Chapter 9

Conclusions and further research

Municipalities are some of the institutions where the complexity and interrelations between different types of data (3D spatial and non-spatial) and users vary to such large extent that current information systems have difficulty in handling and analysing them in their integrity. This status disturbs the process of urban planning and governing more frequently nowadays than a decade ago. This thesis describes an attempt to integrate available technology components and develop new concepts to attain a system that better meets the requirements of users solving urban planning problems or using municipal information. The thesis concentrates on a limited area of the 3D GIS development, i.e. a concept for structuring objects and their characteristics, permitting efficient retrieval and display. The focus is on three-dimensional spatial objects, since the demand for 3D spatial information is most pressing.

9.1 Summary

Development of a 3D GIS for urban development is a huge task requiring extensive research, which cannot be completed with one thesis. This thesis concentrates on a web-oriented 3D GIS model appropriate for both 3D analysis and 3D visualisation of urban data. The thesis begins with a short overview of the achievements in the area of storage, analysis and visualisation of 3D spatial data. Analysis of the state-of-the-art in these areas has revealed 1) conceptual insufficiencies of the current information systems (2D GIS, CAD) to deal with 3D objects, 2) research tendencies to isolate problems of 3D spatial analysis from 3D visualisation, and 3) limited research on exchange of 3D spatial information on the Web. These observations have motivated the key objective of the research, i.e. a GIS model supplying sufficient data for 3D spatial analysis and ensuring efficient data retrieval for 3D visualisation on the Web. Since the object identification and the web-oriented approach for query and 3D visualisation have direct impact on the organisation of data, they are investigated in the research. The 3D GIS model suggested is verified in two ways: 1) analysis of the maintained 3D topological relations and 2) functional tests on a prototype system. The ability to maintain 3D topological relations proves suitability of the model to perform spatial analysis. The functional tests demonstrate the capabilities of the model for web communications and 3D visualisation.

The following text summarises the strategies and basic approaches applied during the research with respect to the objectives of the thesis.

Object identification and data classification

The first objective specified was achieved following a three-step strategy: first, a study on common business models for the investigation of requirements and structuring of information; second, exploration of user requirements for a municipal 3D GIS and, third, formulating user requirements and outlining the scope of the thesis.

The study on common business models has provided knowledge about the methods to approach users and the techniques to classify the information of interest. The approach (i.e. object-oriented) and the ways to collect user requirements (i.e. interviews, study on current data organisation and clients) relevant to the thesis (i.e. development of a conceptual model) were clarified. Following the selected techniques, a study on the types of data maintained in current information systems in a representative municipality, and their present clients, was completed. Moreover, interviews with companies producing 3D data attempted to detect requirements for 3D spatial data and thus contribute to the clarification of objects and their characteristics.

The study of municipal data and departments has revealed that there is a mixture of spatial and non-spatial data, kept and maintained by different information systems, organisations and companies. Objects with spatial extent are currently maintained by GIS and CAD systems, while objects lacking spatial extent are stored in DBMSs, files or folders. The possible users vary from individuals asking for private information to specialists of companies involved in the decision-making process responsible for the development of the town. These observations summarised as a need for an integrated approach for structuring data and a need for an information system capable to serve users with different qualifications, were later considered for the conceptual design and the user interface.

The interview with producers of urban data (as well as similar investigations reported in the literature) helped in exploring the level of realism and interaction, current and needed spatial analysis and frequently used operations.

The different sources of information were analysed to clarify a number of issues needed for the research, i.e. types of data (spatial and non-spatial), spatial relationships, geometric resolution, realism and 3D visualisation, interaction and GUI, operations and outcomes. A generic set of items of interest was specified and referred to later in the thesis. The types of data, the relationships, the geometric resolution and the demanded realism were investigated with respect to the conceptual model. The issues related to clients, 3D visualisation, interaction, operation and outcomes contributed to the selection of system architecture and more specifically to 3D visualisation. The geometric resolution and level of realism were an indication of the data collection procedures to consider.

The outcomes of the investigations were summarised as user requirements of the 3D GIS model and the system architecture (see Chapter 3).

A concept for query and 3D visualisation on the Web

The second objective of the thesis aimed at proposing system architecture for web access, query and 3D visualisation, and clarifying technology-driven requirements. The strategy followed was 1) the possibilities for 3D web-oriented visualisation were studied, 2) the system architecture was assembled and 3) the visualisation requirements were specified.

