A Preliminary Review on 3-dimensional City Model

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ABSTRACT

Modern city system has increasingly become more complex in spatial context, with impressive 3-dimensional features shown on its skyline, such as high-rise buildings, road flyovers, tunnels and underground infrastructure. Focusing on such complex system, Urban GIS, traditionally only concerns about 2-dimensional spatial relationships, has now pushed to analyse, model and manage the 3-dimensional features of the modern urban system. Although numerous works have been reported on the development and applications of 3D city models, which form the foundation of 3D Urban GIS, they mostly serve for visualisation and presentation purposes. Such 3D data models are not capable of dealing with problems of spatial queries that rely on topological relationships, nor can they provide adequate spatial operators for 3-dimensional spatial analysis.

This paper outlines the findings of review on 3D City Model (3DCM). Through the review of existing works on the 3DCM, one may argue that almost no existing model that is optimised for modelling today's 3D cities, although they do serve for specific design purposes well (e.g. visualisation and urban landscape planning). To adequately handle management problems of modern 3D cities, an alternative approach is suggested, by integrating the concepts and techniques of Object-Oriented (OO) GIS with those of Computer Aided Design (CAD). This research pays particular attention on defining and formulating topological relationships between complex spatial objects and corresponding fundamental spatial operators. It is believed that the models developed in this study will form a solid foundation on which applicable 3D urban GIS can be built.

Keywords: Spatial data model, urban GIS, 3D city model, object-oriented GIS

1. Introduction

With economic and technologic growths, modern city has increasingly become more spatially complex. Many urban objects are three dimensional, such as high-rise buildings, complex road bridges, subways and underground infrastructure. Modern city now gradually extends in the third dimension both upwardly and downwardly (Zlatanova and Gruber 1999; Raper 2000). The term of 3D city emphasises that besides the traditional 2D space, the third dimension now needs more attention, as addition of the third dimension will greatly complicate the representation of spatial objects and relationships. For example, suppose that an overpass and a street subway are vertically disjointed, how can we spatially describe this situation? Answering this question is beyond the ability of traditional 2D method (Harvey and Shaw 2001; Raper 2000), because information on the third dimension is required for the representation.

The research of 3-dimensional City Model (3DCM) is a multi-disciplinary study field of urban GIS, Computer Aided Design (CAD) and presentation, and spatial modelling. Though having long been in operation, existing urban GIS systems are mostly based on 2D spatial data models, which fall short of the increasing 3D urban representation needs. In the field of CAD, 3D data models have been extensively studied and developed, some of which are adopted and spatially adapted for geo-referenced applications to describe 3D spatial objects with nodes, edges, faces and bodies (Molenaar 1990, Pigot 1995, Cambray *et al*., 1995, Zlatanova 2000a). However, these models tend to serve general application purposes, thus not specialised for city applications that present spatial characteristics requiring special consideration. In addition, existing 3D spatial data models pay little attention to topological relationships, which is an indispensable content of urban GIS (Zlatanova 2000b). Another strong stream of research on 3DCM originates from the new study field - digital city (Haala *et al.* 1998**,** Brenner 2000**,** Gruber 1998, Ameri and Fritsch 1999). These works aim to automatically extract and visualize 3D city, and provide online services as a social information infrastructure. In digital city, topological relationships between individual objects are less interested because a city or urban community is considered as a whole. Digital city can help to construct spatial database of 3D city, but it cannot provide functions of 3D GIS, which should be capable of describing 3D spatial objects and topological relationships.

Although efforts have been made on the 3DCM research, it seems that the model optimised for 3D city applications is rare. To construct an optimal model, spatial characteristics of modern cities should be taken into account and topological relationships should be efficiently represented and detected. This requires ability to construct a city representation with primary geometric elements and to support corresponding fundamental spatial operators.

This paper presents a review of current research work on 3DCM. Based on the findings, an alternative approach is suggested, by integrating the concepts and techniques of object-oriented method and Computer Aided Design (CAD). The approach abstracts urban spatial entities as objects, which are represented with primary 3D elements (node, edge, face and body) and their combinations. Based on the concept of object, the method supports the multiple representation of Level of Details (LOD). More importantly, topological relationships between objects are described so that 3D topological operations can be implemented.

