



Review

3D geo-database research: Retrospective and future directions

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ABSTRACT

3D geo-database research is a promising field to support challenging applications such as 3D urban planning, environmental monitoring, infrastructure management, and early warning or disaster management and response. In these fields, interdisciplinary research in GIScience and related fields is needed to support the modelling, analysis, management, and integration of large geo-referenced data sets, which describe human activities and geophysical phenomena. Geo-databases may serve as platforms to integrate 2D maps, 3D geo-scientific models, and other geo-referenced data. However, current geo-databases do not provide sufficient 3D data modelling and data handling techniques. New 3D geo-databases are needed to handle surface and volume models. This article first presents a 25-year retrospective of geo-database research. Data modelling, standards, and indexing of geo-data are discussed in detail. New directions for the development of 3D geo-databases to open new fields for interdisciplinary research are addressed. Two scenarios in the fields of early warning and emergency response demonstrate the combined management of human and geophysical phenomena. The article concludes with a critical outlook on open research problems.

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1. Introduction

From an economic point of view, geo-technologies are one of the most rapidly emerging fields, with high predicted growth rates worldwide (Scholten et al., 2009). Typical challenges include the management of globalisation processes, growing world population, and natural hazards.

Human and geophysical phenomena must be considered together to solve these problems. Effective management requires cooperation between the social sciences, geo-sciences, natural sciences, geo-information science (GIScience), engineering sciences, computer science, and mathematics. Geo-databases play a central role as data integration and handling platforms for geo-referenced 2D and 3D data in early warning and disaster management scenarios. Also, 3D planning and modelling in applications such as Building Information Models (BIM), 3D infrastructure planning, and 3D geological modelling may be supported by 3D geo-databases to efficiently store and retrieve plans, maps, and 3D models.

2. Retrospective on geo-database research

A geo-database system extends a traditional business database system by incorporating spatial data types in its data model

and query language. Furthermore, it supports spatial data types in its implementation, including spatial indexing (Güting, 1994). Concepts developed in the fields of geo-databases and spatial databases may be applied to both 2D and 3D geo-applications.

2.1. Milestones in the development of geo-database research

Overviews of geo-database research have been given by several authors (Goodchild, 1990; Guenther, 1990; Laurini and Thompson, 1992; Güting, 1994; Rigaux et al., 2002; Yeung and Hall, 2007; Brinkhoff, 2008).

Without claiming to present a complete list, we list some relevant milestones of geo-database research: Quadtree (Finkel and Bentley, 1974; Samet, 2006), R-tree (Guttman, 1984), Geo-Relational Algebra (Güting, 1988), formal definition of digital topological relations (Egenhofer, 1989a; Egenhofer et al., 1994), Spatial SQL (Egenhofer, 1989b), R*-tree (Beckmann et al., 1990), a model for space-time information (Worboys, 1994), and general search trees (Hellerstein et al., 1995). These milestones, listed here in chronological order, have strongly affected data modelling, the formalisation of spatial operations and spatial data management. In retrospect, Finkel and Bentley (1974), Samet (2006), Guttman (1984), Beckmann et al. (1990), and Hellerstein et al. (1995) had the greatest influence on the development of efficient spatial access methods for spatial information. With Geo-Relational Algebra, Güting (1988) made a significant contribution to the extension of Relational Algebra (the formal basis of currently widespread Relational Database Management Systems)

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to geometric 2D operations on point sets. The extension of spatial data models to the temporal dimension was influenced by Worboys (1994). ROSE Algebra (Güting and Schneider, 1993) allowed geometric operations to be defined formally in object-oriented database management systems. Egenhofer (1989a), Egenhofer et al. (1994), Pigot (1992), and Bertolotto et al. (1994) established formalisations for topological relations between geo-objects. This research significantly influenced GIS practise because topological and geometric predicates could then be embedded into spatial query languages (Frank, 1982; Egenhofer, 1989b; Egenhofer and Frank, 1988). Thus, geo-databases can answer spatial queries such as “What cities with more than 100,000 inhabitants are located within 100 km of the given point?” or “Return the intersecting geometry of the intersection between geological stratum A and fault X.” Significant contributions to 3D geo-modelling have been published by Mäntylä (1988) and Mallet (2002).

2.2. Geo-data modelling in geo-databases

In a given geo-database, data may be modelled in tables (relational database approach) or as objects (object-relational or object-oriented database approach) as parts of a geo-data model.

The separation of disciplines that model various real-world phenomena (topography, geology, atmosphere/climate, and ocean) has led to the definition of a variety of geo-objects, which are usually based on different representations, such as boundary representations and volumetric representations. This variation is not surprising because many factors have played a role in these developments. Traditionally, topographical objects (on the surface of the Earth) are the oldest phenomena modelled and therefore exhibit the greatest variation. Applications relying on geo-models have distinct needs: some applications may require models only for visualisation, while others may require models for analysis and statistics. The nature of the modelled objects also differs. The task of geo-database researchers is to find implementations for geo-models that provide efficient storage and retrieval of the models in geo-databases. Transformation is often necessary to convert a geo-model used for visualisation into a geo-model stored in the geo-database. For example, 3D topology and geometric models used in geology are designed to model volumetric objects. Attributes such as stratigraphy or petrography of the solid are usually included in models of geological solids (Mallet, 2002) (Fig. 1). Attributes may be attached to a specified part

(“sub-object”) of a solid. In contrast, 3D geometric and topological models of topographical objects (for example, visualisation of 3D city models) often require only boundaries (i.e., the hull of the 3D object). While geological and topographical objects have relatively crisp boundaries, climate and ocean models tend to represent continuous phenomena. Finally, it should not be forgotten that many models have been provided by software vendors that have used them for decades simply because of the extended functionality built on top of the models. This tendency does not simplify the task for geo-database researchers or practitioners who need to bring new geo-model data into a geo-database.

The heterogeneity of current geo-spatial geometric and topological data models shows the importance of standards for geo-databases. A single model, such as the standard Relational Data Model in Relational Database Management Systems, does not exist for geo-data models (Zlatanova et al., 2004). Particularly remarkable, however, are geo-data standardisation attempts by the Open Geospatial Consortium (OGC). These standards include the OGC Implementation Specifications for Geographic information: Simple feature access: SQL option, the ISO standard ISO 19107 “Feature Geometry” (Fig. 2) and “SQL / MM Spatial”. Of particular note is XML or the geo-version of XML, Geography Markup Language (GML), which is useful for exchanging spatial data in a unified way (OGC, 2010).

