Map Generalisation in the Web Age

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1. Introduction

Geographic information represents our understanding of the association of phenomena with their location on and near the Earth's surface. When presented in map form, an essential aspect of that information is that it may be adapted in semantic abstraction and level of geometric detail according to the purpose of the map and the extent of the Earth that is being considered at any one time. Representations of small areas in detail result in so-called large-scale maps, while representations of large regions in lesser detail are referred to as small-scale maps. Traditionally cartographers have performed the task of adapting the content and the level of detail of a map to suit its scale and purpose and this process is called map generalisation.

The widespread use of geographic information in computers in the context of geographical information systems (GIS) has brought with it the demand for automation of map generalisation. Ideally when accessing geographic information in a GIS, it would be possible to be able to modify the level of generalisation of the available geo-data entirely automatically. At present no such automatic facilities are readily available in commercial GIS. Some commercial GIS do provide map generalisation tools that the user may apply in a somewhat *ad hoc* manner to selected geometric data. These tools appear however to be targeted at cartographic specialists wanting to derive a generalised dataset from a more detailed one. There are some notable examples of the way in which automated map generalisation tools have been exploited for purposes of professional map production. For example, IGN have used GALBE (this issue) to generalise the entire French road network to produce 1:250000 scale maps from their BDCarto database (approximately 1:50000).

More recently the demand for automated map generalisation, which has been long-standing in the context of conventional GIS, has been reinforced by the prevalence of geographical information access on the internet. There are several types of public access map-based web sites that allow a user to zoom in and out of a particular region, but at present this is usually based on stepping between independent pre-generalised datasets which may differ markedly in their degree of generalisation. It would be desirable to be able to change the level of detail on such systems in a smooth and progressive manner rather than the quantum leap changes that often characterise the current approach. Hand-held computers and mobile phones with small screens can now support the display of small maps, but the size limitations of these devices make it all the more desirable that the level of generalisation be adapted flexibly to meet the needs of individual users.

In the remainder of this article we summarise the process of map generalisation, focusing on the objectives and constraints that govern the generalisation process, the individual map generalisation operators and the interdependence between them. We

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provide a short review of some of the more recent developments in the subject relating to the recognition and preservation of pattern and to control and optimisation methods designed to address the problem of applying multiple interdependent generalisation operators. We then consider the issue of how automated map generalisation functionality may be combined with multi-scale spatial databases in order to support web-based applications that require map generalisation to be performed in "real time". Finally we summarise the contributions of the refereed papers that are presented in this special issue.

2. The process of map generalisation

The activities of map generalisation may be distinguished broadly between those concerned with the choice of the appropriate categories of information that should be represented, which is *semantic generalisation*, and those concerned with simplification of the shape and structure of the graphical symbols that represent individual features, which is *geometric generalisation*.

Automation of semantic generalisation typically requires that the categories of interest are organised hierarchically with the most important categories at the top of the hierarchies and their more specialised subdivisions at progressively lower levels. Such classification systems facilitate the application of rules to decide which major categories are relevant and the level of semantic detail with which they are presented. Knowledge representation structures that are particularly relevant here are domain-specific thesauri, which may be regarded as a type of ontology. There are many instances of different types of thesauri, but in principle thesauri support two types of hierarchical relationship: those of a generic sort that link classes to their parent and child classes, and those of a meronymic (or partitive) sort that link components of an entity to their parent entity and to any further sub-components. These types of relationship are relevant to guiding semantic map generalisation whereby finer or coarser distinctions are made between categories according to the level of abstraction that is appropriate.

Geometric generalisation is complementary to semantic generalisation in that selection of the appropriate categories of information dictates to some extent the type of geometry required to construct the map symbols. For example a small-scale map might only require predominantly the point-referenced locations of cities and towns, a mid-scale map might require the linear boundaries of urban and sub-urban blocks of buildings, while a large-scale map could require the portrayal of the boundaries of individual houses. Geometric generalisation is however very much more complicated than semantic generalisation in that there are multiple types of change that the form and structure of geographic representations undergo as the degree of generalisation increases.