2. Spatial View on Modern City

As a place greatly influenced by human, city has its particular spatial characteristics, which are different from other situations and should be considered in constructing 3DCM. In the section, some of the urban spatial characteristics are outlined.

2.1 Three dimension space

As discussed before, one most important spatial characteristic of modern city is the 3D space. Modern city now is gradually extending in the third dimension both upwardly and downwardly (Chen *et al*, 2000). The term of 3D city emphasizes the 3rd dimension besides the traditional 2D space, since the addition of the 3rd dimension has greatly complicated the representation of spatial objects and relationships. With increasing needs for urban planning, transportation, utilities, tourism and management, 3D city spatial data model has gained more attention, in which height related characteristics (e.g. *overpass*) and thus 3D topological relationships (e.g. crossing *over* or *below*) are of significant importance.

2.2 Regularity and combination

Most urban objects are man-made, such as buildings, streets, road-bridges, pipelines and gardens. Therefore, in a sense modern city can be thought of an aggregation of man-made objects. Many urban features (such as the types, appearances and relations of objects, the city structures and organizations) are subject to human requirements. Compared with natural objects, the urban man-made objects are relatively regular in the terms of shape, distribution, and structure. This makes it possible for data model to abstract and represent urban spatial objects with some primary geometric elements.

In addition, some complex urban objects can be considered as the combination of relatively simple objects. For example, street segments always connect together to form street network and the addition of other related objects (such as bus-stops, traffic lights, parks, *etc.*) further produces urban road transport system. Therefore, the modern city can be modelled as an aggregation of regular man-made objects, which can be spatially described with primary geometric elements (i.e. points, lines, faces and bodies) and their combinations.

2.3 Urban networks

A city is mainly composed of buildings and streets. Street networks form the urban spatial framework. Buildings often have connections to streets. Moreover, street networks also "string" many other urban objects above ground, namely, bus-stops, subway exits, car parks, overpasses, road bridges and so on. For underground infrastructure, a typical example is pipeline networks, which "string", for example, man-holes, valves, hydrants, transformers, switches and substations. Such objects as man-holes and subway exits penetrate ground surface and connect above/under ground spaces. These networks facilitate the urban flows of material, energy and passenger in city. Therefore, in modern city spatial networks become so important that they are indispensable in many urban analyses.

2.4 Spatial relationship

The extension of the third dimension makes spatial relationships more complex. With height information, the 3D spatial relations can be described. As the example showed in Figure 1a, buildings are connected by an overpass with a street running between them. Here, two 3D spatial relationships need to be considered, i.e., the buildings' connection by the overpass and the vertically disjointed relation of the overpass and street. In 2D space, these objects and relationships would be abstracted as Figure 1b, where the overpass is not distinguished because there is no clear difference between a lane and an overpass in 2D representation. In 3D space as represented in Figure 1c, the two relations are clearly represented. Note that spatial relationship discussed in the paper is restricted to topological relation.

Some of the above urban spatial characteristics (such as network, spatial relationship) have been addressed by traditional 2D data model using attributes. However, the space extension has brought different and more complex situations, raising further considerations in 3D space.

3. Urban GIS Applications

City is one of most important fields of GIS application, including urban transportation, utilities management, environment modelling, urban planning, land use and tourism. Most of these applications are based on 2D data models, which fall short of the increasing requirements of 3D urban representation. To represent urban spatial objects and relations, many applications require a 3D spatial data model instead of traditional 2D models.

