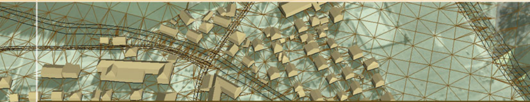
A. Abdul-Rahman
M. Pilouk



Spatial Data Modelling for 3D GIS

Springer

Spatial Data Modelling for 3D GIS

Alias Abdul-Rahman · Morakot Pilouk

Spatial Data Modelling for 3D GIS

Springer

Dr. Alias Abdul-Rahman
Department of Geoinformatics
Faculty of Geoinformation
Science and Engineering
Skudai 81310
Johor
Malaysia
alias@fksg.utm.my

Dr. Morakot Pilouk
ESRI
380 New York Street
Redlands 92373-8100
USA
mpilouk@esri.com

Library of Congress Control Number: 2007932286

ISBN 978-3-540-74166-4 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media
springer.com

Typesetting: by the authors and Integra, India
Cover design: deblik, Berlin

Printed on acid-free paper SPIN: 12038497 5 4 3 2 1

Preface

This book is based on research works done by the authors at the University of Glasgow, Scotland, United Kingdom and the International Institute for GeoInformation Science and Earth Observation (ITC), The Netherlands in 2000 and 1996 respectively. We were motivated to write the book when we began a joint research work in 1992 for our postgraduate theses on Digital Terrain Modelling (DTM) data structuring and eventually DTM software development based on triangular irregular network (TIN) data structure. We realized then that many aspects needed to be addressed especially if an advanced geo information system (GIS) such as 3D GIS system was to be realized. Research in 3D GIS is getting growing in interest and this has really motivated us to do more experiments in the 3D domain. One of the most current interesting issues is spatial data modelling for 3D GIS.

We would like to thank our former supervisors, Dr Jane Drummond of University of Glasgow and Dr Klaus Tempfli of ITC. Various helps received from friends and colleagues at both institutions are also acknowledged. Special thanks go to Mohamad Hasif Nasaruddin, a postgraduate student at the Dept of Geoinformatics, Faculty of Geoinformation Science and Engineering, Universiti Teknologi Malaysia (UTM), Johor, Malaysia for his patient in formatting the manuscript.

This book aims to introduce a framework for spatial data modelling for 3D GIS and it is specifically written for GIS postgraduate level courses. Postgraduate students, researchers, and professionals in Geo Information (GI) science community may find this book useful and it may provide some insights in various spatial data modeling problems. We hope that this book will serve as one of the useful resources in 3D GIS or 3D geoinformation research.

Alias Abdul-Rahman (UTM, Johor, Malaysia)
Morakot Pilouk (ESRI, Redlands, CA, USA)

2007

Contents

Chapter 1 INTRODUCTION

1.1 Why does 3D GIS Matter?

Next generation of Geo Information System (GIS) requires a new way of spatial data modelling. We call the next generation of GIS 3D GIS. Fundamentally, a new digital model has to be developed or established. Exploiting digital computing technology to improve the quality of life, or to prevent or mitigate hazards or disasters, would first require the construction of a model in digital form of the part of the earth and its environment. Such a model, a simplified description of complex reality, can conveniently be used, stored, managed, maintained, distributed, and transported. Even a complex model may be stored on a small scale, in diskettes, tape cartridge or CD ROM, or transmitted via communication networks. A digital model contains spatial and non spatial aspects of reality and provides a basis for operation and communication among the interested parties. A model distinguishes objects an object, or a set of objects, comprises the elements of reality under investigation. Spatial aspects are those related to shape, size and location that pertain to geometric properties. Non spatial aspects include name, colour, function, price, ownership, and so forth, often referred to as thematic properties. Spatial aspects of reality can be well and economically represented in the form of graphics, whereas non spatial aspects, in many cases, can better be represented in text. Graphic representation facilitates rapid understanding of the situation in reality, permitting high level abstraction or description about neighbouring relationships, while the textual representation is more suitable for aspects that cannot be graphically described. A digital model must be capable of relating these two representations. Creating such a model as an artificial construction of reality in a computing environment requires a tool set exploiting the technology both of computer graphics (CG) (Sutherland, 1963, 1970; Foley et al., 1992; Watt, 1993) and database management (DBMS). Geographic information systems (Burrough, 1986; Maguire et al., 1991), and computer aided design (CAD) are examples of such tools. The essential difference between GIS and CAD is the handling of the spatial aspects rather than the non spatial aspects.

