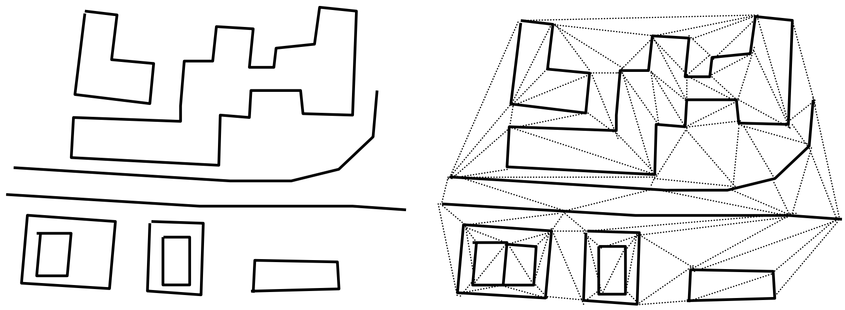

Fig. 4.4 SDS representation of map features according to Bundy et al. 1995

As the SDS gives a fully connected 2-d plenum that implicitly stores object-level topology, useful relationships such as *adjacent* and *between* are evident in the sets of simplexes connecting objects. A number of publications from the University of Glamorgan have systematically reported the implementation of SDS-based generalization operations such as object exaggeration, collapse, amalgamation, boundary reduction and displacement (see section 5.3.2 for details).

The MAGE system is able to deal with many different types of map features and their interaction in a holistic manner. A topographic map surface can be represented in MAGE by a topological data structure based on simplexes which facilitates generalization operations, whereas the semantic structures can be represented by a hierarchy of context frames, each of which encapsulates the knowledge required to recognize, generalize and resolve a cartographic situation. Thus, MAGE as a platform for experimental development of automated generalization operations imposes a degree of objectivity onto the specification of the generalization process that is not usually found in specifications for human cartographers. Attempts with MAGE aim at producing results somewhat similar to those of a human cartographer by taking into account the context of the sub-problems encountered during generalization (Jones et al, 1995; Bundy et al, 1995). Tests were concentrated on the generalization of 1:1,250 scale map to the specification for a 1:10,000 scale map of UK Ordnance Survey (OS). There remains a great potential for further research both into the efficacy and robustness of SDS-based generalization operators and control mechanisms applicable to context frames.

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4.2.4 Germany

Since three decades, automatic cartographic generalization has been at the top of research agenda at the Institute of Cartography, University of Hannover. This institute has so far the longest history of intensive research on automatic generalization in the world. Numerous Ph.D. theses that deal with automatic generalization of various feature categories on topographic maps have been published. The majority of these publications are vector-based because of a two-fold reason: (1) vector database had apparent advantages over raster data concerned with storage capacity and understanding. This was particularly important in 70's when computers were not powerful enough to handle huge cartographic databases; and (2) research of automatic generalization at the University of Hannover was in fact a continuation of previous works, therefore, vector-based strategies were essentially propagated year after year.

Staufenbiel (1973) was the first who did extensive study on the variations of graphic forms of buildings appearing on large-scale German topographic maps (Fig.4.5). Based on a number of geometric threshold values such as the minimal side length, area of and distances between buildings, he developed vector-based algorithms for the automatic recognition of classified buildings and their generalization that included typification, elimination of insignificant buildings, enlargement of small but significant buildings, aggregation, and displacement.

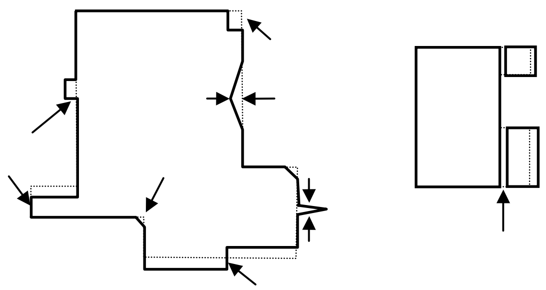

Fig.4.5 Small dimensions on buildings

Lichtner (1976) reported on procedures for displacement of buildings from roads, in which individual vertices of a building are displaced in inverse proportion to their distance from the road. In 1979, he began to notice the importance of automatic set-up of parameters and calling sequences of generalization processes for future system development. In the same year, Lichtner made innovative proposals about the possible applications of raster-data processing in the field of cartographic pattern recognition which has become a new research area in automatic digitization – a prerequisite of entirely automatic design system.

Hentschel tackled in his work (1979) the generalization problem of contour lines. Some of the major issues of automatic generalization he investigated were e.g. how the selection of equidistance between contour lines is influenced by map scale and terrain type, how the simplification of lines is related to their characteristic trend, weighted influences from neighboring lines, and interactive processing that takes consideration of cartographer's thinking.

Although strategies of the above works in 70's were only tested on contrived data, they laid down a ground for continuous investigations, particularly for procedural generalization of line and area symbols for the application of automatic production and updating of German topographic maps at the scale of 1:25,000 with the source map at 1:5,000.

Menke developed in 1983 a complex of algorithms for the automatic generalization of traffic network from the German topographic map at 1:5,000 to 1:25,000. The complex is consisting of the procedures for (1) calculation of middle axes from double-lined roads (2) simplification of extracted middle axes (the method is also applicable to river objects) (3) symbolization of simplified middle axes with widened double lines on the derived map (Fig.4.6). Menke also investigated the appropriate calling sequences of generalization operations for the more comprehensive task concerned with many object categories such as traffic network, hydrographic network, settlements and contour lines. Menke's algorithms and suggested calling sequences built up an essential part in the batch software "Institute of **C**artography, **HAN**nover University, **GE**neralization-Software" (CHANGE).

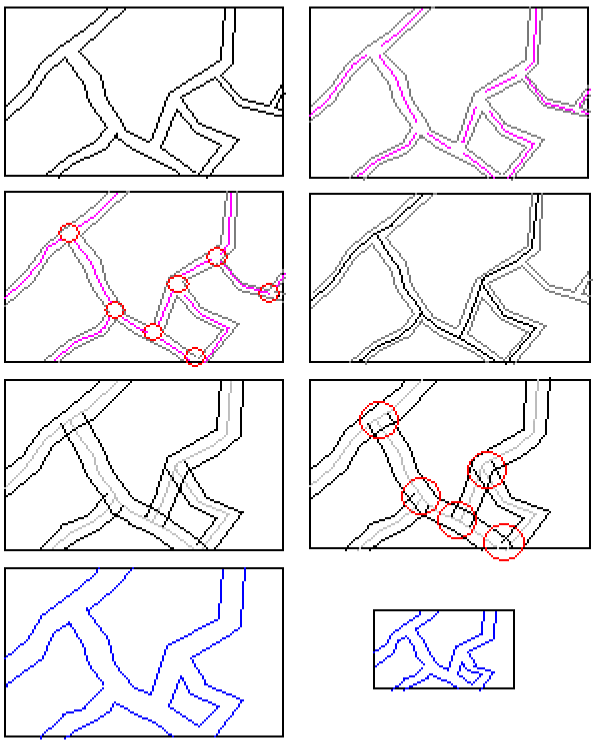

Fig.4.6 Generalization procedure of traffic networks in CHANGE

In 1985, Grünreich systematically studied the data flow from the official real estate map series 1:1,000 to topographic base map series 1:5,000 in Germany, and developed an algorithm that integrated semantic-geometric generalization strategies based on graph theory with Staufenbiel's geometric generalization strategies. The algorithm was applied in a concrete case to derive new area symbols (land parcels, real estates, buildings etc.) for a German basemap 1:5,000 from a digitized real estate map at 1:1,000. Paying attention to semantic transformation caused by classification and aggregation of area objects marked a new period of generalization at higher level. Grünreich also proposed the distinction between model generalization and map generalization, based on his initiative experiences with the construction of object-based **A**mtliches **T**opographisch-**K**artographisches **I**nformations**S**ystem for civil usage in Germany (ATKIS) that essentially comprises an object catalogue (ATKIS-OK) of each Digital Landscape Model (DLM) for data analysis and a symbol catalogue (ATKIS-SK) for each Digital Cartographic Model (DCM) for map production (Grünreich,1988).

In 1989, Meyer reported his work on automatic recognition of typified building patterns, iterative calling sequences of building generalization (simplification of building contours, aggregation of buildings, simplification of aggregated buildings and so on), and geometric measures for the evaluation of generalization results. These algorithms were integrated with Menke's algorithms into CHANGE which thus got the essential configuration of a batch software applied to generalize buildings and traffic network on German topographic maps from scale 1:5,000 to 1:25,000.

A complete CHANGE was introduced by Powitz in 1993. He added an additional component to the system -- automatic detection of graphic conflicts between generalized buildings and street network (Fig.4.7). These conflicts have different characters: some are caused by congestion, that is, too many features are positioned in a reduced map space; some are consequences of coalescence, that is, features touch each other due to exaggerated street width; and finally, some will occur as the result of displacement propagation of other features. Meanwhile, he developed a series of procedural modules for the issues of displacement. CHANGE was implemented under DEC-VMS operation systems either as independent software package or as a component of the photogrammetric interpretation system PHOCUS of Zeiss. Since 1995, CHANGE has been also available on Unix machines with SICAD-OPEN connections.

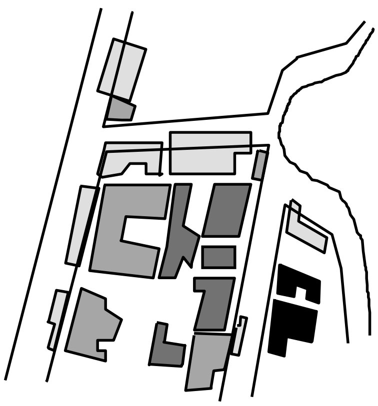

Fig.4.7 Different classes of graphic conflicts between buildings and roads in CHANGE

Researches on knowledge acquisition and formalization, knowledge-based model generalization began in 1992. Major issues include the integration of two dimensional Digital Situation Model and the third dimensional Digital Terrain Model (DTM) into a real seamless three dimensional DLM; investigations of user required resolutions of the DLM; feasibility study about the integration of procedural algorithms, neural nets and declarative rule-bases in object-oriented development environment; and statistical evaluation of CHANGE's performance (Meng & Grünreich, 1993, 1994).

Meanwhile, comprehensive methods of terrain generalization based on object-oriented techniques are being developed that are broken down into a number of steps such as geomorphologic analysis, extraction of structure lines and points on Digital Terrain Model (DTM), adaptive filtering of weighted structure lines, interpretation of terrain types, and quality assessment at geometric, structure and semantic levels (Wilke, 1997). In collaboration with Siemens, displacement algorithms that take advantage of hybrid raster and vector database are being extensively studied and further developed (Fei, 1997).

As a matter of fact, the research achievements incl. the evolution of CHANGE in Hannover has very much profited from other individual attempts conducted elsewhere in Germany, such as the "Institut für Angewandt Geodäsie" (IfAG) in Frankfurt am Main where interactive solutions of displacement, hybrid raster and vector data structures were already systematically studied and tested during 70's and 80's (Christ, 1979; Weber, 1982).

In 1994, a joint research project of model generalization was launched between the University of Bonn and German defense agency (Morgenstern et al. 1994). Objective with the project is to build up a Topographic Information System (TOPIS) for military applications that demand various information densities and precisions, depending on the scope of regions for military actions.

TOPIS is composed of three preliminary Digital Landscale Models: DLM25 with fine resolution corresponding to the topographic map series at 1:25,000; DLM250 with medium resolution corresponding to the topographic overview maps 1:250,000 (while ATKIS selects the scale 1:200,000); and DLM1000 with coarse resolution corresponding to world map at 1:1000,000. The object catalogue in TOPIS (MilGeo-OK) is formed by combining the initial data from ATKIS-OK of DLM25 with military special information in TOPIS data structure (Morgenstern et al. 1995). Model generalization is needed from DLM25 → DLM250, and DLM25 → DLM1000 or DLM250 → DLM1000.