The focus was on VRML since it is the only web standard for visualisation of 3D graphics on the Web. VRML and VR browsers were analysed and experimentally examined with respect to three aspects: 1) applicability for visualisation and interaction with realistic 3D urban worlds, 2) manner of data structuring and 3) current limitations and deficiencies.

The components of the system were selected under two major criteria, i.e. the client-server architecture and the availability of software. Among the different methods for web-access, we have chosen the server-site architecture due to greater possibilities to work on the model. We have employed existing software modules, components and standards with the idea of facilitating and speeding up the development process. The proposed architecture consists of four key components: DBMS, Web server, Web browser, VR browser and communication software (CGI scripts). Such an assemble of separate modules has a number of advantages in several directions (they are listed in Section 9.2).

The extended study on VRML concepts and their implementation by VR browsers, as well as some specifics of the client-server architecture, contributed to the specification of a number of visualisation requirements.

A conceptual model for spatial analysis and 3D visualisation

The specified requirements (user and visualisation) contributed to a clarification of persistent characteristics of real objects, which are of interest for database maintenance. To favour the classification of the characteristics, an extended definition of an object is proposed. The elaboration takes into account thematic and geometric aspects of object's attributes, relationships, behaviour and time (scenario). Thus objects without spatial extent are to be incorporated in the database according to their thematic characteristics and classified according to a thematic classification. Spatial objects that have geometric and thematic properties are to be classified according to the hierarchies in the semantic and geometric domains.

Simplified Spatial Model (SSM)

Since the scope of the thesis was restricted to the geometric domain, the geometric characteristics of objects, i.e. attributes, description, relationships and behaviour, were further elaborated. This thesis advocated the hypothesis that a 3D topological model can be adopted for visualisation and real-time navigation. The presented review and comparison of three 3D topological models has revealed deficiencies concerning either 3D modelling, or spatial analysis or 3D visualisation and interaction. Therefore a Simplified Spatial Model (SSM) to describe 3D geometry and represent spatial relations was proposed. The model is similar in some concepts to 3D FDS and differs mainly in the number of constructive objects. The model maintains two constructive elements, i.e. nodes and faces (arbitrary number of nodes, convex, planar, oriented, without holes), which are used to build four geometric objects, i.e. body, surface, line and point. Nodes constitute faces, points and lines, faces constitute surfaces and bodies. Since the model is not a complete subdivision of the space, two relations, i.e. face-in-body and node-in-body, are explicitly described.

In order to prove the capability of SSM to perform 3D spatial analysis, the ability of SSM to distinguish binary topological relations (according to the 9-intersection model) between geometric objects was extensively analysed. Since the possible relations between simple objects in 3D space were not fully studied, negative conditions applicable for 1D, 2D and 3D space were first derived and then the possible relations were computed. An alternative approach to determine possible relations as well as sketches of all the object configurations has verified the obtained results. Sixty-nine topological relations between two simple objects (regardless of the dimensions of the object and the space) can be identified by the 9-intersection model. Afterwards SSM was estimated for its potential to detect all the possible topological relations. The operations needed to identify all the relations were formally described using set theory notions.

Simplified Spatial Schema (SSS)
Next, the spatial model was utilised as a fundament for geometric description of spatial objects. Among all the components of an object, behaviour, geometric attributes and geometric attributes were implemented. Colour, texture and some parameters introduced for lines and points were the implemented geometric attributes. Two geometric objects, i.e. surface and body, can be textured applying two techniques (texture mapping and texture draping). Behaviour's parameters that correspond to the kind of behaviour "reactions to events" were implemented. The considered components were organised in the Simplified Spatial Schema (SSS), following the principles of the IFO semantic data model. The schema was mapped into a relational data model, which resulted in 25 relational tables.

3D R-tree for dynamic creation of LOD and spatial indexing
A 3D R-tree was built on the "top" of the model. The goal of the R-tree is twofold: 1) restriction of the searching space and 2) the automatic creation of LOD (demanded by visualisation requirements). A bottom-up algorithm selects the optimal combination of three objects with respect to the inclined distance between mass centres and creates the R-tree. The R-tree was implemented in the relational database in additional tables, as every geometric and constructive object obtains a code related to its location in the R-tree. The code provides a relation between the constructive objects and geometric objects and indicates single or multiple usage of a constructive object, which facilitates retrieval and editing of objects.