The use of XML and GML for modelling and sharing spatial data, however, is not undisputed and inflates the amount of data to be handled. This is not surprising, because XML was originally designed for modelling semi-structured data (i.e., linked texts) and not for handling structured and complex geo-data. An advantage of XML is its ability to automatically process documents that meet the rules of a specified grammar (document type definition (DTD) or XML schema). Most database vendors also offer XML solutions for existing database systems or native XML database management systems to manage XML data (Waterfeld, 2001). The storage of GML documents, however, is not integrated into database management systems because not all of the necessary XML schema elements are supported by GML. Instead, GML models are mapped to database models based on simple feature access specification (for example, CityGML). Similar attempts to define geo-data modelling standards have occurred in other domains, for example, GeoSciML (2009) has been developed in geology and TransXML (Scarponcini, 2002) has been developed in transportation. In addition to GML, KML

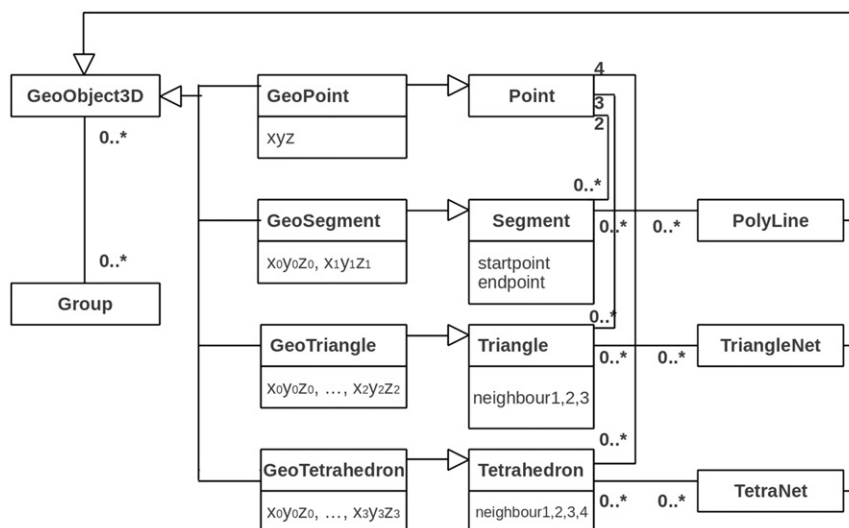


Fig. 1. Conceptual 3D geo-database topological and geometric model for complex natural objects.

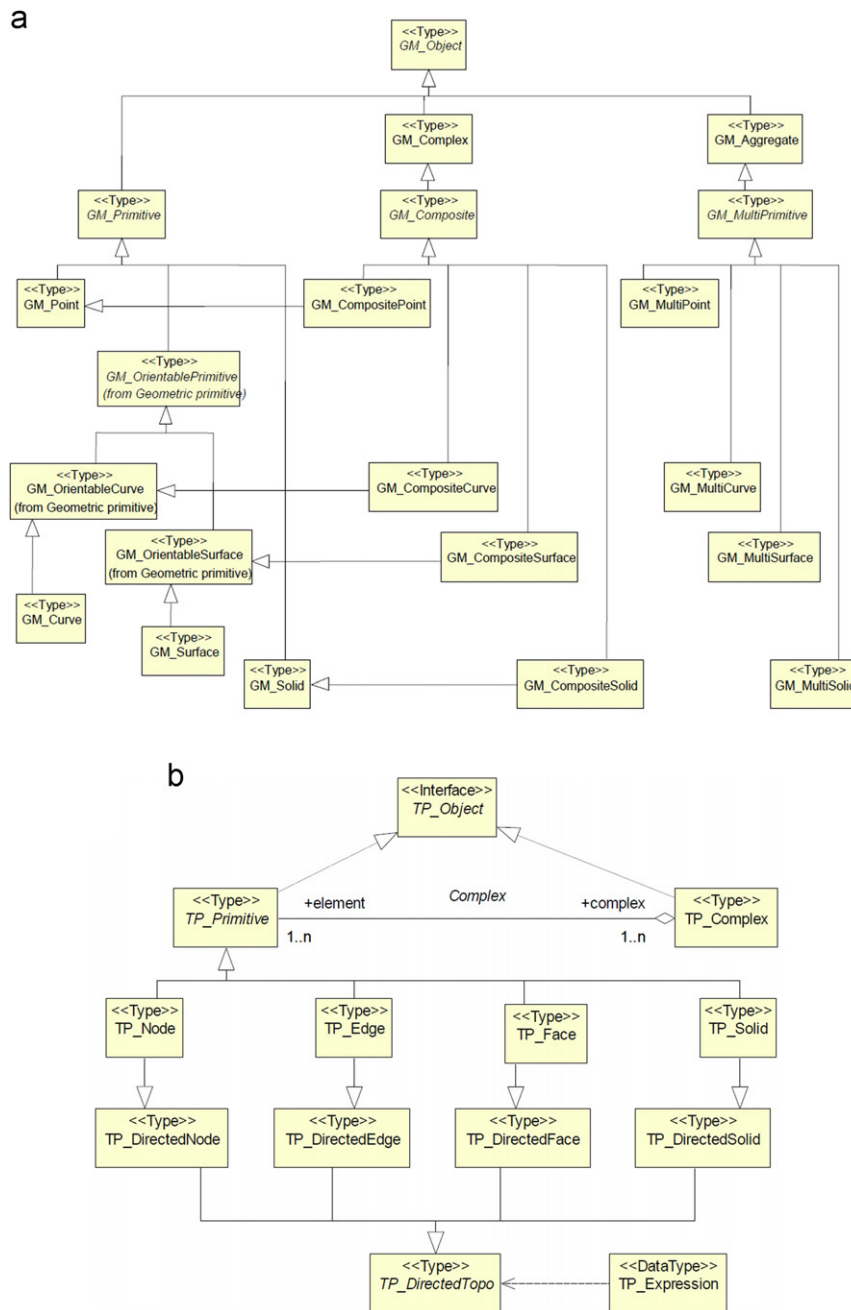


Fig. 2. Conceptual 3D geo-database geometric and topological models for complex man-made objects: (a) geometric abstract model and (b) topological abstract model (ISO 19107).

(Keyhole Markup Language), the markup language for the description of geo-data in client components of Google Earth, has become an OGC standard. KML follows XML syntax and allows the representation of vector and raster data, including a time stamp attribute.

2.3. Geo-data indexing

Since the early 1980s, researchers have examined efficient data management in geo-applications and developed spatial data structures and access methods (Tamminen, 1982; Guttman, 1984; Nievergelt and Hinterberger, 1984; Samet, 2006; Beckmann et al., 1990). However, despite the development of numerous spatial access methods – in contrary to the B-tree (Bayer and Mc Creight,

1972) in the one-dimensional case – none of the multi-dimensional access methods outperformed its competitors. Today, R-tree (Guttman, 1984) and its variant R*-tree (Beckmann et al., 1990) are the most frequently used spatial access methods.

R-tree and R*-tree can be seen as direct extensions of B-tree to access multi-dimensional data. In contrast to other spatial access methods, such as Quadtree/Octree on top of B-tree or Gridfile, R-tree and R*-tree allow the overlapping of cells containing geometric data. Therefore, objects are stored in exactly one leaf node of R-tree or R*-tree. Thus, large objects are not “cut” or stored separately in different leaf nodes of the tree. Furthermore, no space is wasted in R-tree and R*-tree because the user does not have to define a “universe”. The space needed during the application of the tree (minimum and maximum coordinates) does not have to be known before using the tree. In contrast to

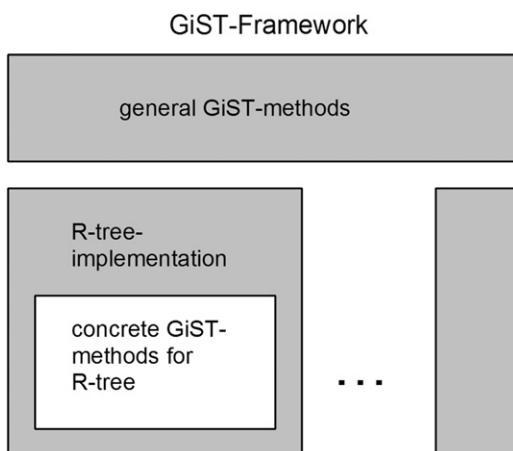


Fig. 3. GiST configured as R-tree seen from the user's perspective.