Systematic investigations and experiments were made to connect the identities and attributes of the same objects at different resolution levels. These attempts have revealed a number of problems concerned with semantic linkage. For example, it is hard to derive object type and a complete set of attributes from primary DLM. Numerical criteria used in primary DLM are no longer suitable in secondary DLMs. As the causes of the problems, all kinds of possible ”dimensional collapses” of the same object type in different DLMs were identified, which makes the research very valuable. Many recent studies of cartographic generalization have tackled the problem of dimensional collapse such as from a 2-d area to a 1-d line or a 0-d point when the model resolution decreases, but few have seriously mentioned or treated the dimensional collapse other way round, i.e. from a 0-d point to a 1-d line or a 2-d area when the space left by eliminated objects has to be filled with the attributes or identities of nearby objects on the same layer. This latter case is significant because ”dimensional collapse” is often accompanied by concept change of objects, i.e. the attributes or even the identity of original objects may have to be reassigned after to dimensional collapse.

In addition to the issues of object linkage and embedding, efforts were also made to define geometrical measures such as area criterion that makes sense for irregular polygons. Algorithmic methods of model generalization incl. selection of discrete objects, filtering of line objects, and aggregation of objects after filtering were tested for the object types ”built areas”, ”vegetation areas”, ”traffic nets” and ”hydrography” from DLM25 to DLM250 (Morgenstern et al. 1996). Based on the test results, proposals were made for an optimal process order of different object types and hierarchical levels of the same object type. For instance, an order is recommended that begins with traffic network, followed by hydrography, settlements and vegetation areas. A processing hierarchy was further recommended for each object type down to individual object parts.

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4.2.5 <u>France</u>

Research intensity in automatic cartographic generalization at the ”**I**nstitut **G**éographique **N**ational” (IGN) in recent years has drawn the worldwide attention in the area of GIS and cartography. The team-work spirit and practical achievements of IGN have become well-known through its numerous activities in research forums such as the GISDATA programme (1993-1996) that was supported by the ”European Science Foundation” (ESF), NCGIA’s initiative in USA, Scandinavian Summer School, workshop of the "Organisation Europeenne d'Etudes Photgrammetriques Experimentales" (OEEPE) (1953-), workshops on progress in automated map generalization of the "International Cartographic Association" (ICA) (1995, 1997) and technical sessions of International Cartographic Conference (ICC, 1997).

Theoretically speaking, the most efficient way to produce map databases at various scales would be the automatic derivation of each database from a single primary database. However, there are a number of impediments standing on the way: (1) in spite of the availability of numerous GISs, automatic derivation of a database at an arbitrary scale from a single primary database is not yet possible; (2) automatic tools that can propagate updates from primary datasets to a series of derived datasets are not yet available; and (3) small scale maps usually need more frequent updating than accurate large scale maps due to economic reasons and the fact that smaller scale databases have more users. This may introduce inconsistencies between databases as it is obviously not allowed to propagate the less accurate updates to more accurate databases. Facing these problems, Ruas proposed a practical solution (1995a):

.to update the basic database as often as possible
.to propagate the updates on the derived databases
.to update more frequently the derived databases
.to replace the less accurate data by the most accurate ones when possible

Prerequisite of this proposal is the development of tools that support the management of multi-source data, meta-data processing, linking and embedding of objects at different scales during transformations such as updating and automatic generalization.

As to the issues concerned with automatic integration of multi-source data, IGN tackled the problems that include the matching process of object entities (Fig.4.8, Fig.4.9), homogenization of the definition, currency and graphic dimension of an object, computation of new attributes and relations, and creation of new objects.

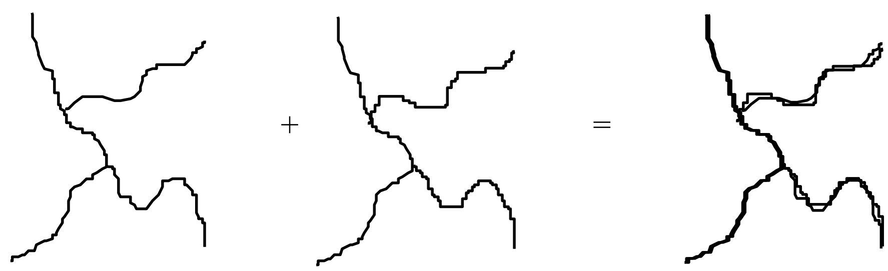

Fig.4.8 Dangling chains and sliver polygons caused by overlay in raster mode (Ruas, 1995a).

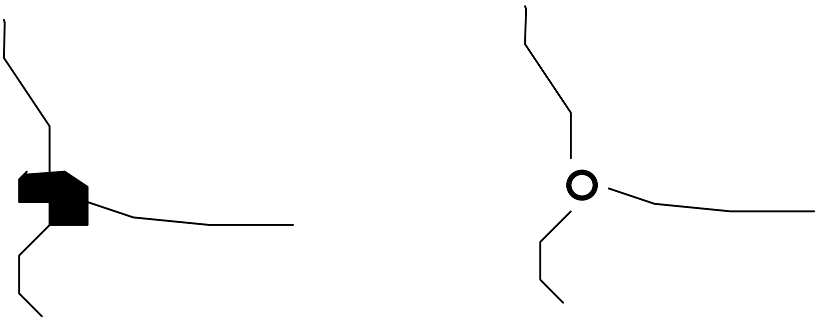

Fig.4.9 Appearance of the same object in different data sources in vector mode

As to meta-data processing, IGN made efforts in aspects such as identification of a set of operators necessary to perform context dependent generalization, acquisition of cartographic knowledge about the priority order of geographical objects to be generalized, calling sequence of operations used to solve a conflict, optimization of algorithm and its parameter values, behavior analysis of an algorithm, evolution of the information during the generalization process etc.

A solution to keep consistencies of objects at different scales is to propagate locally a deformation on its neighborhood by defining a displacement vector that can avoid the creation of intersections and preserve proximity relationships (Fig.4.10).

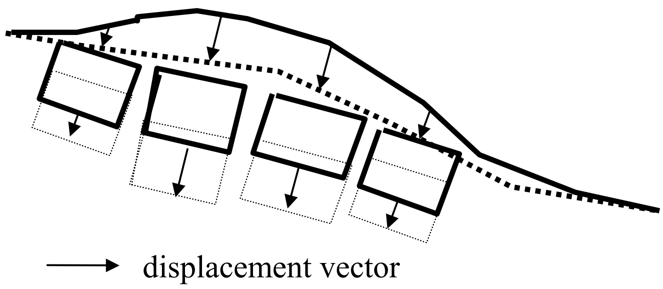

Fig.4.10 Displacement vector (Ruas, 1995a)

Using Arc/Info's programming language AML, IGN developed a number of basic generalization operators such as conflict detection with the help of buffering function applied on line symbols at the final scale, manipulation of object topology by skeletonization, visualization of initial data in background for generalization layer, object selection, displacement of lines and fusion of nodes, line simplification, attribute modification etc. Intensive analysis on the geometric, semantic and distribution characteristics of objects was also made that included the tasks such as identification of special shapes and fractal dimensions of a single feature, space partitioning, proximity and alignment between non-connected features, displacement propagation etc. The analysis has resulted in a number of refined rules that can guide context dependent generalization (Ruas, 1995b; Ruas & Lagrange, 1995)

Two object-oriented platforms ”Stratege” and ”PlaGe” were developed at the IGN’s Cogit laboratory in 1995. They comprise methods of both intrinsic and holistic generalization. Intrinsic generalization means that classical algorithms are implemented and tested. Information such as line characterization is introduced in order to control the choice of an algorithm. Whereas holistic generalization deals with complex structures (e.g. graph, space partitioning, Delaunay triangulation).

On ”Stratege”-platform, Regnauld and Ruas implemented a method for typification of buildings, i.e. reducing the number of buildings while preserving their spatial configuration and density (Regnauld, 1997; Ruas 1997). The method includes following steps:

- identify groups suited for a typification operations using criteria such as proximity base on Delaunay triangulation, cluster indicator based on minimum spanning trees, density indicator and homogeneity indicator of general shape, size and orientation based on statistical calculations etc.

- replace a cluster with a typical object, duplicate the object and distribute them within the range of original group, while reinsert exceptional buildings at their original place when possible

- harmonize the new group with its context such as alignment of buildings along a road that has been smoothed, or reposition the end of the group at a street corner that has been displaced

- Conflict detection and solution by means of diagnostic functions

The global mechanism is controlled by rules which are used either to guide the process or to choose the best solution among different ones (Ruas, 1997).

In collaboration with the University of Edinburgh in UK, IGN also implemented methods on ”Stratege” -platform that allow automatic generalization of complex constellation of roads and buildings such as urban areas. The strategies include the qualification of situation (where to generalize) by modeling constraints on each object, a set of object or on the entire data set, and identification of *”orchestration”* between various generalization operators (how and how much to generalize) by describing characteristics of a situation and constructing mechanisms such as choose, realize, control and backtrack (Ruas & Mackaness, 1997).

Systematic analysis of geometric properties of map features, their spatial relations and feasible generalization algorithms has been intensified at IGN recent years (Ruas & Lagrange 1995). A taxonomic vocabulary was developed that can give a precise and non-redundant global and local description of geomorphologic and structural characteristics of object types, object classes, objects and object parts such as mountain roads, meandering water-streams and so on. The refined geometric modeling makes it easy to identify appropriate algorithm for generalization.

Plazanet made intensive studies on morphological, semantic characteristics of line segments and their cartographic constraints. In map generalization, there is no ”one fit for all” solution because every geographic object is unique concerned with its geometry, form, and surroundings. Even along a single line feature, various generalization algorithms are necessary that should be adaptive to local situations. Similar features can lead to different decisions depending on surroundings and perceptual conditions of human (Plazanet, 1995). For instance, a hairpin bend has to be eliminated in some cases while it is maintained and caricatured if the bend is located in a generally straight road. For a better quality of generalization, Plazanet developed a unique technique that involves the recursive segmentation of a line according to homogeneity degree when it is viewed at different map scales, shape description of each identified segment, and contextual analysis of linear features which are structured in a hierarchical tree (Plazanet, 1996). Knowledge was formulated that contains choices of available algorithms, their calling sequence and parameter values for each morphological class in different types of line features like coastlines, rivers and roads. Algorithmic tools were applied such as frequential representations of coastlines with Fourier series and wavelets, representations of characteristics on sinuous and mountainous roads with cubic arcs. Technique of machine learning was experimented with for the automatic selection of algorithms based on formalized knowledge. A number of measurements for determination of critical points on lines and for evaluation of generalization quality were also extensively investigated.

Plazanet’s comprehensive method was implemented on the ”PlaGe”-platform. As the recursive segmentation facilitates finer descriptions of local situations in the line, i.e. shapes within shapes, it has led to a better understanding of many filtering and smoothing algorithms. For example, Douglas-Peucker algorithm was identified as a filtering method for very lowly sinuous lines, not as a simplification algorithm, let alone a generalization one. In fact, the use of line simplification algorithms in existing GISs is a very uncertain process. Problems were revealed in certain situations such as in dense road bends where available algorithms create completely unacceptable results (e.g. algorithms of Douglas, Lang, Brophy, Thapa, Jenk etc.). To solve these problems, Plazanet developed his own caricature algorithms such as stretching (or *accordioning*) hairpin bend series or eliminating bends in the series when stretching is not sufficient (Fig.4.11).

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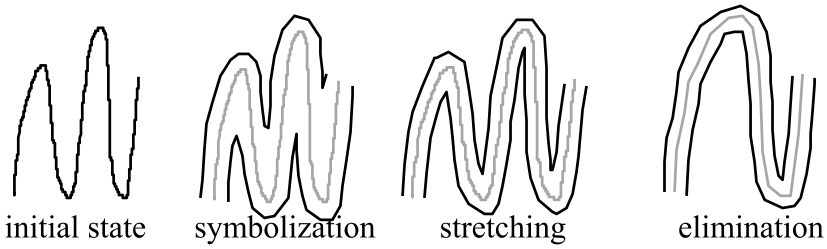

Fig. 4.11 Different treatments of hairpin bends (Plazanet, 1997)

The current version of PlaGe-platform is applied for the automatic context-dependent generalization of line features. PlaGe is in essence an assembly of adopted algorithms (e.g. line filtering and smoothing, conflict detection etc.) and all individual works of line generalization at IGN. PlaGe runs at present on a DEC Alpha station under VMS. Some of the main objectives of PlaGe are to:

- provide data structures that support the management of topology,
- visualize linear data in different ways
- prepare easy implementation and evaluation of additional generalization algorithms
- develop an interface to support generalization techniques
- test different calling sequences of operations and assess their consequences
- experiment with large data sets
- improve modularity of the software for the kernel and the interface

The package of vector-based line generalization forms the key part in current version of PlaGe which contains:

1. a number of algorithms on line simplification
2. algorithms that deal with line caricature and displacement
3. analytical tools applied on line features such as quantitative measurements for line segmentation and qualification stages based on location of characteristic points
4. algorithms of conflict detection such as coalescence of bends, proximity and superposition between two lines and classification of conflicts based on their importance
5. methods of conflict solution

IGN is planning to test on road data production with PlaGe in 1997. PlaGe will also replace the commercial GIS platform MaxMap in production of the 1:100,000 topographic map from the French BD Carto at 1:50,000 (Lecordix, 1997).