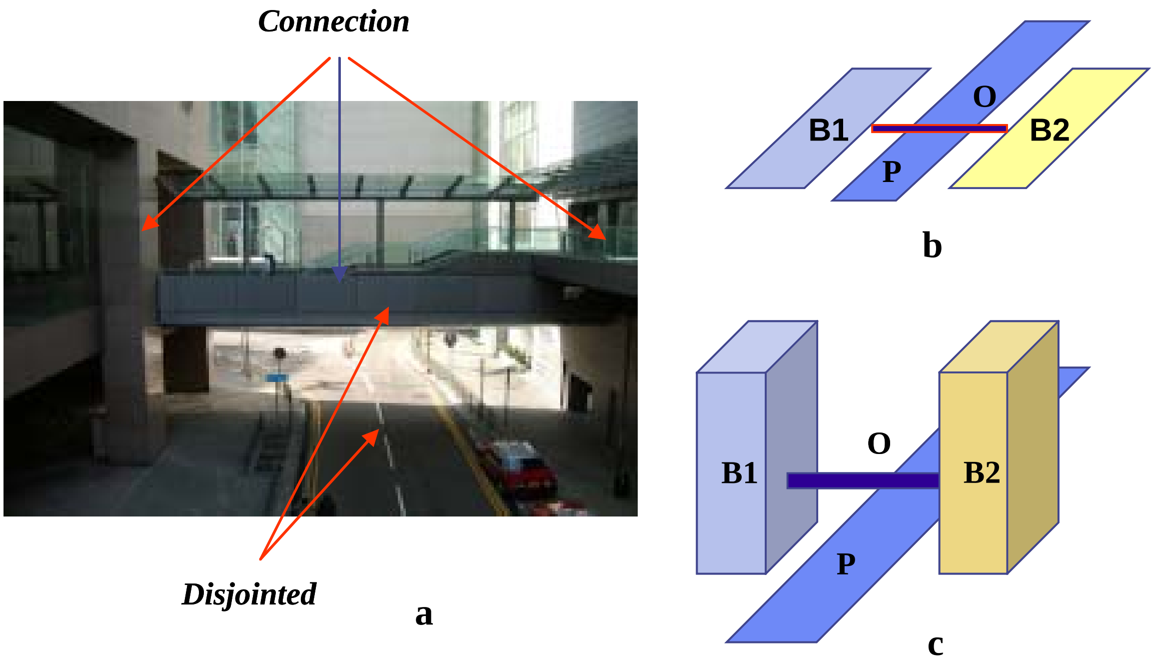

Figure 1. 3D spatial relationship (Hong Kong Central).

3.1 Transportation

Transportation is a growing field of GIS application, known as GIS-T (Shaw 1993). GIS application covers much of the broad scope of transportation, including infrastructure planning, design and management, traffic analysis and control and environmental impact assessment. Intelligent transportation system is a particularly ambition in integrating GIS and communication technologies to a wide variety of transportation services (Harvey and Shaw 2001).

Compared with other GIS applications, GIS-T has a central study subject, namely the transport network. The network is typically described with node-arc model, which is based on planar graph. However, the node-arc model cannot represent some real features, and many existing GIS have limited and clumsy representation of transportation features such as an underpass/overpass and 3D topological relationships (Harvey and Shaw 2001; Spear and Laksmanan 1998). A partial resolution of the planar network problem is to relax enforcement of planar topological consistency. However, this can lead to data integrity problem. Another strategy is to use the expanded intersection representation and restrict turns at underpass/overpass. Harvey and Shaw (2001) contended that a 3D data models is required and a more radical approach to navigable data models for ITS is to abandon the node-arc model entirely. In addition, separation of transportation features into different GIS layers results in a lack of topological information between entities (Shaw, 1993).

3.2 Utilities management

Another important GIS application area is the urban utilities management. Quite a percentage of the urban flows of material, energy and information are completed by urban utility facilities. According to the inherent utility type characteristics, Mahoney (1991) distinguished two general groups, namely, pipe utilities (gas, water, sewage, *etc*) and cable utilities (electricity, telecom and cable television, *etc*). Utilities require GIS to record the transmission and distribution networks, which enable them to forecast demand, plan expansion, and locate plant for maintenance and the provision of service connections. From the spatial distribution point of view, the classification that differentiates underground and ground networks has implications for operational GIS (Mahoney 1991).

Most utilities are currently represented in two dimensions. However, as altitude is related to pressure in certain utility systems, sometimes height information is required. Traditionally, this is achieved by holding the height as an attribute of the planner network. Though this can reduce the map cost and save the overhead of holding 3D topography, it fails to 3 dimensionally analyse the topological relationships of networks with other urban objects, such as relations with transport routes and buildings.

3.3 Urban planning and modelling

Urban design is the process of giving physical design direction to urban growth, conservation and change. Common data is managed by GIS and is used to coordinate activities and reduce duplication of efforts. GIS can deliver very fine scale data, which has profound implication for urban design. Shiffer (1992) developed urban design from a GIS perspective by building an array of tools for sketch planning, visualisation, and local urban analysis which incorporate spatial analytic functionality with various types of multimedia and visualisation. Since modern city is more 3 dimensional, urban planning and modelling should be undertaken in the 3D space. For example, if we want to know the landscape change after constructing a new building, a 3DCM is needed to model the changes for planning decision.