“space-driven” spatial access methods, such as Grid File and Quadtree, R-tree and R*-tree belong to the class of “data-driven” spatial access methods in which the space needed by the trees expands during the addition of data.

To ensure maximum flexibility for different application fields, the Generalised Search Tree (GiST) method (Hellerstein et al., 1995) has been developed. This method extends the concept of the search tree in such a way that the basic search tree logic for database systems is provided in a single data structure. GiST unifies structures such as B-trees and R-trees in a single piece of code. Using concrete-methods implementations of GiST overrides general GiST methods. Thus, GiST may behave like B-tree, R-tree, or any other customised spatial access method. Fig. 3 shows the architecture of a GiST configured as an R-tree seen from the user's perspective. In GiST, the concept of the search key is generalised to include any valid predicate for any date. In practise, the keys are defined by a user-defined object class, which provides a set of methods being queried by GiST. Examples of key structures include intervals of integers, bounding boxes and bounding sets of set-valued data. The key class is open to redefinition by the user. The user, who is the designer of the key class, must implement six GiST methods to control the search, inserting and deleting algorithms of the generalised search tree.

2.4. History of geo-DBMS

Since the 1980s, several geo-database management systems (geo-DBMS) have been developed in response to new requirements for geo-database applications. Examples include extensible geo-database systems such as those introduced in Neumann (1987), the DASDBS Geokernel (Paul et al., 1987; Schek and Waterfeld, 1986; Waterfeld, 1991; Waterfeld and Breunig, 1992), GRAL (Güting, 1988), SIRO-DBMS (Abel, 1989), and STARBURST (Haas and Cody, 1991). Some of these prototype systems have been designed on an object-oriented basis, such as OMS (Bode et al., 1992), O₂/GeO₂ (Bancilhon et al., 1992; David et al., 1993), GEO⁺⁺ (Vijlbrief and van Oosterom, 1992), GODOT (Ebbinghaus et al., 1994), GOODAC (Becker et al., 1996), and GeoToolKit (Balovnev et al., 2004). The latter geo-database prototype provides 3D and 4D geometric data types supporting temporal changes in 3D geo-objects. It has been tested with applications in geography, geology, and geophysics (Breunig et al., 1999). Finally, the EU project CHOROCHRONOS (Koubarakis et al., 2003) has developed spatio-temporal prototype database systems

(Breunig et al., 2003) including CONCERT (Blott et al., 1996), SECONDO (Güting et al., 2004), DEDALE (Grumbach et al., 1998), and TIGER (Böhlen et al., 1998). A number of freeware DBMS, such as PostgreSQL and MySQL, have offered geo-support that later expanded to a spatial extension. For example, PostGIS (Refractions Research, 2008), which is based on PostgreSQL (2010), provides 2D data types and seems to be one the most commonly used prototypes.

Although 10–20 years passed before the concepts of the prototype systems were implemented in geo-database products, their distribution is now increasing rapidly and opening new markets. The concepts of spatial data type, spatial access method and spatial query language have been realised in available Object-Relational Database Systems products implemented as so-called extenders, data blades or cartridges. For example, the OGC implementation specification “Simple feature access: SQL option” is followed in the data models of PostGIS, MySQL, Microsoft SQL server, and Oracle Spatial[®] (Zlatanova, 2006; Ravada et al., 2009). GiST as a spatial access method in secondary storage is implemented as B-tree and R-tree in the open software PostGIS. However, some manufacturers of proprietary GIS continue to manage spatial data in primary memory data structures rather than in geo-databases. For data storage, these manufacturers prefer a solution directly implemented in the file system, ignoring the advantages of geo-databases.

The goal of the predecessors of today's Geographical Information Systems was to automate manual activities such as map drawing. Some of the first GIS products were GRASS (GRASS, 1982), Arc/Info (Morehouse, 1985), TIGRIS (Herring, 1987), SPANS (Kollarits, 1990), THEMAK2 (Grugelke, 1986), and System 9 (1992). With exception of SYSTEM 9, which provided an integrated geo-database for the first time, only the thematic geo-data and not spatial data were stored in these systems. Geometric and topological data had to be processed separately in primary memory without consistency checks of the data or multi-user access. THEMAK2 has been coupled with a database geo-kernel to efficiently manage spatial data and thematic data using a geo-database (Waterfeld and Breunig, 1992).

Geo-database research has developed to a high standard, providing concepts and implementations to support the modelling and handling of geo-referenced data. However, geo-database user concerns and support of specific domains such as city planning, geology, and disaster management have been neglected in this research. It has been claimed by computer scientists and especially database researchers that each user must provide for her/his own specific requirements by building her/his own application-specific data types. However, today GIScience is closing the gap between the computer science world and real-world users of geo-applications. This trend will significantly influence the research and development of new geo-databases.

3. New directions for 3D geo-database research

In the 1990s, one of the pioneers of non-standard database management systems posited that database research should move “from the Kernel to the Cosmos” (Schek et al., 1990), meaning that data should come to the users in new database services. Unfortunately, this farsighted view on future database research has not been transferred to geo-databases. Some geo-databases provide an application-independent “kernel” of geometric and topological data structures and operations. The user, however, is left to combine these useful basic spatial data structures and operations to build specific geo-application services. Data integration services will play a special role in domain-specific software environments.

3.1. 3D data integration: bridging the geo-domains

The distinction between geology, ocean and atmosphere/climate vs. traditional topographical features (such as rivers, buildings, and streets) in 3D topological and geometric models seems to be obsolete. For example, new applications such as facility management and disaster management in cities require information about the interiors of buildings as walkable space (i.e., applying boundary representation). In other applications, such as cadastral surveys and insurance, the volume of a building might be of interest (i.e., applying volumetric representation). In this way, models that have been used predominantly by geologists (Fig. 1) can also be investigated for topographical objects (Peninga and van Oosterom, 2008) and even for indoor modelling (Verbree and Si, 2008).

Geo-databases could provide the framework to define the geometry and topology of nature-formed and man-made objects in a unified way. Today, many applications demand integrated models, requiring harmonisation of domain-specific models and modelling methods. The resolution and complexity of natural and man-made objects is reaching the same level. Nature-formed objects such as terrain models and geological formations are often highly complex, consisting of thousands or even millions of small geometric elements such as triangles or squares. Man-

made objects such as streets and buildings have been traditionally constructed with significantly fewer geometric elements and simpler shapes. However, as the modelling resolution of man-made objects increases (e.g., by considering windows, doors and other indoor elements), the complexity of models is becoming similar to those of natural objects. The combination of man-made and natural objects is important in applications such as building and infrastructure planning (see Fig. 4).

