

AUTOMATED GENERALIZATION OF HISTORICAL U.S. CENSUS UNITS

Martin Galanda, Ryan Koehnen, Jonathan Schroeder and Robert McMaster

Department of Geography, Minnesota Population Center
University of Minnesota

414 Social Sciences Building, 267 – 19th Avenue South, Minneapolis, MN 55455, US
galanda@carto.net, {koeh0017, schr0044, mcmaster}@umn.edu

ABSTRACT

This paper investigates – as part of the National Historical Geographic Information System project (<http://www.nhgis.org/>) – the creation of a multi-scale database of historical US census units. This database will include, at a minimum, three different scales (1:150,000, 1:400,000 and 1:1,000,000) and boundary data for all documented census since 1790. Besides the commitment to the production need, the main challenge in the generalization of these spatio-temporal data is the maintenance of geometric and topological consistency both within a dataset and between datasets for one target scale. We propose to address this challenge through: (1) a generalization framework based on the constraint-based generalization paradigm and the active object approach; and (2) a topological data model linking all datasets, which represent different census years, for one target scale. The framework is implemented in ESRI's ArcGIS environment using ArcGIS 9.0, Oracle, C# and ArcObjects. The implementation of the model generalization process was completed and successfully tested for the three target scales of the final database. Model generalization accomplishes the removal of redundant points and the removal of boundary-change sliver polygons. The implementation of the cartographic generalization process is still on-going and has focused, until recently, on different approaches for the enlargement and elimination of too small census units or detached parts of a census unit as well as on the reduction of the outline granularity of census units' boundaries. Results that were automatically generalized with the current version of the prototype exhibit satisfying quality based on a preliminary visual evaluation.

Keywords: automated generalization, historical boundary data, constraint-based approach;

INTRODUCTION

The National Historical Geographic Information System (NHGIS) is a five year project funded by the US National Science Foundation and conducted by the Minnesota Population Center and the Department of Geography at the University of Minnesota (<http://www.nhgis.org/>). The project will produce a comprehensive and Web-accessible database of US census data back to 1790, including spatial data at the tract- and county-level as well as most associated attribute data for these and other census geometries. The completed database will support interactive visualization and robust spatio-temporal analysis of historical US census data at multiple scales. *This paper investigates the automated generalization of historical US census units for the creation of a multi-scale database.* This database will include, at a minimum, a cartographic model of all boundaries in each census decade at three different scales: 1:150,000, 1:400,000 and 1:1,000,000. The cartographic models are derived from a single base dataset through methods of automated generalization. The base dataset stores geometries of state, county and census tract boundaries for all documented censuses since 1790 at a scale equivalent to approximately 1:100,000. The 1990 and 2000 census boundaries are drawn directly from TIGER data (<http://www.census.gov/geo/www/tiger/>). Census tract boundaries of earlier decades were created through the on-screen digitizing of paper maps published by the US Bureau of the Census, utilizing additional TIGER line features when appropriate (McMaster and Lindberg 2003).

The legibility of census units on a map relies not only on an appropriate amount of detail along the census units' boundaries but also on their size and width. Hence, the generalization of census units

should treat the units as whole polygons rather than only linear features. Although the automated generalization of polygonal data has in the past received considerably less attention than line generalization, some algorithms for the generalization of polygonal subdivisions have been presented, amongst other, by Mueller and Wang (1992), Jones et al. (1995), Bader and Weibel (1997) and Galanda and Weibel (2003). A framework for the comprehensive, automated generalization of polygonal subdivisions was presented by Galanda (2003). The US Census Bureau provides generalized boundaries of census units for a scale range of 1:500,000 to 1:5,000,000 using a semi-automated approach based on the Douglas-Peucker line simplification algorithm (Douglas-Peucker 1973) and the elimination of some very small polygons (US Census Bureau 2004).

Multi-scale databases should preserve topological consistency (both within individual map objects and between map objects) across scales (Edwardes et al. 1998, van der Poorten et al. 2002). Producing a multi-scale database of historical census boundaries, i.e. multiple temporal snapshots of census units, also requires maintaining *geometric and topological consistency over time*. Geometric consistency implies that if census units of different census years share a boundary in the base dataset, these census units must also share a generalized boundary in each digital cartographic model. Geometric consistency often goes along with topological consistency, i.e., the preservation of the topological relationships between census units of different census years.