Geographical Information Systems (GISs) represent a powerful tool for capturing, storing, manipulating, and analysing geographic data. This tool is being used by various geo-related professionals, such as surveyors, cartographers, photogrammetrists, civil engineers, physical planners (urban and rural), rural and urban developers, geologists, etc. They use the tool for analysing, interpreting, and representing the real world and understanding the behaviour of the spatial phenomena under their respective jurisdictions. Almost all of the systems used by the geoinformation community to date are based on two-dimensional (2D) or two-and a half-dimensional (2.5D) spatial data. In other words, one may find difficulty processing and manipulating spatial data of greater dimension than 2 in the existing systems, resulting in inaccurate or at least very incomplete information. Furthermore, manipulating and representing real world objects in 2D GIS with relational databases are no longer adequate because new applications demand and increasingly deal with more complex hierarchical spatial data than previously supported by the relational model. It has been suggested in the literature that the abstraction of complex spatial data could be handled more effectively in object-oriented rather than in relational database environment (Egenhofer and Frank, 1989; Worboys, 1995).

The limitations of the current 2D GISs, especially in geoscience, have been reported in the literature by Jones (1989), Raper and Kelk (1991), Rongxing Li (1994), Houlding (1994), Bonham-Carter (1996), and Wei Guo (1996). The limitations mentioned relate to data dimensionality and data structures. Single valued z-coordinate data such as a point (x, y coordinates) with the z-coordinate representing height presents no data handling difficulty in such systems, but it is inadequate for data with multiple z-values (Bonham-Carter, 1996; Raper and Kelk, 1991) such as ore bodies and other important three-dimensional real world entities. A major impediment to establishing 3D GISs is associated with inappropriate spatial data structures, as reported in Jones (1989) and Rongxing Li (1994). These two authors have proposed voxel data structures for 3D data as a solution to the data structuring problem, but no real operational system was developed based on the structure. The problem was also highlighted in the geological field by Houlding (1994). True representations and spatial information, for example sub-surface 3D objects, could not be successfully achieved with 2D systems. 3D visualisation tools alone (for example Advanced Visualization System (AVS), Voxel Analyst of Intergraph, and other Digital Terrain Model (DTM) packages) were not able to truly manage such data as demanded. For example Wei Guo (1996) experimented with the 3D modelling of buildings by using Molenaar's (1992) formal data structure in the relational database environment together with AutoCad as a 3D visualization tool; AutoCad was used to generate the building models. In the literature, a common suggestion has been that the existing GISs were able to handle most of the 2D spatial data, but had difficulty in handling 3D spatial data and beyond, therefore, an extension of the existing systems to at least a third-dimension (3D) is one of the solutions suggested by GIS researchers.

Another observation is that the literature cites no work on three-dimensional GIS coupled with object-oriented technology. Given that the weakness of conventional off-the-shelf 2D or 2.5D GISs are revealed when three-dimensional real world entities are considered, it is understood that object-orientation and three-dimensionality are not more often jointly considered. Some works have focussed on 3D issues such as work reported in Fritsch and Schmidt, 1995; Kraus, 1995; and Fritsch, 1996. But all of these attempts were based on the relational database environment. Therefore, this research monograph looks at both 2D and 3D spatial data modelling and the development of a geoinformation system using relational and object-oriented technology to attempt to solve 3D problems in the GIS environment.

1.2 The Need for 3D GIS

We live in a three dimensional (3D) world. Earth scientists and engineers have long sought graphic expressions of their understanding about 3D spatial aspects of reality in the form of sketches and drawings. Graphical descriptions of 3D reality are not new. Drawings in perspective view date from the Renaissance period (Devlin, 1994). 3D descriptions of reality in perspective view change with the viewing position, so their creation is quite tedious. Traditional maps overcome this problem by using orthogonal projections of the earth. However, they offer a very limited 3D impression.

These traditional drawings and maps reduce the spatial description of 3D objects to 2D. Using computing technology, however, knowledge about reality can be directly transferred into a 3D digital model by a process known as 3D modelling. A 3D description of reality is independent of the viewing position. Adequate cover of the aspects of reality under investigation requires its understanding from many different viewpoints. The disciplines of geology (Carlson, 1987; Bak and Mill, 1989; Jones, 1989; Youngman, 1989; Raper and Kelk, 1991), hydrology (Turner, 1989), civil engineering (Petrie and Kennie, 1990), environmental engineering (Smith and Paradis, 1989), landscape architecture (Batten, 1989), archeology, meteorology (Slingerland and Keen, 1990), mineral exploration (Sides 1992), 3D urban mapping (Shibasaki et al., 1990; Shibasaki and Shaobo, 1992), all draw on 3D modelling for the efficient completion of their tasks.