Both ”Stratege” and ”PlaGe” are expanding quickly as more and more fresh results are being appended by IGN-personnel. Recently, Morisset & Ruas (1997) have developed a context-related method to identify a subset of roads that preserves the function of the initial road network. By simulating the every day movements of human subjects within the real road network according to best route principles, they valued each road based on its frequency of use, and its geometric dimension as well as semantic attributes. The values or weights are then used as context information to guide the selection.

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4.2.6 Finland

Since years, the Finnish Geodetic Institute has been engaged in the researches of incremental generalization for multiple representations of geographical objects. One of the problems of multiple representation concerns the abstraction levels of geographical objects that should be stored. Interactive or semi-automatic methods were feasible to create a series of abstract representations starting from the base model, but they are not optimal for real-time maintenance of geographical at multiple representation levels. Therefore, a mechanism is needed that could automatically propagate the updates of base model to higher abstraction levels. This propagation process of updates is called incremental generalization (Kilpeläinen & Sarjakoski, 1993). In order to realize automatic incremental generalization, the Finnish Geodetic Institute made attempts to detect inconsistency between objects at different levels and define the relations of the objects that influence each other in the multiple representation database.

Meanwhile, automatic procedures of incremental generalization generalization were developed which take the advantages of hybrid raster and vector mode. That is, the input data is in both raster and vector mode. Vectors are rasterized and combined with raster data to one data layer, automatically generalized, and finally vectorized. Deterministic raster modeling techniques of so-called ”map algebra” are applied that include the generalization operators such as reclassification, resampling, aggregation, merging of heterogeneous features, hierarchic amalgamation of small area features and smoothing of area contours. A final simplification procedure is then applied on vectorized area contours. The parameters such as size, width, inlets or outlets, semantic relations of classes and topological relations are tuned for different generalization tasks. One of the case studies with these generalization operations is related to the production of land cover data from Finland for the European Community project CORINE (Coordination of Information on the Environment). The generalization can be carried out with single batch process in most cases and the results are said to able to meet CORINE’s quality specifications of 85% overall accuracy, and position accuracy of 100m (Jaakkola,1997). The same approach is proved also feasible for the generalization of area symbols of topographic maps.

Recent researches at the Finnish Geodetic Institute are extended to tackle the problem of present WWW-based spatial data transfer such as heavy network traffic and slow response time caused by Common Gateway Interface-functionality in database access. With HyperText Markup Language (HTML) it is difficult to implement an efficient user interface and the display of spatial data is restricted in fixed raster form with no editing functions. Therefore, Java-programming language that has inherent object model is preferred for the design of new end-user interface for the visualization of multiple representations of geographic objects (Kilpeläinen et al., 1997). The objectives with Java-programming are to transfer editable object-oriented vector graphic data via Internet, which means that data owners will be given flexibility to make their data value-added by defining methods such as generalization functions related to the database objects, and data receivers will be able to down load program modules together with datasets.

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4.2.7 China

China began the researches of computer assisted generalization by the end of 70s at Wuhan Technical University of Surveying & Mapping, and the Defense Institute of Survey & Mapping. A remarkable character in Chinese cartography is the comprehensive knowledge in cartography and geomorphology. The rich resources of empirical principles & theories accumulated during the long history of manual cartography in eastern world have been successfully integrated with the excellent textbooks from former Soviet Union and Eastern Germany (1976 and before), and mapping systems from western countries (since 1976). Numerous case studies from both eastern and western world were analyzed and compiled in the textbook ”Map Generalization” (Wang, et al., 1st edition in 1979). In fact, more and more text books and journals of western cartography and GIS are melting into Chinese context at an increasing speed, but not vice versa.

Among the major attempts are the development of algorithms for statistic modeling of morphological characteristics of map features, distribution regularities, and spatial & semantic interrelationships (e.g. clustering, typi-

fication, multi-variable classification, regression analysis of correlations, calculation of entropy on syntax level) (He, 1997a,b), scale-dependent selection of traffic networks and settlements, calculation of middle-axes of double-line features, data reduction and smoothing of coastlines and stream lines, optimization of text placement, and simplification of digital terrain model.
Adaptive criteria and weighted Töpfer's radical law were tested for the generalization of topographic features in different geomorphologic environments such as glacial relief, karst landscape, rocky mountains, yellow soil plateau, wind-eroded hills, desert area, water-eroded plain areas etc. Douglas-Peucker algorithm was modified to meet special requirements such as generalization of sounding lines on nautical chart, which demands that line segments can only be moved in the seaward direction when deleting insignificant details (Li & Tian, 1997). Neural networks were constructed to guide feature selection (Tian, 1997).

In addition to the emphasis of geomorphologic consistence on maps at different scales, Chinese researchers are also extensively studying cognitive factors of map design (Hua, 1997; Nan, 1997). Experiments include modeling the changed visual perception of generalized map symbols, quantification of visual map loading as a function of variables like ”inked” area of map symbols, fractal dimension of lines, complexity of pattern structure and color contrast. One of the obligatory tasks for programmers of generalization methods is the training with the skills of ”thinking in graphics”.

An expert system for thematic map design with generalization as an important component was implemented at Wuhan Technical University of Surveying & Mapping in 1992. The system is being upgraded to contain the functions of multi-scale presentations based on object linking and embedding strategy (Wu, H. 1997). Another interactive topographic map design system was implemented in 1995 at the Defense Institute of Surveying and Mapping with complex generalization operators such as aggregation, displacement and name placement (Wu, F. 1997). A group of young researchers and Ph.D. students are developing an automatic military commanding system with functionality of real-time production of thematic maps for infantry, real-time generalization of sight field with varying view points in mountainous areas and modeling of virtual reality.

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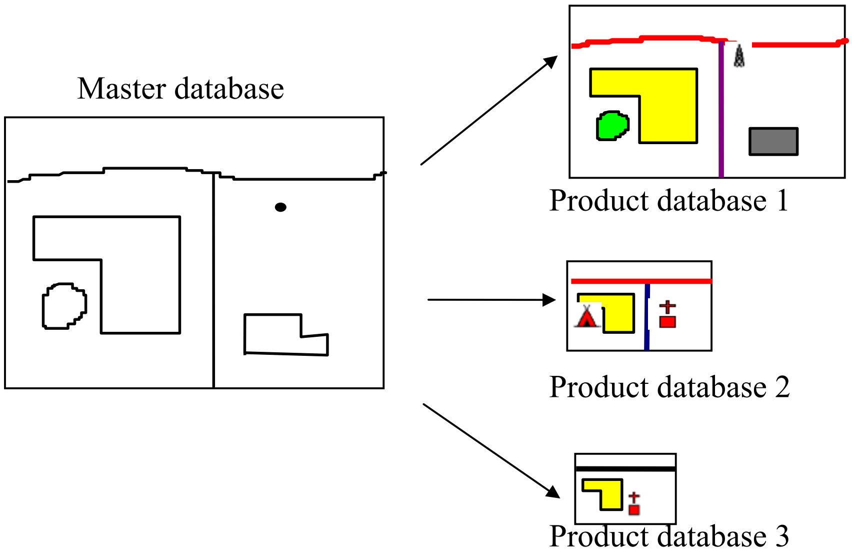
4.2.8 Sweden

Swedish Cartographic Society with ca. 1300 members is one of the largest and oldest members in the International Cartographic Association (ICA). Recent years' digital mapping activities incl. the production of official map series, Internet settlement maps and New National Atlases have won very good reputations in the world. It is now also possible via Internet to have an overview of the available official DLMs delivered by National Land Survey of Sweden: GSD-Terrain Elevation Databank (1:10,001 - 1:30,000), GSD-Green Map in vector and raster form (1:30,001 - 1:75,000), GSD-Place Names (1:30,001 - 1:75,000), GSD-Blue Map in vector and raster form (1:75,001 - 1:150,000), and GSD-Red Map in vector and raster form (1:150,001 - 1:300,000). These databases are established and maintained through scanning and/or manual digitization of manually generalized maps at corresponding scales. Demands on these basic datasets are increasing as more and more users have become aware of the importance of GIS for a better planning of their everyday life. However, consistent and economic updating of the databases at multiple scales can not be realized without comprehensive automatic generalization mechanisms.

In 1995, T-Kartor company proposed a concept of "Master / Product databases" (MDB-PDB) for the generation of road information maps at multiple scales on request of Swedish National Road Administration. The objective with the concept that has been now implemented in T-Kartor's Cartographic Production System (CPS), a software based on ESRI's products ARC/INFO, ArcView and ArcStorm, is to build up a framework for the automatic derivation of cartographic products from a single master database (Fig.4.12). *"The recent version of the MDB-PDB model is available for users running ARC/INFO on a UNIX platform. Development efforts are currently focused on implementation of the MDB-PDB model using the ESRI products ArcView 3.0 and Spatial Database Engine (SDE). This implementation will be platform independent"* (Johnsson, 1997). Functions of automatic object linkage and generalization are not yet available.



MDB's object geometry + attribute => PDB's symbols

Fig.4.12 T-Kartor's concept of Master/Product databases

Although the necessity of generalization research has been obvious since many years in Sweden, no research team has been founded due to lack of financial support. National Land Survey purchased once a geometric algorithm dealing with simplification of individual lines developed in Canada in 70's. The only reported work on automatic cartographic generalization in Sweden is Schylberg's Ph.D. thesis at the Royal Institute of Technology, Stockholm in 1993. Schylberg systematically analyzed the cartographic constraints on applications of image processing techniques such as amalgamation, simplification and deletion in the generalization of vegetation features in raster mode. With amalgamation treatment, narrow gaps between objects of the same class or different parts of the same objects can be filled. Simplification is used to round off sharp edges of objects. Deletion does not only mean the elimination of small objects, but also the reassignment of the removed areas with new attributes.

Typical constraints include, for example, which classes of objects are allowed for what kind of operation, in which order the identified operations should be processed, how much and when an area is allowed to shrink or dilate. The sub-area that is created by shrinking and/or expanding is termed as a patch. Whether a generalization operation is necessary or not is largely dependent on the shape, size and neighborhood relations of patches. For instance, if a dilated object does not touch another object (or object part), i.e. the patch has only the same object (or object part) in its neighborhood, then there is no need to perform the amalgamation. Likewise, if a patch covers object(s) from other object classes, then no amalgamation is allowed. If a patch is larger than a certain percentage of the total area of an object, then no simplification is allowed. Measures were established to describe patches associated with the objects in question, e.g. search distance criteria, smallest objects, shape criteria like border percentage and size criteria like area percentage.