The desire to preserve geometric and topological consistency over time is motivated by the potential use of the data. Any analysis and visualization of change of census variables over time should emphasize real changes rather than artifacts resulting from the automated generalization process. The visualization of change through cartographic animations requires keeping the cartographic noise caused by boundary-change sliver polygons to a minimum, in order to allow proper perception of change by the user (Harrower 2003). Otherwise, Chrisman (1989) and Zeeuw et al. (1999), amongst other, showed the impact of sliver polygons on the qualitative and quantitative analysis of change.

This paper proposes a framework for the automated generalization of administrative boundary data (i.e. US census units), which are not only hierarchically nested within one dataset but also across different datasets representing different temporal snapshots of one geographical area. This spatio-temporal aspect of map generalization combined with the need to maintain geometric and topological consistency constitutes a new and, so far, unique challenge in generalization research. The following sections outline a generalization framework for historical US census units, discuss implementation issues and preliminary results and, finally, draw conclusions leading to an outlook on future work.

GENERALIZATION FRAMEWORK

The generalization of census units follows a *top-down approach* while considering the hierarchical structure of states, counties and census tracts. Higher-order census units help to establish independent partitions of lower-order census units and constrain their generalization. For instance, counties are generalized on a state by state basis and state geometries must not change during the county generalization. The top-down approach (1) guarantees the homogeneous generalization of census units at one hierarchical level; (2) helps to define the spatial context of map objects and, accordingly, generalization operations; and (3) allows the parallel processing of states and counties during the generalization.

The number and complexity of census units decreases steadily from 2000 to 1790. Hence, *generalization is performed backwards in time*, in order to minimize topological and geometric conflicts between census units of different decades that have to be resolved during the generalization process. That is, the 2000 census is considered as the master decade.

The *constraint-based generalization paradigm, together with active objects* is well established and is the most successful approach to comprehensive, automated map generalization for the time being (Harrie and Weibel 2005). The qualities of this generalization approach were demonstrated in research (Ruas 1999, Barrault et al. 2001, Duchêne 2004) as well as map production of National Mapping Agencies (Lemarié 2003, Lecordix 2004). Therefore, the proposed framework for the creation of a

multi-scale database of historical US census boundaries relies on the constraint-based generalization paradigm and draws also from the active objects model.

Ruas (1999) distinguished two groups of constraints with respect to the generalization process, namely *constraints of generalization* and *constraints of maintenance*. Constraints of generalization are the motor of generalization as any violation of one of these constraints indicates a need for generalization. Constraints of maintenance relate to properties of map objects that should be preserved during the generalization process. These constraints can be either strict (must be respected) or flexible (should be maintained as faithfully as possible). In other words, the generalization process is driven by the fulfillment of constraints of generalization while constraints of maintenance restrict potential solution spaces. Galanda (2003) identified four constraints of generalization for the automated generalization of polygonal subdivisions: ‘Redundant Points’, ‘Outline Granularity’, ‘Narrowness’ and ‘Minimal Area’. Table 1 summarizes how applying generalization operations to satisfy each of these constraints would likely impact the subsequent satisfaction of the other constraints.

Secondary C. / Primary C.	Redundant points	Outline granularity	Narrowness	Minimal area
Redundant points		<i>minimal, but helps to speed up their solution</i>		
Outline granularity	<i>improved</i>		<i>improved / degraded</i>	<i>minimal</i>
Narrowness	<i>minimal</i>	<i>minimal</i>		<i>minimal</i>
Minimal area	<i>improved</i>	<i>improved</i>	<i>improved</i>	

Table 1: Impact of the solution of conflicts related to one constraint of generalization (primary constraint) on the satisfaction of another constraint of generalization (secondary constraint) attached to the same census unit.

This interrelation of conflict resolution and constraint satisfaction suggests a potential sequence of constraint fulfillment. For instance, conflicts with the ‘Redundant Points’ constraint should be solved first in the generalization process given the fact that its resolution has only minimal impact on the satisfaction of other constraints and allows an increase of computation performance due to a reduced number of vertices. The ‘Minimal Area’ constraint should also be among the first constraints handled as its satisfaction leads automatically to an improvement of the satisfaction of all other constraints. The solution of an ‘Outline Granularity’ conflict may improve or degrade an object’s compliance with the ‘Narrowness’ constraint. Thus, ‘Narrowness’ conflicts should be solved prior to ‘Outline Granularity’ conflicts. This preliminary sequence of constraint fulfillment at the polygon level can be adjusted at run time by considering an object’s characteristics as well as its spatial and semantic context. The relative position of constraints within this sequence is called priority. The higher the priority of a constraint the earlier in the generalization process it will be handled.