A 3D model is the basis of a system providing the functionality to accomplish the task in hand. Scott (1994) has summarized the work of Bak and Mill (1989), Fisher (1993), Kavouras and Masry (1987), Raper (1989), Raper and Kelk (1991), and Turner (1989), to provide a set of functions that can be expected from 3D modelling. These studies should provide the means for constructing a 3D model from disparate inputs; permit the maintenance of existing models; facilitate effective 3D visualization with, for example, orthographic, perspective or stereo display with hidden line/surface removal, surface illumination, texture mapping; spatial analyses enabling the calculation of volume, surface area, centre of mass, optimal path as well as spatial and non spatial search and inquiry.

CAD is a typical CG tool for 3D modelling used in car, machinery, aircraft and spacecraft designs, the construction industry, and architecture. CAD focuses on the geometric aspect of the model and its 3D visualization. An example would be a perspective view with hidden line and surface removal, surface illumination, ray tracing, and texture mapping. The question arises whether CAD can support all the tasks required in the disciplines listed above. Attempts have been made to use CAD for tasks in earth sciences requiring 3D modelling and functionality. However, it cannot immediately be assumed that CAD is suited to these tasks, for the following reasons.

- CAD was developed to solve problems in the design of man made objects with well or predefined shapes, sizes, spatial relationships and thematic properties. CAD does not provide the tools for data structuring, or dealing with objects lacking such well-defined shapes, sizes, spatial relationships and thematic properties. Neither is it capable of analysing spatial relationships, nor coping with the disparate data sets and uncertainty typically encountered in GIS. For example, CAD will not reliably maintain the neighbourhood relationships between objects important in earth science analyses, because these relationships may not be considered significant in the design.
- Designing an object, such as a building, is a subjective matter. All aspects of objects and their relationships have to be decided by a human designer; there is little that can be automated. Earth science applications seek to model existing objects, with shapes, sizes and interrelationships outside human control. Here, automation is desirable because of the large number of objects involved. Some relationships important for spatial analysis have to be created automatically. CAD does not usually provide a function for this kind of automation.

- CAD starts the object definition from 3D. When objects are broken down in 2D components, the relationships between them are known. Earth science applications typically model components of reality separately, mostly in 2D, and are dominated by the application view, available tools and information. The components have to be combined and their interrelationships discovered at a later stage. This is quite difficult, since CAD does not usually provide sufficient tools to derive the relationships between the separate components.
- CAD creates a complex object by combining several components possessing such simple geometry as a cube, cylinder, or sphere. The operations of transformation, union, and intersection can be readily applied to such components to obtain the complex object. Earth science applications usually treat a complex object as a whole. Decomposition into primitives is comparable to reverse engineering, the opposite of CAD. The modelling approach used by CAD may not therefore always be suitable for earth science applications. Geometric primitives of an even lower level, such as points and lines, are needed to represent complex reality beyond man made objects.

These geometric primitives also determine the related operations which CAD may not be capable of providing.

A more suitable tool for earth science applications would be a GIS providing a 3D modelling capability, that is to say, a 3D GIS. At the time of writing, a GIS capable of providing the functions listed above list with full 3D modelling capability is not commercially available. Most GISs still limit their geometric modelling capability to 2D so that the 3D representation, analysis and visualization provided by CAD are not possible. Most endeavours to model the third dimension can be found in the representation of terrain relief and in digital terrain models (DTM). DTM can facilitate spatial analyses related to relief, including slope, aspect, height zone, visibility, cut and fill volume, and surface area, and the 3D visualization of a surface, as in a perspective view. However, the basis of DTM is a continuous surface with a single height value for every planimetric

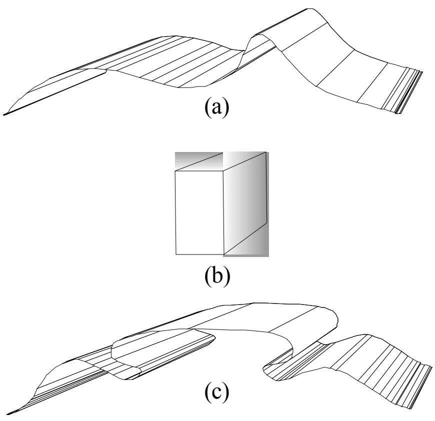


Fig. 1.1 Single-valued surface (a), 3D solid object (b) and multi-valued surface (c).

location (see Figure 1.1a). DTM cannot accommodate a 3D (solid) object, or a surface with multiple height values at a given planimetric location (see Figure 1.1b and Figure 1.1c, respectively).