In addition, there are other urban GIS applications, most of which are also based on 2D data model. As discussed before, in the term of spatial characteristics modern city becomes more spatially complex. Though not all of the urban applications now must require the 3D spatial representation, many do require, such as transportation, utilities and urban planning. 3DCM has now been considered as one major direction of the spatial information research.

4. 3D in Digital City and Virtual Reality

One strong stream of efforts focuses on digital city, which regards city as a social information infrastructure for urban life, including shopping, business, transportation, education and welfare. Many projects upon digital city are undertaken, such as US digital cities by America Online, Digital City Amsterdam, Virtual Helsinki, Digital Kyoto (Ishida *et al*, 1999). Rapid growth of computer technology (*esp*. those of web, computer graphics) provides a strong impetus to digital city research. Research on digital city has been reported (Haala *et al.* 1998**,** Brenner 2000**,** Gruber 1998, Ameri and Fritsch 1999). In the section, efforts on digital city research will be briefly reviewed to analyse the strengths and weaknesses of digital city for 3D city representation.

Many researchers (Haala *et al.* 1998**,** Brenner 2000**,** Gruber 1998, Ameri and Fritsch 1999) discussed methods that automatically extract urban objects (*esp*. buildings) with imagery, ground plans and other data sources. Brenner (2000) surveyed the reconstruction of building models from laser scanning Digital Surface Model (DSM) and digital ground plans. He developed the ATOP approach, a framework for the fully automatic generation of city models. Ishida *et al* (1999) undertook a project to develop a digital city for Kyoto based on the technologies of GIS, 3D, animation, agents and mobile computing. They proposed the concept of digital cities as a social information infrastructure for urban life, with 3 layers architecture (*information*, *interface* and *interaction layers*). These efforts focus on the algorithms and data sources for practically efficient reconstruction, visualisation and navigation of city, while specific individual objects and topological relationships are almost not considered. One exception is the self-developed data structure (V3D) put forward by Wang and Gruen (1998), which is a boundary representation (Brep) model. Based on the concept, they developed a system to facilitate city reconstruction. However, their attention also was focused on the generation of 3D city.

In summary, digital city is efficient at the generation and visualisation of city， and provision of online services. Due to the lack of ability to deal with individual urban objects and spatial relations, digital city is not able to provide GIS spatial operations, *esp*. spatial analyses. However, digital city can offer photo-realistic representation and efficient data generation. Digital city and 3D GIS view city at different spatial scales, so that they can be complementary. 3D GIS can be a part of digital city, and provide spatial location related functions in the social information infrastructure in digital city.

One field closely related with digital city, is Virtual Reality (VR) technology. The developments of VR present a more comprehensive way of interacting with spatial data. To embed 3D GIS within VR environment, Verbree *et al* (1999) proposed a multi-view approach based on three types of visualisation: plan view visualising the data as a conventional map, model view providing a 3D bird-eye’s view on a partly symbolic and simplified 3D representation, world view giving a full immersive and photo-realistic 3D display. This concept of multi-view summarises the relations between the traditional 2D map, 3D GIS, digital city and VR. The details are increasing with scales. Each view provides a specific understanding of real world, with different abstraction.

Zlatanova and Bandrova (1998) reported that VR systems result in insufficient means for GIS analysis because most of them are not designed to deal with semantic information and spatial analysis is hardly in focus. Spatial analysis that is based on topological relationships is often considered the most important task in a geo-information application. To 3DCM, two issues can be raised, namely, how to represent urban objects and their topological relationships and what kind of techniques to apply for detecting these relationships. Maintaining information about neighbouring objects (i.e. topology) is the most widely used approach for representing topological relationships (Zlatanova and Bandrova, 1998). In this respect, some data structures encapsulating different spatial objects have been reported (Molenaar 1992, Cambray 1993**,** Guo 1998, Zlatanova 2000a, Pfund 2001), and the models (independent of spatial data model) to represent and detect topological relationships are also available (Egenhofer 1989, 1994, Egenhofer and Franzosa 1991, Guo 1998, Zlatanova, 2000a). However, the discussion of describing and detecting topological relationships from the point of 3D data model is rarely reported, if any (Guo, 1998).