Links between the model and existing data collection procedures
With respect to the fourth research objective, existing reconstruction procedures were studied and adapted to create the tables of SSS containing geometric description and attributes. To experience the complexity of operations needed to collect geometric data for SSS, the following approaches were tested: 1) a semi-automatic procedure for reconstruction from aerial photo images and 2) transformations of existing digital data. The existing procedure for manual extraction of objects and automatic creation of 3D FDS was extended to convert data to SSS.

To experience the texture extraction and texture mapping, the following procedures were examined: 1) an automatic procedure to extract texture from aerial photo images and 2) a manual mapping of images onto geometric shapes (faces, surfaces) in commercial software. The textures for the texture mapping mechanism were obtained by transformation of CAD or VRML files containing the texture co-ordinates. The images for texture draping mechanisms were rectified and resampled according to the rules of VRML specifications.

A number of programs were developed to prove that the conversion between SSS and other geometric and graphic representations is feasible.

Evaluation and verification of the proposed concepts

The final verification of the proposed 3D GIS model was completed by tests on a prototype system. Three case studies dealt with different aspects of the concepts developed. The case studies were conducted on the prototype system following the query-visualisation approach proposed. The prototype system was composed of freeware software modules, i.e. Apache server, MySQL RDBMS, Perl programming language and Perl libraries to access databases and create HTML documents. The first case study tested the suggested GUI, i.e. framed HTML windows with sections for specifying query, obtaining results and 3D visualisation. Several fill-out forms illustrated query and 3D visualisation of spatial queries. GUI, on the same principle, demonstrated database editing by typing the data to be corrected (co-ordinates, IDs).

The second case study presented the outcomes of the algorithm for R-tree. To test the idea of the maximal preservation of the building's horizon, three criteria to group objects were tested. The algorithms were tested on two test sites.

The last case study estimated the performance of SSS. The performance test aimed at demonstrating the improved possibilities of SSS (compared with 3D FDS) to store information and complete visualisation queries, and thus prove the hypothesis used to define SSM. Two separate tests assessed the database size needed for both SSS and 3D FDS and the time to traverse SSS and 3D FDS tables to complete (and visualise) queries. The tests were carried out on two test sites represented according to SSS and 3D FDS. 3DFDS and SSS were implemented without the tables that maintain the explicit relationships; however, all the other objects were identical in both logical models. The experiments have estimated: 1) database traversal and 2) total time for delivery to client station. Three times were registered: without indexing and R-tree coding, with R-tree coding, and with indexing (B-tree) and R-tree coding. The tests were completed for a number of representative spatial queries, i.e. " show all the objects (basically buildings) with particular IDs".

9.2 Outcomes

The work on the research has resulted in new concepts and experimental software that will be briefly reviewed below.

An extended object definition was suggested and utilised for integrated structuring of spatial and non-spatial objects. The object definition is based on four notions to characterise objects, i.e. attributes, relationships, behaviour and scenario considered separately in the geometric and the semantic domains. A spatial object is represented by **GDsc**, **Gatt**, **GR**, **GB** and **GS** (see Chapter 5). The definition enables maintenance of spatial and non-spatial objects, enlarges the scope of characteristics to be considered, allows separate hierarchies for each object component to be built, offers a systematic way to introduce new characteristics, permits a separation of visualisation, spatial and thematic queries, allows substitutions of spatial models, and hierarchical schemas.

The Simplified Spatial Model (SSM) to re-present 3D geometric objects was formally defined (see Chapter 5). The major conceptual characteristics of the model can be summarised as follows:

- it consists of geometric objects, constructive objects and explicit relations
- two constructive objects constitute the four geometric objects
- the singularities between point, line and surface objects and their intersections with constructive objects are forbidden
- singular constructive objects with respect to the interior of body objects (i.e. face-in-body and node-in-body) are permitted
- it is defined on the basis of indexed sets and family of sets
- operations needed to construct the model and derive object's boundaries and binary relations between simple objects are the basic set theory operations, i.e. union, difference and intersection
- operations needed to ensure planarity, convexity, connectivity and inclusion are based on metric calculations.

The model ensures a correct 3D visualisation, faster (compared with 3D FDS) traversal of the database, the full set of binary topological relations (between simple objects) and standardisation of operations (i.e. intersection, union and difference).

The Simplified Spatial Schema (SSS) was introduced as an implementation of a subset of the object components related to the geometric domain. SSS adopts SSM for the geometric description and the concept for geometric attributes and behaviour (see Chapter 7). SSS ensures (in addition to the characteristics of SSM) realistic 3D visualisation, creation of dynamic worlds and enables graphic query of objects (within the system architecture).