3. Geometric generalisation operators

The main types of geometric transformation are: reduction in the number of discrete features that are portrayed (geometric selection); reduction in the detail of individual line, area and surface features (typically reduction in sinuosity); amalgamation of neighbouring features, whether point, line or area-referenced; reduction in dimensionality, or collapse, from area-referenced features to line or point referenced features; exaggeration of the size of significant features that would otherwise be too small to perceive; typification, or caricature, of the form and distribution of features that have been reduced in number to retain the original character; and displacement of the location of features to ensure that adequate separation distances are maintained between neighbouring features.

The individual transformations of geometric generalisation will often impact upon each other. Thus exaggeration of features could increase the density of a part of a map, triggering the requirement for further selection operations resulting in elimination of other features. It could also reduce the separation between neighbouring features resulting in the need for a displacement operation. Displacement of one object could of course lead to further violation of a separation threshold and hence the need for further displacement, or for some other conflict resolution action, such as amalgamation. This interdependence between operations introduces the need for high-level procedures and optimisation techniques to control the application of the individual operators.

4. Objectives and constraints

The intention of map generalisation control processes is to produce the best result possible subject to a set of constraints. At a broad level, the objective of map generalisation may be regarded as one of creating a map of a given scale that retains as much as possible of the relevant source information subject to cartographic considerations of legibility. This objective can be quantified to some extent with respect to several factors that constitute constraints. These factors include topology, proximity, size, shape and pattern.

Topological constraints are primarily concerned with the need to ensure that the simplified representations of the selected features retain original relationships of containment and connectivity. For example, settlements should remain within their proper parent regions and hence should not cross to the wrong side of administrative boundaries or of rivers and roads. Equally, linear features such as rivers and roads should not become intersected with parts of themselves or of other features that they did not cross originally. Most of the early automated procedures for feature simplification paid no attention to the problem of topological consistency. More recently some topologically consistent generalisation methods have been developed such as those of De Berg et al (1998), Saalfield (1999) who introduced a modification of the Douglas-Peucker algorithm to re-introduce points the removal of which would introduce inconsistencies, and van der Poorten et al (2002) and Ai et al (2000) who described methods based on constrained Delaunay triangulation in which all simplification operations retain topological consistency.

Size constraints are intended to ensure that map symbols do not become too small to be clearly discernable. In practice minimum sizes of map symbols may vary according to the type of symbol. A linear symbol of width 0.2 mm may be quite distinct while a point symbol of the same diameter may be difficult to see. Implementation of size constraints is relatively straightforward in that objects that fall below the given threshold may be deleted or, if they are regarded as particularly important, they may be exaggerated in size in order to obey the constraint.

Proximity constraints specify minimum separation distances between map symbols of various types and are intended to ensure that the individual symbols are easily distinguished from each other. Some individual operators to displace map symbols in order to retain separation distances were described for example by Nickerson (1988) for linear features and by Bundy et al (1995) for area objects. However, as indicated above, displacement operations can be expected to introduce further proximity conflicts and as a result their solution requires more complex procedures such as the optimisation methods summarised below.

Constraints of shape and pattern are intended to preserve these original characteristics of individual features and of sets of neighbouring features. They are less easily formulated than the other constraints as there are many ways in which these characteristics may be defined in terms of lower level geometric parameters such as angularity, convexity, rectilinearity, elongation, collinearity, density and autocorrelation. A number of researchers have investigated generalisation methods that are based on shape analysis. Plazanet et al (1995, 1998) and Lecordix et al (1997) considered the use of for example Guassian smoothing, wavelets, Fourier analysis, inflection points and machine learning techniques applied to line simplification, while Gold and Thibault (2001) and van der Poorten and Jones (2002) investigated the use of Voronoi and Delaunay triangulation based methods respectively in order to characterise linear features in terms of skeleton branches. Regnauld (2001a) used minimum spanning tree methods to detect clusters of buildings and Mackaness (1994) used cluster analysis methods to detect aggregations of objects. A notable development in automating the retention of pattern was the use initially by Højholt (1995) of Kohonen networks to maintain the distribution pattern of a set of buildings in which individual buildings are eliminated in order to maintain an appropriate density level for a given scale. The paper by Sester and the paper by Allouche and Moulin (both this issue) provide further evidence for the practicability of the approach.