5. 3D Data Model and 3DCM

3D data model is called solid model in computer graphics (CG), where some models are widely used in CAD. GIS researchers have extended these 3D CG models to represent geo-referenced objects (Molenaar 1990, Pigot 1995, Zlatanova 2000a). Researchers of 3D CG are interested in algorithms and structures for processing large 3D data in real time (Lindstrom *et al.* 1996), photo-realistic visualisation (Gruber 1998) and extended VR tools for interaction with model. However, the corresponding work in GIS community is directed to more fundamental levels, i.e. the development of models for maintaining 3D topology as the basis of 3D GIS (Molenaar 1990, Pigot 1995, Pilouk 1996). Zlatanova (2000a) commented that the existing research on 3D models is quite extensive and rudimentary but fragmented, and she thought that only some of them are intended or appropriated for 3D GIS or representing spatial relationships by topology. With respect to 3D data model for GIS, it's still an area open to discuss. Special investigations on 3D urban mode are even fewer (Zlatanova, 2000a).

In the section, three typical 3D spatial data models will be examined on whether they are appropriate to construct 3DCM.

5.1 3D data model

Raper (2000) summarized the representation schemes for solid modelling by three groups: constructive, boundary and space decomposition models. These methods have been extended and applied in GIS. Guo (1998) offered a similar classification of 3D geo-representation models including four groups: tessellating, vector, hybrid and analytical models.

Constructive solid models represent a point-set as a combination of primitive point-sets. Each primitive is represented as an instance of a primitive type and combination operations (i.e. union, intersection, difference, complement). Some researchers have used the methods to represent buildings (Li 1994). However, these models cannot represent some complex morphology among geo-phenomena due to the inherent limitations of the underlying parametric approach (Raper, 2000).

Boundary representation (Brep) models decompose phenomenon into bodies, faces, edges and vertices (Raper, 2000). This requires a construction process capable of generating valid Brep. Unlike wireframe method, which represents objects with lines, arcs and points but without plane and face and thus cannot well describe topological relation, Brep method describes spatial objects by their boundaries (points, edges and faces). Bodies, faces, arcs and nodes are linked together through corresponding boundary relations, in which topological relationship is recorded implicitly or explicitly. In addition, the boundary relation is useful to keep topological consistency through Euler formula. But Brep cannot describe the interior variation of body or plane objects. Raper (2000) pointed out that despite the complex data structure and the data update difficulties, Brep method provides a total topological decomposition and would be the favourite for 3D city model. Pfund (2001) agreed that the Brep method is appropriate for urban GIS and he developed a prototype of 3D Vector-GIS. The 3D Formal Data Structure (3D FDS) put forward by Molenaar (1990, 1992) is widely thought of the classic 3D spatial Brep data model.

Space decomposition models represent a point-set as the union of disjointed regions of the space called cells. Approaches based on voxels are known as spatial occupancy enumeration (SOE). To reduce the huge data volume, SOE is improved with voxel indexing and compression (Octree), run-length encoding or 3D discrete topology. One widely used derivative method, Tetrahedral Networks (TEN), is appropriate for complicate spatial phenomena without boundaries (such as mine, geological body), but weak at linear and planar object representing. Generally, these methods are raster-based and are efficient in representing surface and body interior, such as geology, mineral, ocean and air. But, they cannot describe individual objects and the topological relationships, so that they are not suitable for most urban applications and 3DCM.

5.2 3D Spatial data models

In most urban applications, operations on individual spatial objects and relationships are necessary and dominant. For example, where is the *bus-stop* NEAR the *university*? Which one (if any) can LEAD TO the *railway station* more conveniently? In the two queries, urban objects (e.g. *bus stop*, *university*, *station*) are considered individually, so do the spatial relationships (e.g. NEAR, LEAD TO) between spatial objects. Spatial data organised in form of vector can efficiently meet these needs in above example. Sections below review several vector-based data models for 3D GIS by researchers from different fields with different point of views, which would offer valuable concepts and methodologies for 3DCM.

