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Research Article

Framework and Workflows for Spatial Database Generalization

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Abstract

Spatial database generalization deals not only with geometrical simplification, but also with changes in database schema and content. The purpose of this research is to suggest methods for database generalization through the abstraction of a detailed spatial database. To accomplish this goal, this study suggests a framework for database generalization, and then defines operators that reflect the changes in database schema and content within the generalization process. A set of operator sequences (workflows) is used to specify and arrange the operators required to abstract a given feature. In order to assess the validity of the suggested method, a prototype system is developed. The results show that the efficiency of generalization can be improved, and data loss or distortion reduced as well.

1 Introduction

Different GIS applications, for the environment, natural resources, agriculture, landscape, transportation, land use, urban planning, etc., require different degrees of detail of geographic data for spatial analysis depending on their purpose. Geographic data abstraction of different levels is extremely important and a major research issue in the GIS field (Jones et al. 1996, Devogele et al. 1996).

Multiple levels of data abstraction in GIS have their origins in multi-scale map generalization, which was previously undertaken manually by cartographers. Today, the generalization may be divided into cartographic generalization, which is used to simplify the geometric representation of features, and database (or model) generalization, which is concerned with geographic information of various levels of abstraction (Brassel and

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Weibel 1988, Müller et al. 1995, Weibel and Christopher 1998). The most significant difference between the two types of generalization is the requirement for database manipulation in the latter (Müller et al. 1995).

Database generalization involves the geometric generalization of features, including modifications of spatial and aspatial data, topology, and relationships between feature classes. Furthermore, the selection and ordering of operators are very important because the sequence of operators affects the efficiency of generalization, as well as loss or distortion of information. Previous studies have considered some of the parameters for generalization depending on each operator: triangulation (DeLucia and Black 1987, Chithambaram et al. 1991, Jones et al. 1995, Poorten and Christopher 2002); distance (Douglas and Peucker 1973, AGENT 1999, Ratschek et al. 2001); distance/angular (McMaster 1987), and number of objects (Töfer and Pillewize 1966). However, these studies are not dealing with the sequences of operators and changes in database schema required for spatial database generalization.

The purpose of this research is to propose methods for database generalization by abstracting more detailed spatial databases. In order to achieve this goal, this study proposes a framework for database generalization, and also defines operators to reflect changes in database content and schema within the generalization process. A set of operator sequences (workflows) is utilized to specify and arrange the operators required to abstract a given feature. A prototype system is developed so that we can assess the validity of the suggested method.

2 Conceptual Framework for Spatial Database Generalization

The feature class can be described as a set of similar features that include spatial (geometric attributes) and aspatial data (thematic or non-geometric attributes). When the level of spatial database abstraction is raised or lowered, feature classes, spatial and aspatial data (features), topology, and relationships between feature classes are altered. For instance, when the feature class *Building* is abstracted to a high level, smaller isolated buildings are eliminated, while adjacent buildings are grouped together to form *Buildingblock*. This generalization process involves the creation of a new *Buildingblock* class (schema change), the aggregation of spatial data on buildings into this *Buildingblock* class (spatial data generalization), and the derivation of aspatial data such as the number of buildings and their sizes (aspatial data derivation). Moreover, the process requires the modification of topology and maintenance of spatial relationships such as the *Disjoint* between the classes *Building* and *Road* (schema change).

Figure 1 illustrates the conceptual framework for spatial database generalization. From the viewpoint of feature transformation, the database is divided into three categories: data model, spatial data, and aspatial data. When the level of abstraction is changed, feature classes, topology, and the relationships between classes are redefined at the model level (schema change), while at the data (content) level, spatial data is geometrically simplified (spatial data generalization), and aspatial data is maintained or derived to fit the new class definitions (aspatial data derivation). Changes in feature types or the generation of new feature classes within the generalization process lead to schema change. Spatial data generalization and aspatial data derivation may take place independently or interdependently. It is also important that the consistency of topological and spatial relationships be managed when the level of abstraction is changed (Dettori and Puppo 1996).