Based on such constraint analysis, a rule base was established to guide the procedure of each individual processing operation. Following execution procedures were defined by Schylberg:

- Amalgamation (Fig.4.13)

Segmentation of object classes to be generalized → Selection of objects larger than the size criteria → Buffering objects outward (dilation) → Buffering objects inward (shrinkage) → Identification of patches → Selection of patches according to amalgamation constraints → Updating objects with accepted patches

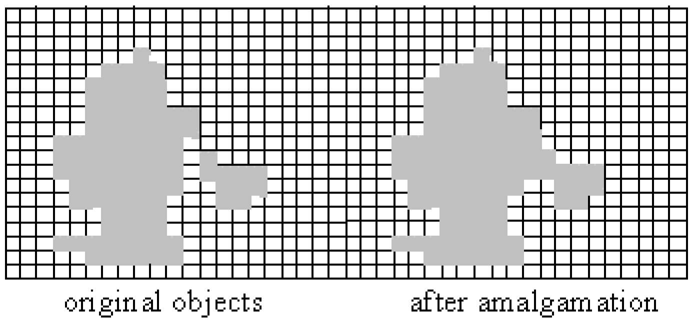


Fig.4.13 Amalgamation (Schylberg, 1993)

- Simplification (Fig.4.14)

Segmentation of object classes to be generalized → Selection of objects larger than the size criteria → Buffering objects inward (shrinkage) → Buffering objects outward (dilation) → Identification of patches → Selection of patches according to simplification constraints → Updating objects with accepted patches

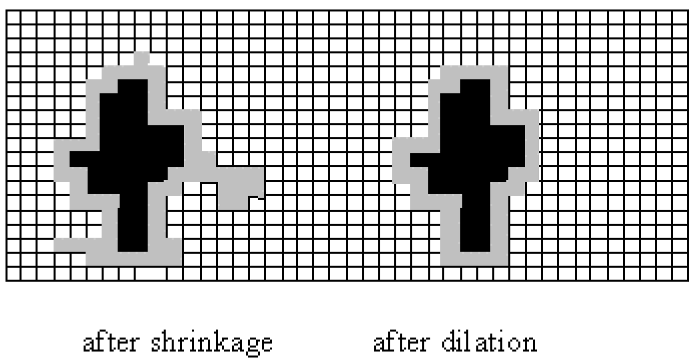
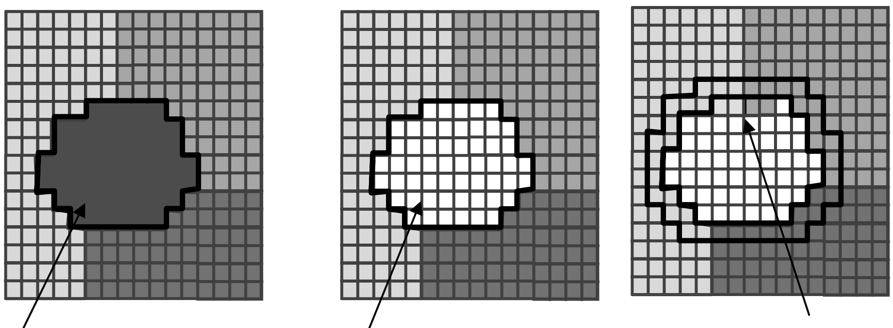


Fig.4.14 Essential operations of simplification (Schylberg, 1993)

- Deletion (Fig.4.15)

Elimination of objects smaller than a given size → Filling the gaps left by the removed objects with values from the surrounding objects

The gaps are either reclassified to the dominating surrounding object when it is allowed according to the rule base or subdivided into many surrounding objects. In case of subdivision, surrounding objects are successively zoomed in toward the gaps, assigning the pixels of gaps with the attribute of the neighboring pixel that is mode. This zoom-in process and mode operation continues until the expanded object area is completely filled with new values.



Object to be eliminated Gaps after elimination Filling the gaps

Fig.4.15 Procedure of deletion according to Schylberg (1993)

Schylberg also tested various combinations of amalgamation, simplification and deletion in different orders for the generalization of vegetation features. By comparing with a manually produced map by the National Land Survey (LMV), he concluded that amalgamation, simplification and deletion order seems to work well.

No research projects on automatic cartographic generalization have been launched in Sweden after Schylberg. The recent investigations of VBB Viak AB in collaboration with the University College Gävle/Sandviken, thanks to the support of Swedish Armed Force and ”Stiftelsen för Kunskaps- och Kompetensutveckling” (KKS) can therefore be considered as a new try to intensify and continue the previous work for a wider scope of applications.

4.3 Commercially available generalization tools

The stagnation period of generalization research was well-reflected in information industry. Only a few companies like Simens Nixdorf, Zeiss and Intergraph have so far played active roles in approaches of automatic generalization, either in form of sponsoring research projects at academic institutions or recruiting researchers to carry out the projects within companies. Due to the fact that generalization research is a difficult undertaking and no rapid return of investment can be expected, Zeiss and Intergraph had to retreat from the front line a couple of years ago and concentrate themselves on more lucrative projects. On the other hand, there is a recent upsurge of interest in generalization by commercial GIS vendors such as ESRI, Smallworld and LaserScan. *”Although the reasons for this*

Smallworld and LaserScan. *"Although the reasons for this are unclear: is it customer driven, or are the vendors waking up to the deficiencies of their products?"* (Robinson, 1993). Maybe the most apparent reason is that a GIS without comprehensive generalization component can hardly survive in today's super-competitive information society. As a result of increasing awareness, many generalization algorithms and comprehensive packages have been and will be soon commercialized as a component in GIS.

A number of SICAD-based software components or packages (e.g. "SiGen" in SICAD 5.1 under BS2000 operating system, "GISELLE schematics generator" of Siemens/Nixdorf and Corena A/S in Norway, "Line simplification package of SRS GmbH Dresden" in SICAD 5.1 under BS2000 and SICAD/OPEN under IRIX) were reported in detail by Morgenstern et al. (1994). These products provide graphic editing and some generalization functions such as data reduction, symbol shifting and scaling, line smoothing, object elimination and interactive tuning of generalization parameters.

The development of batch-program CHANGE for the generalization of buildings and roads on German topographic maps from 1:5000 to 1:25000 was sponsored by Zeiss Company, therefore, CHANGE was originally integrated into the photogrammetric interpretation system PHOCUS of Zeiss under DEC-VMS. CHANGE has been now also ported to UNIX machines as independent package. For a certain scale range, CHANGE can provide default parameters and generalization sequences that are stored as batch directives.

MGE Map Generalizer (MGE/MG) developed by Intergraph Corporation is an interactive platform and works under UNIX. MGE/MG deals with small scale derivation from large scale database, theoretically without limitation of scale range. A number of visualization tools in MGE/MG are also available to assist the interactive generalization processes (Lee, 1993). Available algorithms in MGE/MG include:

. selection by geometric or graphic criteria
. line collapse (line to point, area to line)
. simplification with eight algorithms -- Nth point thinning, Douglas, Lang, VectGen, Point relaxation, Reuman-Witkan, Area clarification, Area preservation
. smoothing with three algorithms -- Brophy, Simple average, Weight average
. point and area aggregation
. area squaring
. detection of proximity
. typification in order to reduce the density of points

Unlike CHANGE, the essential decisions in MGE/MG such as tuning generalization sequence, parameters of each algorithm and number of iterations for each particular task must be made interactively by system users. MGE/MG has been tested for different generalization tasks in countries from USA, United Kingdom, Germany, Spain, Sweden, the Netherlands to

China etc. In Spain, for example, MGE/MG is used to derive a topographic map at 1:100,000 from the Mapa Comarcal of Catalonia at 1:50,000, and to produce an atlas composed of different maps at different scales (Baella, 1997).

The Ordnance Survey (OS) in the United Kingdom has integrated MGE/ME functions with the OS datastructure for the derivation of smaller scale OS map series from 1:10,000 as the largest scale of British national mapping (Gower & Pepper, 1997).

The National Mapping Agency of the Netherlands TDN made an inventory of culture-dependent generalization rules from 1:10,000 → 1:50,000 → 1:100,000 → 1:250,000 → 1:500,000 data models and the corresponding maps. It is investigated for each feature class which generalization operators are used at every scale-change, for instance, houses are represented as small area in 1:10,000, aggregated at 1:50,000 and 1:100,000, collapsed to point symbols at 1:250,000, and finally maybe eliminated at 1:500,000. This inventory is intended to guide the interactive work with MGE/MG (Bakker, 1997).

4.4 Comments on current generalization researches

In spite of intensity and extent of generalization research worldwide, a feasible and practically convincing strategy is not yet available that can solve some bottleneck problems that have long been identified.

What are available are essentially limited solutions to oversimplified generalization issues based on pure geometric measures at a research stage rather than industrial stage. ”This may be seen, for a part, as a result of the difficulty of embracing a wider spectrum on the basis of more or less individual efforts” (Lagrange, 1997). Most of commercially available generalization packages are procedural systems based on vector-data and have only limited intelligence in dealing with geometric aspects of the databases. None of them can automatically model the semantic relationships between map features and resolve graphic conflicts. Although they can save up to 30% of labor intensity in well-defined generalization tasks with limited scope, many users are still suspicious of proclaimed potentials of these system because they cannot tell the user when and where they fail. That is, users face the burden to select the best suitable algorithm, tune the parameters and sequences, detect and correct the failures. The high demand on users competence makes such procedural systems less attractive if they can not reach a success rate of higher than 80%.

4.4.1 <u>Lack of meta-methods</u>

Some algorithms are not at all suited for map generalization because they do not pay attention to cartographic principles. Nevertheless, these algorithms are used for purposes for which they were never really intended (Müller et al 1995). Not very much has been done on evaluation and validation of what already exists. This has resulted in a tendency of reinventing the wheel or blind modifications of a well-known algorithm. On the other hand, too often the same tool with the same parameters, or the same displacement vector - is blindly applied to different types of data, which results in at best *”a compromise 'solution' (e.g. rivers looking like roads), and at worse nonsense (e.g. buildings with non-square corners)”* (Robinson, 1993). Quite often, aggregation operators have been frequently tested on island symbols -- an object type that does not allow any aggregation according to cartographic principles. Feasibility study should be strengthened to add wings to available methods. The method to define the applicability, limitation, parameter setting of a method belongs to a kind of meta-method which is as important as meta-data to data, in particular, when real-time data access and ”on-the-fly” generalization are demanded.

4.4.2 Insufficient knowledge formalization

It is still a challenge to acquire and formalize the deeper layer of knowledge which is not in the guidelines but in the mind of the practitioner. Expert cartographers *”admit themselves that they find it difficult to rationalize their decisions into a set of formalized rules”* (Müller et al 1995). Principles in textbooks are often either too generally or too specially formulated. Given the complexity of the generalization process, it would be useful to approach a combination of knowledge acquisition techniques such as conventional interviews, observation of experts at work, inventory of text documents and maps (reverse engineering), machine learning, neural networks and interaction systems. It is worthwhile to notice that all these techniques need a significant working tool – visualization. *”GIS requirements for visualization include conceptual, technological and evaluatory solutions”* (Buttenfield & Ganter, 1990). While cartographic presentations of spatial/temporal data are constantly assisting us to detect ‘lie’ and represent ‘truth’, visually depicting the validity and performance of generalization methods will improve our understanding of expert knowledge and system behavior beyond the limit of verbal description. The purpose of knowledge formalization is not to translate knowledge that already exists in one programming language (e.g. geometric measures and rules) into another language, rather to introduce explicitly or implicitly the influence of high-level knowledge into computer systems (e.g. semantic relations, structural pattern of objects, instinct and common sense that guide the generalization etc.). Only when the knowledge at highest abstraction level is captured, can robust generalization system be implemented.

4.4.3 Lack of intellectual data structure

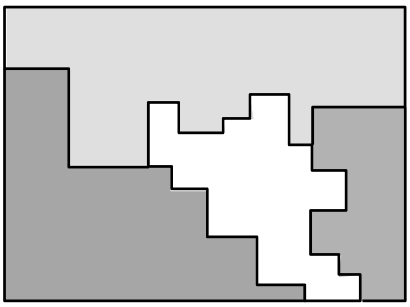
The data models and data structures are not yet capable of supporting comprehensive approaches. Not so many researchers have realized the importance of an intellectual data structure to the overall performance of a comprehensive generalization system. It is no longer an advantage of those methods that are insensible to data structure or compatible to the most primitive data structure, but slow in performance. A generalization system that deals with data structure and methods separately, instead of optimizing their mutual relationships, is not competitive, because the mechanical accumulation or expansion of components does not necessarily make an efficient and adaptive system. In other words, whether method banks (e.g. algorithms, parameters, rules, facts) and data models can work in concert will be a decisive concern for the future system design. The orchestra effect of system components needs further investigations, perhaps in conjunction with the growing investment in object-oriented techniques in countries like USA, UK, France, Germany and Finland where experiments with the design of object-oriented data models for multiple presentations have been intensified recent years. There are some pragmatic proposals such as individually marking each object in the map with attributes showing in which display-scales the object should be included in the map and in which geometric shapes (Hϕjholt proposed, 1997). Adding a generalization mark to a dataset will increase the value of the data, thus enhance a competitive capability of a data distributor.

