Multiple Representations in GIS: Materialization Through Map Generalization, Geometric, and Spatial Analysis Operations

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Abstract. Geographic information systems (GIS) deal with data which can potentially be useful for a wide range of applications. However, the information needs of each application usually vary, specially in resolution, detail level, and representation style, as defined in the conceptual-representation modeling phase of the geographic database design. To be able to deal with such diverse needs, while maintaining an efficient, non-redundant geographic database, GIS must offer features that allow multiple representations for each geographic entity of phenomenon. This paper presents a framework for the implementation of multiple representations in GIS with minimum data redundancy, based on a comprehensive set of basic operators from computational geometry, spatial analysis, and map generalization. These operators are used to transform a representation into another, less detailed, or to generate various presentations (visual variations suitable for output, on paper or on the screen) from a given representation. Strategies for the use of such transformations in the implementation phase are presented. The strategies contemplate the situations in which a primary representation can be used to generate others, that can be materialized or not, and situations in which no primary representation is identifiable. Objects defined as requests for updates and requests for synchronization are used to organize the propagation of changes from a representation to the others.

1. Introduction

Geographic information systems (GIS) are tools designed to collect, manipulate, and present large volumes of spatial data. In order to fulfill their users' needs, GIS use several presentation media, such as charts, maps, plans, and schemes. In these media, as well as in computer screens, cartographic techniques developed hundreds of years ago are employed in order to preserve the user's familiarity with conventional portrayal of man-made or natural phenomena. Most GIS offer visualization features that are very similar to the ones traditionally employed in conventional cartography. Data are organized in layers, in the manner of series of superimposed maps. Frequently, data are divided into map sheets, reflecting the cartographer's usual work environment.

This concern with the implementation of the traditional cartographic processes is present in the internal architecture and database schema adopted by most GIS, making it hard to conceive a truly generic spatial information system, and making some applications difficult to develop. Besides, commercial GIS typically incorporate the cartographic processes in such a way that it becomes very difficult to maintain multiple representations for each geographic object. Multiple representations allow applications that perceive spatial reality in different ways to share the same geographic database. Without this capability, applications that demand the same information, but with a different representation or level of detail, end up requiring the development of new data layers. This introduces *redundancy* in the database and generates *consistency* problems throughout update operations [ECD94].

This paper explores strategies for the implementation of multiple representations in GIS, through the use of map generalization, geometric, and spatial analysis operators. These operators are used to define transformations in the original representations, to produce new (derived) representations or to generate visualizations that are adequate for some output media, while avoiding redundancy and reducing storage space. With these tools, it becomes possible to specify the mapping between the conceptual-representation and implementation stages of geographic applications design in a way that allows the integration of multiple representations in a meaningful and practical way.

Some works are related to the problem of multiple representations in GIS, although with a different approach than the one presented here. [KiSa95] proposes an incremental approach to generalization, which can be applied to the updating of multiple representation geographic databases. This approach explores the modularity of the generalization process, defining a generalization hierarchy and analyzing dependencies between generalization operators. As a result, updates at a base level can be automatically propagated to generalized representations. However, topological inconsistency problems among the representations can arise [ECD94], and a formal model for detecting and dealing with these inconsistencies is described in [Paiv98]. [KiJo94] regards multiple representation geographic databases as an alternative to automated generalization, since the necessary generalization tools are still at a primitive level, and presents an object-oriented framework in which real-world objects are catalogued and associated to all corresponding representations within the database. In a similar approach, other works concentrate on data structures that try to integrate the various representations for the same real-world object. [FrTi94] describes a multi-scale cartographic tree, adequate for replacing a representation with another as zooming operations take place.

As opposed to these efforts, this paper concentrates on the data modeling and implementational aspects of the multiple representation problem in GIS. The potential of this approach is demonstrated throughout the paper, and reinforced by references to works by several researchers in the development of map generalization, geometric, and spatial analysis tools that can be applied to the problem.

The remainder of this paper is organized as follows. Section 2 discusses the conceptual differences between *representation* and *presentation* in a GIS environment. Section 3 presents a data modeling framework for multiple representations. Section 4 introduces strategies for implementing multiple representations, based on a set of geometric, map generalization, and spatial analysis operators, which are used in transformations between representations and between a representation and a presentation. Finally, Section 5 presents an example, and Section 6 concludes the paper and indicates directions for future work.

2. REPRESENTATION AND PRESENTATION

Incorporating the spatial characteristics of objects to a data model involves choosing an adequate *representation* for each one of them, *i.e.*, a way to code their location, geometric shape, and topological behavior. For this, there are two major classes of concepts [MCS+94]: *geo-fields*, adequate to represent phenomena which vary continuously in space, such as environmental variables, and *geo-objects*, used to represent individual entities, such as man-made objects. The spatial component of a geo-field can be represented in a GIS in several ways [Borg97]: as a *tesselation* (most frequently a grid or an image), a set of *isolines*, a set of *sample values*, a *triangulated irregular network* (TIN), or as *adjacent polygons*. The spatial component of a geo-object is usually represented as a simple geometric shape, such as a *point*, *line*, or *polygon*. Additionally, the representation of a geo-object can include its role in a network, as a *node*, a *bidirectional arc*, or a *unidirectional arc*. This classification of the types of representation for geo-fields and for geo-objects will be used throughout this paper.