5. Control and Optimisation Methods

The interdependence of map generalisation operations and the need to provide some means of control of their application has been recognised for some time. Some of the first systematic efforts at providing control mechanisms focused on the use of rule-based systems and a set of articles documenting various approaches to rule-based generalisation were published more than a decade ago (Buttenfield and McMaster, 1991). Much of this earlier work failed to provide convincing examples of map generalisation in practice, though some demonstrable success was achieved with the CHANGE system (Powitz, 1992), which has continued in use. Part of the problem lay with the inadequacy of the implementations of the basic generalisation operators that were executed by the rules. Another problem was the difficulty in establishing appropriate sets of rules. Some efforts to address this latter problem have been made through machine learning techniques for knowledge acquisition (Weibel et al, 1995). In this issue, Mustiere et al demonstrate that a rule based system for line generalisation can be very effective, but they highlight the overhead of generating appropriate rules manually. They show that machine learning methods of generating rules can resolve this problem.

In planning the generalisation of a large dataset, a pragmatic approach, aimed at containing the problems of propagation of conflict between neighbouring objects, is to partition the dataset. For topographic map data, a road network can help in providing a natural partition**.** Robinson and Lee (1994) provided an early example of this, and the approach has been adopted more recently in the AGENT project for map generalisation (Ruas, 1999). In the latter project, subdivisions provided by the road network are controlled by so-called meso-level agents, where macro level agents control the whole map, and micro-level agents are responsible for individual map features. The meso-level agents introduce some control over the lower level agents through the use of a plan which controls the strategy for applying generalisation operators and resolving conflicts.

Over the last five years there has been considerable interest in applying a variety of optimisation approaches to solve the problem of controlling generalisation operators. These methods are intended to resolve conflicts among multiple objects and in some cases in the context of multiple generalisation operators. In general, optimisation methods provide means for generating multiple possible states of an object, or set of objects, in combination with methods for evaluating the quality of the map at any given point in time. Typically they work iteratively towards reducing conflicts (or improving quality) by repeated modification, and in some cases repeated evaluation, of the current state.

An early example of a study of iterative improvement methods was that of Ware and Jones (1998) who compared simulated annealing and discrete gradient descent methods applied to the displacement of area objects in order to reach an objective concerning minimum separation distances, subject to constraints of maximum distances that objects could move. The study demonstrated the superiority of simulated annealing in that particular test. Subsequently simulated annealing methods have been applied to the control of multiple objects using multiple generalisation operators (Ware et al 2003).

Finite element methods (FEM) were developed in the context of mechanical engineering in order to simulate the effects of stresses upon proposed physical structures, assuming specified physical properties for the components of the structures. Højholt (2000) applied FEM to the cartographic problem of maintaining separation distances between buildings and roads, allocating different degrees of rigidity to the various map objects and introducing stresses that were a function of the separation distances between map objects. The results were promising, though problems arose concerning the imposition of precise constraints on the distances that objects were allowed to move and on minimum separation distances. In this issue Bader et al demonstrate the application of FEM to the problem of building displacement and show how the method can be employed, through its iterative application, to maintain minimum separation distances and to retain original patterns.

The problem of maintaining separation distances between linear features has also been addressed with the application of snakes, which is a technique from image processing. It models the context of a line in terms of internal forces inherent to the feature and external forces that are exerted by the neighbouring environment. Burghardt and Meier (1997) introduced this method to cartography and showed how displacement can be applied to a linear feature in which neighbouring lines exert external forces resulting in the resolution of proximity conflicts.