4.4.4 Lack of objective evaluation of computer generalized data

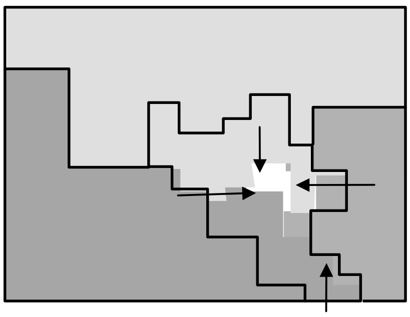
Generalization will influence some of the components of data quality (Müller et al 1995), including location accuracy (displacement), form and size accuracy (simplification, typification, dimensional collapse), attribute accuracy (classification, aggregation), consistency (uneven applications of spatial or temporal abstractions) and completeness (selection and merging operations). Such influences are not necessarily equal to a quality decay. Yet, there is still a hesitation or even misunderstanding of generalization consequences among GIS users. Therefore, cartographers have to convince the users of fact that generalization is neither photographic enlargement / reduction (a change of display space, resolution and visibility, but not the abstraction level) nor screen zooming in/out (a change of display space and visibility, but not resolution and abstraction level). Generalization is a cognitive process with the purpose of creating visibility and legibility that are adaptive to display space, resolution of display media, perception level and application requirements of its audience. Evaluating generalization results should be purpose-driven and criteria for quality assurance should be differently ordered. So far, evaluation of computer-assisted map generalization results is conducted by comparing with manually generalized maps. Information theory has been applied since decades to calculate entropy measures of a source map and derived map (Bjørke,1997; He, 1997) at syntactic level, not yet at semantic and pragmatic levels which are more important. Comprehensive numerical measures are mostly based on vector-data. Although calculation of objectwise measures is more convenient in vector mode, raster mode might offer greater potential for a rigorous, consistent, and replicable approach to both generalization and error modeling. Limited literature has attempted to formalize the specification of generalized geographic data in ways that are consistent with the concepts of scientific measurement, and has compared such methods for vector and raster representations. In raster mode, geographic data form a continuos space without gaps. Raster representations provide an explicit measure of geographic detail in the cell size, i.e. resolution. In vector mode, the reality is conceived as collections of discrete point, line, or area objects, potentially overlapping, and embedded in an otherwise empty space. Vector representations do not provide an objective measure that is characteristic of the representation's level of geographic detail. Statement such as *"Sweden has 9600 lakes"* clearly requires a specification of levels of geographic detail to qualify as scientific observations. As compared with the concept of resolution in raster mode, metric measures in vector mode are rather unstable due to diversity of object constellations. This is analog to a fuzzy concept "hot" in comparison to standard and precise 'Celsius degree'. The lack of objective specification of level of geographic detail in generalization rules contributes significantly to inaccuracy and uncertainty (Goodchild, 1996). An in-depth analysis of measurement techniques, constraints of their embedding in the generalization process, should pave the way for more comprehensive systems (Lagrange, 1997).

4.4.5 Lack of cognitive and temporal considerations in generalization methods

Many generalization algorithms are producing generalization-like results. There can be many different ways, for example, to fill the gaps caused by elimination. Cells can be filled with the value of its dominating neighbors cells. One can also imagine that the natural boundaries of neighboring areas expand dynamically toward the gaps at constant speed or weighted speed (Fig.4.16). Both methods will finally swallow up the gaps, but they have nothing to do with the semantics of these areas. Similarly, a smoothed and pleasant looking edge does not necessarily represent the true nature of underlying object. These generalization-like results will increase the uncertainty, if not errors, of derived map products.



a) Gaps after elimination



b) Dynamic expansion based on boundary's natural shape

Fig.4.16 Gaps and method of filling gaps

In order to keep the truth during generalization, more attention to the nature of data must be paid (not only the geometric form and size, but also the context. However, *"the efforts to integrate specific generalization tools into operational and automated systems have been frustrated by our inability to define adequately and to exploit the notion of context"* (Edwards, 1997). Analysis of cognitive factors during map interpretation will thus help us find out what is relevant information for which purpose. Certain special relations between object classes can only be detected by professional human interpreters, such as coexistence of vegetation types, causal relations between geological structure and climate. Such information is crucial for local solutions.

Another reason for generalization-like results is that current generalization methods have not yet taken sufficient advantage of temporal information. Many spatial data have in fact a close correlation with time influence. An object is easily recognized if it changes against its background (shape, position or quality). This temporal information can not only simplify a generalization task that deals with spatial dimensions, but also reduce the uncertainty of data (e.g. including the time series of satellite images can result in more natural classification on geologic maps).

4.4.6 Lack of cost/benefit study

Cost/benefit study is an important factor for software acceptance. A few practical experiments with software such as CHANGE and MGE/ME did not reveal encouraging responses. High demands on users' competence and heavy burden of interactivity are among the primary problems, but none of the studies have ever mentioned the performance of the software concerned with speed. No doubt that the acceptance of a generalization software that is slower than human cartographer will be questioned by users who need real-time performance, even though the software has minimal interactive demands.

5 Methods of automatic generalization

As mentioned in Chapter 4, the majority of generalization methods, no matter in which country, have been so far developed on vector database. Test data are usually manually digitized source maps of National Mapping Agencies. Generalization tasks are usually scale-driven derivation of smaller scale landscape models or topographic maps. The only exceptional case where generalization methods have been primarily based on raster base is digital terrain model. There is a trend that new generalization methods are being implemented on hybrid database. For example, positional and line features (e.g. symbolized settlements, roads and rivers) are processed in vector mode, whereas natural area features (e.g. forest coverage and land use) in raster mode. Buildings in large-scale maps (as area symbols) are exclusively handled in vector data because the orthogonal angular characteristic of building outlines can be better-kept in vector data. Quite often, raster and vector modes compensate each other to extract characteristic features of an object, to detect conflicts in raster mode and to displace a feature in vector mode. An introduction and analysis of the available methods will obviously go beyond the scope of this report, therefore, the subsequent sections will only highlight a subset of basic methods.

5.1 Generalization in vector mode

5.1.1 Point reduction and line approximation

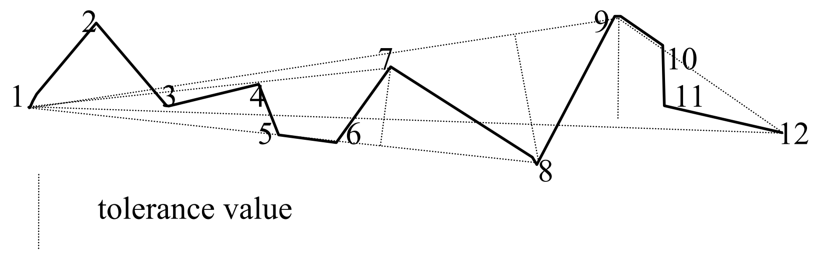


Fig.5.1 Principle of Douglas-Peucker algorithm

Douglas-Peucker algorithm has been most frequently cited and studied. It defines a straight line segment between the first point (called the anchor) and the last point (called the floater) on a curve (Fig.5.1). Perpendiculars between the line segment and each of the original points are then measured. If in the first iteration the length of all perpendiculars is less than the present tolerance value, the line segment is deemed adequate to represent the line, all points except the anchor and floater are deleted and the algorithm is terminated. If any of the intermediate points fall outside the tolerance band, the line is split into two parts at the furthest point (point 9 in Fig.5.1) and the process is continued on the two resulting parts. This procedure is repeated until the length of all perpendiculars is found to be less than the preset tolerance value. The larger the tolerance value, the more points will be eliminated.

Douglas and Peucker´s filtering algorithm has proved to have the ability of (1) selecting from the original coordinate string a set of critical points that approximate the line vertices quite well and preserve accuracy, (2) minimizing the overall drift of the filtered line from the original, and (3) preserving the spatial variation of hypsography data across a range of simplification scales (Ji, 1989). However, filtering is not sufficient to characterize a line. The selection of the furthest point beyond the tolerance as a critical point to be retained is unreliable because this point may be located on spikes (errors) or minor shapes of an object, depending on context situations. Manual line generalization is more concerned with preserving salient shapes than with selecting specific points (Visvalingham & Williamson, 1995). In essence, Douglas-Peucker is only suitable for the purpose of data reduction, saving storage space and obtaining quick display. *”The high performance of Douglas-Peucker algorithm on mathematical evaluations may be interpreted as being indicative of its relative merits as weeding algorithm, but not necessarily as evidence of its superiority as a generalization algorithm”* (Visvalingam and Whyatt 1990). Douglas-Peucker algorithm has been frequently modified by adding new constraints, such as deletion is allowed only toward deeper side of a sounding line on nautical charts (Li & Tian, 1997). Most of modified Douglas-Peucker algorithms show better results on natural features such as coastal lines, rivers, isolines and roads in mountain areas than man-made features like buildings.

Visvalingham and Williamson developed in 1995 an algorithm that makes multiple passes over the line. On each pass, it eliminates the point which it regards as least important. A variety of metrics may be used to measure the importance of points, e.g. concept of effective area: the triangular feature formed by connecting the point with its two neighbors. It measures the areas by which the current line would be displaced as a result of removing that single point. Each time only the point with the smallest effective area will be removed. All points are tagged with effective area and their elimination sequence is recorded. The tagged points may then be filtered at runtime by interactive fine-tuning of the tolerance parameter.

Li and Openshaw tried in 1992 a scale-dependent generalization algorithm that can approximate line shape (Fig.5.2). The procedure is divided into a number of iterative steps:

1. determine the size of smallest visible object at map scale
2. starting from the first point A in the string, draw a circle with diameter double so much as minimal size, which intersect the point C on the line
3. draw a circle with AC as diameter. The center 'a' along the straight line section AC is selected as a point along the generalized line.
4. starting from C and repeat 2-4.

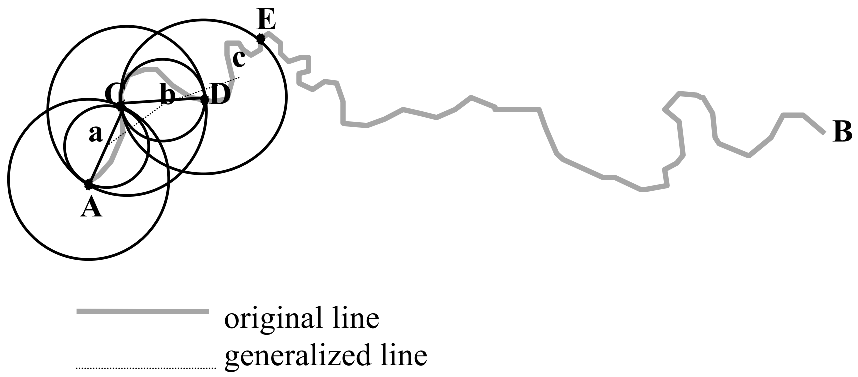


Fig.5.2 Principles of line generalization according to Li and Openshaw 1992

The same method can be realized in raster mode that is faster, or in hybrid way (the location of the middle points is determined by vector algorithms, and the method is run in raster mode). Li and Openshaw took a river segment as example to illustrate that the generalization algorithm produced a closer result to manual generalization than Douglas-Peucker. However, this method is not without drawbacks. It is possible, e.g. that more than one position from different parts of a line intersected by the circle. It is obviously undesirable to take the last intersection point and delete the whole loop connected by very thin bottle-neck (Fig.5.3). On the other hand, if the first intersection point in the chain is selected, then two line segments which are very close together may be crashed together in the same raster cell, although self-crossing can be protected by the raster-based algorithms.

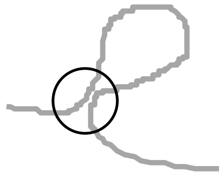


Fig.5.3 Problems with Li & Openshaw's method

Other mathematical methods that have been used for line generalization include:

Polynomial function for the approximation of a set of discrete points that are distributed over a region or along a polyline;

Least-squares method for the description of local forms;

Frequential techniques such as Fourier series and wavelets for the description of curvature along a line with a set of coefficients, each coefficient being related to a spatial frequency, hence with a wavelength that approximates the size of the features detected. The low frequency coefficients characterize the global shapes and have to be kept unchanged; the high frequency coefficients represent the small details and must be cut off. The coefficients whose wavelength is close to the targeted resolution have to be increased, in order to enlarge relevant details.