The representation of a spatial object does not entirely determine its *visual aspect*, i.e., the way in which the object will be shown to the user, on the screen or on paper. For each representation, there can be one or more *presentation* alternatives, that are adequate to communicate the meaning of geographic data according to the user's needs. Therefore, it is necessary to make a clear distinction between representation and visualization of geographic data. This paper will hereby use the term *representation* in the sense of a coding of the spatial object's geometry (regarding aspects such as resolution, spatial dimension, level of detail, and geometric behavior), and the term *presentation* in the sense of visualization, or graphical aspect (regarding parameters such as color, line type, line thickness, and fill style) of geo-fields and geo-objects.

3. DATA MODELING FRAMEWORK

3.1 AUTOMATED MAP GENERALIZATION

In the production of map series, the cartographer selects which phenomena from the larger-scale map are to be shown in the smaller-scale map, introducing modifications to filter out excessive detail and to maintain a constant density of information, considering factors such as the map's purpose and the amount of empty space. This process is also used in the creation of a map from observations and measurements of the physical reality. The problem is that this kind of work is based on the cartographer's expertise, including his/her aesthetic sense. This process is known as *cartographic* or *map generalization*[1] [McSh92], and its direct incorporation to a GIS environment is proving to be a rather complex problem.

The development of geographic databases cannot be restricted to the cartographic paradigms, since the demand for georeferenced information is becoming more complex [MWLS95]. Typical cartographic limits, such as the ones imposed by map sheets and fixed scales, are no longer acceptable. Furthermore, since data conversion costs are usually high, there is a tendency towards widening the spectrum of geographic information usage within organizations, thus motivating data sharing among applications.

Geographic information can be richer (than cartographic information), *unless it remains a simple digital duplication of existing base maps* [LaRu94]. Therefore, the GIS should manage a multiple-usage

[1] Observe that generalization, when used in the cartographic sense, has a similar, though different, meaning from the one usually encountered in database literature. In both cases, the term is used in the sense of the reduction of the complexity of information. In databases, generalization means information abstraction, the suppression of detail in order to widen the meaning of the information [ElNa94]. In cartography, it means suppressing unnecessary detail, in order to produce a less detailed version of a map [Nyer91].

database, from which data are retrieved and viewed in any convention usually adopted by cartography, in a continuously varying range of scales, and with an adequate density of information. Moreover, the visual aspect of geographic objects must be adjusted to the usage defined by the application. To accomplish this, a GIS must produce one or more visual aspects, with an adequate level of detail, from a given object class. This process is called *automated generalization*, and still requires a lot of human intervention to ensure good results [Spie95].

3.2 Geographic data modeling and multiple representations in GIS

If several applications must share a geographic database, the GIS is given the responsibility of allowing representations that are adequate to *each* application, and is therefore required to work with *multiple representations* of each object. Based on each of these representations, the user can count on usual GIS features that allow countless variations on the visual attributes (symbol, color, line type, line thickness, hatching pattern) to generate results in the form of maps, plans or schematics. The combination of multiple representations and flexible visualization features allows the GIS to fulfill the demands of all applications that share geographic information.

The GIS must be capable of managing and presenting the contents of the geographic database, reflecting the concepts and notions each user has about his/her work universe. To achieve this, decisions regarding generalization and the adoption of multiple representations for geographic objects must be made, considering the schema of every application that manipulates those objects. The following sections will explore the connection between generalization and data modeling, and the requirements for a multiple representation mechanism in GIS.

3.2.1 Conceptual generalization

The needs of each geographic application regarding the representation of objects are determined during the data modeling process. At the end of the modeling process, a *schema*, that is, a coherent description of the database structure, is achieved. A similar abstraction process is employed in cartography, whenever it is necessary to build a model of the real world that can be represented in a map. This process is called *conceptual generalization*[2]. It is used to reduce the spatial and semantic resolution, and also to allow analysis and map production to take place. Conceptual generalization is mainly concerned with the content and structure of the database (which, in conventional cartography, corresponds to the basic data set used in the compilation of the map), regardless of the visualization capabilities. In *map generalization*, on the other hand, the main concerns are about visual aspect, which is assessed from parameters such as readability, clarity, ease of interpretation, and others [MWLS95].

3.2.2 Requirements for multiple representations in GIS

In order to fulfill the requirements of conceptual generalization, the geographic database must be able to retrieve several representations for each real world object, throughout a wide range of scales. In this environment, the GIS must be capable of deciding which representation should be used, according to the application's needs.