The optimisation method of Least Squares Adjustment (Harrie 2000, Sester 2000 and in this issue) works iteratively in an effort to minimise the difference between an actual solution and a specification of the required solution. The specification is in practice a set of equations that express constraining parameters such as angles, lengths and separation distances in terms of the original coordinates of an initial map and of the incremental changes in these coordinates required to reach the solution. In general the specified constraints may be to some extent contradictory in which case the solution may be a compromise between the constraints. The equations that define the problem include residual values that will hold the differences between the ideal constraint values and those actually achieved. Hence they provide measures of the success of a particular solution. In Harrie's initial application of least square methods to the problem of displacing building and road objects, the constraints were of several types including those of line stiffness, curvature, the angle at which lines cross each other and separation distances between neighbouring objects. In a subsequent application (Harrie and Sarjakoski 2002), the constraints are extended to combine displacement with parameters that control line simplification and object exaggeration.

In an agent-based environment, Regnauld (2001b) has proposed using conventional artificial intelligence search methods such as hill climbing to resolve conflicts among multiple objects. The potential of resolving conflicts through simple communications between multiple agents representing map features has been demonstrated in Li et al (2002). Here conflicts between building objects are resolved by enabling objects to request neighbouring objects to move, resulting in a propagation of displacement among the multiple map features.

6. Online map generalisation and multiscale databases

Support for map-based applications on the web, for purposes such as navigation and local service discovery, would ideally enable maps to be generated "on the fly" at arbitrary levels of generalisation. The challenge to automated map generalisation is considerable. As indicated earlier, at present the requirement is met typically by providing access to maps at a limited number of fixed scales, which often entails considerable leaps in detail level from one scale to another.

There are a few strategies that may be envisaged in order to improve on this situation. One approach is to store a greater number of pre-generalised maps, such that the difference between successive scale maps is smaller. In this issue, Lehto and Sarjakoski demonstrate the alternative approach of online access to generalisations of a single large-scale representation on demand to the required level of detail. They use XML-based methods to perform simple generalisation tasks on the fly.

To date, all demonstrations of fully automated generalisation from a single large scale database are either quite limited in the range of generalisation operations that can be performed or are not performed in a time that is applicable to online applications. A compromise approach strikes a balance between pre-generalisation and online generalisation (Jones et al 2000). The principle is that a multi-resolution spatial database is used to store low-level geometry that is attributed with scale-specific data that enable lines or polygons of a required level of detail to be reconstructed from their component vertices. Such a database may then be combined with high performance graphical conflict resolution software to ensure that the resulting map is clearly legible.

Multi-scale or multi-resolution spatial databases of the sort described by for example Jones and Abraham (1987), van Oosterom (1990), Becker et al (1991) and Zhou and

Jones (2001), classify the constituent vertices of geometry objects according to their scale significance and employ an algorithm to reconstruct selected geometry to the required level of detail at the time of database retrieval. Although the zero-width line and boundary geometry could be guaranteed topologically consistent through the use of a suitable pre-generalisation procedure, such consistency cannot be guaranteed for arbitrary symbols sizes (as thick line symbols might introduce overlaps between neighbouring features). Thus a post processing conflict resolution stage can be introduced to displace or if necessary delete map symbols to avoid overlap and maintain proximity constraints. The post processing may be implemented with optimisation-based methods such as those described earlier. References to web-based demonstrations of a multi-scale database and of online conflict resolution procedures may be found in Zhou and Jones (2001) and Li et al (2002) respectively. In Zhou and Jones (2003) a multi-representation approach is adopted in which stored vertices are classified and subsequently retrieved according to both a scale parameter and the style of generalisation.

7. Articles in this special issue

We now provide an overview of the articles published in this special issue. The first three papers are concerned with the development of optimisation techniques for building simplification, object typification, amalgamation and for displacement. The next article addresses line simplification, using rules to provide high quality generalisation in complex situations. The fifth article is also concerned with online access, focusing on the use of mobile devices, while the final article presents methods for three-dimensional generalisation of buildings.