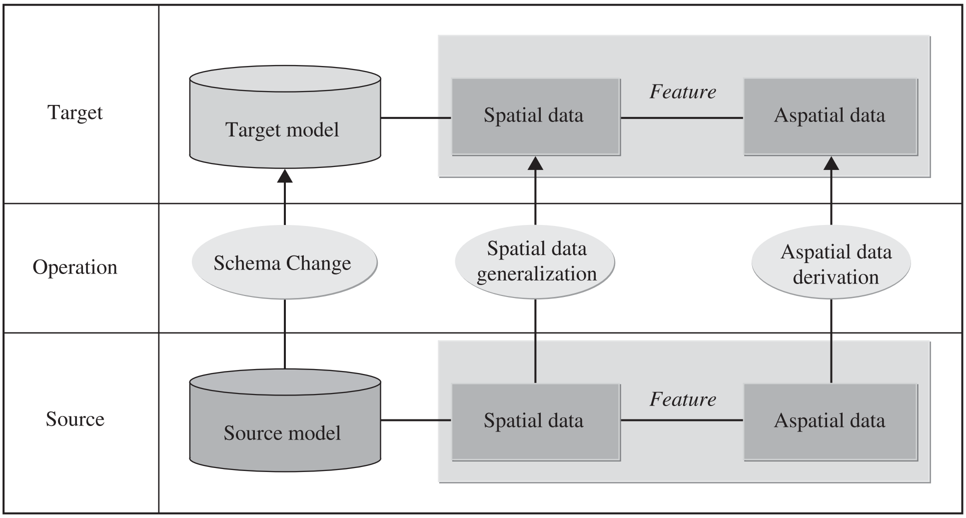


Figure 1 Conceptual framework for spatial database generalization

3 Operators

3.1 Selection of Operators

There are a number of studies on algorithms and operators used to change the geometric representation or topology of features (Beard and Mackaness 1991, McMaster and Shea 1992, Lee 1993, Smaalen 1996, Peng and Tempfli 1996, Dettori and Puppo 1996, ESRI 1996, Galanda and Weibel 2002, Galanda 2003, Ware et al. 2003, Li et al. 2004). The operators used to generalize a spatial database should be defined to include spatial data generalization, aspatial data derivation, and schema change as described above. The operators suggested in previous studies took some consideration into the factors of the generalization, but neglected to include the required schema changes.

This study redefines the operators, *Preselection*, *Elimination*, *Simplification*, *Aggregation*, *Collapse*, and *Classification*, presented by ESRI (1996). These operators were selected to transparently reflect concepts of database generalization based on changes in database schema and content. The definition of operators was made to reflect the changes in class (instances (features), spatial data, aspatial data, and feature type) and relationship (topology, spatial relationships (OGC 1999), and cardinality) required for database generalization. The changes in the content of a spatial database caused by the implementation of the operators are summarized in Table 1.

3.2 Definitions of Operators

3.2.1 Preselection

Preselection is an operator that selects the feature classes from the source database that are to be included in the target database. The selection criteria are determined based on either the purpose of the GIS application or the target map scale. Only the feature

Table 1 Content changed by operators

	Category						
	Class				Relationship		
Operator	Number of features	Spatial data	Aspatial data	Feature type	Topology	Spatial	Cardinality
Preselection	–	–	OE	–	M	M	–
Elimination	C	–	–	–	M	M	M
Aggregation	C	N	N	C	N	OE	U
Collapse	–	N	–	C	N	M	–
Classification	C	N	N	–	N	OE	U
Simplification	–	N	–	–	M	M	–

Note-: Not related, C (Changed): Change the status, U (updated): Updated in the source, N (new): Generation of new values, M (maintained): Maintains the original status, OE: Optionally erased

classes chosen by *Preselection* are subject to generalization by other operators. This operator allows the selection of feature classes needed in the target database, and offers the option of erasing the aspatial data of the selected feature classes. Topology and spatial relationships are maintained.

3.2.2 Elimination

Elimination is an operator that removes features within each feature class that are unsuitable given the purpose of the application. It has both spatial and aspatial conditions. The number of features in each class may decrease, but topology, spatial relationships, and cardinality are maintained.

3.2.3 Aggregation

Aggregation is an operator that generates new feature classes by aggregating neighboring or adjacent features. The newly generated feature class may have associated aspatial data derived from the changes in spatial data. This operator is used to aggregate both point or area features, but the results will be area features. Topology is reconstructed, spatial relationships between classes may or may not be maintained, and the cardinality between classes may be altered.