With the features usually found in commercial GIS, the most common response for this need is the implementation of a separate data layer for each required representation. These representations coexist, effectively introducing redundancy, and leading to problems related to data maintenance and integrity control in the geographic database. Keeping multiple representations offers a possible solution to this problem. Redundancy can be reduced by the introduction of some interdependence between representations. Maintenance presents additional problems, such as making sure updates will take place in all representations when one of them is modified, or ensuring topological consistency among representations [Paiv98].

Solving these questions requires a clear separation between the representation of the objects in the database and their possible presentations, on the screen or on paper. Some GIS architectures have this property. In the model proposed in [CCH+96], four abstraction levels are identified: *real world*, *conceptual*, *representation*, and *implementation*. In the conceptual level, real world objects are modeled in a high degree of abstraction, but only in the representation level object classes are associated to one or more representations, according to the requirements of the application. This model is similar to the traditional

[2] In cartography literature, the expressions *model generalization* or *model-oriented generalization* are used [Weib95]. However, in order to avoid conflict with data modeling terminology, this paper will use only the expression *conceptual generalization* [Smaa97], which is another alternative that is used in the literature, along with *statistical generalization* [BrWe88].

ANSI-SPARC database systems architecture [ElNa94], including the representation level. This level does not exist in conventional database systems, since multiple representation capabilities are seldom required.

An alternative is presented in [Borg97], in which the conceptual and representation levels are merged. This is based on the idea that, for each spatial object, it is necessary to have at least one primary representation, without which the modeling of spatial relations with other objects cannot be carried out. Alternative representations can also be modeled at this conceptual-representation level, and the relationship between each representation and other objects can be indicated explicitly. Redundancy among the various representations can be controlled at the transition between the conceptual-representation and the implementation level. At that time, methods that will be used to generate and update a representation from another one must be specified. The conceptual-representation schema just indicates the need for alternative representations, and supplies the basic characteristics of each one. Likewise, transformations that produce visualizations are also specified at the implementation level, considering the limitations of the underlying GIS for the generation of various presentations from a given representation.

4. STRATEGIES FOR IMPLEMENTING MULTIPLE REPRESENTATIONS

4.1 IMPLEMENTATION STRATEGIES

If the conceptual-representation schema does not include the demand for multiple representations, the transition to an implementation schema can be accomplished in a straightforward manner. However, if multiple representations are required, the mapping must take advantage of the semantic relationship that exists among the various representations of the same object. If this connection is not adequately explored, the implementation will have to face redundant data storage and multiplied updating efforts.

We propose three different strategies to that effect, based on the existence of a primary representation, *i.e.*, a representation that can be used to generate some or all of the others (secondary representations), by means of the adequate transformations. The primary representation, if there is one, should be the most detailed and comprehensive of all representations that have been outlined at the conceptual-representation schema, and it is the only one that the user should be allowed to update.

The proposed strategies are outlined as follows:

- **Unification:** adoption of a single representation for storage in the database. Secondary representations are to be obtained directly from this primary one, through transformation operations. Secondary representations are temporary, and will not be stored in the geographic database.
- **Derivation:** definition of a primary representation, as above, which is the only one that can be modified by the user. Secondary representations are generated from this one, through transformation operations, and will be stored in order to avoid the reprocessing time. To coordinate the updating of objects belonging to secondary representations, each modification or updating on primary objects generates a *request for updates*, which is defined as an object that records the nature of the modification and indicates the need for a regeneration of the corresponding secondary objects. Depending on the characteristics of the objects and on the complexity of the transformation operations, this regeneration can be performed locally or globally, and it can be executed immediately or in the future.
- **Replication:** definition of more than one primary representation. Each one of these representations is maintained separately by the user. Modifications on objects belonging to any primary representation generate *requests for synchronization* directed towards the corresponding objects in the other primary representations. These requests are made available to the user, so that he/she can arrange for the proper modifications in the identified objects at a convenient time, or according to the frequency of updates determined in the implementation schema. Secondary representations can be defined from any primary representation, through derivation.

In the above strategies, an important role is played by *request for updates* (RFU) and *request for synchronization* (RFS) objects. These can be implemented as simple "to-do" lists, which document and organize the need to propagate changes to other representations. In the case of RFU, these changes can be carried out using the same transformation operators that have been used in the initial generation of the secondary representation. Depending on the characteristics of the transformation, it may or may not be possible to perform a local update. Also, the transformation may take a considerable amount of time to be completed, and so the appropriate time to carry it out must be decided. One alternative is to let the user decide, in a project-oriented manner: the propagation of changes will be initiated when some updating phase has been completed. In the case of RFS, there may be no automated transformation operators that allow the propagation of changes. Therefore, RFS objects act as guidelines to the users, documenting the need to perform the corresponding modifications to the other primary representations, manually if necessary.

Most of the time, the work involved in keeping additional independent representations is reduced by the use of transformations between representations, which allow updating to take place only in the primary representation(s). The following sections will describe how transformations can be implemented using a collection of map generalization, geometry, and spatial analysis operators.

