A MULTI-LEVEL APPROACH FOR 3D MODELING IN GEOGRAPHICAL INFORMATION SYSTEMS

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ABSTRACT:

The paper focuses on the problem of 3D data modeling within Geographical Information Systems (GIS) .
The approach presented here brings a solution to manage the diversity and the complexity of 3D data in a Geographical Information System. Our approach is not to use one unique model but 2 levels of modeling in order to describe the whole 3D scene.
The first level uses a 3D topology composed of nodes, edges, and faces. A volume is defined by its shell. This model insures object's consistency. Each object is composed of constructive structure, e.g. a house is a set of three constructive structure which are the roof, the wall and the floor. Each constructive structure is made of structural primitives. Several components of one object or several objects could share the same topological primitive.
The second level uses a network topology composed of nodes and arc. It could describe physical networks as well as abstract networks. Road network is an example of physical networks in which road sections are classed as arc and crossroad or buildings are classed as node. Abstract networks allow creating a link between objects, which are possibly physically independent ones from the other. Buildings sharing the same Intranet network could illustrate those "abstract networks". This level is very useful to support queries on classical networks or to materialize dependencies between objects. Computation of optimal path on graph is also related with this level of structuring.

RESUME :

Le propos de cet article est d'aborder les problèmes de modélisation des données 3D au sein d'un système d'information géographique (SIG).
Nous proposons ici une solution pour manipuler des données 3D complexes et diversifiées dans un système d'information géographique. Notre approche n'est pas d'utiliser un modèle unique de données pour décrire l'ensemble des informations d'une scène 3D, nous préférons une modélisation suivant 2 niveaux descriptifs.
Le premier niveau décrit une topologie 3D de composition s'appuyant sur les primitives nœud, arête, face et volume. Un volume est défini par son enveloppe externe. Ce modèle assure une cohérence 3D des objets. Chaque objet est composé de structures constitutives, une maison se décompose par exemple en toit, murs et sol. Chacune de ces structures constitutives se décompose elle même en primitives structurelle (nœud, arête, face, volume).
Le deuxième niveau de description s'appuie sur une topologie de réseau classique fondée sur des primitives de type arc et de type nœud. Ce niveau topologique peut décrire aussi bien des réseaux physiques réels que des réseaux abstraits. Le réseau routier est un réseau physique alors qu'un réseau intranet reliant différents bâtiments d'une entreprise sera qualifié d'abstrait. Ce niveau de modélisation est très utile pour répondre à des requêtes classiques sur réseaux (de type calcul d'itinéraire par exemple) et permet de matérialiser des dépendances entre objets.

1. INTRODUCTION

Huge communities of geographical and spatial data users as geologists, militaries, town planners or communication and utility managers are interested in a GIS being able to handle the third dimension. Lot of commercial solutions that can be found on the GIS market don't actually deal with a true 3D description of objects. Most of the time they are limited to a simple 3D extrusion of 2D outlines, which could be sufficient to provide a general idea of the 3D aspect of the scene. Unfortunately, because they use a unique z altitude for each couple of (x,y) coordinate, such models have important lacks in term of interaction and manipulation of 3D data

In order to fill this gap, several research teams have been involved in that issue and some interesting 3D topological models have therefore been developed for a few years. Among the different solutions proposed, we can find two main tendencies:
Some models, generally inspired by CAD products, are essentially based on geometrical description of the object. Simple topological characteristics could possibly be added.

Other models give more weight to topological aspects. Those models are often issued from GIS communities and they suggest a 3D extension of classical 2D topological models. They

introduce new topological primitives, new topological relationship and they manage to extend 2D classical model to the third dimension.
Each of those models owns some advantages as well as some disadvantages. Geometrical models offer faster time in computing but they are not able to bring efficient solutions to solve more specific problems like network analysis or data coherence issues.
In this paper we focus on the topological issues and we present a conceptual model fitted to the needs of our multidimensional geographical information system prototype.

2. TOPOLOGY IN GIS

2.1 Definitions

Topology is the mathematical study of objects properties which are preserved through deformations, twistings, and stretchings.