Although raster-based systems which could be regarded as 3D GISs are available, they may not be able to maintain the knowledge about reality available in the original data set. This knowledge may be lost because of problems in resolution and resampling. As a remedy, the original data set would have to be stored separately from the model, for example, for:

- recreating the model if the result proves to be unsatisfactory because of unsuitable mathematical definition
- creating another model with different resolution
- merging with another data set to create a new model
- archiving as a reference to, or evidence of, the model.

These activities imply the need to store original data in an appropriate structure ready for future use. Necessary information about the data should be attached to each data element. In DTM for instance, information that a line is a breakline should be kept because it will have an impact on the interpolation. Similarly, other information can be attached which influences data handling strategies.

Since neither CAD nor GISs can at present fulfil the requirements of earth science applications, further research and development of a 3D GIS would seem appropriate.

Who needs 3D GIS?

As in the popular 2D GIS for 2D spatial data, 3D GIS is for managing 3D spatial data. Raper and Kelk (1991), Rongxing Li (1994), Förstner (1995), and Bonham-Carter (1996) present some of the three dimensional application areas in GIS, including:

- ecological studies
- environmental monitoring
- geological analysis
- civil engineering
- mining exploration
- oceanography
- architecture
- automatic vehicle navigation
- archaeology

- 3D urban mapping
- landscape planning
- defence and intelligence
- command and control

The above applications may produce much more useful information if they were handled in a 3D spatial system, but 3D spatial objects on the surface and subsurface appear to demand more complex solutions (e.g. in terms of modelling, analysis, and visualization) than the existing systems can offer.

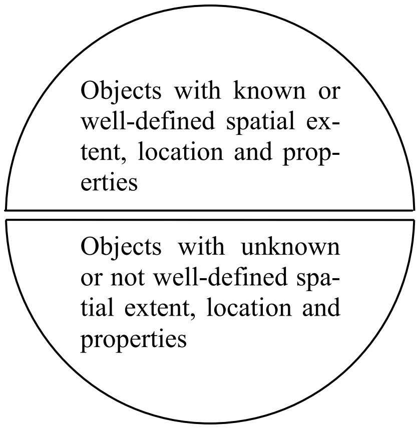


Fig. 1.2 Two types of real world objects with respect to their spatial extent.

1.3 The Need for 3D Spatial Data Modelling

In addition to the problem of creating a system capable of offering 3D modelling and functionality, there is a further problem concerning the type of 3D model chosen as the basis for 3D GIS. The model contains knowledge about reality, so we consider below the types of real world objects it must represent. Two kinds of real world objects may be differentiated in terms of prior knowledge about their shapes and location, as shown in Figure 1.2. In reality, objects from the two categories coexist. Traditional GIS models the objects of each category independently with the result that two separate kinds of systems or subsystems have been developed.

Raper (1989) has also defined these two categories of objects. The first category, regarded as 'sampling limited', is for objects having discrete properties and readily determined boundaries, such as buildings, roads, bridges, land parcels, fault blocks, perched aquifers. The second category, known as 'definition limited', is for objects having various properties that can be defined by means of classification, using property ranges. For example, soil strata may be classified by grain-size distribution; moisture content, colloid or pollutant in the water by percentage ranges; carbon monoxide in the air by concentration ranges, and so forth. Molenaar (1994a) regards these objects as 'fuzzy spatial objects'.

Separate modelling of these two categories of objects tends to contradict the reality, which leads to difficulties in representing their relationships. Such a question as, 'how many of the people working in a 50-storey office building are affected by polluted air generated by vehicles in nearby streets during rush hours?' cannot be answered until the two separate models are combined, as shown in Figure 1.3. Modelling them together with more accurate representation of their relationships in the 3D environment requires the integrated 3D modelling.