3.1.1. Unified modelling of geometry and topology

Geo-databases will also play an important role in bridging the geometric modelling of man-made and natural geo-objects. Therefore, it is useful to provide geometric primitives such as points, line segments, triangles, and tetrahedrons for both man-made and natural objects to construct more complex objects consisting of surfaces and solids. At a more abstract level, it also makes sense to distinguish between “AboveSurfaceObject”, “SurfaceObject”, and “BelowSurfaceObject” features (see Fig. 5). The geo-database then serves as a toolbox to access the geometries of complex geo-objects.

Unified topological modelling of natural and man-made objects requires a general approach based on clear mathematical theory and independent of the dimension and scale of geo-objects. Such a topological data structure must manage the

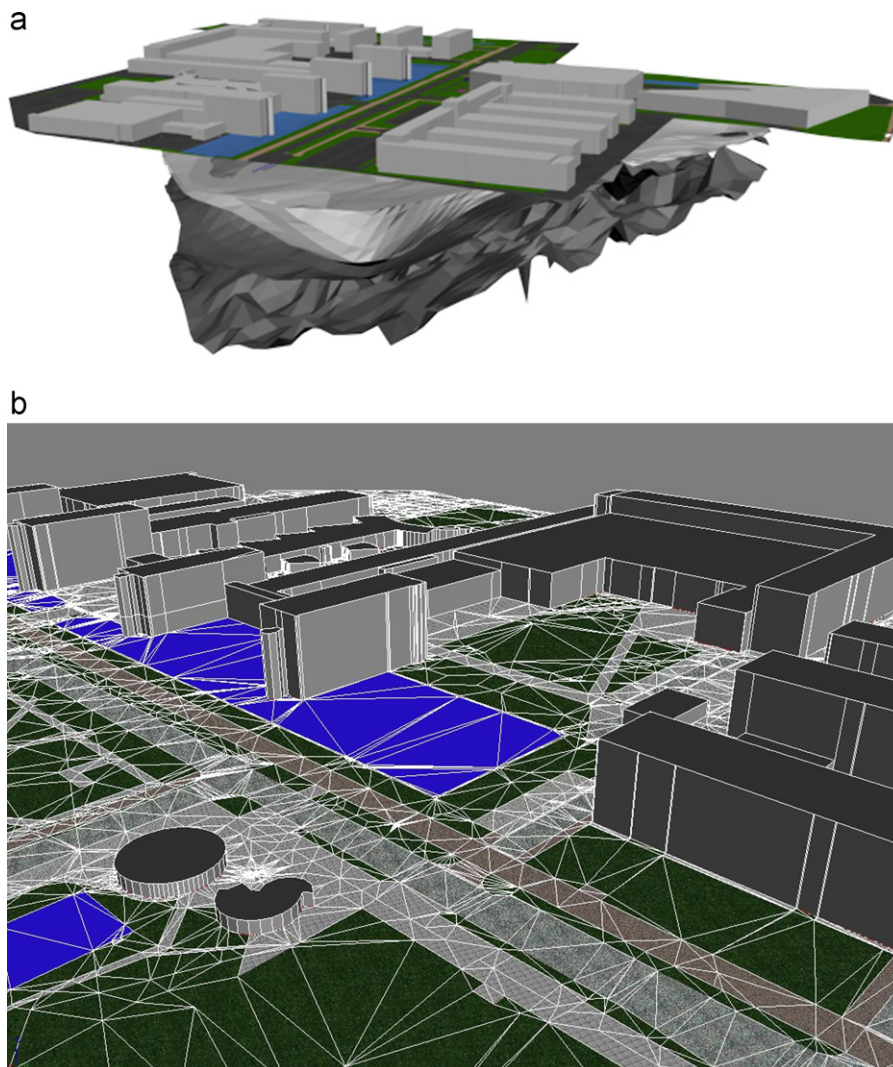


Fig. 4. Integration of natural and man-made objects: TUDelft campus modelled by Ludvig Emgard, Delft University of Technology, The Netherlands: (a) rendered snapshot and (b) triangulated surface features.

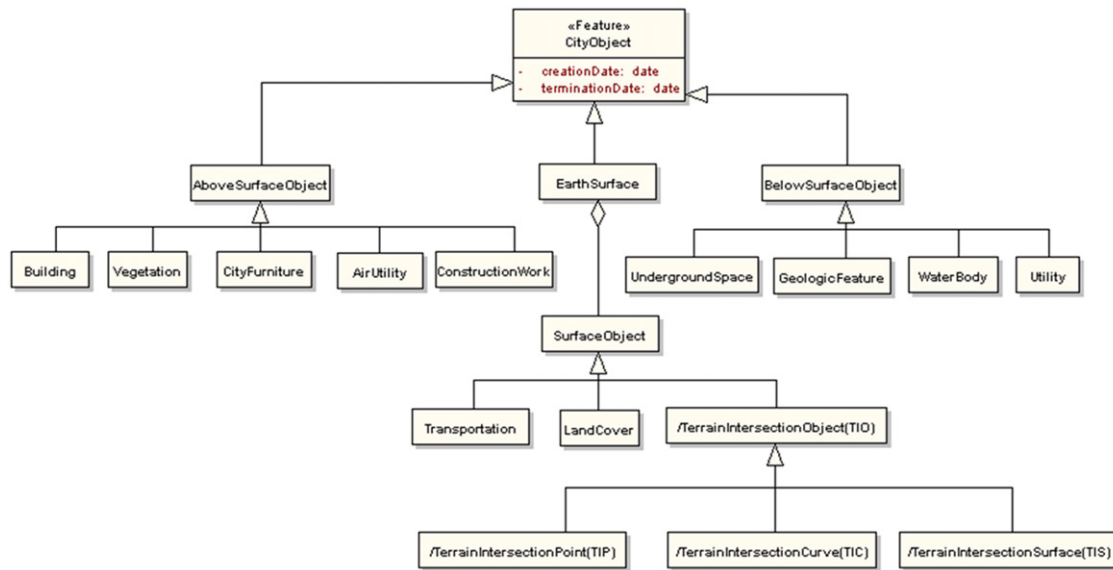


Fig. 5. A conceptual model for integrated man-made and natural objects (ocean and climate are not included) (Emgard and Zlatanova, 2008).

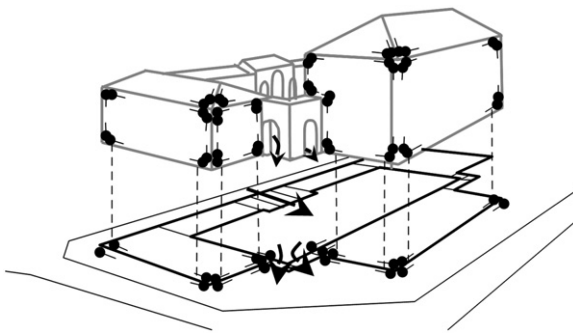


Fig. 6. Osnabrück Palace represented using G-Maps (constructed by Andreas Thomsen).

topology of complex spatial objects in two and three dimensions. New research (Thomsen et al., 2008) stresses that *d-Generalised Maps (d-G-Maps)* (Lienhardt, 1994) and the closely related *Cell-Tuple Structures* (Brisson, 1994; Penninga and van Oosterom, 2008), which for practical purposes can be considered equivalent (Lévy, 1999), are well suited as a dimension-independent and general approach for geo-scientific data modelling and data handling. G-Maps may be embedded in 2D or 3D space. In 3D space, for example, tuples describing a G-Map or Cell-Tuple Structure contain unique combinations between nodes, edges, faces, and solids. It is possible to navigate through topology by following nodes, edges, faces, and solids of one or more objects. G-Maps and Cell-Tuple Structures may be implemented as in-memory graph representations or as networks of tuples made persistent as relations in an Object-Relational Database Management System (ORDBMS). Fig. 6 shows the example of Osnabrück Palace as part of a 3D city model represented with G-Maps. Note that the archways represented in Fig. 6 require real 3D modelling. The G-Map data structure illustrated in Fig. 6 may be used not only to represent buildings (see Fig. 7(b)) but also to represent natural objects such as geological formations (see Fig. 7(a)). For example, the darts may connect neighbouring solids or surfaces belonging to a solid.