The generalization process cycles iteratively through all census units, one census unit at a time. The sequence in which each census unit is generalized is controlled by its compliance to the constraints of generalization prior to the generalization process. According to the active objects model, if a map object’s geometry conflicts with a particular constraint, the object can propose plans – i.e., generalization operations and corresponding parameters – that allow the object to improve its compliance to the constraint (Ruas 1999, Barrault et al. 2001). The generalization process selects a plan that is appropriate given the severity of the constraint violation and the map object’s spatial and semantic context. To optimize the generalization, several plans may be applied and the best can be selected by evaluating how well each plan satisfies the constraints of generalization and maintenance for the current object, and how each plan impacts the satisfaction of constraints attached to the object’s neighbors.

Our model for the generalization of historical US census units for one target scale has three different stages: model generalization, cartographic generalization and local cartographic generalization. Each

of the generalization stages relies on the discussed principles of constraint-based generalization. However, the number of constraints applied as well as the specification of constraints may vary.

(1) *Model Generalization (MG)*

Model generalization is used to derive a digital landscape model for each scale (e.g., DLM-X) from the base dataset (DLM-0). This process involves the selection of relevant object classes, the elimination of small polygons (typically boundary-change slivers), and a subsequent removal of redundant points through low-tolerance line simplification operations.

(2) *Cartographic Generalization (CG)*

Cartographic generalization denotes the generalization of geographic data for the purpose of visualization. It derives a digital cartographic model for the master decade (e.g., DCM-X₂₀₀₀) from the DLM established for a certain scale (e.g., DLM-X).

(3) *Local Cartographic Generalization (LG)*

Local cartographic generalization deals with the generalization of features that do not exist in the master decade. The geometric primitives that occur in two consecutive decades in the DLM of the target scale (e.g., DLM-X) are generalized during the later decade's DCM generalization (e.g., DCM-X₂₀₀₀) while boundaries that changed between the two decades are generalized through local cartographic generalization of the earlier DCM (e.g. DCM-X₁₉₉₀). This process is repeated for all decades other than the master decade working backwards in time – compare figure 1.

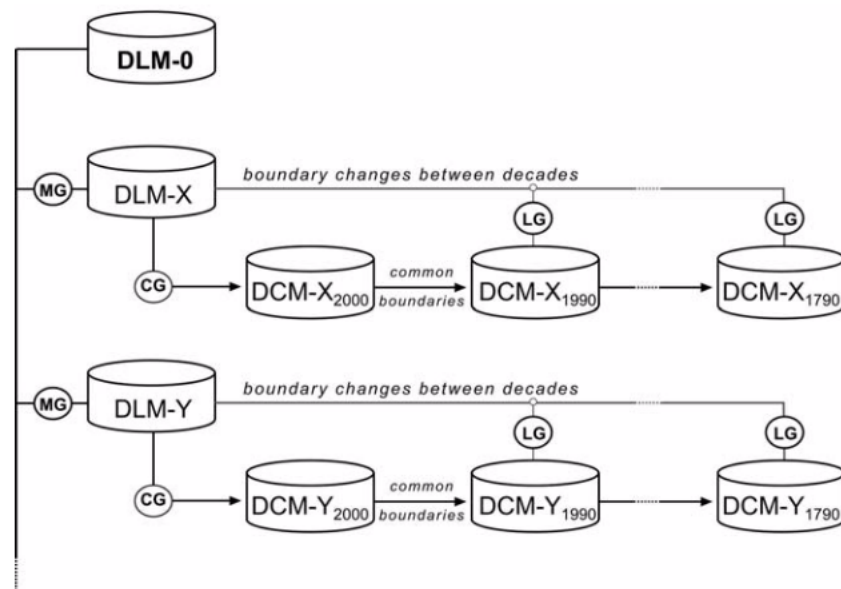


Figure 1: Creation of DLMs and DCMs for different target scales (here: X and Y) and different census years (here: 2000, 1990 and back to 1790) from a single base dataset (here: DLM-0).

This sequence of model generalization, cartographic generalization and local cartographic generalization is run independently for every scale stored in the final multi-scale database.