5.1.2 Fractal analysis

Fractal analysis deals with invariance properties of irregular and fragmented objects through a change in scale and has been frequently applied for the development of line simplification algorithms. It turns out that certain types of natural lines- particularly coastlines- do have a fractal tendency. These objects can therefore be described by two basic concepts: fractal dimension and self-similarity.

The concept of fractal dimension cuts across the logic of Euclidean geometry. In fractal geometry, dimension is considered as a continuum, the fractal dimension of a curve can be any value between 1 and 2 (and a surface between 2 and 3) according to the complexity of the curve. Self-similarity means that the curve is made up of copies of itself in a reduced scale. The number of copies n and the scale reduction factor d can be used to determine the fractal dimension D, $D=log(n)/log(d)$. Practically, the D value of a curve is estimated by measuring the length of the curve using various step sizes (Wang, et al. 1995). Self-similarity could be statistically determined by the length of an open line versus the step size, or the area of a closed line versus its perimeter (Nakos, 1997). The length increases as step size decreases. In this sense, the fractal dimension describes the line complexity or roughness when step size is constant. Other measures such as fractal mean and fractal variance can be derived to describe average line complexity, and spatial variations (Ji, 1989). Since generalization of fragmented objects can be assumed as a self-similar transformation, the same fractal dimension should be preserved at different scales. In other words, fractal dimensions can be used as a criterion to evaluate results of a line simplification method.

In fact, it is statistically possible that a curve described by tolerance d2 can keep the same fractal dimension as a curve described by tolerance d1. This indicates that the generalized curve can preserve the graphic characteristics when scale denominators change from M1 to M2. Based on fractal analysis, Wang et al. developed a method in 1995 that can automatically produce suitable tolerance value for each map scale. Nakos designed in 1997 both filtering and interpolation algorithms that can preserve constant fractal dimension.

Fractal analysis should be better applied as a compensation method. As a matter of fact, traditional cartographers pay more attention to other aspects than statistical similarity or fractal dimensionality when generalizing lines. That is, a fractal filtering method may be useful when compared with the original object in reality, but it does not make sense when compared with the manually generalized versions of the features on existing maps.

5.2 Generalization in raster mode

5.2.1 Image processing

Most of raster-based generalization methods were originated from the area of image processing & analysis, such as calculation of neighborhood distance and direction, overlay, edge detection, construction of spline surface or minimal-energy surface, low-pass filter, convolution operation, shrinkage and expansion. When image processing methods are combined in a suitable way under certain constraints (e.g. preserving morphological characteristics), they can perform the typical generalization such as elimination, amalgamation, dilation, erosion, smoothing, conflict detection etc.

Li & Su tested in 1993 various combinations of the two morphological operators dilation and erosion for the generalization of raster features as illustrated in Fig.5.4 where small area parcels with the same semantic meaning but varying size and shape are distributed over a region.

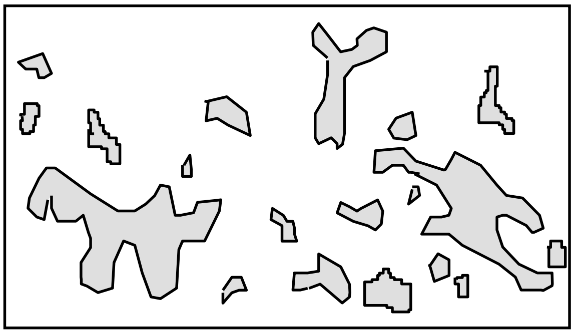


Fig.5.4 Test data for morphological operations

Dilation: $A \oplus B = \{a+b : a \in A, b \in B\} = \bigcup_{b \in B} A_b$

Erosion: $A \Theta B = \{a : a+b \in A, b \in B\} = \bigcap_{b \in B} A_b$

Where A is the image to be processed and B is called the structure element, which can be considered to be an analogy to the kernel in convolution operations.

Typical structure elements are:

(1) 1 right pixel

```
1 1 1                                  1
1(1)1      1                            (1)
1 1 1    1(1)1      1(0)1                  1
square   triangle   horizontal   diagonal
```