An algorithm for 3D R-three spatial structuring was proposed to speed up the traversing of data and create LOD on the fly (see Chapter 8). The experiments have shown that the relative positions and the size of highest buildings remains unchanged. The utilisation of MBB for LOD does not preserve the street structure of the town and therefore a birdseye look does not give a good result. Introduced coding of **GO** and **CnsO** facilitates topological relations by an indication of the common **CnsO**.

A visualisation approach to query and display non-spatial and 3D spatial data on the Web was proposed (see Chapter 4). The components utilised have a number of advantages. The utilisation of CGI scripting makes use of HTTP protocol, existing scripts and HTML forms. The employment of RDBMS to maintain data allows: 1) spatial, thematic and mixed analysis to be carried out, 2) SQL standard language to be employed and 3) facilitation and optimisations in maintenance and control of data. The utilisation of Web browsers and VR browsers to specify queries and visualise results ensures propagation of basic Web design criteria over the 3D GIS: functionality (support of a variety of file formats), portability (independence from software and hardware availability), scalability (visualisation of arbitrary large documents), extensibility (provide new capabilities, which do not exist in the minimal configurations), etc. The utilisation of VR browsers for visualisation reduces the task of the programmer in the creation of the VRML document and enables basic virtual reality techniques. The basic disadvantage is related to the CGI scripting and the limited functionality of the client site.

Examples of GUI (i.e. a number of CGI scripts), employing Web browser windows and VR plug-ins were developed (see Chapter 8). The CGI scripts illustrated the query and visualisation (especially 3D visualisation) of:

- information about a particular object (geometric or semantic)
- information according to a thematic, spatial or mixed criterion defined in SQL statements
- any information about the database defined in free SQL statements
- complex queries.

Software for linking the model to existing data collection procedures and 3D object reconstruction was developed (see Chapter 7).

Software for data transformation between SSS and other data formats (3D FDS, DXF, VRML, Prolog, OpenInventor) was developed (see Chapter 7). The software is capable of converting both geometric description and geometric attributes (colour, texture, texture co-ordinates).

The possible binary topological relations between simple objects in 1D, 2D and 3D space were outlined. The number of negative conditions used to derive all the relations is the smallest reported in the literature (see Chapter 6).

9.3 Conclusions

The investigations, experiments and various issues addressed in this research have contributed to the following conclusions.

The attention given to urban problems to be solved in a municipality has confirmed that the scope of the 3D GIS model has to be extended. *The 3D GIS model has to accommodate spatial and non-spatial objects rather than geo-referenced objects and semantic information attached to them.*

The study on technology advances and limitations has contributed to the specification of a geometric description, geometric attributes and geometric behaviour in order to facilitate 3D visualisation. *Besides the traditional semantic data and data about shape, size, location and 3D topology, the 3D GIS model has to accommodate radiometric properties and behaviour about spatial objects*. Database storage of the remaining scene components is not necessary in our visualisation approach. The VR browser supports illumination and shading models, camera positions are computed on the fly.

The theoretical elaboration and experimental tests have proven that the spatial model defined, i.e. SSM, can be used to maintain, spatially query and visualise 3D data. This is to say that in principle *a spatial model can be defined to support both 3D topology and visualisation*.

The 3D R-tree structuring implemented to restrict the search space and create LOD on the fly has performed excellent results. Indications were given that the MBB boxes of the R-tree may be used for directional analysis. *A 3D R-tree built on top of a topological model may be considered as a powerful tool to speed up database traversal, create flexible LOD and extent the scope of the detectable spatial relationships.*

The prototyping performance tests and the examples of GUI have illustrated the feasibility of the approach for a 3D GIS on the Web, proposed in this thesis. *Web server, CGI scripts, Web and VR browsers can be integrated in an alternative solution to the start-*

from-scratch systems to query, visualise and explore urban data. VRML is an effective tool for 3D visualisation and virtual reality exploration of 3D urban worlds.

SSS (resp. SSS+) is a logical model of the findings of this thesis related to the geometric domain. *SSS, which maintains semantic characteristics, shape, size, location, colour, texture, behaviour and 3D topological relationships about spatial objects, is a 3D GIS model supporting 3D realistic visualisation and 3D spatial analysis.*

The study on 3D topological relations has revealed not only the very limited number of possible relations but also the limited number of relations needed for objects of urban areas. In this respect, *the needed spatial operations to perform spatial analysis have to be developed after the specification of all the components of the spatial objects*.