4.2 TRANSFORMATION OPERATIONS

A transformation operation consists in generating a *less detailed representation* or a *presentation* from a more detailed one. In the first case, the transformation is said to be a *transformation to a representation* (TR) operation; in the latter, it is said to be a *transformation to a presentation* (TP) operation. Much caution must be taken in the definition of these operations, since, naturally, a transformation cannot introduce new information to the database. Considering this, each transformation must be accomplished with nothing more than the existing data, manipulated by the appropriate operators and their parameters. These operators comprise fundamental geometric, map generalization, and spatial analysis tools, and are described next. Sections 4.3 and 4.4 describe the situations in which TR and TP operations apply these operators.

4.2.1 Geometric operators

Many algorithms that allow the manipulation of geometric shapes are available from computational geometry. These can be easily adapted to a GIS environment, dealing mostly with vector representations such as point, line, and polygon. It is beyond the scope of this paper to describe each of these geometric operators, but the main ones are widely known (Table 1). See [Edel87], [ORou94], and [PrSh88] for a detailed description of each of these operators.

Table 1 - Geometric operators

Line simplification: reduce the number of vertices in a polygonal line, based on some alignment criterion.
Polygon triangulation: divide a polygon into non-overlapping neighboring triangles.
Centroid determination: select a point that is internal to a given polygon, usually its center of gravity.
Skeletonization: build a 1-D version of a polygonal object, through an approximation of its medial axis.
Convex hull: define the boundaries of the smallest convex polygon that contains a given point set.
Delaunay triangulation: given a point set, define of a set of non-overlapping triangles in which the vertices are the points of the set.
Voronoi diagram: given a set of sites (points), divide the plane in polygons so that each polygon is the locus of the points closer to one of the sites than to any other site.
Isoline generation: build a set of lines and polygons that describe the intersection between a given 3-D surface and a horizontal plane.
Polygon operations: determine the intersection, union, or difference between two polygons.

Observe that many of the operators listed next, in Sections 4.2.2 and 4.2.3, are in fact based on fundamental geometric constructs and algorithms, including some of the listed above. Despite that, they are better classified as map generalization or spatial analysis operators, since their application is mostly context-specific.

4.2.2 Map generalization operators

Several efforts have been geared towards understanding and systematizing the map generalization process [BrWe88, RSM78, NiFr86, McSh88], with several alternatives for the division of the process in stages. Most of the times, there has been an attempt to imitate the cartographer's behavior, proposing operators that would be similar to the stages of manual generalization work. The work by McMaster and Shea [McSh92] stands out, for proposing a more comprehensive view, focused on digital cartography systems. The work defines a set of ten operators that work on graphical representations, and another two which are based on attributes of the spatial elements (Table 2). Some of these operators can be used considering well-defined rules, while others are only applied successfully by the experienced cartographer, who is able to employ subjective criteria in his/her decisions.

Table 2 - Map generalization operators

Spatial transformations
Simplification: reduce the number of vertices employed to represent the element, in order to produce an appearance that is similar to the original, though simpler. Example: elimination of unnecessary vertices in the representation of a river.
Smoothing: displace the vertices used in the representation, in order to eliminate small disturbances and to capture the main tendencies as to the graphical shape. Example: smoothing of a contour line, in order to make its appearance more "natural-looking".
Aggregation: join point elements which are very close to each other, representing the result with the limits of the area occupied by the point set. Example: transformation of a set of points representing occurrences of a given disease into the affected area.
Amalgamation: join nearly contiguous and similar areas, by eliminating borders between them. Example: amalgamation of city blocks into an "urban occupation" area, disregarding the streets that separate them, since they have become too narrow to represent.
Merging: join two or more parallel lines that are too close to each other into a single line. Example: transformation of a river, represented by its banks, into a single-line representation of the river on its axis.
Collapse: reduce the dimension of the representation of an object, caused by its representation's size reduction. An area element (2-D) that becomes too small due, for instance, to scale reduction, would be represented as a line (1-D) or point (0-D). Example: transformation of municipal boundaries into a point, for a road map.
Refinement: discard less significant elements, which are close to more important ones, in order to preserve the visual characteristics of the overall representation but with less information density. Example: elimination of the less important creeks and streams in the representation of a hydrographic basin. In the opposite sense, this operator is often named **Selection**.
Exaggeration: increase the dimensions of elements considered important for the map but, if represented in their real dimensions, would be too small to be perceived visually. Example: exaggeration of the dimensions of a bay, to register its position in a small scale map.
Enhancement: modify the characteristics of a symbol, in order to make it more adequate to visualize in smaller scales. Example: relative increase in the size of a bridge symbol in a road map.
Displacement: intentionally shift the position of a feature, in order to make it distinct from other, which is too close or superimposed with it. Example: displacement of a municipal border line, in order to distinguish it from a river, which is the actual boundary landmark.
Attribute transformations
Classification: group of objects into categories which share identical or similar characteristics. Example: reduction of the number of soil categories in a pedologic map.
Symbolization: adopt a visual appearance for an object based on its essential characteristics, specially after the results of a classification. Example: adoption of a symbol which is dependent on the population to represent cities