The active object approach supports the development of optimized solutions for each map object through the evaluation of several alternative solutions. Our framework limits the search for alternative solutions by imposing a single set of *a priori* constraint priorities. Selecting from multiple potential solutions derived by varying constraint sequences could yield a better solution in many instances, but such optimization may dramatically increase the required processing time, which is an essential consideration when generalizing a massive, complex database. In some cases where the automated solution is extremely sub-optimal, we will adjust the solution through interactive post-processing. The automation process will facilitate post-processing by generating a flag (or score) indicating whether (or how well) each map object satisfies each constraint after the automated generalization is

completed. It will then also be possible to evaluate generalized solutions quantitatively by comparing the satisfaction scores of map objects before and after the generalization. Examining the relative number of map objects meeting a certain constraint may emphasize deficits of specific algorithms or measures.

An advantage of the constraint-based generalization model this framework employs is that its implementation can easily be modularized. That is, the production of generalized datasets can start as soon as one constraint and at least one corresponding generalization algorithm are implemented while other algorithms and constraints are incrementally added and functionality is improved. As development progresses, conflicts that are not related to any implemented constraint will not be resolved appropriately. When such deficits are recognized during the qualitative evaluation of preliminary results, constraints and measures can be continually improved and added to address the most significant defects.

IMPLEMENTATION

The implementation of the outlined framework is done in ESRI's ArcGIS environment. Data are stored in an Oracle Database that is accessed for automated generalization through ArcSDE while the generalization framework is implemented in C# and ArcObjects. Implementation work is done simultaneously at two levels, the database level and the generalization level. The first level relates to the data handling during the generalization process while the latter level deals with the creation of a DLM and DCMs for each particular target scale. Generalization operates, so far, exclusively on census tract data since the preparation of historical county data is on-going. Table 2 provides an overview on the status of the implementation of the model and cartographic generalization.

		<i>Algorithm</i>	<i>Topologically consistent across time</i>
<i>Constraints for Model Generalization</i>	Minimal area	- removal of boundary-change slivers	yes
	Redundant points	- Douglas-Peucker algorithm - angle/area simplification	yes
	Constraints of maintenance	topological constraints are preserved implicitly; possible shape change of census units is constrained	
<i>Constraints for Cartographic Generalization</i>	Minimal area	- removal of polygons from multi-polygons - enlargement of isolated polygons	yes
	Outline granularity	- "enhanced" Visvalingam-Whyatt Algorithm - <i>research and implementation on-going</i>	yes
	Narrowness	<i>planned for late 2005</i>	
	Constraints of maintenance	topological constraints are preserved implicitly; others are not considered	

Table 2: The status of implementation work distinguished by model and cartographic generalization as well as generalization constraints.

The implementation of the model generalization has been completed and tested for target scales up to 1:1,000,000 for different US counties. Figure 1 shows the results of model generalization for an extract of Dane County, Wisconsin, at different target scales. Model generalization involves two generalization operations.

The first operation deals with the automated removal of small and elongated polygons from the base polygon dataset, which is a union of all boundaries for one target scale. The polygons considered boundary-change sliver polygons are identified through an area-perimeter ratio. The area of such a polygon is assigned to the neighbor in the base polygon dataset with the longest common boundary.

The data offers another hook for the identification of the neighbor that the area of the removed polygon should be assigned to, that is the neighbor across the common edge that occurs with the littlest frequency throughout all the decades. However, empirical experiments showed that in general such a solution leads to less satisfying results. The changes in the base polygon dataset are automatically propagated to all decades – compare the areas highlighted by ‘R’ in figure 2. If such a change implies that a census tract is split in any decade or a census tract’s shape is significantly distorted the second longest edge is tried out. This process is continued until a satisfying solution is found or all edges have been tried out. In the latter case the polygon is not removed. The second generalization operation during model generalization relates to the removal of redundant points with the help of the Douglas-Peucker algorithm (Douglas and Peucker 1973) and an angle/area simplification algorithm, that removes vertices where the enclosed angle and area is considered insignificant – compare the areas highlighted by ‘S’ in figure 2.