3D Formal Data Structure

The 3D Formal Data Structure (3D FDS, Molenaar 1990) is defined by a conceptual model with 12 conventions for partitioning physical objects. The model consists of three fundamental levels, namely, feature (related to a thematic class), four elementary objects (point, line, surface and body) and four primitives (node, arc, face and edge). Arcs are straight lines and faces are planar. Arcs and faces cannot intersect, but arcs and nodes are permitted to exist inside faces or bodies. Body has one outer surface and can have several non-nested bodies or holes. The 3D FDS model was intensively discussed from different points of view, e.g. analysis by Pilouk (1996), topology by Bric *et al*. (1993), implementation by Rikkers *et al.* (1993), object-orientation by Tempfli and Pilouk (1994), visualisation and navigation by Zlatanova (2000a). Detailed review on 3D FDS can be found in the work of Zlatanova (2000a). 3D FDS is based on the fundamental of single valued map, i.e. node, arc, face or edge can appear in the description of only one geometric object of same dimension (Molenaar, 1998). The idea is to partition the space into non-overlapping objects and thus ensuring 1:1 relationships between the primitives and the objects of same dimension, e.g. surface and face.

With respect to the model, some issues are still open to discuss, e.g. formalism of definition for geo-objects, description and determination of spatial relationships. Guo (1998) thought that 3D FDS is without strict definition and inappropriate to the objects with irregular and complex boundaries.

V3D of CC-Modeller

To construct an approach for 3D city generation, Wang and Gruen (1998) developed a semi-automated topology generator (CyberCity Modeller) for 3D objects, in which a hybrid data structure (V3D) was proposed. It not only models 3D objects, but also combines raster images and attribute information for each object. The terrain objects are grouped into four different geometric object types: point, line, surface and body. Two data sets are attached to each object type: thematic data and geometric data. The image data can be attached to the objects of surface, body and DTM.

The distinct feature of V3D model is that the geometric information is combined with attribute information (including DTM and image). The framework can facilitate the analyses involving both spatial and non-spatial information. However, the V3D model aimed at the automatic reconstruction of 3D city and less attention has been attached to the spatial analysis and other functions.

Data Model of GeoToolKit

Balovnev *et al* (1997) developed an objected-oriented geo-database kernel system (GeoToolKit) for the development of 3D/4D applications, *esp*. those with large amounts of spatial data. GeoToolKit deals primarily with two basic notions: a *SpatialObject* and a *Space* (a collection of spatial objects). A spatial object is defined as a point set in the 3D Euclidean space. A discrete object is modelled as a specialisation of the abstract spatial object class. Complexes are approximated and represented as homogeneous collections of simplexes.

Object-oriented method is key nature of GeoToolKit, which helps to construct the object hierarchy. The *Group* gathers spatial objects of different types into a collection and then is treated as a single object. In this way, complex objects can be easily operated. However, this model is the development basis for general application and is not specialised for 3D city.

As the Table 1 shows, the three models are all vector and boundary based, which partition spatial objects as points, lines, faces and bodies (or similar geometric primitives). The 3D FDS extensively explored the representation of spatial objects. The semantic and geometric information was efficiently organized by V3D structure while the data model of GeoToolKit demonstrated the potential of object-oriented concept in 3D database. These models have been experimented in applications, which proved that they could be adopted and adapted for 3D city modelling (Molenaar 1990, Zlatanova 2000a, Wang and Gruen 1998, Balovnev *et al.* 1999).

Table 1. Comparison of the three 3D data model of GIS.

	3D FDS	**V3D**	**GeoToolKit**
Characteristics	Brep, linear and planar constraints, 4 geometric elements, weakness on topological relationship		
Authors	Molenaar M, *ITC, Netherlands*	Armin Gruen, Xinghua Wang, *Swiss Federal Institute of Technology*	Balovnev O, Breunig M, Cremers A B, Serge Shumilov, *Univ. of Bonn*
Aiming at	GIS systems	Digital city	Data structure of software
Geometric primitives	Node, arc, face, edge	Point, line, surface, body	Point, line segment, triangle, tetrahedron
Geometric objects	Point, line, surface, body	Point, edge, facet, entity	Point, line, plane, box
Topological relationship	None	A little	None
Features	Single valued map	DTM, image, entity	OO, Space, Group
Applicability to 3DCM	Basically acceptable	Basically acceptable	Basically acceptable

These 3D spatial data models provide a firm base for 3DCM design. But these models have some weaknesses as follows.

1. These models are developed from the extension of 3D data models in computer graphics, and they are general 3D spatial data model. With respect to urban applications, they are not optimal because 3D city has its own spatial characteristics as discussed before.