There is much discussion about the ideal sequence of the application of these operators [Monm91a], with some authors expressing doubts on whether such sequence exists. Anyway, much research has been directed at seeking practical ways to implement each operator in a GIS and digital cartography environment, in an attempt to completely automate the map generalization process. Some efforts are geared towards simplifying the generalization process, considering particular aspects of some class of applications, such as transportation networks [Mack95, ViWi95, KrPe98], hydrographic networks [MoCa96], or relief [WaJo92, Weib92]. Some works propose the creation of special data structures [Oost93, BJF95, FrTi94, JBW95], while others advocate the use of generalization for map production or for the creation of simpler databases using the appropriate GIS tools [More95].

4.2.3 Spatial analysis operators

Spatial analysis is employed when it is necessary to determine how geographic objects are organized in space, in such a way that allows people to gain insight about the spatial distribution or organization of the phenomena under study. This discipline is strongly based on the human capacity of distinguishing spatial patterns, communicated through graphs and maps.

Table 3 - Spatial analysis operators

Spatial analysis operators
Buffer construction: create a polygon that contains all points of the plane closer than a given distance to a given object. **Polygon overlay:** determine the intersection between two sets of polygons. **Selection:** retrieve objects from an object set, based on spatial or alphanumeric criteria. **Classification:** separate objects in groups, according to a set of criteria **Symbolization:** divide the objects in classes, according to some characteristic, and associate to each class a different symbol. **Spatial interpolation:** determine the value of a variable at a given point, based on information from other points. **Grid analysis:** manipulate information contained in tesselations (mostly in the form of digital images), including **vectorization** (extract points, lines and polygons from an image), **rasterization** (transform points, lines, and polygons into an image), **image classification** (group cells according to their value), **resampling** (change the dimensions of the image by means of interpolation on the original cells), and others.

Spatial analysis can be used to eliminate or summarize detail, in order to facilitate the understanding of the behavior of some spatial process [Chou97]. In these situations, spatial analysis becomes similar to map generalization. A selection of spatial analysis operators is presented in Table 3, emphasizing those that are useful in the context of transformations to representations or presentations.

4.3 TR OPERATIONS

Transformation to representation (TR) operations can be defined as sequences of operators that are applied to a class of objects, in order to generate an alternative representation for that class from existing data. TR operations are characterized in two situations:

- the resulting and the original representations are different in nature (for instance, a polygon representation is transformed into a point representation), or
- the resulting and the original representations are of the same kind, but the resulting class is less detailed (for instance, a new representation for a river class is obtained by selecting the most important rivers and simplifying the lines).

Table 4 - Object to object transformations

From \ To	Point	Line	Polygon	Unidirectional arc	Bidirectional arc	Network node
Point	Selection (S)	NEI	Buffer construction (S); aggregation (M); convex hull (G); clustering (G)	NEI	NEI	Superimposition (A)
Line	Collapse (M)	Selection (S); simplification (M); smoothing (M); merging (M)	Buffer construction (S)	NEI	Superimposition (A)	NEI
Polygon	Collapse (M)	Skeletonizing (G)	Selection (S); simplification (M); smoothing (M); amalgamation (M); buffer construction (S)	NEI	Skeletonizing (G)	NEI
Unidirectional arc	Collapse (M)	Drop direction and network topology (A)	Buffer construction (S)	Selection (S) and elimination of unnecessary nodes (A)	Drop direction (A)	DNMS
Bidirectional arc	Collapse (M)	Drop network topology (A)	Buffer construction (S)	NEI	Selection (S) and elimination of unnecessary nodes (A)	DNMS
Network node	Superimposition (A); drop network topology (A)	DNMS	Buffer construction (S)	NEI	NEI	Selection (S) and merge broken arcs (A)

NEI - Not Enough Information
DNMS - Does not make sense
S - Spatial analysis operator
M - Map generalization operator
G - Geometric operator
A - Auxiliary operator

Considering the already mentioned representation varieties, as geo-objects (points, lines, polygons, unidirectional arcs, bidirectional arcs, nodes) or geo-fields (isolines, tesselation, samples, TIN, adjacent polygons) [Borg97], each pair of representation varieties can be analyzed next. In several combinations, the transformation simply does not make sense, and in others existing information does not suffice. In most cases, however, there are viable paths for the transformation, using the previously mentioned operators, along with some auxiliary operators. These auxiliary operators usually do not produce a transformation by themselves, but perform simple tasks, such as copying the geometry (`superimposition`), or striping topological information from arcs or nodes to produce lines or points.

Table 4 shows all possible pairs of geo-object representations, and the possibilities for application of the previously listed operators to accomplish the transformation. A number of problems arise when trying to transform non-topological representations (point, line and polygon) into topological ones (node, arc), and vice-versa. For example, even though points and network nodes are both 0-D representations, transforming points into nodes only makes sense if the result is used as part of a network. Transforming nodes into points, on the other hand, demands a simple `superimposition` operation, discarding all topological (network) information. The same happens between lines and arcs, either unidirectional or bidirectional.