Fig. 7(a) shows an example of 3D topological modelling of an open cast mine in the Lower Rhine Basin (Siehl, 1993) internally

represented with G-Maps. Single tetrahedrons representing the geometry of the open cast mine are smoothly integrated into the topology of the Lower Rhine Basin modelled with G-Maps. This 3D model has been constructed by the geological group at Bonn University, Germany (Siehl, 1993). Fig. 7(b) represents the same idea (i.e., tetrahedron subdivision and topological modelling) applied to simple (extruded) buildings.

3.2. Bridging 2D and 3D worlds

Figs. 4 and 5 demonstrate the integration of surface objects with above-surface objects and below-surface objects, implying the integration of 2D and 3D objects. The 2D world is digitally represented as a map and the 3D world is realised as a 3D model, both being implemented in completely different data models. The 2D and 3D worlds are minimally integrated; usually, GIS platforms support only the visualisation of Digital Elevation Models (DEMs).

Well-known GIS data models use a layer-based approach. Combining different attributes of one object stored in one or more than one layer is not directly supported by the layer-based approach. Unfortunately, this approach prevents direct application in object-oriented environments and extension to the 3D world. Nevertheless, it may be useful to integrate 2D layers into 3D models. As a first step, topographical objects (man-made or nature-formed) that are typically perceived as 2D, such as rivers and roads, can be considered. This type of integration has been suggested by Gröger and Plümer (2005) and further developed in CityGML. Although the first version of CityGML still distinguishes between 2D surface features and terrain (represented as 2.5D, 3D TIN), ongoing research seeks to integrate surface features and terrain into one surface by introducing “terrain intersection curves” for all features that touch/intersect the terrain (Emgard and Zlatanova, 2008). Fig. 4(b) illustrates integration of all surface features (and features that touch the Earth’s surface) in one model.

In general, there is no impediment to integrating a 3D city model with a 2D city map in a geo-database by using a unified 2D and 3D modelling approach. For example, G-Maps can be used as a dimension-independent data structure and a unified topological

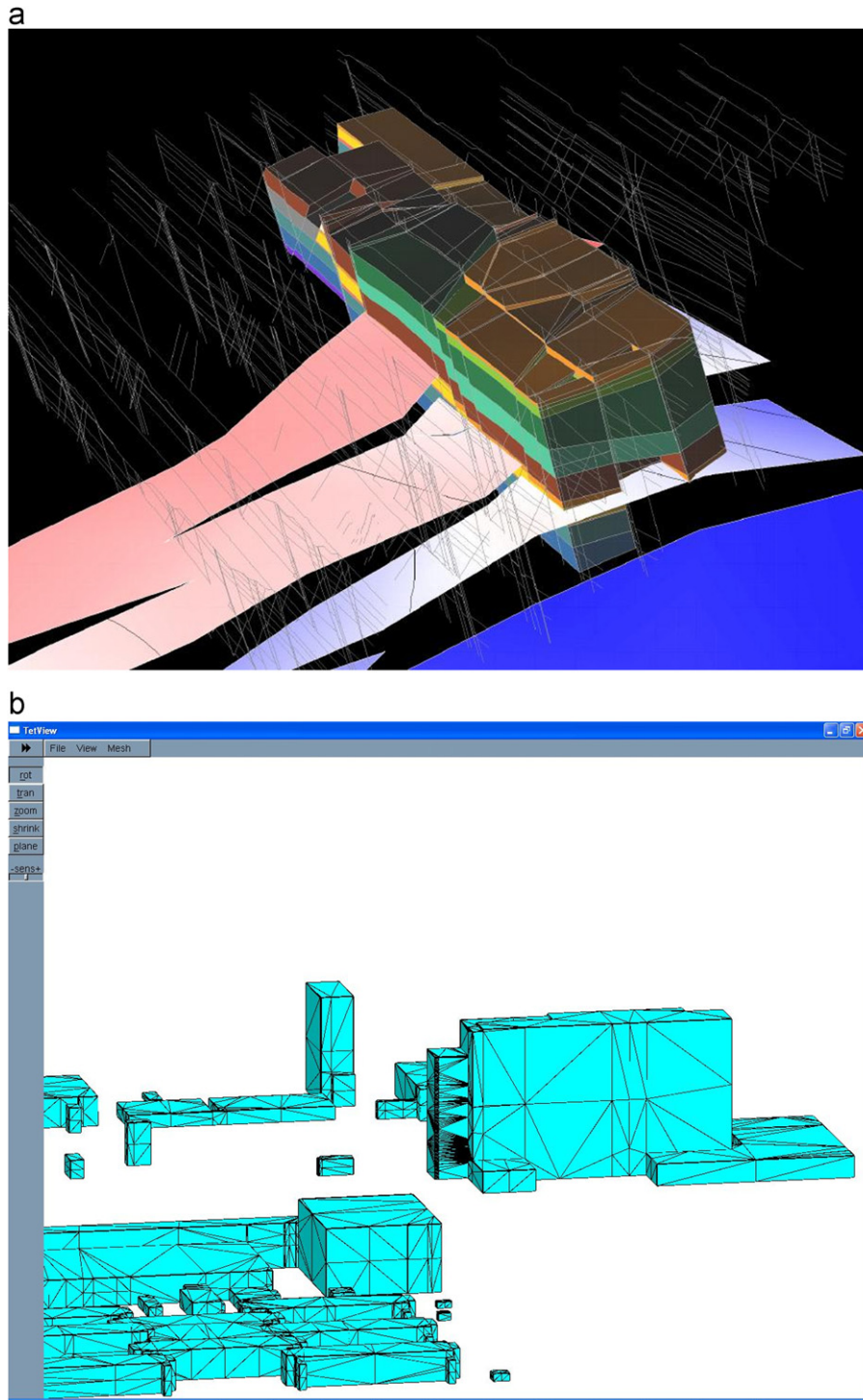


Fig. 7. Natural and man-made objects: (a) Lower Rhine Basin, Germany, overlaid with a complex geological 3D model of an open cast mine internally modelled with G-Maps (edited by group of Agemar Siehl, Bonn University with Gocad software, distributed by Paradigm Ltd.); (b) TU Delft campus buildings (Peninga and van Oosterom, 2008).