There is also a formal definition for a topology defined in terms of set operations. A set X along with a collection T of subsets of it is said to be a topology if the subsets in T obey the following properties:

1. The (trivial) subsets X and the empty set ϕ are in T.
2. Whenever sets A and B are in T, then so is $A \cap B$.
3. Whenever two or more sets are in T, then so is their union

Although this definition of topology is rigorous, it remains abstracted and quite distant from geomatic's people concern.

Moreover the term "topology" used in geomatics does not refer to the theories surrounding this definition, but is rather located within the framework of graph theory.

A graph is a binary relation in a set. If vertex are the elements of this set and edge the couples of vertex in relation, one can say that a graph is also the data of a couple (V, E) where V is the set of vertex and E the set of edge, formed by couples of vertex (Langlois,1994).

In other terms, a Graph G=(V,E) consists of a set of vertices, V, and a set of edges, E. Each edge e member of E is a pair, e=(u,v), where u and v are member of V.

But most of the time in geographic information the term topology tend to group together all the relations between objects as well as topological relations, order relations, or even directional relations.

2.2 Interest of 3D Topology

Whether it is through 2D GIS or 3D GIS, the use of topology is interesting on several points where it comes to complete the information conveyed by a purely geometrical description.

Owing to the fact that some geometrical calculations on inclusions, adjacencies, boundaries or network analysis are expensive in term of computing resources, the International Organization for Standardization (ISO) recommend to lean on the combinatorial structures of the topological complexes and to convert geometrical calculations in combinatorial algorithmics.

Insuring a better coherence of data is a second advantageous contribution of the topology. This coherence limits the errors of spatial analysis and avoids some display aberration connected to geometrical incoherencies.

(Zeitouni, 1995) explains that the first interest of topology lies in its spatial semantic arguing that the way objects are laying out in a given space constitutes a natural model more easily understandable by users.

Sometimes topology is presented as being able to limit the size of data bases. It is true that topology allows avoiding redundancies led by duplicated geometrical primitives, but a detailed topological description can also be very voluminous.

Unfortunately topological information storage is not exempt from every constraints. Beyond the possible problems of data volumes to be stored, the major inconvenience of a topological description is linked to integration and data update issues. The availability of 3D data is a real problem today from which it is difficult to cast off the framework of a three-dimensional geographic information system.

2.3 3D Topological Models

Although previous published works seem to assert that a boundary description suits well with 3D topological problems, two lineages of models distinguish themselves:

- A first classic approach decomposes the topological space in 4 fundamental types of primitive which are node, edge, face and volume.
- A second approach inspired by combinatorial topological cards (DCEL or winged-edge structure) introduces the concept of primitive associating edge with face.

We shall present there only the main lines of these models, knowing that they can be variously declined according to the objectives to reach.

2.3.1 Classical Modeling

This rather simple approach of topology is adopted by numerous authors of whom Martien Molenaar (Molenaar, 1990). It consists in associating the four basic primitives that are node, edge, faces and volumes with construction and inclusion relations. The basic skeleton of this conceptual model is summarized in Figure 1.

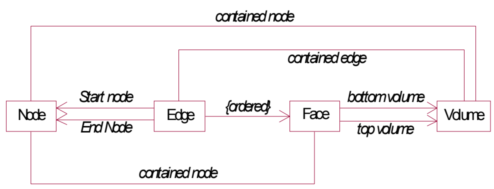

Figure 1 :Basic skeleton of classical topological models

Numerous variations were proposed from this skeleton.

(Molenaar, 1990) introduces the notion of directed arc between edge and nodes. However the model is limited to the case of planar faces, implying that topology depends on geometry.

ISO organization take its inspiration with this model but recommends a total independence between the topological model and the geometrical model.

A software package developed under the DARPA image understanding program defines an interesting topological concept which is the k-chain, where k is the number of dimension of the element linked by the chain. An 0-chain is a sequence of points, a 1-chain is a sequence of connected edge, a 2-chain is a sequence of connected face.

Kevin Trott resumes partially this concept of k-chain in his proposition of 3D extension for VPF format. He names "ring" such sequence of edge and "shell" such sequence of face (Trott, 1999). Contrary to the software Target Jr the notion of volume is present in Trott's model (Target Jr describes only boundaries of volume).