The paper by Sester on optimisation approaches for generalization and data abstraction describes the use of two optimisation techniques for purposes of map generalisation. Least squares adjustment (LSA) methods are applied to the problems of building outline simplification and to object displacement, while the neural network method of Kohonen’s Self Organizing Maps (SOM), also known as Kohonen Feature Maps, is applied to the problem of typification of sets of buildings. The building simplification procedure starts by reducing the number of edges by removing offsets, extrusions, intrusions and corners, component edges of which fall below some threshold size, and extending adjacent edges where necessary. The result is then rectified by enforcing right-angled corners. LSA is then used to shift the location of the edges laterally to bring the simplified shape as close as possible to the original shape. The application of LSA is also demonstrated for purposes of displacement of building objects and of linear features. Interior constraints for lines made of sequences of edges are defined relating to edge lengths, angles between edges and orientation of edges. Exterior constraints are defined to control the distances between objects, while additional constraints affect the possible movement of objects.

Kohonen Feature Maps is applied by Sester to the problem of typifying sets of buildings. The objective is to reduce the number of buildings while maintaining their original density distribution (i.e retain original clusters). The initial set of data objects (buildings represented by points) are treated as stimuli that attract neurons corresponding to a randomly selected subset of the original buildings. The paper demonstrates the combination of both optimisation methods in order to integrate a set of buildings derived from one scale with a road network at another smaller scale. The buildings are simplified in shape before applying the typification procedure that is subject to constraints of minimum distances between objects.

Allouche and Moulin address the problems of object typification and amalgamation. They present an automated technique that enables individual regions in which there are many objects packed closely together to be replaced with a single polygon that is representative of that region. These regions, which each contain a large number of objects relative to their area, would not be suitable for display at some reduced scale. Their approach is made up of a number of stages. In the first stage, the total number of objects is reduced by some user defined percentage, while at the same time preserving their density distribution. Objects in the derived data set (a randomly selected subset of the original objects) are referred to as codebooks.

Density distribution preservation is achieved through displacement of codebooks, using a Kohonen SOM. Codebooks are then clustered into groups, each of which corresponds to a single high-density region. The clustering technique presented exploits topological relationships that exist as a by-product of stage one and depends on the fact that codebooks will be concentrated in regions containing large numbers of objects that are too close together. The original objects belonging to each dense region are identified by performing a localised search around constituent codebooks. The final stage employs an algorithm to replace all objects belonging to the same cluster with a single polygon. This works by repeatedly refining an initial Delaunay triangulation of all objects belonging to a cluster. Note that the overall technique requires the use of point objects. In the examples given in the paper, the original data set consists of polygon objects (building footprints), each of which is represented by a single point based on the polygon's centre of gravity.

Bader et al present an optimisation method for implementing the displacement operator that is based on a finite element modelling technique. The article is notable for addressing the issue of maintaining pattern among multiple features in the course of map generalisation. They consider the particular problem of displacing buildings in order to resolve proximity conflicts, whereby individual map symbols for buildings are too close either to other building symbols or to neighbouring road symbols. Groups of buildings that are close to each other, and hence which may be subject to an alignment that needs to be retained, are modelled by a sequence of elastic beams, called a ductile truss.

The beams are chained together by connecting nodes, where the nodes represent the locations of buildings while the beams represent associations between the buildings. The beams are given stiffness properties that reflect the degree of association between the respective buildings. The closer the buildings the stiffer are the corresponding beams. The truss is deformed iteratively, using forces based on neighbouring objects, until minimum distance constraints are met, or some maximum number of iterations has been performed. Experimental results demonstrate the effectiveness of the approach with regard to maintaining alignments among groups of buildings. It is pointed out that achievement of this objective is sometimes at the expense of positional accuracy. As with all displacement procedures, their successful application can be expected to be in concert with other generalisation operators such as elimination, typification and amalgamation.