3.2.4 Collapse

Collapse is an operator that transforms area features into line or point features. When this operator is applied, feature types should change. Topology is newly created, but spatial relationships between classes are maintained.

3.2.5 Classification

Classification is an operator for connected line or adjacent area features. If the features are adjacent and have identical attribute values, merging their common edges may result in the designation of new areas. In contrast, for lines, interlinking features with identical attribute values will result in single edges. There are some cases when attributes will be re-categorized. Aspatial data measured on an interval or ratio scale can be converted using appropriate arithmetic functions. Topology is reconstructed, and spatial relationships may or may not be maintained. Cardinality between classes may be altered because new identifiers are assigned to newly classified features.

3.2.6 Simplification

Simplification is an operator used for line area features to simplify unnecessarily detailed geometric data without fundamentally altering the basic shapes. It does not affect aspatial data in any way. Topology and spatial relationships between classes are maintained.

4 Workflows

4.1 Criteria for Operator Selection and Sequence

4.1.1 Criteria for operator selection

To change the level of data abstraction, one or more operators must be used to generalize the database. It is important to properly select the operators to be applied to a feature. Lee (1995) presented the necessary considerations for conducting data generalization and workflows for vegetation, hydrography, individual buildings, and developed areas. Baella (2003) suggested the workflows for generalizing a 1:5,000 scale database (orography, hydrography, communication, built up areas) as a 1:25,000 scale database. Cecconi (2003) suggested a generalization process for an on-demand mapping service on the web with a viewpoint of real-time map generalization of road networks, buildings, river features, etc. However, the abovementioned studies did not identify the criteria for selecting operators for feature classes nor the criteria for determining the processing sequence of selected operators.

All feature classes have feature types such as point, line, and area. Definitions of operators are closely related to feature types. Operators are limited in application by feature type. For example, the operator *Simplification* cannot be applied to point features, while the operator *Collapse* can only be applied to area features.

The characteristics of a feature also affect whether an operator can be applied. For instance, when the operator *Aggregation* is applied to features that cannot be clustered (e.g. electric poles), it is difficult to give any meaning to the result. In general, *Aggregation* is applied only to clusterable features, except in special cases. *Classification* is applied to line features (e.g. roads) that have connectivity. Feature characteristics can be classified into several categories: *Cluster*, *Connectable*, *Adjacent*, etc.

In summary, interdependencies exist among operators, feature types, and feature characteristics. Operators to be applied to feature classes are selected according to their interdependencies. The relationships among feature types, feature characteristics, and operators are described in Table 2.

Table 2 Classification of feature types and characteristics

Feature type	Feature characteristics	Possible operators
Point	Clusterable	Elimination, Aggregation
	Unclusterable	Elimination
Line	Connectable	Elimination, Classification, Simplification
	Unconnectable	Elimination, Simplification
Area	Adjacent	Elimination, Classification, Simplification
	Clusterable	Elimination, Aggregation, Simplification, Collapse
	Connectable	Elimination, Classification, Simplification, Collapse
	Unclassified	Elimination, Simplification, Collapse

♦ *Preselection* is omitted because it is prioritized in the process of spatial database generalization.

4.1.2 Criteria for operator sequencing

Processing speeds and the results of database generalization vary depending on the order in which operators are applied. Therefore, the sequence of operators is crucial. Two factors can be used as criteria to determine a proper order. First, database generalization focuses on the content, completeness, and accuracy of the derived data (ESRI 2000). For these purposes, it is necessary to reduce data complexity while minimizing data distortion and loss during the generalization process. Second, operators should be applied in a sequence that maximizes the efficiency of the generalization. The number of features and volume of data processed vary depending on the sequence of the operators, which can affect processing time and computing resources.

Minimizing data distortion and loss and maximizing efficiency are conflicting goals. Database generalization inevitably reduces accuracy. Thus, because accuracy is crucial for GIS data, the minimization of data loss and distortion takes precedence over processing efficiency when determining the order of the operators.