2.3.2 3D Extensions of Topological Map

With regard to a simple model dealing with only composition relations, the model of 2D topological map brings the notion of edge cycles around nodes. This notion of edge cycles could be found in numerous 2D models as DCEL structure (David, 1991) and winged-edge data structure.

In the extension of this concept to the third dimension Kevin Shaw (Shaw, 1998) and Arnaud De La Losa (De La Losa, 1999) suggest articulating the 3D objects description around edge by introducing a new primitive named EFace in (Shaw, 1998) and (Arc, Face) couple in (De La Losa, 1999).

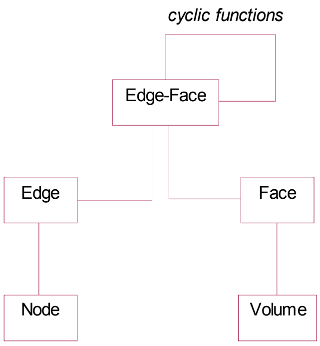

Figure 2 : 3D Topological map extension model

Figure 2 clearly shows that face primitive and edge primitive are not directly connected any more. Connections are made by operators or functions applied to this Edge-Face new primitive.

The introduction of this new primitive is the keystone of the 2 models, but they differ from one another in many aspects examined in 2.3.1.

2.3.3 Other Topological Models

Both approaches we have described represent main trend in topological modeling. However some more marginal attempts, that are not without interest, should be mentioned.

2.3.3.1 The Face Adjacency Hypergraph

(Floriani, 1988) considers as topological information only the relations of adjacency. Furthermore the face adjacency hypergraph makes a distinction according to the dimension of the adjacency (adjacency according to a point or according to an edge) (Figure 3).

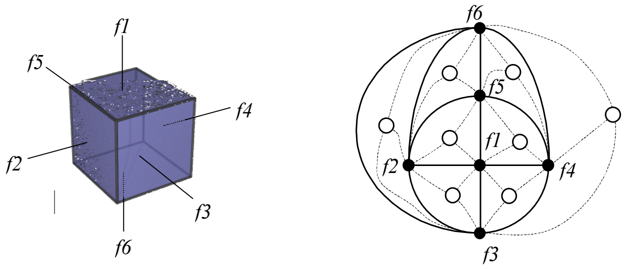

Figure 3 : Face adjacency hypergraph

2.3.3.2 Horizontal and Vertical Specification

(Zeitouni, 1995) introduces the notion of horizontality and verticality to take into account the specificity of the geographic data. The MNT is connected with 3D objects by the relation "is posed on".

3. A 3D GIS PROPOSITION

Within the framework of a preliminary study on modeling and exploitation of multidimensional geographic database, we have thought about a conceptual data model which is more convenient for our GIS objectives, needs and constraints.

3.1 Our Objectives

In order to determine the adequate conceptual data model, it is important to define well the objectives to achieve.

One of our main objectives is to be able to model data of various dimensions, that is to say punctual, linear, planar and voluminous data. Furthermore, the selected model should be able to describe any 3D object shapes.

We do not want to limit ourselves to the 2,5D as it is often the case in commercial 3D GIS extensions. It should be possible to model objects with one or more z value for a given couple of (x, y) coordinate. Many objects need this specification to be modeled, e.g. trees, bridge, archway, or simple buildings with door and windows modeled.

The algorithms of intervisibility, optimal path or network analysis should be able to be applied without difficulties on our data.

The prototype realized from this model should be able to perform algorithmic computation in "real time". The general ergonomics should not suffer from slow computations.

Data should be interactively editable without loosing their coherencies.

It should be possible to import 3D data without any trouble.

3.2 Needs, Constraints and Technical Choices

In the universe we try to describe, edge are very unusually shared by more than two faces. So cyclic relation, i.e. the notion of couple (edge - face), does not fit with our needs. Thus we decide to adopt a classical boundary modeling approach.

We are not interested by the insides of building, so relations of inclusions within volumes do not appear to us as a priority. We do not store these relations but they could be found by geometric computation.

Spatial partitioning is not useful in our scenario; on the contrary it could give rise to some problems in few spatial situations. That's why we have chosen to model volumes by their external shelves instead of modeling them in the strict sense of a volume entity.