The problem of line generalisation is the subject of the paper by Mustière. Specifically, the paper tackles the issue of how to acquire and formalise cartographic knowledge in order to guide the application of transformation algorithms during the process of road generalisation. Six such algorithms are considered: Max Break and Min Break (single bend enlargement); Plaster and Gaussian Smoothing (small bend smoothing); Accordion (hairpin series enlargement); and Schematisation (bend removal). The research question addressed is how best to translate non-formalised cartographic guidelines into formalised rules that will control the choice of when and where to apply a particular transformation algorithm during the generalisation of any given road.

Two techniques are presented, both of which use a knowledge-based approach, where rules are used to decide the choice of algorithm. The first, GALBE, consists of an empirically determined set of simple rules. These rules are driven mainly by a single measure, namely line coalescence. Experiments show the technique to produce overall good cartographic results. However, the author points out that in complex situations the results are not satisfactory. This is seen as being due to the relative simplicity of the rules used. A second shortcoming of the approach lies in the fact that, due to the empirical nature of the process construction, it took a long time to develop; introducing new tools into the process, or developing a similar process for other feature classes, would be time consuming.

In order to overcome these problems, the author presents a second technique, based on supervised machine learning algorithms. These algorithms are given manually classified example data from which rules are learned automatically. Each example consists of a road (described by a set of measures), a set of symbolic descriptors, the generalisation operation to be carried out, a set of applicable transformation algorithms, and finally the chosen transformation algorithm. Experiments show that the machine learning approach produces results that are, in most cases, of a similar cartographic quality to GALBE; in the most complex cases, the machine learning results are usually better.

The world of mobile telecommunications provides many opportunities and challenges for personalised presentation of geoinformation on hand-held devices with display facilities. Map generalisation has a key role to play here and the paper by Lehto and Sarjakoski provides a novel example of how XML technology can be employed to implement generalisation while online. They demonstrate how the Extensible Stylesheet Language Transformation (XSLT) facility can be used to apply some generalisation operators in the course of transforming an XML document encoded in GML (Geographical Markup Language) into an SVG (Scalable Vector Graphics) document. The simplest generalisation operator to implement is that of selection, since this is equivalent to an XSLT select operation. Other operators such as building outline simplification and area object amalgamation (via convex hull) are implemented using Java language extensions to XSLT. The authors have found that at present there is a greater time delay due to wireless data communications than to the data processing itself. In their conclusions the authors point out that application of this type of approach with large scale ranges can be expected to be combined with multiple representation (or multi-scale) spatial databases.

Three-dimensional generalisation is the subject of the article by Mayer. This is a topic that has received very little attention up to now. It can be expected to become of increasing interest however as greater use is made of visualisation of 3D landscapes for purposes such as environmental impact assessment. The article is concerned with the issue of boundary simplification, i.e. line reduction, applied to the particular case of buildings. The methods described are based on scale spaces. The term scale space is used in the field of pattern recognition to refer to a class of operators that reduce the level of detail of geometric forms. One type of such operators detects changes in curvature and is used in combination with Guassian smoothing to remove detail from linear features. Mathematical morphology operators use so-called structuring elements to modify the boundaries of regions in images. These latter operators can be used to produce expansion and contraction effects which can result in simplification such as boundary smoothing, merging of neighbouring features and elimination of relatively small features. Such methods have been shown to have potential for use in map generalisation by several authors (e.g. Su et al, 1997, applied to raster images and Thapa, 1988, using curvature-methods for linear features).

The article by Mayer is notable for combining both mathematical morphology and curvature methods and applying similar principles to vector rather than raster data (see however Muller and Wang, 1992, for an earlier exploration of a vector approach to expansion and contraction operations for aggregation in 2D). The extension to three dimensions is novel and, as the authors indicate, this work represents a preliminary investigation that demonstrates the potential of the approach.