2D and 3D data model could be attached with the corresponding geometric 2D and 3D data. However, some issues must be taken into consideration when integrating 2D and 3D. First, the user must carefully consider which features from 2D maps should be taken into the 3D model. As Fig. 7(b) illustrates, the complexity of TIN can become extremely, high even in case of major surface features (such as streets, water, and gardens). Second, it is important to reconsider the resolution at which the features are represented. Many existing 2D data sets contain a large number of vertices along the polygons delineating a feature, which also

complicates the TIN of the surface. Finally, not all layers existing in a 2D GIS will be integrated in a single 3D model. It might be still necessary to distinguish between domain-specific 3D models, for example, a 3D cadastral model, a 3D model of topography, and a 3D model of land use.

3.3. New user interfaces for 3D geo-databases

To date, geo-database research has only selectively examined the development of novel user interfaces (see Vosiard, 1992).

Great potential exists, and new user interfaces should be explored. The emergence of virtual reality (VR) environments such as Google Earth and Visual Earth has made access to and sharing of 3D models quite natural. Despite many deficiencies (e.g., difficulties in visualising underground features or attributes), the success of these visualisation tools is greater than that of traditional 3D web-based viewers (based on VRML and X3D). Similar success is expected for CityGML (since it contains semantic values of the features) if more efficient browsers and viewers are developed promptly.

The inclusion of augmented reality (AR) methods, which overlay 3D models as virtual information with the physical environment in real time, is one of the possible new user interfaces for geo-database use. Approaches for mobile augmented reality systems have been described by [Reitmayr and Schmalstieg \(2003\)](#), [Breunig et al. \(2005\)](#) and other authors. For planning and analysis and for the management of natural disasters such as flooding, the real world can be overlaid with 3D models stored in a database. To date, however, geo-database and AR development have been treated separately. Medicine (with the development of "glass patients") has taken a pioneering role by using virtual storage of data obtained prior to an operation, such as CT ([Suthau et al., 2002](#)). However, the connection to powerful databases is still missing. In the field of geo-technology, the coupling of geo-database technology with AR could be used to support the planning of buildings and structures (towers, bridges, dams, tunnels) ([Wursthorn et al., 2004](#)).

[Fig. 8](#) shows how the AR interface of a geo-database might look. In the flood scenario application shown in [Fig. 8\(a\)](#), the user could view objects represented as 3D models in the geo-database along with the height of the simulated water levels around the buildings. In addition, real objects in the environment (in this case, buildings at the University of Karlsruhe) could be viewed in video mode. In the geo-database query interface, typical spatial database queries could be formulated, such as "How many cubic metres of water will be in the building if the water height is one metre above ground level?" A similar scenario from TU Delft is shown in [Fig. 8\(b\)](#). Augmented reality has been used in a variety of applications, including urban planning ([Zlatanova and van den](#)

[Heuvel, 2002](#)) and visualisation of utilities ([Roberts et al., 2002](#)). Augmented reality is a promising technology for 3D visualisation of the real world, keeping in mind the complexity of models and representations as discussed above. 3D models generally result in large data sets, which require special techniques for rapid visualisation and navigation. In contrast, only a few objects must be visualised in applications of AR technology, guaranteeing better performance. Recent developments in AR technology can also be found in the fields of context-based navigation ([Ten Hagen et al., 2005](#)), ubiquitous mapping ([Morita, 2007](#)), and neogeography ([Goodchild, 2009](#)). Augmented reality remains challenging, however, due to the high requirement for positioning, synchronisation of virtual and real objects and movements of the human body.

3.4. 3D/4D geo-information systems

In recent years, interest in 3D/4D geo-information systems has increased significantly ([Breunig 1999, 2001](#); [Shumilov et al., 2002](#); [Siebeck, 2003](#); [Wu and Xu, 2003](#); [Coors and Zipf, 2004](#); [Schaeben et al., 2003](#); [Güting and Schneider, 2005](#); [Zlatanova and Prosperi, 2006](#); [Breunig and Zlatanova, 2006](#); [Abel, 2006](#); [Rahman et al., 2006](#); [Sprague et al., 2006](#); [Frank et al., 2007](#); [Oosterom et al., 2008](#); [Lee and Zlatanova, 2006](#); [Neutens and De Maeyers, 2010](#)). Climate modelling, the study of mass movements after natural disasters, and oil and geothermal exploration are well-known applications that depend inherently on temporal 3D modelling. In most cases, down-scaling from 3D to 2D is possible, but not up-scaling from 2D to 3D or 4D. Therefore, 3D geo-modelling ([Mallet, 2002](#)) is a sophisticated research that is urgently needed to construct new 3D/4D geo-information systems. Surprisingly, the definition and implementation of operations supporting geo-scientific interactive 3D modelling have not been studied systematically. However, such operations are necessary for editing and managing spatial objects in interactive geological and geophysical modelling tools ([Siehl, 1993](#); [Götze and Lahmeyer, 1988](#)). [Fig. 9](#) shows a small part of a geological 3D model of the Lower Rhine Basin, Germany, managed by a 3D/4D Geological Information System.

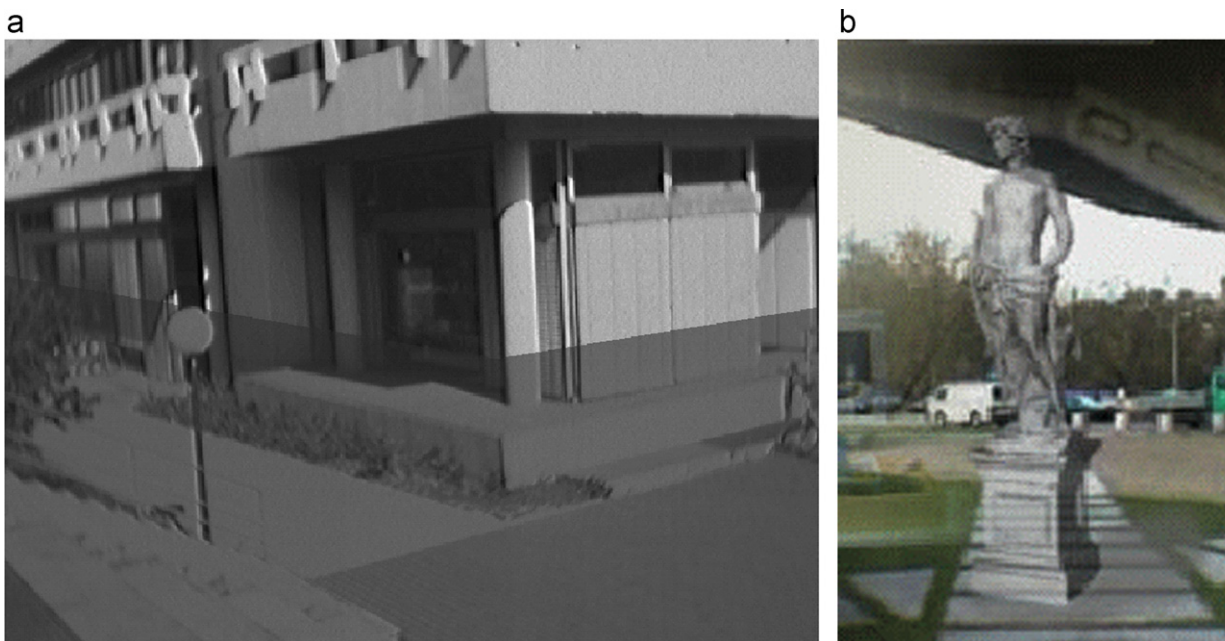


Fig. 8. Future AR interface for geo-databases: (a) overlay of the simulated water level on the topography of a building model (figure from IPF, University of Karlsruhe, [Breunig et al. 2005](#)); (b) overlay of a new planned decoration (statue) on the TU Delft campus ([Zlatanova et al., 2002](#)).