2. Topological relationships have not adequately addressed in these models so that they are weak at topology related spatial operations, which is indispensable in urban GIS.

3. There may be such situation that the scale is required to vary so that a spatial object has different representation status. For example, at a given scale, a street is described as a series of planes while it would be a polyline at a coarse scale. Object-oriented and LOD methods should therefore be adopted to satisfy the multi-representation. The above models have not considered the situation of multi-representation.

6. Discussion and Concluding Remarks

6.1 Summary of related researches

Driven by increasing demand for 3D city representation, efforts have been made on 3DCM in several fields, including digital city, computer graphics and GIS. Research in these fields can be summarised as follows:

- As to *modern city*, it has some spatial characteristics, including 3D space extension, regularity of objects, urban networks, 3D spatial relationship. These characteristics should be specially handled in designing spatial data model for 3D city, since the space extension have resulted different situations from traditional 2D model.

- In *urban GIS applications*, the traditional 2D model is still dominant. Some applications have been confronted with the representation inefficiency of 2D data model and called for alternative data model for 3D city representation.

- Research on *digital city* has explored the representation, visualisation and generation of 3D urban objects, which are useful in the construction of social information infrastructure. However, the considerations on *individual objects* and *urban spatial relationships* are limited so that digital city cannot satisfy the requirements of 3D city representation completely.

- Some *3D spatial data models* have been put forward by spatially adapting existing 3D models of computer graphics. However, these models are general ones, and not special for 3D city. To construct efficient spatial data model for urban applications, special considerations are required to be attached to urban spatial characteristics.

Though significant progress has been achieved in 3DCM, there is still much work to be done before one can reach a satisfactory data model for 3D city. Sun *et al* (2002) contended that no existing 3D data model can satisfy urban requirements of spatial objects and relationships. They also thought that 3D data model should take account of the properties of 3D objects and their spatial relationships and that 3D data model based 3DCM would be the promising direction.

6.2 Challenges on 3DCM

To construct an optimal 3DCM, spatial characteristics of modern city should be taken into account and spatial relationships are required to be efficiently represented and detected. It should be capable of efficiently constructing a city with primary elements and supporting corresponding fundamental spatial operators.

A 3DCM should be 3-dimensional, vector-based, object-oriented and supporting topological operators. First of all, 3DCM should treat the three dimensions (the two planar dimensions and the vertical dimension) equally so that any spatial objects in the 3D space can be geometrically described and further operated. Only in this way, 3DCM can be regarded as a true 3-dimensional city data model. Urban objects are mostly individually considered and operated, so that 3DCM should be vector-based to support this requirement and the Brep method seems to provide an appropriate basis for this. Some complex objects can be treated as the combinations of primary geometric elements, so that object-oriented method can be adopted to deal with this situation. In addition, object-oriented method can support LOD to provide multi-representation of urban objects at different spatial scales. It is widely agreed that topological relationships and related operations distinguish GIS from other information systems. Gruen and Wang (1999a, 1999b) argued that an appropriate data model should not only represent the geometrical information (e.g. shape, length, area) but also implicitly or explicitly describe topologic relationships, such as adjacency relations and link relations. Topology in 3D space becomes more complex, and information of the third dimension is indispensable in the representation. Therefore, 3DCM should be able to represent and detect topological relationships.

With this understanding, we can outline the concept of 3DCM. Firstly, four primary geometric elements are defined: node, edge, face and body. Urban entities are treated as objects according to the object-oriented concept, so that they can be represented with these primary geometric elements or the combinations. Brep method is adopted to describe urban objects using their boundary relations, but extension is made to support LOD in 3DCM. A spatial object can have different geometric representations depending on the rendering scale. This is achieved by designing 3DCM as an object-oriented model.

At the level of primary geometric elements, 3D topological relationships between these elements will be defined. There are 10 groups of relationships between the four element types, and each group includes detailed relationships. Based on these primary relationships, those of complex spatial objects can be further formulated, so can the corresponding fundamental spatial operators. Egenhofer (1989, 1994, 1995) has devoted research to binary topological relationships and put forward the well-known 9-intersection model. However, his discussions were mainly focused in the 2D space. Topological relationships in 3D space need further efforts. To be applicable in urban situations, spatial characteristics of modern city should be taken into account when constructing 3DCM. It is worth noting that network related operations will be paid particular attention its special importance in modern city.

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