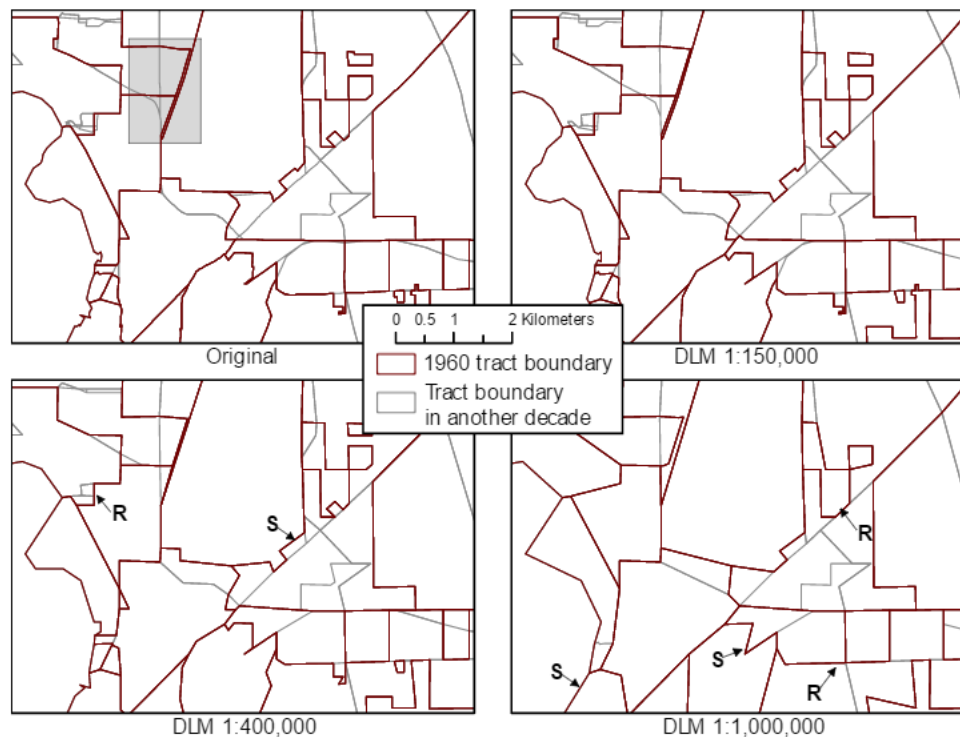


Figure 2: Model generalization of US Census boundaries in Dane County, Wisconsin, for the scales of 1:150,000, 1:400,000 and 1:1,000,000. The area in the gray box in the upper left is represented at a larger scale in Figure 4.

Implementation with respect to cartographic generalization has concentrated, until recently, on the ‘Minimal Area’ constraint. That is, polygons violating this constraint can be either removed if they belong to a tract that is represented by multiple polygons or enlarged when they are isolated polygons. All other instances of conflicts with the ‘Minimal Area’ constraint can not be solved for the time being. Since such conflicts occur in significantly smaller numbers than conflicts with the other two constraints of generalization, implementation is currently focusing on the ‘Outline granularity’ constraint. A violation of this constraint triggers a line simplification algorithm, the Visvalingam-Whyatt algorithm (Visvalingam and Whyatt 1993) in the current version of the prototype. Since this algorithm implements a global approach to line simplification intrinsic characteristics of a line geometry, for instance, rectangular angles or a series of bends, are ignored and artifacts may be created. In order to overcome, at least partly, these limitations, the Visvalingam-Whyatt algorithm was enhanced in such a way that approximately rectangular angles are preserved. Figure 3 portrays the result of combined model and cartographic generalization for tract boundaries along the Florida coastline for a scale of 1:400,000. In a next step, local approaches to line simplification, which simplify a linear feature based on the result of a spatial analysis of its geometry and the application of different generalization operations on unique and homogeneous parts of the geometry (Wang and Mueller 1998, Mustière and Duchêne 2001), will be investigated and implemented.