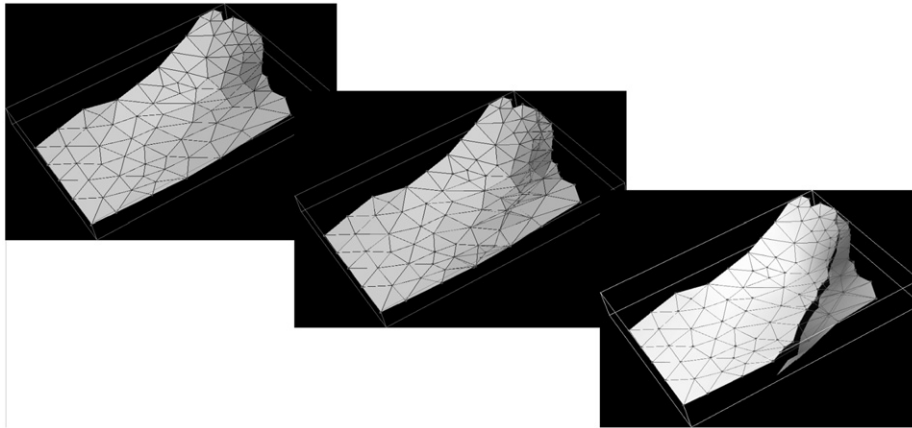


Fig. 9. Changing geometries and topologies during the Oligocene in part of the Lower Rhine Basin, Germany.

Future key areas for research include spatio-temporal data models, temporal geometry and topology operations in geo-database systems, spatio-temporal integrity checking of geometry and topology, and spatio-temporal similarity search (pattern comparison of 3D objects). To model 3D changes over time to simulate geological processes, changes in both geometry (expansion) and topology (discretisation) must be considered. Thus, the design and implementation of geometric and topological database operations for moving 3D objects is a focus of interest.

3.5. Evaluation of geo-sensor networks

Sensor networks have a wide range of applications, including geological and environmental monitoring. Sensor networks can be roughly divided into two categories: applications with essentially static node topology and applications with highly dynamic node topology. Nodes in the first class do not move or move only very little, and changes in topology occur by node failures. Examples include applications for nature conservation (Schwiebert et al., 2001; Mainwaring et al., 2002), health and environmental monitoring (Ailamaik et al., 2003), and volcanic monitoring (Werner-Allen et al., 2005). The second class of applications is characterised by dynamic topology due to sensor movements. Examples include car navigation aiming to innovative driver assistance and deformation analysis for buildings such as bridges and tunnels.

Currently, wireless sensor networks in economics and science are used to record individual parameters, such as temperature and humidity, at fixed periodic time points using a priori-specified query predicates of the sensor database. However, spatio-temporal queries and reactions to certain internal combinations of parameters are not adequately supported by these sensor networks. Future research is likely to focus on spatio-temporal data storage for geo-sensor networks. Query approaches for static and restrictedly dynamic sensor networks must also be developed, as well as methods for the analysis of measured data provided internally by the network. The longevity requirement of the sensor network must be balanced with the measuring frequency and use of the data. For example, nodes of the network should “sleep” during time intervals when they are not explicitly activated by sensor-database queries. The use of large quantities of relatively cheap sensors promises, for example, a qualitative improvement in measurement methodology in the development of new climate models and their applications (weather forecasting, climate research). Sensor networks have great potential to

examine different assumptions for the first time in many regional climate models (Mariño et al., 2008).

In the European context, the location and temporal monitoring of infrastructure such as railway networks during storm damage, snow or other unforeseen events has been discussed previously (EU Research, 2009). In addition, peer-to-peer (P2P) communication between indoor sensors or between sensors located on moving objects, such as ships or cars, is becoming increasingly important.

4. Scenarios

The following scenarios show that interdisciplinary applications in the context of early warning against natural hazards and emergency response require 3D geo-databases as central tools for data handling.

4.1. Early warning systems against natural hazards

Geological events such as earthquakes, landslides, and tsunamis are primarily triggered by physical processes, but they affect all humans located nearby. When humans are affected, a geological event becomes a disaster, requiring early warning of the affected human population. Early warning includes the analysis of geological processes long before an event takes place as well as short-term warning procedures.

The purpose of an early warning system against natural hazards is to predict events for the protection of lives and property (Smith, 2004). To achieve reliable early warning, the available data must provide information to serve as a reliable basis for warning decisions and preventive measures. Data preparation is a weak point in the early warning chain (Breunig et al., 2007).

Fig. 10 illustrates the workflow for an early warning system scenario (Breunig et al., 2007). First, information, measured values and textual descriptions are collected by authorities and affected persons. Filtering and interpretation of the data takes place in components of the early warning system. GIS and simulation results based on 3D and 4D data and operations derived from the geo-database provide important information to complement the collected data. Finally, information filtering leads to decisions and actions, including warnings and directives to be executed by the responsible authorities.

Fig. 11 shows a part of the “Isar valley” in South Germany which has been selected as application area for further studies in Breunig et al. (2007). In this area, the height difference of the

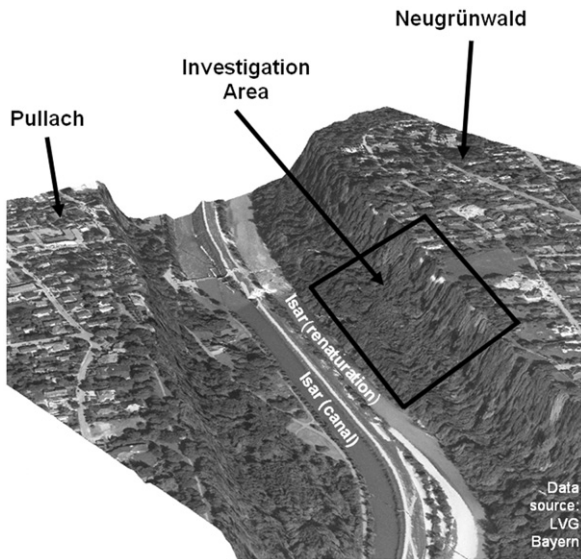


Fig. 10. Isar Valley early warning application area.