8. Conclusions

In the current environment of distributed access to information on the internet, automated map generalisation remains one of the major challenges in maintaining and presenting geographical information. The ability to retrieve geo-information, with a content and level of detail that meets the users' requirements, occurs in the context of the many professional applications of GIS as well as within the growing number of public access services on the web that employ geographical information. Achievement of automated map generalisation in the current environment depends upon solving long-standing problems of the implementation of individual operators for map generalisation, and the development of procedures to control these operators. It also requires techniques that facilitate fast networked access to generalised data from both desktop computers and mobile devices, some of which introduce challenging demands concerning for example the presentation of maps on small screens and the presence of limited data bandwidths.

The papers in this special issue illustrate progress towards the current objectives of automated map generalisation, through the application of a variety of computational techniques, focusing variously upon optimisation techniques, knowledge based methods, XML technology and three dimensional approaches.

9. References

Ai, T., Guo, R. and Liu, Y., 2000, *A binary tree representation of curve hierarchical structure based on Gestalt principles*. 9th International Symposium on Spatial Data Handling, Sec. 2a, 30-43.

Becker, B., Six, H-W., Widmayer, P., 1991, *Spatial Priority Search: An Access Technique for Scaleless Maps*. SIGMOD Conference 1991, 128-137

Bundy, G. Ll., Jones, C.B. and Furse, E., 1995, *Holistic Generalization of Large Scale Cartographic Data*. In J-C Muller, J-P Lagrange and R. Weibel (editors) GIS and Generalisation Methodology and Practice, Taylor and Francis, 106-119.

Burghardt, D. and Meier, S., 1997, *Cartographic displacement using the snakes concept*. In W Foerstner and L. Pluemer (editors) Semantic Modeling for the Acquisition of Topographic Information from Images and Maps, Basel, Switzerland, Birkhaeuser.

B.P. Buttenfield and R.B. McMaster (editors), Map Generalization: Making Rules for Knowledge Representation (Longman), 1991.

de Berg, M., van Kreveld, M. and Schirra, S., 1998, *Topologically correct subdivision simplification using the bandwidth criterion*. Cartography and GIS, 25:4, 243-257.

Gold, C. M. and Thibault, D., 2001, *Map Generalization by Skeleton Retraction*. Proceedings of International Cartographic Association Conference, Beijing,China, 2072-2081.

Harrie, L.E., 2000, *The constraint method for solving spatial conflicts in cartographic generalisation*. Cartography and GIS, 26:1, 55-69.

Harrie, L., and Sarjakoski, T., 2002. *Simultaneous Graphic Generalisation of Vector Data Sets*. GeoInformatica, 6:3, 233-261.

Højholt P., 1995, Generalization of build-up areas using Kohonen-networks, *Proceedings of Eurocarto XIII*, Ispra, Italy.

Højolt, P., 2000, *Solving space conflicts in map generalisation: Using a finite element method*. Cartography and GIS, 27:1, 65-73.

Jones, C.B. and Abraham, I.M., 1987, *Line generalisation in a cartographic database.* Cartographica, 24:3, 32-45.

Jones C.B, Abdelmoty, A.I., Lonergan, M.E., van der Poorten, P. and Zhou, S., 2000, *Multi-scale spatial database design for online generalisation*. 9th International Symposium on Spatial Data Handling, Beijing, 7b.34-44.

Lecordix, F., Plazanet, C. and Lagrange, J-P., 1997, *A platform for research in generalization: application to caricature*. Geoinformatica, 1:2, 161-182.

Li M., Zhou S. and Jones C.B., 2002, Multi-agent Systems for Web-Based Map Information Retrieval. GIScience 2002: Geographic Information Science, Second International Conference, Boulder, CO, USA, Lecture Notes in Computer Science 2478, Springer, 161-180.

Mackaness, W.A., 1994, *An algorithm for conflict identification and feature displacement in automated map generalisation*. Cartography and GIS, 21:4, 219-232.

Muller, J.C and Wang, Z., 1992, *Area-Patch Generalization: A Competitive Approach*. The Cartographic Journal, 29:2,137-144.

Nickerson, B.G., 1988, *Automated cartographic generalisation for linear features*. Cartographica, 25:3, 15-66.