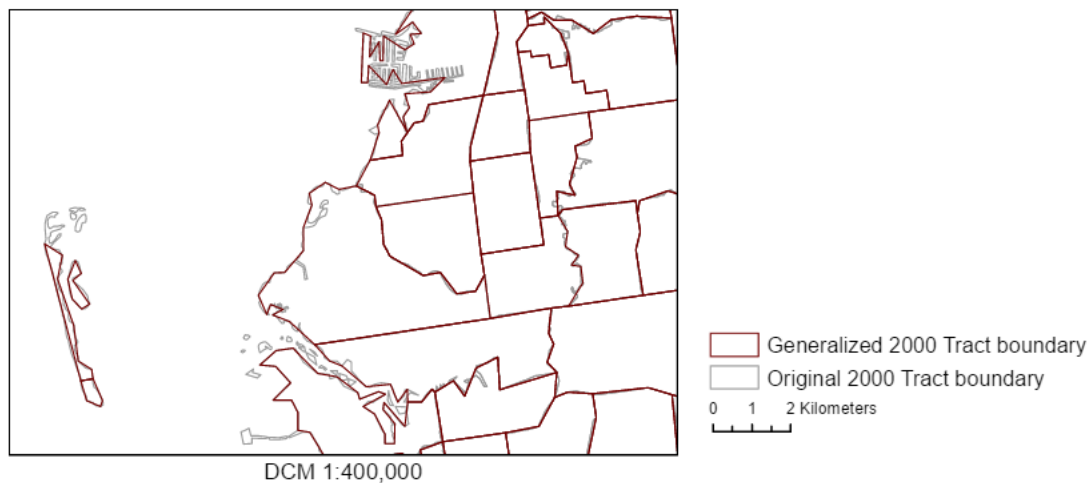


Figure 3: The result of combined model and cartographic generalization of the 2000 census tracts along the Florida coast line for a scale of 1:400,000.

The implementation of generalization functionality is driven by the desire to preserve geometric and topological consistency within a dataset and across datasets of one scale. Note that, after model generalization and, thus, before cartographic generalization, the base DCMs for all decades are derived from the data stored in the DLM. In order to meet this consistency requirement, the DLM and all DCMs for one scale are structured in such a way that each model represents a topologically sound polygonal subdivision. Each model's boundaries overlap with boundaries in the base polygon dataset. In other words, rather than specifying topological relationships between all pairs of DLM and DCMs, the base polygon dataset is used as a mediator between the DLM and DCMs of one scale. Through this model, generalizing features for any DCM will automatically propagate changes into all other DCMs where the generalized feature occurs.¹ In doing so, geometric consistency is guaranteed *per se* while topological violations can be created between the updated feature and other features in the currently generalized DCM or in any other DCM. Figure 4 represents an inset of figure 2 that highlights some of the issues related to topological consistency.

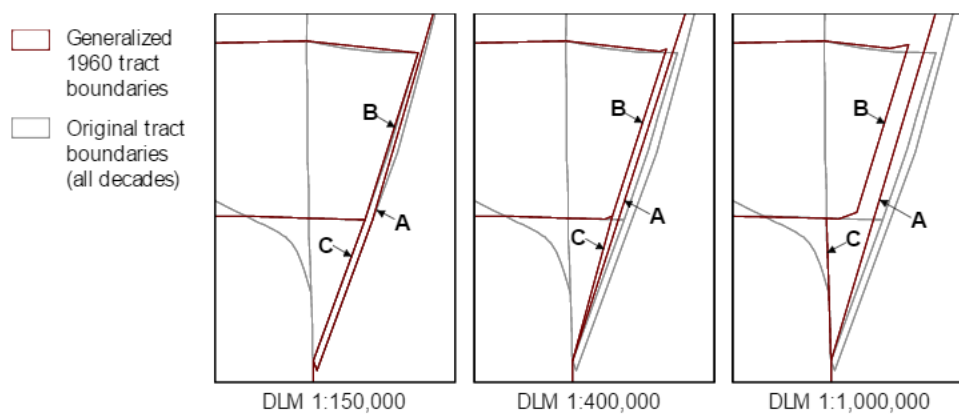


Figure 4: Preservation of topological consistency between decades during the removal of redundant points in model generalization. This area corresponds to the boxed area in Figure 2.

¹ In more precise ArcGIS terms, definitions of each decade's census tracts are stored in unique polygon feature classes of a geodatabase. An additional base polygon feature class stores the union of all census tract feature classes. A geodatabase "topology" stipulates that all boundaries in each tract feature class must be "covered" by a boundary in the base polygon feature class. When the generalization process alters geometries in any given feature class, it does so through a "topology graph", which ensures that the alterations are propagated to any geometry in any feature class that coincides with the same geometry in the base polygon feature class.

While the removal of redundant points at the scale of 1:150,000 does not lead to any topological conflict it does for the two smaller scales. Compare the generalized *edge A* and the original *edge B* at the scale of 1:400,000 and 1:1,000,000. *Edge C* shifts significantly at a scale of 1:1,000,000 due to the removal of the corresponding base polygon at this scale. When necessary, topological consistency is ensured algorithmically. For the time being, we apply a local vector-based displacement operation on all features that intersect with the area of change that is derived from the combination of the original and generalized geometry – see, for instance, the change of *edge B* at the scales of 1:400,000 and 1:1,000,000 as a consequence of the generalization of *edge A*. In the future, we intend to make use of optimization techniques for the propagation of geometry changes of a census unit to its neighborhood in all DCMs, in order to use a global approach to propagation rather than a sequential approach (Bader 2001).