Modeling complex surfaces, like NURB, is not an immediate necessity and is even problematic in term of performance for intervisibility computation. Therefore, our faces will be planar (and our edge rectilinear).

We describe 3D objects by their faces but edges have no utility within the framework of our GIS. We prefer to describe each face by an ordered list of nodes instead of an ordered succession of edges. We know that this is a limitation for the creation of faces with holes, but these last ones can be easily decomposed into 2 hemi-faces.

In order to keep inside and outside information, faces are modeled with their orientation. Edges are also directed.

A geographic object should be able to be associated with one or more topological description. On one hand it should be possible to describe its 3D intrinsic structure (a building will be described by wall, roofs and grounds which composes it) and on the other hand it should be possible to associated an object to one or more network topological primitives (e.g. a building can be associated to a node in a road network).

An object should be able to be decomposed into a set of elementary structures. A building is decomposed into 3 elementary structures: walls, roof and ground. These three elementary structures are themselves constituted of topological primitives which are nodes, edges, faces and volumes.

Network modeling is very different from structure object modeling. According to this important point, we have separated network modeling and structural object modeling in two different data conceptual model.

3.3 Our Conceptual Data Model

3.3.1 General Presentation

The 3D model retained for our 3D GIS prototype takes into account various points presented in previous paragraphs.

The UML Diagram of the Figure 5 summarizes our conceptual data model. Some of the relations between classes are not explicitly named in order to avoid displaying an unreadable figure.

On one hand geographic data is described in its 3D structure by a model based essentially on composition relations and on the other hand the same geographic data could be associated with a network in a network primitive form.

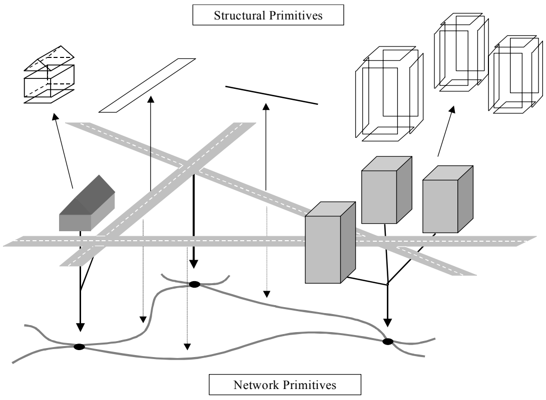

Figure 4 : Two modeling levels

On figure 4 you can notice that the structure of buildings consists of a set of face, the structure of the main roads consists of faces too but the structure of minor roads consists of edges.

Each of these objects or group of objects can be associated with network primitives. On Figure 4 we see that the house is associated to a node, like the building's block which is associated to a unique node, while roads are associated to arcs. Let us note that the crossroads on the top of the figure without any 3D description is also associated to a node.

3.3.2 3D Structural Object Description

The model used for this description is quite simple. Each object is composed into an aggregate of constitutive structures. A building possess 3 main structures which are roof, walls and ground. Each of these constitutive structures is itself decomposed into structural primitives of different dimensions. The basic primitive is the vertex, geometry is supported by vertices, i.e. each vertex is associated to a coordinate triplet. Edges and faces are described by their vertices and possess an orientation. Volumes are described by the faces which surround them. The notion of hole or cavity is not directly expressed on this model, they should be described by joining several primitives. By composition of these primitives any shape can be described whatever its spatial dimension is.
This model satisfies and guaranteed our constraints of coherence on 3D objects.

Note that there is not direct relations between faces and edges which compose their boundaries. The advantage of this conceptual choice is to limit the number of topological relations and thus to limit the complexity of the model. On the other hand our modeling is not the best one for a step by step navigation among topological primitives.