The effects of dilation and erosion are illustrated in Fig.5.5 - Fig.5.7

```
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0
0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0
0 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0
0 0 0 1 1 1 1 1 1 1 0 0 0 0 0 0
0 0 0 1 1 1 1 1 1 0 0 0 0 1 0 0
0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 0        1  1  1
0 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0        1 (1) 1
0 0 0 1 1 1 1 1 0 0 0 0 0 0 0 0        1  1  1  structure element B
0 0 0 0 1 0 0 0 0 1 0 0 0 0 0 0
0 0 0 0 1 1 1 1 1 1 1 0 1 0 0 0
0 0 0 0 0 0 1 1 1 1 1 1 0 0 0 0
0 0 1 0 0 0 1 1 1 1 1 1 0 0 0 0
0 0 0 0 0 0 1 1 1 1 1 1 1 1 0 0
0 0 0 0 1 0 1 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Fig.5.5 Raster area A formed by ‘1’ pixels, and structure element B

0 0 0 0 0 2 2 2 2 2 0 0 0 0 0 0
0 0 0 0 0 2 1 1 1 2 2 2 0 0 0 0
0 0 0 2 2 2 1 1 1 1 1 2 0 0 0 0
0 0 2 2 1 1 1 1 1 1 1 2 0 0 0 0
0 0 2 1 1 1 1 1 1 1 2 0 2 2 2 0
0 0 2 1 1 1 1 1 1 2 2 0 2 1 2 0
0 0 0 2 1 1 1 1 1 2 2 2 2 2 2 0
0 0 0 2 1 1 1 1 1 1 1 2 0 0 0 0
0 0 0 1 1 1 1 1 0 2 2 2 0 0 0 0
0 0 0 2 1 2 2 2 2 1 2 2 2 2 0 0
0 0 0 2 1 1 1 1 1 1 1 2 1 2 0 0
0 2 2 2 2 2 1 1 1 1 1 1 2 2 0 0
0 2 1 2 0 2 1 1 1 1 1 1 2 2 2 0
0 2 2 2 2 2 1 1 1 1 1 1 1 1 2 0
0 0 0 2 1 2 1 2 2 2 2 2 2 2 2 0
0 0 0 2 2 2 2 2 0 0 0 0 0 0 0 0

dilation of A by B ('2' pixels form the expanded area)

Fig.5.6 Morphological dilation of area A by structure B (Li & Su, 1993)

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 2 2 2 0 0 0 0 0 0 0
0 0 0 0 0 0 2 1 2 2 2 0 0 0 0 0
0 0 0 0 2 2 2 1 1 2 2 0 0 0 0 0
0 0 0 2 2 1 1 1 2 2 0 0 0 0 0 0
0 0 0 2 2 1 1 1 2 0 0 0 0 0 0 0
0 0 0 0 2 1 1 1 2 0 0 0 0 0 0 0
0 0 0 0 2 1 1 2 2 2 2 0 0 0 0 0
0 0 0 2 2 2 2 2 0 0 0 0 0 0 0 0
0 0 0 0 2 0 0 0 0 2 0 0 0 0 0 0
0 0 0 0 2 2 2 2 2 2 2 0 2 0 0 0
0 0 0 0 0 0 2 1 1 1 2 2 0 0 0 0
0 0 2 0 0 0 2 1 1 1 1 2 0 0 0 0
0 0 0 0 0 0 2 2 2 2 2 2 2 2 0 0
0 0 0 0 2 0 2 0 0 0 0 0 0 0 0 0
0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

Erosion of A by B ('2' pixels form the eroded area)

Fig.5.7 Morphological erosion of area A by structure B (Li & Su, 1993)

Different combination and iteration of dilation and erosion can lead to a number of new operators such as closing, opening, elimination, displacement (Li, Z. 1994). With the help of all these operators, one can define the generalization procedure of area patch as follows (Su & Li , 1995):

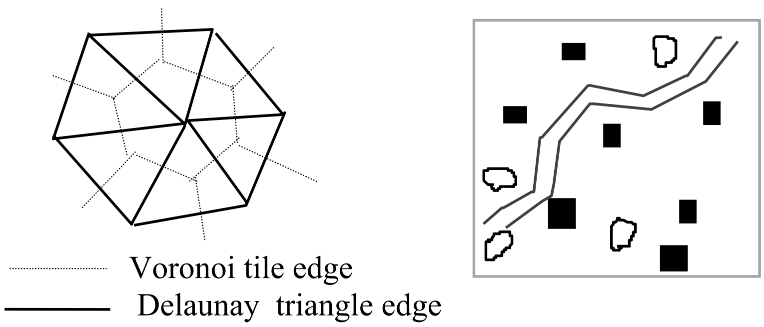
(a) determine the size of structuring element
(b) apply erosion to all area features (to eliminate areas that are smaller than structuring elements)
(c) restore those survived parcels after erosion
(d) apply dilation to all the area parcels after restoration (to exaggerate patches, to aggregate closely located parcels and to smooth the contours of parcels)
(e) apply erosion to dilated image but with a structuring element smaller than the one used in dilation for the sake of preserving similar area before and after generalization, and
(f) apply a post-processing such as reselection of small areas in order to keep the distribution pattern

Raster-based image processing methods are easy and simple to handle. Certain conflicts can be avoided, for example, if the generalization of steep elevation data is carried out on digital elevation model instead of contour lines. But these methods do not pay attention to complicated semantic, structural and context constraints of objects, therefore, can only be applied to process simple test data. For example, it is difficult, if not impossible, to partly exaggerate a characteristic part of an area boundary in raster mode. The same structure element applied to all area parcels that have different forms and sizes can only result in generalization-like effects.

5.3 Data structure

5.3.1 Voronoi diagram

The Voronoi diagram also called Thiessen polygons, or the Dirichlet tessellation, subdivides the map space into a set of convex tiles whose boundaries are the perpendicular bisectors between adjacent data points representing map object (Fig.5.8a). Objects with adjacent tiles are considered to be themselves adjacent, or neighbors. A Voronoi region can be constructed around any map object (Fig,5.8b). The map objects may be points, line segments, or even complex objects. One possible way of drawing tiles around map objects is to include within the tile all map locations that are closer to that object than to any other. The tile boundaries are thus equidistant between pairs of map objects, and are represented within the dual triangulation as a triangle edge. Each triangle thus represents three equidistant boundaries between three map objects -- the triangle circumcentre. The resulting tile set is the Voronoi diagram, and the dual graph is the Delaunay triangulation.



(a) (b)

Fig.5.8 Relationship between Voronoi and Delaunay triangulation

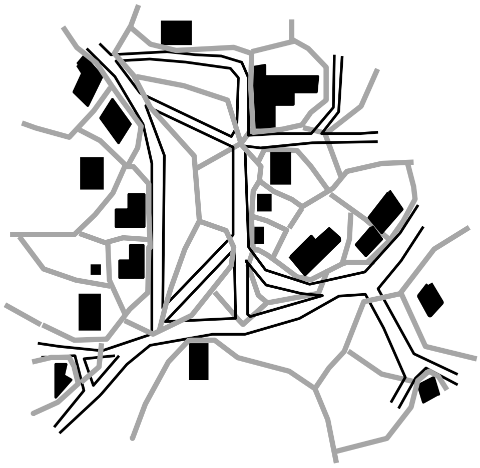


Fig.5.9 Voronoi diagram of a map according to Gold (1992)

In the Voronoi diagram of a map (Fig.5.9), one will get the concept of adjacency which is similar to human common sense. As the Voronoi zone around each object is the region closer to the object than to any other -- thus adjacency of objects is equated with Voronoi zones having a common boundary, i.e. a house is adjacent to a road although they do not intersect.

Applications of Voronoi diagram include:

- Extraction of middle axis of double line features such as roads and rivers, i.e. object collapse. 'Close' pairs of points have middle axis drawn between them in an approximately linear fashion.

- Delaunay triangulation that can be easily derived as dual graph of Voronoi diagram. Thus the visual estimation of the relative contribution of neighboring data points is not based on metric decisions, but on the relative positions of the neighboring data points in a Voronoi sense.

- Detection of clusters. With the help of Voronoi neighborhood definition, clusters that form compact Voronoi regions can be easily identified (Fig.5.10). This is a prerequisite for typification of a cluster composed of similar shapes.

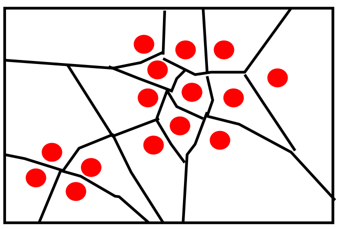
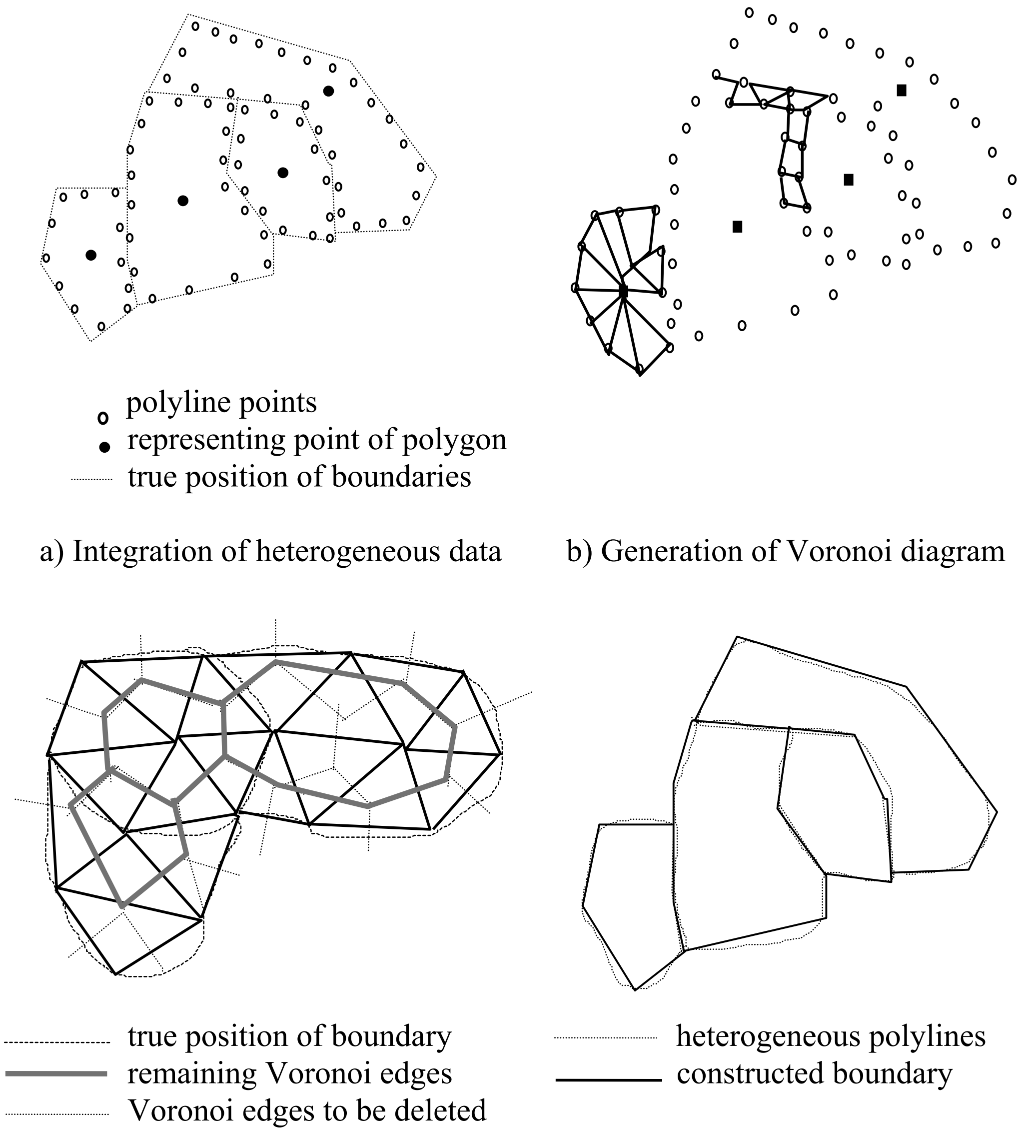


Fig.5.10 Voronoi diagram for identification of clusters (Gold, 1992)

- Automatic deletion of sliver polygons caused by integration of different data sources (Fig.5.11a-d). With Voronoi diagram, boundaries can be uniquely constructed without gaps and overlaps. The basic procedure consists of two steps. At first, a Voronoi diagram is generated for all polyline points and representative points of each polygon (Fig.5.11b). A "dissolve" option is then used to delete Voronoi edges between points within the same object (Fig.5.11c).



a) Integration of heterogeneous data b) Generation of Voronoi diagram

c) Illustration of dissolve option d) After dissolve operation

Fig.5.11 Deletion of sliver polygons (the idea is inspired by Gold,1996)

5.3.2 Constrained Delaunay Triangulation (CDT) and SDS

The pure Delaunay triangulation is notable for providing a direct solution to the all nearest neighbors problem for a set of point sites, in that each vertex is connected to its nearest neighbors. CDT is a modification of a conventional Delaunay triangulation, in which edges, belonging to vector-defined map objects, are enforced as edges within the triangulation. The constraining edges act as barriers to visibility of nearby vertices that are on the opposite sides of such edges. In practice, for polygonal and linear objects, their nearest neighboring objects are usually directly connected by triangle edges. Exceptions occur particularly where there are constraining edges that are relatively long. The neighboring objects to a specified object can be found easily by a search procedure that starts with the triangles externally connected to the object. The triangulation is a complete representation of a specified region, in that every point of the triangulated region belongs either to the interior of a single triangle or to an edge or a vertex of one or more triangles. The precision of coordinates can be arbitrarily high and the fact that space is partitioned into triangles makes measurement of areas of parts of objects and of parts of free space relatively straightforward. Topological relationships between points, lines, and areas can be explicitly represented within a triangulation data structure.

One of the most important properties of the CDT for map generalization is that of the rich proximity relations (Jones et al, 1995; Peng, 1995). Proximity relations may be easily understandable in case of objects that are connected to each other. But disjoint objects can also have proximity relations (Delaunay neighborhood) as long as any part of them are connected by a Delaunay triangle edge. The Delaunay neighbors of an object are not necessarily its nearest neighbors in geometric sense. Distant points may be accepted as neighbors in sparse areas, whereas relatively close objects may not be accepted as neighbors in dense areas if they occur behind other closer objects.

The Simplicial Data Structure (SDS) based on CDT provides an explicit topological representation that overcomes the problems inherent in Euclidean geometry. This makes it easy to do measurement, maintain topology, and detect proximal and even semantic relations between objects (Bundy et al. 1995).

Geometric generalization operators that can been implemented with SDS include object exaggeration, collapse, amalgamation, detection of conflicts and displacement.

5.3.2.1 Object exaggeration

SDS uses the triangulation to determine displacement vectors for each of the vertices on the boundary of the object. This is a method of changing size is different from a simple geometric scaling operation. The latter may cause conflicts between different parts of concave objects, whereas the triangulation will work without conflict for certain concave objects as well as working in general for convex objects (Fig.5.12).

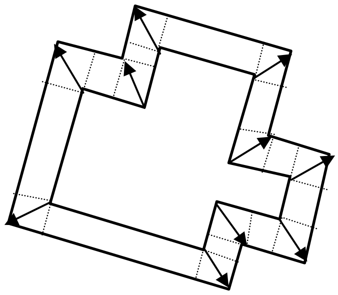


Fig.5.12 Object exaggeration (Jones, et al, 1995)

5.3.2.2 Object collapse

Object collapse is obtained by generating skeletons from triangulated area objects. The skeletons are formed by connecting points derived from the center of the circumcircles of the triangles. A skeleton of a ribbon-shaped object can be generated by connecting the centers of virtual triangle edges that connect opposite sides (Fig.5.13).

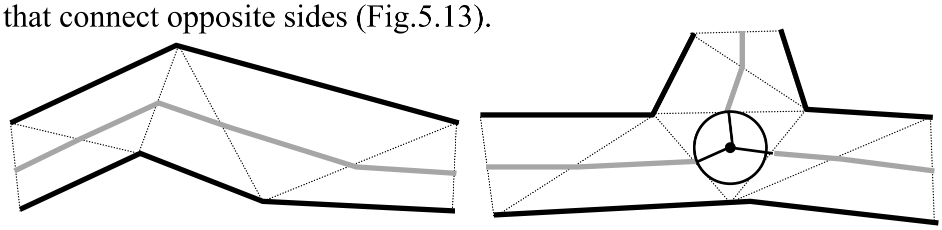
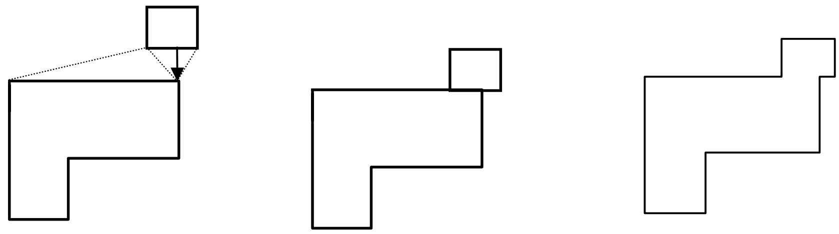


Fig.5.13 Object collapse according to Jones, et al.1995

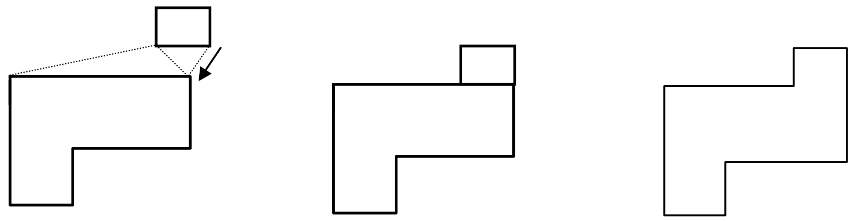
The gaps at junctions of ribbon-shaped features can be filled by using the center of the inner circle of the completely internal triangle that occurs at the junctions. Join the center with the skeleton line segments that are most closely aligned, and finally inserting line segment between the third skeleton line segment and this center. The shape of the generated center line is sensitive to asymmetric changes in the width of the feature to be collapsed, so that the generated line may initially be unacceptably angular. Therefore, this method would need a preprocessing of original object or a complemental method such as ”water-lining principle” reported by Christensen in 1996.