CONCLUSIONS and OUTLOOK

This paper outlined a new challenge for research on cartographic generalization: the automated generalization of historical, hierarchically structured boundary data for multiple decades and scales. We outlined a framework for the creation of a multi-scale database that will store historical US census units from 2000 back until 1790 at the scales of 1:150,000, 1:400,000 and 1:1,000,000. The framework combines a constraint-based generalization paradigm and active object approach, in order to compromise between the ability to find the best solution possible and the efficient use of computer resources. The latter point is a commitment to the production need and the amount of data that has to be processed. The main challenge in the generalization of spatio-temporal data relates to the maintenance of geometric and topological consistency not only within a dataset but also within all DCMs of a single scale.

We propose to address this challenge through both our generalization strategy and our topological data model. For instance, one strategy we have chosen is to perform generalization working from 2000 backwards in time. This should maximize generalization efficiency because the number of census tracts has steadily increased through time, meaning that a majority of all historical census tract boundaries exist in 2000, and once these features have been generalized for 2000, they will not need to be generalized again where they appear in earlier decades. Our topological model is well-suited for generalization of historical census units because it links all DCMs of one scale through a base polygon dataset. When geometries for a single decade's DCM are updated using this model, geometric consistency through time is established automatically while topological consistency can be ensured algorithmically.

The creation of all DCMs for one scale is split into three different stages, i.e. model generalization, cartographic generalization and local cartographic generalization. The ongoing prototype development works within the ArcGIS environment using C# and ArcObjects. The implementation of the model generalization process was completed and successfully used for the creation of digital landscape models at the three target scales of the final database. Model generalization is accomplished through the removal of redundant points and of base polygons considered to be sliver polygons. While the implementation of model generalization is completed the one of cartographic generalization is still ongoing. The current version of the prototype can partly resolve conflicts related to the 'Minimal Area' and 'Outline Granularity' constraint. A preliminary visual examination of accomplished results showed a satisfying quality. A more thorough qualitative and quantitative evaluation will be undertaken once the implementation is completed and work focuses on the fine-tuning of generalization parameters rather than pure implementation work.

After the implementation of the outlined framework our research will continue into two independent directions: (1) the consideration of additional feature classes and (2) the improved conflict resolution for complex real world phenomena. First, we would like to enhance the outlined framework so that it is able to consider feature classes other than administrative boundaries. For instance, large inland water bodies are not only important land marks on thematic maps but also reduce significantly the land area of states and counties and, hence, influence many area-related census variables. Other linear features (e.g. rivers and roads) that are coincident with administrative boundaries could be used to

impose constraints on the generalization of census units, in order to avoid artifacts (e.g., ‘spikes’ in straight roads) and allow integration with other data sources. The consideration of features other than administrative boundaries introduces additional levels of complexity such as the need to handle features across administrative boundaries and at a meso level (Ruas 1999, Barrault et al. 2001).

The second direction of future work will focus on improved conflict resolution through the development of methods for the characterization of conflicts and the development of algorithms that are able to consider thoroughly the generalized feature type (e.g., coast line or river delta). Existing generalization algorithms such as the Douglas-Peucker (Douglas and Peucker 1973) or Visvalingam-Whyatt algorithm (Visvalingam and Whyatt 1993) are able to generalize highly complex features such as the Mississippi delta in such a way that constraints of generalization are met to a certain degree, but constraints of maintenance are violated since the feature’s intrinsic structure is ignored and geographic meaning is lost. Hence, we intend to develop (1) a suite of methods of spatial and semantic analysis allowing the characterization, and (2) algorithms for the comprehensive generalization of these complex phenomena.

Acknowledgements

This work is supported by the National Science Foundation under Grant No. BCS0094908 – an infrastructure grant provided for the social sciences. We are also grateful for the constructive comments of the reviewers that helped to improve the paper.