Powitz, B., 1992, *Computer-assisted generalization – an important software tool for GIS*. International Archives of Photogrammetry and Remote Sensing, 30:4, 664–673.

Plazanet, C. Affholder J-G. and Fritsch E., 1995, *The Importance of Geo-metric Modeling in Linear Feature Generalization*, Cartography and Geographic Information Systems, 22:4, 291-305.

Plazanet, C., Bigolin, N. M., and Ruas, A.,1998, *Experiments with learning techniques for spatial model enrichment and line generalization*. GeoInformatica, 2:4, 315–333

Regnauld, N., 2001a, *Contextual building typification in automated map generalisation*. Algorithmica, 30:2, 312-333.

Regnauld N., 2001b, *Constraint based mechanism to achieve automatic generalization using agent model*, Proceedings GIS Research UK GISRUK 2001, University of Glamorgan, 329-332.

Robinson, G. and Lee, F. (1994). *An automatic generalization system for large-scale topographic maps*. Innovations in GIS (ed. M. Worboys), London: Taylor and Francis, 53-64.

Ruas, A., 1998, *A method for building displacement in automated map generalization*. International Journal of Geographical Information Science, 12:8, 789-803.

Ruas, A., 1999, *The role of the meso level in urban generalisation, ICA commission on Map Generalisation working group, ICA 1999*. Available online at http://www.geo.unizh.ch/ICA/Documents/Workshop99/ruas/aci-ws-99-ruas.html.

Saalfeld, A., 1999, *Topologically consistent line simplification with the Douglas-Peucker algorithm*. Cartography and GIS, 26:1, 7-18.

Sester, M., 2000, *Generalization based on Least Squares Adjustment*. International Archives of Photogrammetry and Remote Sensing, 33:B, 931-938.

Su, B., Li, Z., Lodwick, G. and Müller, J-C., 1997, *Algebraic models for the aggregation of area features based upon morphological operators*. International Journal of Geographical Information Science, 11:3, 233-246.

Thapa, K., 1988, *Automatic Line Generalization using Zero Crossings*. Photogrammetric Engineering and Remote Sensing, 54:4, 511-517.

van der Poorten, P.M., Zhou, S. and Jones, C.B., 2002, *Topologically-consistent map generalisation procedures and multi-scale spatial databases*. Springer Lecture Notes in Computer Science 2478 (GIScience 2002), 209-227.

van der Poorten P.M. and Jones, C.B., 2002, *Characterisation and generalisation of cartographic lines using Delaunay triangulation*. International Journal of Geographical Information Science 16:8, 773-794

van Oosterom, P., 1990. Reactive Data Structures for Geographic Information Systems. PhD thesis Department of Computer Science, Leiden University, December 1990.

Ware, J.M. and Jones, C.B., 1998, *Conflict reduction in map generalisation using iterative improvement*. Geoinformatica, 2:4, 383-407.

Ware, J.M., Jones, C.B. and Thomas, N., 2003, *Automated cartographic map generalisation with multiple operators: a simulated annealing approach*. The International Journal of Geographical Information Science, 17:8, 743 – 769.

Weibel R., Keller S. and Reichenbacher T., 1995, *Overcoming the Knowledge Acquisition Bottleneck in Map Generalization : the Role of Interactive Systems and Computionnal Intelligence*. Proceedings of 2nd International Conference on Spatial Information Theory (COSIT 95), 139-156.

Zhou S. and Jones C.B., 2001, *Design and implementation of multi-scale databases*. In C.S. Jensen, M. Schneider, B. Seeger and V. Tsotras (editors) Advances in Spatial and Temporal Databases, 7th International Symposium, SSTD 2001, Lecture Notes in Computer Science 2121, Springer Verlag, 365-384.

Zhou, S. and Jones, C.B., 2003, *A Multi-representation Spatial Data Model*. In T. Hadzilacos et al. (editors) Advances in Spatial and Temporal Databases, Proceedings of the 8th International Symposium on Spatial and Temporal Databases, Lecture Notes in Computer Science 2750, 394-411.