For example, when both *Elimination* and *Aggregation* need to be applied to a feature, it is recommended to apply *Aggregation* first. Even though it is more efficient to use *Elimination* first, this sequence may raise the degree of data distortion or loss. For the same reason, *Classification* may be applied before *Elimination* for adjacent area features.

However, when any of *Collapse, Simplification, Classification* (for connectable features) are applied with *Elimination*, the operators should be ordered for maximum processing efficiency, because the sequence of their use will not affect the accuracy of the results. Applying *Elimination* before the other operators can reduce processing time because the number of features to be processed is reduced. In addition, applying *Collapse* before *Simplification* can also reduce processing time since the volume of data for processing is reduced. Optimal sequences are thus *Aggregation* or *Classification* (adjacent) – *Elimination* – *Collapse* or *Classification* (connectable) – *Simplification.*

4.2 Workflows

This research presents the base workflows (Table 3) derived using the criteria for operator selection (feature types and characteristics, Table 2) and those criteria for determining

Table 3 Base workflows

Features			Base Workflows	Operators
Examples	Types	Characteristics		
Elevation point, Bus stop	Point	Unclusterable	Workflow1	Elimination
Tree	Point	Clusterable	Workflow2	Aggregation Elimination
Road(centerline), River(centerline)	Line	Connectable	Workflow3	Elimination Classification Simplification
Contour	Line	Unconnectable	Workflow4	Elimination Simplification
Parcel, Administrative area	Area	Adjacent	Workflow5	Classification Elimination Simplification
River, Road	Area	Connectable	Workflow6	Elimination Collapse Simplification
Building	Area	Clusterable	Workflow7	Aggregation Elimination Collapse Simplification
Bridge, Reservoir	Area	Unclassified	Workflow8	Elimination Collapse Simplification

operator sequence (i.e. minimizing data loss and distortion and maximizing process efficiency).

Point features may be applied to *Aggregation* or *Elimination*, but not to operators defined only for line or area features such as *Collapse*, *Classification* and *Simplification*. Point features without the *Clusterable* characteristics have to be applied to *Elimination* (*Workflow1*); otherwise, *Aggregation* and *Elimination* have to be applied (*Workflow2*).

Line features may be applied to *Simplification*, *Elimination* and *Classification* except operators defined for point or area features such as *Aggregation* and Collapse. *Elimination*, *Classification* and *Simplification* are applied to line features that have *Connectable* characteristics (*Workflow3*). *Elimination* and *Simplification* are applied to line features that do not have *Connectable* characteristics (*Workflow4*).

Classification, *Elimination* and *Simplification* are applied to adjacent area features, but not to *Aggregation* and *Collapse* (*Workflow5*). Area features with *Connectivity* (e.g. roads, rivers, etc.) are processed with *Elimination*, *Collapse* and *Simplification*, but not with *Classification* and *Aggregation* (*Workflow6*). Area features with *Clusterable* characteristics are processed with *Aggregation*, *Elimination*, *Collapse* and *Simplification*, but not with *Classification* (*Workflow7*), and other area features are processed with *Elimination*, *Collapse* and *Simplification*, but not with *Classification* and *Aggregation* (*Workflow8*).

When a feature type is modified by a base workflow in the generalization process, other base workflows may be applied depending on the user's requirements and modified feature types and characteristics. A systematic rule management system is required to automate the complicated generalization process. This study, however, focuses on each individual workflow, and excludes such a complex workflow.

5 Examples of Spatial Database Generalization

5.1 Examples

The example of a spatial database built from a topographical map (scale 1:1,000) maintained at the Korea National Geography Institute will be used throughout the remainder of the paper to illustrate spatial database generalization using the base workflows presented in Table 3. In particular, this case study explores the processes and results of applying *Workflow2*, *3*, *5*, and *7* to each of the classes *Tree, Road(centerline), Parcel and Building*. Some of the parameters of operators, for example, are the values (scale: 1:24,000) offered by the USGS (1964), and the parameters, for which USGS values were not available, are empirical values obtained from repetitive applications in this research. The classes *Tree*, *Road(centerline)*, *Building* and *Parcel* were selected using *Preselection*, and other classes related to these classes were also included. The basic spatial data operation functions of the ArcInfo Version 8 GIS (ESRI 2000) were embedded in the prototype system for these examples.