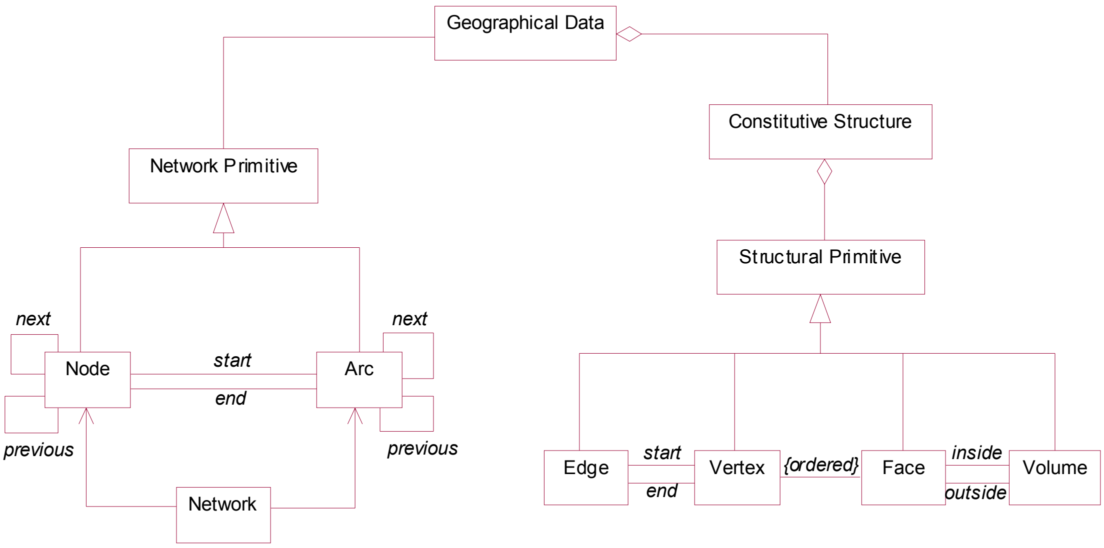

Figure 5 : UML diagram of the conceptual model

3.3.3 Network Topology

Network topology does not lean on the same primitives that structural topology. Primitives used here are those that one finds classically in 2D GIS modeling, i.e. node and arc. Our network modeling is a multi-value planar topological graph. No geometry is associated to these primitives, we do not propose graphic representation of these graphs. There is a full independence between structural topology previously seen and network topology.

A node is a primitive connected to incoming arcs and outgoing arcs. A node is linked to next and previous nodes according to the orientation of arcs (incoming and outgoing).

An arc is a directed primitive. It is connected with its start node and its end node. It is also connected with preceding arcs and following arcs.

The objective of this modeling is to be able to handle as well as possible all network analysis and queries. So it is well adapted to map out a route on a road network, to simulate pollution on a hydrological network or to look for electrical sub-networks.

4. CONCLUSION

The first characteristic of the data model which we have just presented is to completely dissociate 3D object modeling and interconnections between those objects. Our structural model of objects is certainly not the most complete, but it is perfectly advisable for our needs because it allows a minimal but sufficient topological description and its simplicity makes it rather sober and light to avoid being limited by long data access delay. Furthermore, more a data model is simple, easier are import, update and maintenance operations.
At last, networks are classically modeled by a multi-value planar graph. This structure has demonstrated its efficiency in network analysis for a long time.

REFERENCE

David, B., 1991. Modélisation, représentation et gestion de l'information géographique, une approche en relationnel étendu. Thesis, University of Paris VI.

De La Losa, A., Cervelle, B., 1999. 3D Topological Modeling and Visualisation for 3D GIS. Computers & Graphics, 23(4), pp. 469-478.

Floriani, L., Falcidieno, B., 1988. A Hierarchical Boundary Model for Solid Object RepresentationACM Transactions on Graphics, 7(1), pp. 42-60.

Langlois, P., 1994. Formalisation des concepts topologiques en géomatique. Revue internationale de géomatique, Vol. 4, pp 181-205.

Molenaar, M., 1990. A Formal Data Structure for three dimensional vector maps. In: 4th international symposium on spatial data handling, Zurich, Switzerland, Vol. 2, pp. 830-843.

Shaw, K., Abdelguerfi, M., and Ladner, R., 1998. VPF+: A VPF Extension Providing 3D Modeling and 3D Topology. In: Image '98 Conference, Scottsdale, Arizona, pp. KB1-KB8.

Trott, K. and Greasley, I., 1999. A 3D spatial data model for terrain reasoning. In: 4th International Conference on GeoComputation, Mary Washington College in Fredericksburg, VA-USA.

Zeitouni, K. and De Cambray, B., 1995. Topological Modelling for 3D GIS. In: 4th International Conference on Computer in Urban Planing and Urban Managment, Melbourne, Australia.