Special situations can arise when new network representations are derived from existing ones by `selection` operations In this case, the topological integrity of the network must be maintained. If nodes are selected, then arcs connected to dismissed nodes must be discarded or merged into neighboring arcs. The same happens when arcs are selected: nodes which are connected to zero or two arcs must be eliminated as well.

Table 5 shows all possible combinations among geo-field representations, and the operators required to accomplish the transformation. Many of the operators listed are typically associated with image processing or remote sensing, such as `resampling`. However, geometric algorithms also play an important role, such as `isolines generation` and `Delaunay triangulation`. Other typical spatial analysis functions, such as `spatial interpolation` and `selection`, are also used.

Table 5 - Field to field transformations

From \ To	Isolines	Tesselation	Samples	TIN	Adjacent polygons
Isolines	Selection (S); spatial interpolation (S)	Spatial interpolation (S)	Selection (S) of isoline vertices	Selection (S) of isoline vertices and Delaunay triangulation (G)	Spatial interpolation (S)
Tesselation	Isolines generation (G)	Resampling (S)	Selection (S) of cells	Selection (S) of cells and Delaunay triangulation (G)	Classification (M, S)
Samples	Delaunay triangulation (G) and isolines generation (G)	Spatial interpolation (S)	Selection (S)	Delaunay triangulation (G)	Voronoi diagram (G)
TIN	Isolines generation (G)	Spatial interpolation (S)	Selection (S) of vertices	Selection (S) of vertices and Delaunay triangulation (G)	Classification (M, S)
Adjacent polygons	DNMS	Rasterization (S)	Centroid determination (G)	Polygon triangulation (G)	Classification (M, S)

DNMS - Does not make sense
S - Spatial analysis operator
M - Map generalization operator
G - Geometric operator
A - Auxiliary operator

Transforming from a geo-field to a geo-object representation demands attention to the semantics of the phenomenon involved. If it is something for which a geo-field representation was chosen primarily, then it must be a space-filling phenomenon, that is, a variable which takes on a different value at every geographic location. Nevertheless, these transformations are useful in situations where only some values of the variable are necessary. For instance, the relief of a city, represented either as a TIN or as a set of contour lines, can be used to generate a set of elevation points at each street intersection, so as to give the reader of a map an idea of the slope of each street segment, without cluttering the map with too many lines. In spite of these applications, several field-object transformations simply do not make sense, and therefore should not be allowed in the implementation model. Table 6 shows all the possible field to object transformations, and indicates the cases in which the transformation does not make sense.

Table 6 - Field to object transformations

From \ To	Point	Line	Polygon	Unidirectional arc	Bidirectional arc	Network node
Isolines	DNMS	Selection (S)	Spatial interpolation (S)	DNMS	DNMS	DNMS
Tesselation	DNMS	Vectorization (S)	Vectorization (S)	DNMS	DNMS	DNMS
Samples	Superimposition (A)	DNMS	Buffer construction (S)	DNMS	DNMS	Superimposition
TIN	Selection (S) of vertices	DNMS	Classification (M, S)	DNMS	DNMS	DNMS
Adjacent polygons	Collapse (M)	Skeletonizing (G)	Selection (S)	NEI	Skeletonizing (G)	DNMS

NEI - Not Enough Information
DNMS - Does not make sense
S - Spatial analysis operator
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The final combination, geo-object to geo-field, rarely makes sense. Since objects are used to represent individual phenomena, there is often not enough information to build a field representation, in which there must be a value for each point in space. There is only one case in which an object to field transformation can make sense. In the generation of Voronoi cells from a set of points, space is divided into adjacent polygons with no additional information. This is natural, considering that each point in space has a closest neighbor which belongs to the original point set. Variations of the Voronoi diagram, such as higher-order Voronoi diagrams or line-based Voronoi diagrams [ORou94] can also be applied here.