5.1.1 Tree (Point, Clusterable) → Workflow2 → Forest

Tree is abstracted into *Forest* with *Workflow2* (*Aggregation – Elimination*) because *Tree* is a point feature with *Clusterable* characteristics (Figure 2). When *Aggregation* is applied to *Tree*, it generates a new class, *Forest*, an area feature. The aspatial data *Age* of class *Tree* becomes *Average_Age of Forest*, and the number of feature instances becomes *Count*. Within this process, the spatial relationship (*Road-Disjoint-Tree*) plays a role in preventing the overlapping of the newly generated *Forest* with *Road*.

5.1.2 Road(centerline) (Line, Connectable) → Workflow3 → P_Road(centerline)

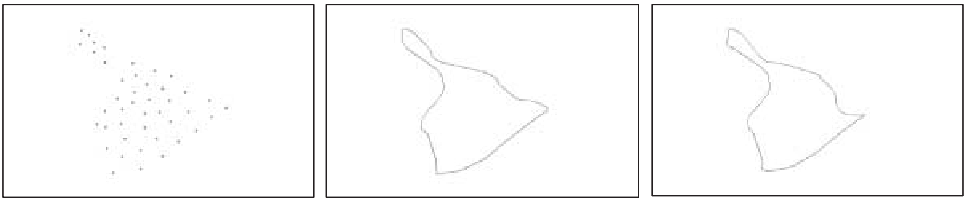
Road(centerline), a network structure with *Connectable* characteristics, is abstracted with *Workflow3* (*Elimination – Classification – Simplification*) (Figure 3). First, *Elimination* is applied to *Road(centerline)* in order to exclude the features which satisfy the conditions of unwanted edges and share pairs of connected nodes, thereby generating a principal *Road* (*P_Road(centerline)*). When *Classification* is applied to *Road(centerline)*, it preserves the attributes of the super class *Road* and upholds the existing inheritance relationship. *Length* is re-computed to create the new aspatial data *Sum_Length*.

5.1.3 Parcel (Area, Adjacent) → Workflow5 → Landuse

Parcel is abstracted into *Landuse* with *Workflow5* (*Classification – Elimination – Simplification*), since it is an area feature and has the *Adjacent* characteristics (Figure 4). *Classification* merges *Parcels* with identical attribute values to generate *Landuse*. *Average_Price* is computed from *Price,* and *Count* is determined from the number of features. In the process, the spatial relationship *Building-Within-Parcel* is converted into *Buildingblock-Within-Landuse*.

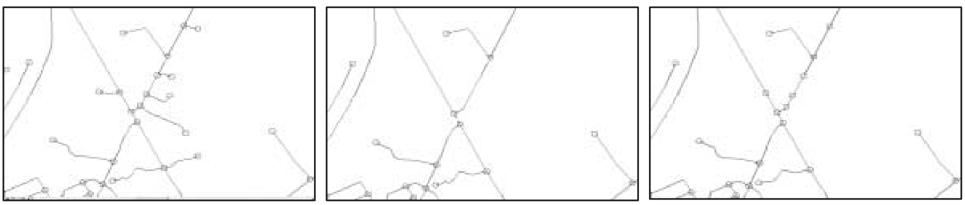
5.1.4 Building (Area, Clusterable) → Workflow7 → Buildingblock

Building is an area feature with *Clusterable* characteristics, and as such can be abstracted with *Workflow7* (*Aggregation – Elimination – Collapse – Simplification*)