5.3.2.3 Area object amalgamation

There are various kinds of amalgamation operations used to different area objects. For man-made objects, it is suitable to use the direct-merge operator that maintains the alignment of objects by moving them together directly (Fig.5.14a) and the snap-merge operator that attempts to align the nearest parallel edges of objects (Fig.5.14b). For natural objects, it is better to apply the plastic-merge operator that allows natural objects to be molded together forming a smooth boundary derived from skeleton approximation (Fig.5.14c) and an adopt merge that allocates the triangles of an intervening region to the class of the separated objects (Fig.5.14d).

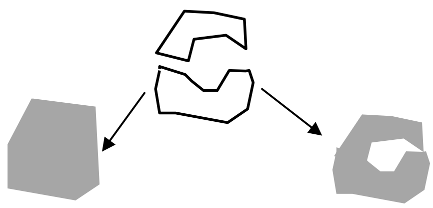


(a) Direct merge



(b) Snap merge

(c) Middle axis as smooth boundary, or weighted axis toward the more important object



(d) Adopt merge operation for natural features.

Fig. 5.14 Amalgamation with SDS (Jones et al. 1995)

5.3.2.4 Conflict detection

Objects within the triangulation may be subject to various transformations without losing connectivity. Enlargements and displacements of map objects can result in triangles being pushed across the location of other stationary triangles. The triangle ABC in Fig.5.15 becomes inverted when one of its vertices crosses the line of an opposite edge. The direction of the triangle edges, relative to the triangle center, is reversed as a consequence. Since all triangle edges are explicitly ordered within the data structure, inversions and, hence, possible overlaps between different map objects can be detected by checking for reversal in edge ordering.

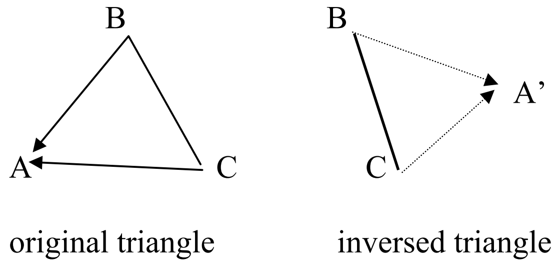


Fig.5.15 Detection of conflicts by triangle inversion

When inverted triangles are detected, potential resolution displacement vectors can be calculated from the heights of triangles. Conflicts can be resolved by applying the largest of these vectors to each vertex of an object. The length of the vector can be extended by an amount that produces an acceptable separation between the objects. The method is applicable for resolving local conflicts (Jones et al, 1995). Another method is called safe displacement, by which every object is surrounded by a group of triangles which do not enclose any other part of the given set of objects. The polygon formed by the external edges of the triangles is defined as the safe-region of the enclosed object. The object can freely move inside the region without hitting or crossing any other objects. The safe displacement is then conducted under the condition that a certain distance between two objects (a buffer zone on the object) is preserved (Peng, 1995).

5.3.3 Generalized Area Partitioning (GAP)

GAP is a basic technique used for "on-the-fly" generalization of area maps like choropleths. On-the-fly map generalization does not produce a second dataset, as this would introduce redundant data. It tries to create a temporary generalization, e.g. a volatile display of geographic data at an arbitrary scale on the screen, from one detailed geographic database. The quick responses demand the application of specific data structures, because otherwise the generalization would be too slow (Van Oosterom, 1993, 1995). With help of GAP technique, each area feature can be stored at a hierarchic level that corresponds with its relative importance within the mapping area (a function of size and type in certain context), each point on the map will belong to exactly one of the areas or polygons, that is, there are no overlaps or gaps, no matter which display scale or resolution is required.

The creation of a GAP is based on following topological data structure (Fig.5.16):

1. a node (0-cell) contains its point and a list of references to edges sorted on the angle
2. an edge (1-cell) contains its polyline, length and references to the left and to the right face

3. a face (2-cell) contains its weight factor, area, and a list of sorted and signed references to edges forming the outer boundary and possibly inner boundaries.

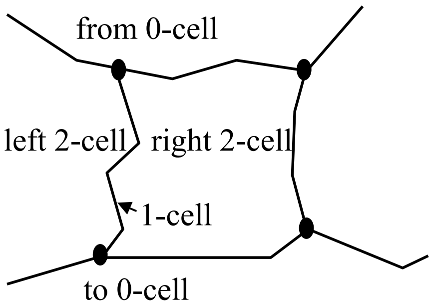


Fig.5.16 Topological structure of a polygon

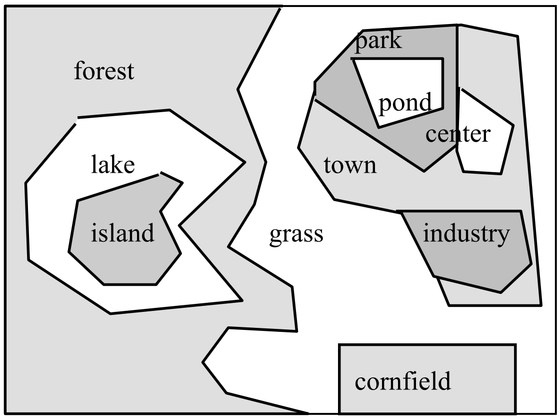
The construction of GAP is then divided into following steps:

1. for each face, an unconnected empty node in the GAP-tree is created
2. remove the least important area feature α from the topological data structure
3. find the neighbors of α and determine for every neighbor β the length of the common boundary L(α,β).
4. fill the gap by selecting the neighbor β with the highest value of the collapse function
   C(α,β) = max [f(L(α,β), CompatibleTypes(α,β), weight factor(β)]

   The CompatibleTypes(α,β) determines how close the two feature types of α and β are in the feature classification hierarchy associated with the dataset (e.g. tundra and trees are closer than tundra and industry).

5. store the polygon and other attributes of face α in its node in the GAP-tree and make a link in the tree from parent β to child α.
6. adjust the topological data structure, importance values and the length of common boundaries for every neighbor δ of the adjusted face β to the new collapsed situation.

Repeat the steps 2. - 6. until all features in the topological data structure are stored at the corresponding importance level. The last remaining area feature, i.e. the most important area will form the root of the GAP-tree. En example is illustrated in Fig.5.17. According to this principle, importance hierarchy can be pre-computed for large datasets and stored in the GAP-tree. A generalization task has thus become a retrieval task from the GAP-tree. That is, as soon as a scale or resolution is determined by a user, a threshold level of importance will be automatically identified. All objects above this level will be then extracted from the GAP-tree. Meanwhile, for the calculation of object attributes, only one level down the object has to be visited and not the whole subtree below the parent node. This makes data access very quick and efficient. After data retrieval, a simple linear version can been derived from the GAP-tree by putting the features in a list based on their level in the tree. The top level feature will be the first element of this list, the second level features will follow, and so on, e.g. grass, forest, cornfield, town, lake, center, park, industry, island, pond in Fig.5.17. When the polygons are displayed in this order, a generalize map can be produced.



An example of land-use map

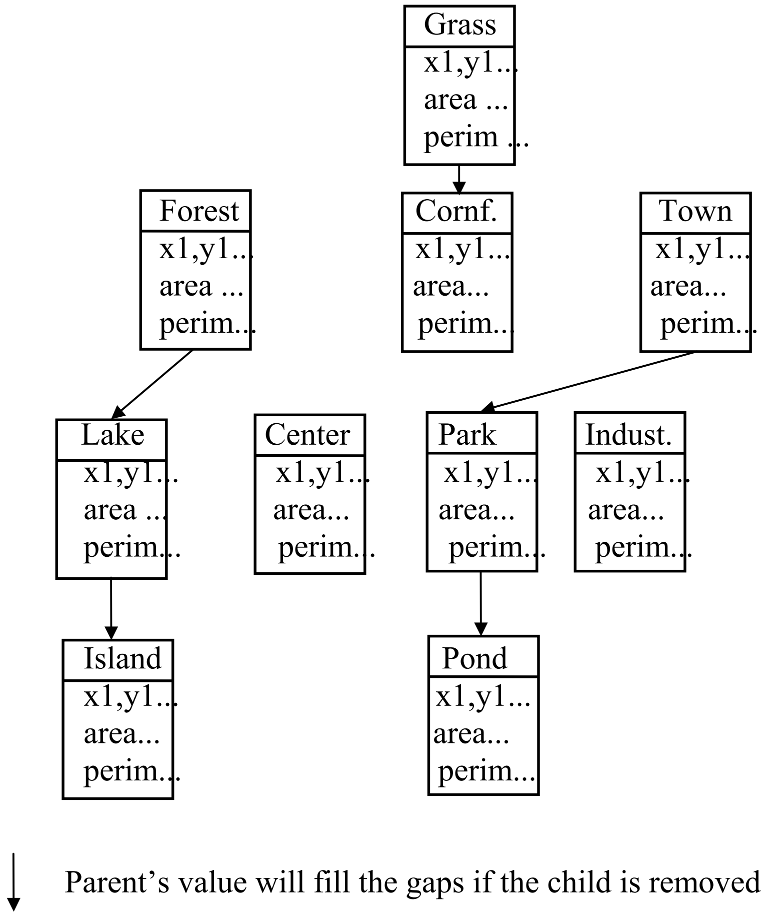


Fig.5.17 GAP-tree of a land use map (Van Oosterom, 1995)

5.3.4 Binary Line Generation tree (BLG-tree) and Reactive tree (R-tree)

The working principle of BLG-tree is very similar to GAP-tree, but the former is used to ”on-the-fly” generalization of line features. Creation of a BLG-tree is based on Douglas-Peucker algorithm. That is, points along a polyline are stored in a hierarchical order that corresponds with the Douglas-Peucker selection criterion. This order can be pre-computed, therefore can avoid the expensive execution of Douglas-Peucker algorithm each time a data reduction is needed. BLG-tree is continuous in detail level, and can be implemented with a simple binary tree (Fig.5.18).

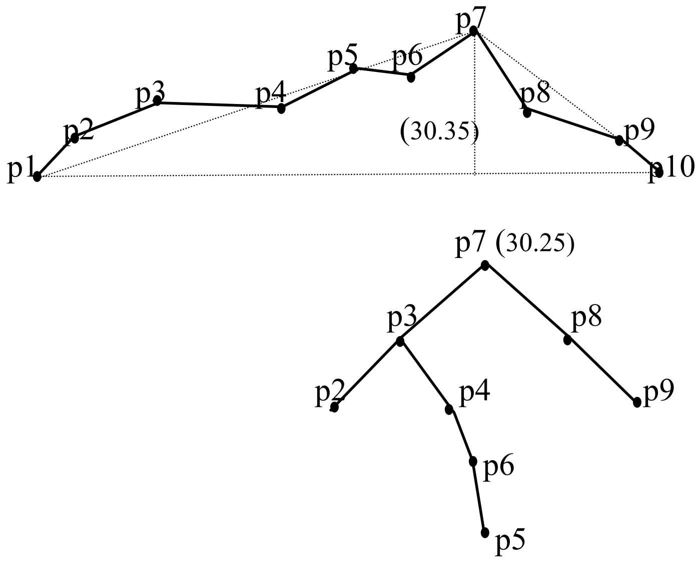


Fig.5.18 Binary Line Generalization tree (Van Oosterom, 1995)

Since Douglas-Peucker algorithm is embedded in data structure, real-time display at arbitrary scale is possible. Such intellectual data structure is particularly important for Internet data distribution.

R-tree is another structure for ”on-the-fly” generalization that has similar properties to BLG-tree. The main differences between the R-tree and BLG-tree are that the internal nodes of an R-tree can contain both tree entries and object entries, and the leaf nodes in normal object partitioning structure can occur at higher levels of R-tree. The motivation behind this is to store those small but more important features at higher levels of a tree.

According to R-tree, the further one zooms in a screen map, the more tree levels will be addressed. During map generalization based on data retrieval from the R-tree, one should try to choose the required importance value so that the number of objects to be selected corresponds with scale or resolution. If the displayed region covers a large mapping area, i.e. the scale is small, only the more important objects should be selected. Otherwise, less important objects must also be selected (accessing the nodes in a certain region of the tree). The total number of accesses is more or less the same for a well-constructed R-tree. Therefore, the interaction time is almost constant.

According to Van Oosterom, 1995, the implementation of R-tree data structure in the GIS has proved to be very effective for point, line, and area features. A generalized map display can be created within a few seconds from datasets that are larger than 100Mb.

6 Conclusion

This report has introduced in wide sense the concept and necessity of cartographic generalization in the context of digital geographic information processing and Internet data distribution. Actual research results and commercial products on automatic cartographic generalization from different countries are summarized and analyzed. A number of the remaining problems of current generalization tools are pointed out and reasoned. Some of the most popular generalization methods incl. their applications are explained with examples. These methods include data reduction and approximation of vector lines, elimination, expansion and erosion of raster areas, strategies of deeper knowledge acquisition, and intellectual data structures for the description of semantic relations between objects and ”on-the-fly” generalization.

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8 Index of Abbreviations

ATKIS (**A**mtliches **T**opographisches **K**artographisches **I**nformations**S**ystem)

CERCO (**C**omité **E**uropéen des **R**esponsables de la **C**artographie **O**fficielle)

CHANGE (Institute of **C**artography, **HAN**nover University, **GE**neralization-Software)

DCW (**D**igital **C**hart of the **W**orld)

EGIS (The Joint European GI Conference and EUROGI)

ESF (**E**uropean **S**cience **F**oundation)

ICA (**I**nternational **C**artographic **A**ssociation)

IfAG (**I**nstitut **f**ür **A**ngewandt **G**eodäsie)

IGN (**I**nstitut **G**éographique **N**ational)

MEGRIN (**M**ultipurpose **E**uropean **G**round **R**elated **I**nformation **N**etwork)

NCGIA (**N**ational **C**enter for **G**eographic **I**nformation and **A**nalysis)

OEEPE (**O**rganisation **E**uropeenne d'**E**tudes **P**hotgrammetriques **E**xperimentales)

OS (**O**rdnance **S**urvey)

USGS (**U**nited **S**tates **G**eological **S**urvey)