4.4 TP OPERATIONS

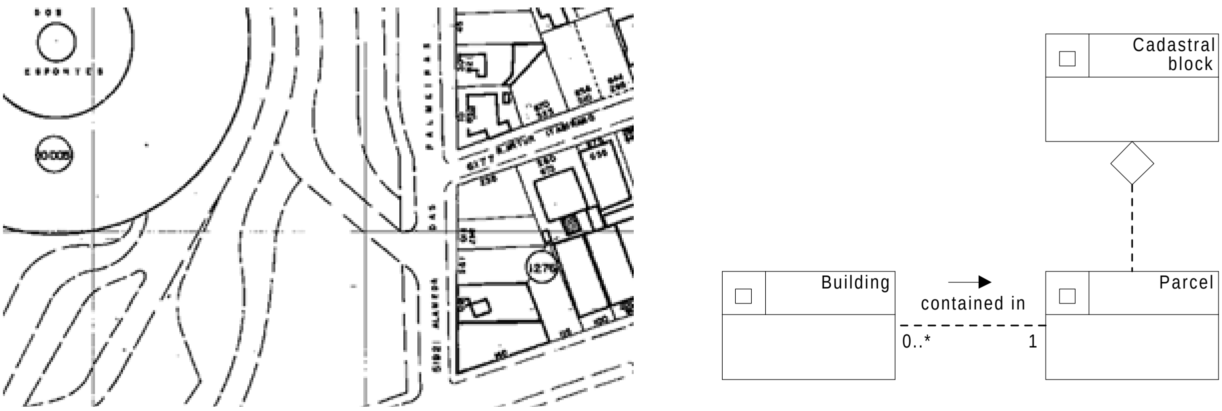
As opposed to TR operations, an operation is said to be a *transformation to a presentation* (TP) when the nature of the representation and the detail level are maintained, but distortions are introduced (displacement, for instance) or visualization parameters (such as color, line type, or hatching pattern) are modified. TP operations are designed mainly to use the assimilation capabilities of the human visual system to improve comprehension of the information content of the database. Therefore, TP operations are mainly concerned with the choice of more convenient graphic attributes for geo-fields and geo-objects, and also with map generalization operators that are specifically attached to the production of more readable output, such as `displacement`, `exaggeration`, `enhancement`, `refinement`, and `symbolization`. TP operations can be used, for instance, when the application requires showing cities as points, with a different symbol for each population range. Another example is the creation of a road map in which bridge symbols are intentionally enlarged, so as to reach a minimum viewing size.

Several TP operations can be executed using any commercial GIS product. Some features, such as the possibility for varying a symbol based on some attribute or on the viewing scale, are available only in the more advanced products. Beyond such basic features, TP operations require more complex map generalization operators, which are not widely available.

5. DISCUSSION OF AN EXAMPLE

One of the main interests of urban GIS applications regarding basic data is about analyzing the rate of expansion of the city through neighboring areas. This can be evaluated by following the creation of new streets and blocks, and the occupation of these blocks with new houses and buildings. Three independent applications that need to use data on the urban expansion are described next.

Taxing cadastre. This application works with blocks, which are divided into parcels, which in turn contain buildings. These parcels and buildings are the main target of the application, which needs to record every property in the city and its characteristics, in order to be able to calculate ownership taxes for each one. Figure 1a shows a cadastral plan sample, and Figure 1b shows a schema fragment that reflects this structure, according to the OMT-G model[3].



(a) (b)

Figure 1 - (a) Cadastral plan in 1:1000 scale and (b) application schema in OMT-G

1:25,000 scale mapping. This application's goal is to generate a city map in 1:25,000 scale, in which the street network is shown. Some reference points are required to guide the reader, including some of the most important buildings. Blocks must be presented using colors which reflect their occupation status: if the most of the parcels contain buildings, the block is shown in red; if most of the parcels are unoccupied, the block is

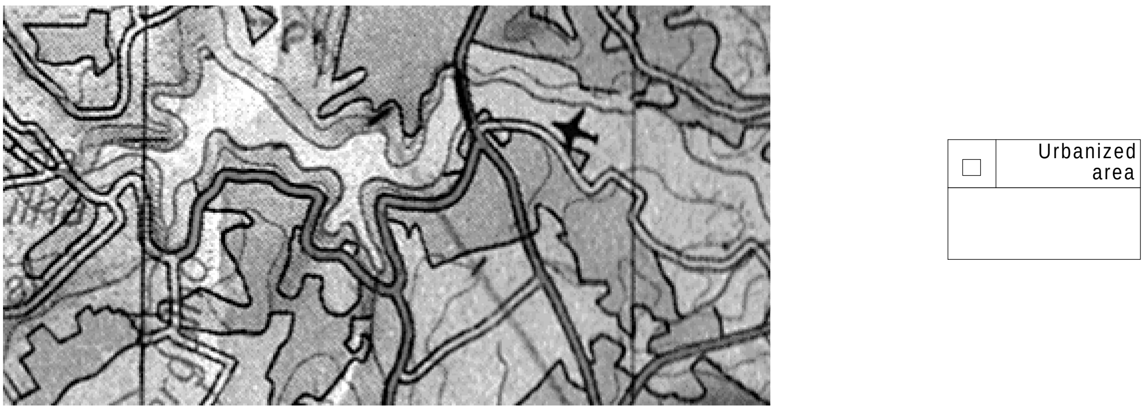
[3] OMT-G [Borg97] is an extension of the OMT model for geographic applications. OMT-G provides primitives for representing spatial data, supports spatial relationships and allows the specification of spatial integrity rules (topological, semantic and user integrity rules) through its spatial primitives and spatial relationship constructs.

shown in green. Figure 2a shows a sample of the results, and Figure 2b shows a fragment of this application’s schema.