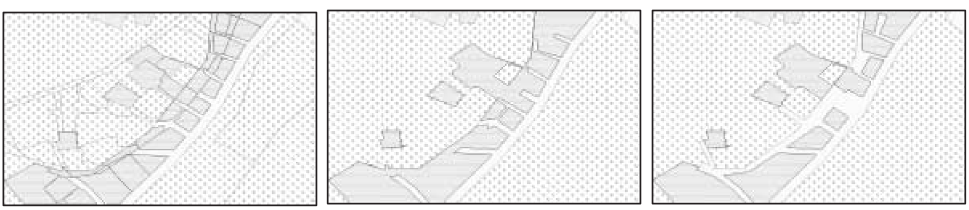
Tree-*Source DB* Workflow2 A_Workflow2

Figure 2 Result of *Workflow2*



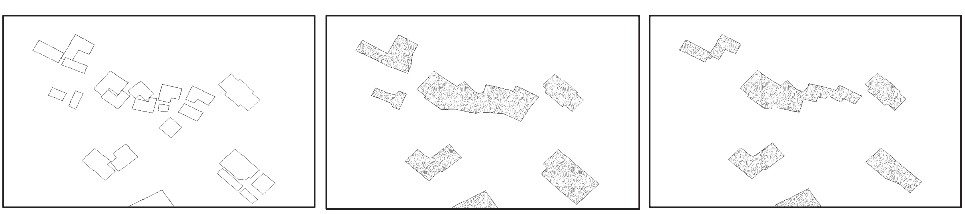
Roadcenter-*Source DB* Workflow3 A_Workflow3

Figure 3 Result of *Workflow3*



Parcel-*Source DB* Workflow5 A_Workflow5

Figure 4 Result of *Workflow5*



Building-*Source DB* Workflow7 A_Workflow7

Figure 5 Result of *Workflow7*

(Figure 5). *Aggregation* merges *Buildings* with the same value that exist within a certain distance to each other to generate the new class *Buildingblock*. Based on the aspatial data of *Building*, attributes such as *Sum_Footarea*, *Sum_Pop*, and *Average_Storage* are calculated for *Buildingblock*. The spatial relationship *Road-Disjoint-Building* prevents the overlap of the new class *Buildingblock* with *Road*.

5.2 Result Summary

The results of spatial database generalization may include compilation errors, so the results should be accessed with appropriate methods. The methods used to evaluate the results of map generalization (João 1994, 1995; Brazile 1998; Jansen and Kreveld 1998) may not be suitable for assessing the results of spatial database generalization because they mainly emphasize expressional simplicity from a cartographical viewpoint. Chrisman and McCranahghan (1991) suggest using positional accuracy (spatial accuracy), attribute accuracy (aspatial accuracy), logical consistency, completeness, and lineage as criteria for the measurement of the accuracy of spatial databases. Richardson and Müller (1991), Li and Openshaw (1993), and João (1995) assessed positional accuracy of the generalization results by comparing the differences between the results computed by automated generalization and those computed by hand operations on line features. These commentators insisted that the former was superior to the latter; that is, the results of generalization suggested by these studies and the topographical map (1:25,000-scale) were compared, and the results showed that the automated generalization produced much better results. It is because objects or features in hand-operated maps are often exaggerated or their locations are moved in order to increase legibility. It is not an appropriate evaluation method to compare the positional accuracy based on the results of spatial database generalization and that generated by hand operations.

Aspatial data can be derived as new aspatial data or may not be modified at all depending on the generalization types of spatial data. Derived attribute accuracy is differentiated by algorithms and their conditions applied for spatial data generalization. Thus, it is fairly difficult to evaluate attribute accuracy.

In addition, lineage is not affected by generalization because it is metadata, and logical consistency and completeness constraints are maintained during the generalization process and included in the definition of operators. Töpfer's Radical Law (Töpfer and Pillewizer 1966), which originated from cartographic representations, quantitatively tests the number of represented objects based on scale.

Evaluation items suggested above (positional accuracy, attribute accuracy, logical consistency, completeness, lineage, etc.) have a limitation on assessing the results of database generalization. Due to the limitations, the results of base workflows and alternative workflows (designated by the prefix "A_", Table 4) were compared and evaluated indirectly in terms of efficiency and degree of data loss and distortion. The results of the four base workflows were compared with those of alternative workflows.

First, the number of features, and their areas and perimeters were tested for the possibility of data loss or distortion. The results of *Workflow2* (*Tree* → *Forest*) and *Workflow7* (*Building* → *Buildingblock*) were more, wider and longer for all factors than those of *A_Workflow2* and *A_Workflow7*, and had different feature shapes (Table 5, Figures 2 and 5). The results of *A_Workflow3* showed the same geometrical shape of features as *Workflow3* (*Road(centerline)* → *P_Road(centerline)*), but had more features. The results of *A_Workflow3* contained nodes that were not found in the results of *Workflow3* (Figure 3). Compared with *Workflow5* (*Parcel* → *Landuse*), *A_Workflow5* produced more features, which increased the number of isolated features (Table 5, Figure 4). It means *A_Workflow3* and *A_Workflow5* were generalized and fragmentized into more features compared to *Workflow3* and *Workflow5*.