The process of data collection is closely related to the generation rules of the conceptual model. *The balance between geometric and texture detail has to be established prior to the construction phase of the 3D modelling.*

Urban planners and municipality clients are likely to benefit from our approach in several directions:

- enlarged scope of queries to be performed, i.e. 3D spatial, non-spatial, mixed,
- possibilities to query graphically objects in a virtual environment
- visualisation of 3D spatial queries in a virtual environment
- virtual reality navigation and exploration of 3D worlds
- possibilities to visualise outcomes of queries in different file formats
- an appropriate access to the information by a variety of users
- access to the information from any office via the Internet
- moderate means to edit data over the Web and visualise the changes.

The study on user requirements has provided little learning about demanded functionality of 3D GIS. However, the new concepts developed in this research, as well as the prototype system, can be used for a new exploration of user demand and further detailing of some of the ideas.

9.4 Further research

Several of the issues related to the conceptual model and the approach for query and visualisation proposed in this thesis need further investigations, developments and experiments. The ones directly related to this research are:

3D GIS model:

As already mentioned, the thesis did not elaborate on the complete set of spatial and non-spatial objects derived in Chapter 3. The next challenge is related to:

- incorporation of fictional objects, which still has open questions e.g. type of geometric representation (line objects or surface objects), physical properties (3D visualisation),
- incorporating non-spatial objects. For example, incorporation of the jurisdictional group, which comprises objects that have thematic properties and location, raises questions such as representation of location (point in the 3D space or association with a building), thematic relations (owns, lives in, works at) between spatial (e.g. building) and non-spatial (e.g. people) objects

- dealing with two and more geometric representations per object, e.g. boundary and parametric. The possible questions to investigate are: maintenance, operators for consistent transformation from one to another representation
- further investigation on inheritance of properties of composite objects.

Geometric behaviour:

- an extension of the SSS to comprise multiple behaviour per objects, which is expected to be the more frequent case,
- object protection on database level.

Operations:

The operations necessary to construct the model are still lacking. Some of them are:

- operations for planarity, convexity and discontinuity as they are defined in the model.
- operators for consistency check: node-on-line, node-on-face, node-in-body, line-on-face, line-in-body, intersection of lines, face-on-face, intersection of faces, face-in-body
- 3D overlay, which is based on the same operation for consistency check and 3D editing.

Generic operations (according to classification given in Chaper 2) for 3D editing: add, delete and update of nodes, faces, points, lines, surfaces and bodies.

Spatial analysis:

- Development of algorithms to perform complex analysis: 3D buffer zones, visible space, clouds (e.g. of pollution), etc.
- The thesis resolved the 3D topological relations between simple object. However, further investigations are needed on binary relations between non-simple geometric objects
- Investigation on the utilisation of the 3D R-tree to support directional analysis.

System architecture for query and visualisation on the Web:

Components:

- Experiments with OODBMS. Since the conceptual model is object-oriented, OODBMS might bring some advantages in description of composite objects.
- The access to the DBMS is based on CGI scripting, which has limitations on the client side. Java applets instead (or in addition) should be explored to reduce some of the connections to the server.
- Extending the possibilities for editing on the client site. One solution might be in the direction of Java applets for tracking the changes inside the VRML and transporting the changes to the database; another direction might be the realisation of another concept, i.e. CORBA to access remote data.

3D Visualisation:

- 3D symbols for visualisation of lines and points. The initial experiments have shown that the type of symbol (e.g. billboard or model) affects the time for delivery and parsing.
- The emphasis in this research was on correct visualisation of faces. 3D visualisation by lines still has to be tested since some of the objects (e.g. the group of fictive objects) may not be successfully visualised by faces.
- Visualisation of text information in VRML. The standard means of VRML to control 3D text are still rather limited and require extensions.

LOD:

- The LOD discussed in this thesis regard only bodies, i.e. buildings. Further investigations are needed for surfaces in order to compose LOD for surfaces.
- The algorithm presented ensures only rigorous LOD to observe the model from a ground level. An automatic 3D generalisation (in cartographic contexts) may give better results for any observing point.

Despite some initial ideas, the research did not experience the creation of LOD on the fly. Delivery of the VRML document(s) containing the LOD to the client station may require a special approach.