(a) (b)

Figure 2 - (a) 1:25,000 scale map (Prodabel, 1992); (b) OMT-G application schema

Urbanized area. The limits of the urbanized area are drawn periodically, in order to evaluate the city’s most intensive expansion directions. The urbanized area consists on one or more polygons that encompass all the areas which can be characterized as urban, that is, in which there are blocks that have been defined by the street network and that are mostly built upon. Figure 3a shows an example of the final results, and Figure 3b shows a fragment of this application’s schema.



(a) (b)

Figure 3 - (a) Urbanized area in 1:250,000 map (IBGE, 1979) and (b) OMT-G schema fragment

It is clear that the `Block` class is present in all three schemas, either directly or indirectly. However, the variation defined in the taxing application is the most detailed of all, since in it the blocks are assembled from neighboring parcels. Also in the taxing application it is possible to determine the degree of occupation of each block, which is required in the other applications. Therefore, the blocks from the taxing cadastre should be used as a primary representation, from which 1:25,000 blocks and the urbanized area can be derived.

This option is shown in Figure 4, where the relationships through TR operations are indicated by continuous lines, and TA operations are indicated as dashed lines. The required operators are indicated above each line. Between the cadastral block and the 1:25,000 block, the representation’s nature is not changed, and it is only necessary to classify the blocks according to the degree of occupation and to define graphic attributes accordingly. Therefore, a TA operation suffices. Between the cadastral block and the urbanized area, it is necessary to select the blocks that are mostly occupied, and to amalgamate them whenever they are closer than a specified distance. The resulting polygons can be simplified, in order to take on a more natural look in smaller scales. Figure 4 also indicates the derivation of the `Main Building` class from the `Building` class that is included in the taxing application, through a selection operation. This TR operation assumes the existence of an “importance factor” that can be associated to each building and that can be used to guide the selection process.

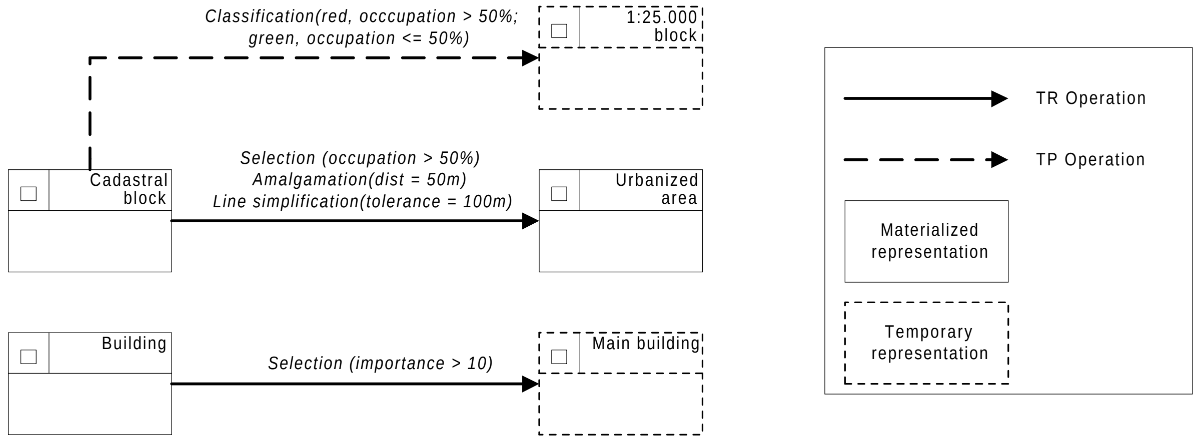


Figure 4 - Multiple representations implementation schema

6. CONCLUSIONS

Commercial GIS products are still a long way from the incorporation of reasonably adequate multiple representation features. Generally speaking, current products only include some basic generalization commands, batch tools, and visualization parameters, and cover just a few specific aspects, such as line simplification, symbol variation, and activation/deactivation of full layers based on the viewing scale. Counting on only these features, data collection procedures for the creation of geographic databases tend to focus on increasing the precision and detail level, creating representations that are to be used in all applications. This effectively limits the possibilities for data sharing among groups of users, since the detail and precision required by an application can be, in some other application's point of view, too low (thereby requiring new data collection efforts) or too high (excessively consuming computational resources).

From an implementation point of view, it is noteworthy that several of the operators described earlier are still at an experimental development phase, and have not been incorporated to commercial GIS products yet. This is specially true in the case of operators which, in the traditional cartographic process, depend strongly on the experience and intuition of an experienced cartographer, such as `displacement`, `exaggeration`, and `enhancement`. Despite that, there are several proposals for automation of these operators [BJF95, JBW95, Monm89, Monm91b].

This paper has shown that, based on a comprehensive set of operators, the implementation of multiple representations in GIS with minimum data redundancy is achievable. In the approach proposed, requests for updates and requests for synchronization are used to organize the propagation of changes, by means of transformation operations, from one representation to the others. Future efforts include studying how *user views* can be used to provide transparency concerning the use of secondary representations, and how *version control* can be useful as a tool to achieve updating and synchronization between representations. In addition, an implementation of the strategies and transformations presented here is planned, based on a commercial GIS package.

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