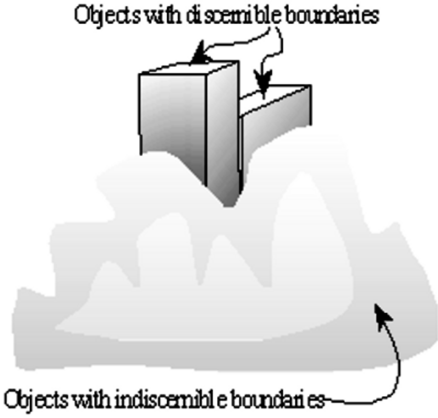


Fig. 1.3 An example of two types of real world objects

Note also that the properties of an object may be well defined in some specific dimensions and ill defined in others. For example, given a DTM data set representing a surface, the planimetric extent of regions at the elevation of 100 metres above mean sea level cannot be defined until the result of interpolation based on a mathematical definition (for example, linear interpolation) is obtained. That is to say, although the spatial extent of this region may be known in the z-dimension, the spatial extent in planimetry (x, y) has still to be discovered. The model must contain the aspect allowing the appropriate operation, such as interpolation or classification, if the required description of the properties of an object is to be obtained.

Apart from the problem of the separate modelling of the two types of objects, there remains the further problem of the separate modelling of an object's components. These components are relief and planar geometry associated with thematic properties. This separation has resulted in independent systems and data structures, DTM and 2D GIS, respectively. The consequences are data redundancy, which may lead to uncertainty when the two data sets are combined and only one data set has been updated.

DTM can facilitate several GIS analyses and visualization taking into accounts the third dimension. The spatial information stored in DTM and in GIS, however, can only be related through coordinates. This implies that relationships between different components may not be properly represented because of metric computation instead of topology. To overcome this, information derived from DTM must be converted into a form GIS can recognize. For example, information about a slope or height zone must first be converted into a thematic layer of GIS for further overlaying before the spatial analysis can be carried out. Imagine having information about the relief, planimetry and themes integrated into one model, so that conversion of such information as slope, height zone and so forth were no longer necessary. Such a question as, ‘which land parcels are subject to one-metre flooding?’ could be answered from one model. Integrated modelling of this kind is evidently also required for 3D GIS.

1.4 Problems Associated with Spatial Modelling for 3D GIS

Establishing a 3D GIS while taking into account the integration of the necessary components and different types of objects requires the solution of the following problems related to the spatial model representing reality:

1) Design of a spatial model
   - design of an integrated data model, or a scheme, permitting the derivation of a unified data structure capable of maintaining all the components of the geometric representation of real world objects, whether obtained from direct measurements or from derivations, in the same database. Each geometric component must be capable of representing a real world object differently understood by different people.

2) Construction of a spatial model
   - development of appropriate means and methods for 3D data acquisition;
   - coordinate transformation into common georeferencing when different components are to be included into one database;
   - development of a data structuring method that unites the data from various inputs of multi sources into an integrated database capable of being maintained by a single database management system;
   - design of thematic classes to organize representation of real world objects with common aspects into the same category;
   - solving the uncertainty arising from discrepancies from different data sets during the integration process and converting the uncertainty into a ‘data quality’ statement to be conveyed to the end user.

3) Utilization of a spatial model
   - utilization of existing components, such as 2D data and DTM (backward compatibility) and preparation of those components for future incorporation into the higher-dimension model (forward compatibility) to save the costs of repeating data acquisition.

- development of additional spatial operators and spatial analysis functions;
- development of maneuverable graphic visualization permitting the selection of appropriate viewpoints and representation enabling convenient, adequate uncovering of the details of objects stored in the database;
- design of 3D cartographic presentation of information, including name placement, symbol, generalization, etc.;
- design of a user interface and query language allowing users access to the integrated database;
- development of a spatial indexing structure that speeds up data retrieval and storage processes for the integrated database, including specific (database) views for each user group and guidelines keeping these views updated according to the core database;
- development of tools for navigating among different models stored in databases at different sites and computing platforms.

4) Maintenance of spatial model
   - design of updating procedures, including the development of consistency rules ensuring the logical consistency and integrity of the integrated database, especially during the updating process.

1.5 Previous Work

The status and progress of research in the 3D GIS field within the scope of this monograph and the identification of solutions and remaining problems are made clear from the following review of previous work.

The development of data models for a 3D GIS has branched in two directions. The first is the full 3D approach that looks directly into the design of a data model suitable for 3D GIS. Molenaar (1989) proposes a formal data structure (FDS) for a 3D vector map which may be regarded as a generalization of the 2D version of FDS. Shibasaki and Shaobo (1992), Rikkers et al. (1993), Bric (1993), Bric et al., (1994), and Wang (1994) have reported experimental use of 3D FDS.

The second approach comes from the viewpoint referred to as the 'integration of DTM and GIS'. DTM became a discipline in its own right in the late 1950s (Miller and Laflamme, 1958). Fritsch (1990) has recognized the work of Makarovic (1977) as a proposer of this integration. Males (1978) though not addressing the integration issue, demonstrated the use of a