Table 4 Alternative workflows

Feature Class	Base Workflows		Alternative Workflows	
Tree	Workflow2	Aggregation Elimination	A_Workflow2	Elimination Aggregation
Road(centerline)	Workflow3	Elimination Classification Simplification	A_Workflow3	Classification Elimination Simplification
Parcel	Workflow5	Classification Elimination Simplification	A_Workflow5	Elimination Classification Simplification
Building	Workflow7	Aggregation Elimination Collapse Simplification	A_Workflow7	Elimination Aggregation Collapse Simplification

Table 5 Results of the comparison between base-workflows and alternative-workflows

		Measurement items				
Feature classes		Number of features	Area(m^2)	Perimeter (m)	Data Volume (KB)	Speed (sec)
Tree	Org	718	–	–	38	–
	W2	8	23,874	2,470	3	35
	A_W2	8	22,947	2,321	3	35
Road(centerline)	Org	853	–	151,139	257	–
	W3	743	–	145,942	149	20
	A_W3	769	–	145,942	152	40
Parcel	Org	13,057	35,917,756	2,445,478	7,284	–
	W5	2,575	33,872,269	1,012,027	1,244	1,258
	A_W5	2,621	33,826,873	1,012,045	1,258	779
Building	Org	7,301	1,083,773	313,663	2,308	–
	W7	1,157	1,226,561	166,298	280	465
	A_W7	706	735,792	99,574	146	57

Org: original feature class, W: base workflow, A_W: alternative workflow (using different operator sequences)

Second, to evaluate processing efficiency, processing times were compared. Processing efficiency is important because of the large volume of spatial data manipulated in the generalization process. The processing times of *Workflow5* and *Workflow7* were longer than those of *A_Workflow5* and *A_Workflow7* (Table 4). In contrast, *Workflow3* was faster than *A_Workflow3*. The processing times of *Workflow2* and

A_Workflow2 were identical, but the processing times of *Workflow2* can be longer in cases when many features exist.

Third, in order to compare the conciseness of the results, data volumes were examined. *Workflow2* and *Workflow7* yielded larger data volumes than their alternatives (as for *Workflow2*, data volumes will be bigger when there are many features). However, *A_Workflow3* and *A-Workflow5* ended up with more data volume than the alternatives.

Based on these experimental results, the results of generalization are differentiated depending on operator sequences, so it is fairly important how to arrange the sequences of operators. Even though base workflows cannot be the ideal workflows, base workflows can be the method to minimize data loss or distortion.

6 Conclusions

When a target database is abstracted from a detailed source database, schema changes such as changes in feature classes and relationships occur. This study suggests a conceptual framework for abstracting spatial databases by systematizing schema changes. Operators reflecting the processes of schema changes were defined, and sets of workflows were proposed. After experimenting with a prototype system to validate this method, several conclusions were generated.

First, this approach makes it possible to generalize spatial databases suitable to diverse GIS applications corresponding to the requirements of the user. Spatial databases are generally constructed using data from several maps. During the procedures, maps with similar contents but different scales are often included. It is a time-consuming and costly process to input and integrate maps of various scales and their attribute data. Furthermore, the use of several sources of map data may result in inconsistencies. Database generalization has the potential to save large amounts of time and cost, creates spatial databases tailored to users' needs in a timely manner, and prevents users from inputting maps with similar contents but different scales.

Second, the findings of this research are expected to provide important specifications for the development of CASE tools for producing spatial databases suitable to various GIS applications, as well as map generalization. This method has the potential for generalizing large-scale maps into smaller scales, and creating maps of differing themes across varying scales.

The changes in geography that are constantly occurring should be reflected in maps of various scales and spatial databases in as close to real time as possible. Current methods that involve each individual update create inconsistencies between databases, take a lot of time, and need more funding. If more studies are devoted to the automated update of generalized databases based on the defined processes of spatial database generalization, we will be able to reduce database maintenance costs and preserve data consistency.

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