REFERENCES

- Bader, M., 2001, Energy Minimizing Methods for Feature Displacement in Map Generalization. Ph.D. thesis, Department of Geography, University of Zurich.
- Bader, M., and Weibel, R., 1997, Detecting and Resolving Size and Proximity Conflicts in the Generalization of Polygon Maps. *Proceedings 18th International Cartographic Conference*, Stockholm, Sweden, 1525–1532.
- Barrault, M., Regnauld, N., Duchêne, C., Haire, K., Baeijs, C., Demazeau, Y., Hardy, P., Mackaness, W., Ruas, A., and Weibel, R., 2001, Integrating multi-agent, object-oriented and algorithmic techniques for improved automated map generalization. *Proceedings 20th International Cartographic Conference*, Beijing, China, 2110–2116.
- Chrisman, N.R., 1989, Modeling error in overlaid categorical maps, in *The accuracy of spatial databases*, edited by M.F. Goodchild, and S. Gopal (London: Taylor & Francis), 21-34.
- Douglas, D.H., and Peucker T.K., 1973, Algorithms for the Reduction of the Number of Points Required to Represent a Digitized Line or its Character, *The Canadian Cartographer* **10**(2), 112–123.
- Duchêne, C., 2004, Généralisation cartographique par agents communicants: Le modèle CartACom. Application aux données topographiques en zone rurale. Ph.D. thesis, Université Paris VI Pierre et Marie Curie.
- Edwardes, A., Mackaness, W., and Urwin, T., 1998, Self Evaluating Generalization Algorithms to Automatically Derive Multi Scale Boundary Sets. *Proceedings 8th International Symposium on Spatial Data Handling*, Vancouver, Canada, 361–372.
- Galanda, M., 2003, Automated Polygon Generalization in a Multi Agent System. Ph.D. thesis, Department of Geography, University of Zurich.
- Galanda, M., and Weibel, R., 2003, Using an Energy Minimization Technique for Polygon Generalization, *Cartography and Geographic Information Science* **30**(3), 259–275.
- Harrie, L., and Weibel, R., to appear summer 2005, Modelling the Overall Process of Generalisation, in *Challenges in the Portrayal of Geographic Information: Issues of Generalisation and Multi-Scale Representation*, edited by A. Ruas, W. Mackaness, D. Richardson, and T. Sarjakoski (Oxford, UK: Elsevier Science Publishers).
- Harrower, M., 2003, Designing effective animated maps, *Cartographic Perspectives* **44**(Winter 2003), 63-65.
- Jones, C.B., Bundy, G.L. and Ware, J.M., 1995, Map Generalization with a Triangulated Data Structure, *Cartography and Geographic Information Systems* **22**(4), 317–331.
- Lecordix, F., 2004, TOP100 based on BD Carto® database, Research Service, Innovative mapping techniques. Retrieved 2/27/2005, from http://www.laser-scan.com/papers/Prototype_anglais.pdf.
- Lemarié, C., 2003, Generalisation process for Top100: research in generalisation brought to fruition. *Proceedings 5th Workshop on Progress in Automated Map Generalization*, Paris, France.
- McMaster, R.B., and Lindberg, M., 2003, The National Historical Geographic Information System (NHGIS). *Proceedings 21st International Cartographic Conference*, Durban, South Africa, 821-828.
- Mueller, J.C., and Wang, Z., 1992, Area-Patch Generalization: A Competitive Approach, *The Cartographic Journal* **29**(2), 137–144.

- Mustière, S., and Duchêne, C., 2001, Comparison of different approaches to combine generalization algorithms: GALBE, AGENT and CartoLearn. *Proceedings 4th Workshop on Progress in Automated Map Generalization*, Beijing, China, URL <http://www.geo.unizh.ch/ICA/>.
- Ruas, A., 1999, *Modèle de généralisation de données géographiques à base de contraintes et d'autonomie*, Ph.D. thesis, Université de Marne-la-Vallée.
- US Census Bureau, 2004, Cartographic Boundary Files, Scale, Generalization, and Limitations of the Cartographic Boundary Files. Retrieved 2/27/2005, from <http://www.census.gov/geo/www/cob/scale.html>.
- van der Poorten, P.M., Zhou, S., and Jones, C.B., 2002, Topologically-Consistent Map Generalisation Procedures and Multi-scale Spatial Databases, in *GIScience 2002*, edited by M.J. Egenhofer and D.M. Mark (Berlin, Heidelberg: Springer-Verlag), 209-227.
- Visvalingam, M., and Whyatt, D., 1993, Line generalization by repeated elimination of points, *The Cartographic Journal* **30**(1), 46–51.
- Wang, Z. and Mueller, J.C., 1998, Line Generalization Based on Analysis of Shape Characteristics, *Cartography and Geographic Information Systems* **25**(1), 3–15.
- Zeeuw, C.J., Bregt, A.K., Sonneveld, M.P.W., and van den Brink, J.A.T., 1999, Geo-Information for Monitoring Land Use, From Map Overlay to Object-Structured Noise Reduction. *Proceedings 10th International Workshop on Database and Expert Systems Applications*, Florence, Italy.