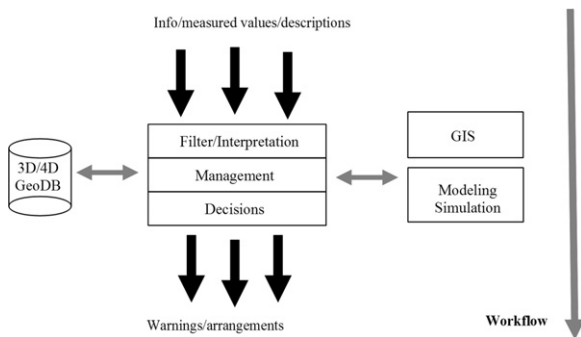


Fig. 11. Workflow for an early warning system.

slope reaches up to 40 m and the potentially endangered human infrastructure is located near the edge of the slope. Because of the risk potential, the area is observed by the responsible authorities (Bayerisches Landesamt für Umwelt), and corresponding sensor measurements (inclinometer and extensometer) and geodetic surveys are available. Further data include the digital topographic data, groundwater level measurements, drilling profiles, and geotechnical material parameters. In Breunig et al. (2007) the combination of different methods from spatial data mining, geo-databases, GIS, simulation, and linguistics (extraction of spatial information from texts) is examined to support the endangering assessment of landslides. In the project the service-oriented geo-database architecture DB4GeO/DB3D (Breunig et al., 2004, 2009; Bär, 2007) is used.

Fig. 12 shows an example of a database query on the digital elevation model for the selected area. The following list demonstrates examples of internet-based access to the geo-database architecture via a standard web-browser currently implemented using REST (Fielding, 2000). For example, the following spatio-temporal database queries may be answered by DB4GeO/DB3D:

- “Get one specified geo-object at a specified time step”.
- “Get all geo-objects contained in a 4D space at a specified time step”.
- “Get one specified geo-object and all of its time representations in one response”.

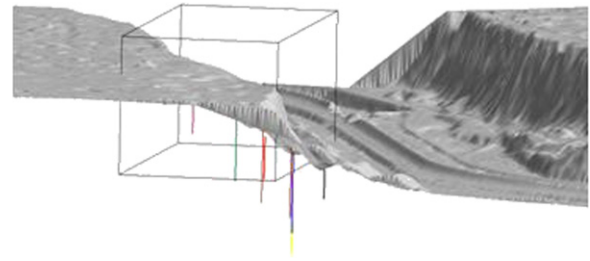


Fig. 12. Example of a spatial-database query for surface and drilling data (model constructed by Gocad Software, distributed by Paradigm Ltd.)

“Get all geo-objects and all of their time representations in one response”.

The REST requests for these four sample queries, which can be sent to the geo-database via a standard web browser, are as follows:

```
http://server/projects/p1/area1/object?getTimeStep(STEP)
http://server/projects/p1/area1/all?getTimeStep(STEP)
http://server/projects/p1/area1/object.gml
http://server/projects/p1/area1/all.gml
```

These basic queries may be combined by the user to perform complex geo-database services, such as “4D-to-3D service” providing 3D objects from a 4D model (Breunig et al., 2009).

4.2. Emergency response

The goal of emergency response is to save human lives and to reduce property damage. Emergency response activities are usually coordinated by command and control systems (CCS). Presently, typical CCSs focus on sharing information; significant attention is paid to well-defined and spatio-temporally extended GIS functionality or to advanced 3D visualisations. Only recently has research been directed toward the use of 3D outdoor and indoor models for evacuation of buildings (Lee, 2004; Meijers et al., 2005; Zlatanova et al., 2005; Becker et al., 2009). For example, Meijers et al. (2005) suggest a 3D indoor modelling approach to facilitate navigation out of buildings. Their modelling approach takes into consideration the reconstruction procedure (laser scanning). They suggest an indoor space subdivision to derive an appropriate network for computation of optimal paths. The proposed model still does not integrate information from the progression of the disaster (e.g., the spreading of fire, smoke, and flooding). At present, such computations are available only in dedicated applications (e.g., for computing plume volume or flooding area) or for training and simulations.

In this context, developments in BIM are of great importance. Building information models are capable of containing both geometric and semantic information, and they are intended to cover all stages of the building or facility lifecycle (i.e., from conceptual design to maintenance to demolition). Recent studies in this field demonstrate that it is possible to transfer the required level and amount of 3D geometric and semantic information from an industry-standard Building Information Model (Industry Foundation Classes, IFC) into a geospatial environment.

5. Outlook—new technical solutions for geo-databases

Despite the progress observed in many fields, we still lack the ultimate 3D model that will allow us to integrate different representations and models from different domains. Transformation between specific representations, such as B-Rep and

tetrahedron networks, is a pragmatic solution to this problem. Concerning geometry and topology, the two data models (geometric and topological) presently suggested by OGC and implemented in many DBMS will be in use for a long time. It has been proven that geometric models perform better in visualisation and some operations. However, topology is expected to be beneficial when topological relationships are investigated. Topological models will certainly guarantee data consistency. Research and development are needed in both types of models. Although primitive 3D functionality has been implemented in some databases, such as Oracle Spatial[®], geometric models need further maturation and extension of their spatial functions. Important functions related to 3D models include consistent conversion to GML models for export and information sharing and generic functions for data reduction, such as generalisation, back-face culling, and field-of-view.

Currently, no commercial geo-DBMS can maintain 3D topological models. Several implementations of 2D topology exist, and some mainstream vendors promise native support of 2D topology (e.g., Oracle Spatial 10i). Still, many issues demand attention. For example metadata for topological models might be a workable solution to the challenge of 3D topological models (e.g., Oosterom et al., 2002). Such metadata would permit maintenance of many topologies in a single geo-DBMS. Another important aspect is the development of (spatial) indexes for topological models. Presently, the spatial index works well only with geometric models. Last but not the least, operations on topological models, including conversion to geometric models, are important. We expect that the 9-intersection model will perform better when implemented in a topological model than when implemented in a geometric model.

Maintenance of multiple representations to be used as Levels-Of-Details is another critical aspect of large three-dimensional models (Thomsen et al., 2008). The consistent management of multiple representations is still far from being formalised. Currently, there are no formal rules for transition from one 3D LOD to another. Development of such rules might be a breakthrough in 3D generalisation techniques. Such rules will permit only the most detailed model to be persistently stored because any other LOD could be derived on demand.

Although not critical for most natural objects, management of texture and mechanisms for texture mapping and texture draping are critical for management of realistic 3D topographical object models. Man-made 3D features are often textured with images from the real world. As 3D models continue to develop, textures will be required for maintenance. Textures can be understood as 'presentation' attributes of 3D objects. Appropriate indexing of texture images is required.

To model more real-world phenomena, 3D models must be extended with new representations such as parametric shapes, freeform curves and surfaces, as discussed in (Breunig and Zlatanova, 2006). The 3D spatial functionality regarding such complex 3D spatial data types must be further defined. The role of databases remains an open question: can they be seen primarily as repositories of data or as systems that provide certain functionality? In our opinion, functionality should be developed (or extended) according to the extent of objects to be maintained in the database. As soon as 3D geometry (with extended primitives) and topological models are supported, a database should provide functions and operations for validity, generic analysis and seamless conversion between models. Import and export should be also synchronised with 3D geo-data standards.

Progress in sensor products clearly demands the attention of database researchers. A database should be able to efficiently manage un-processed raw data such as large point clouds (which are problematic for current point data types) derived from bathymetric, air, ocean and other sensor measurements and

observations. Persistent storage of raw data will support the 3D modelling process, allowing re-use of source data while constructing a 3D model.

6. Conclusions

Building upon a 25-year retrospective of geo-database research, we have outlined new directions for 3D geo-database research that will open new fields of interdisciplinary study. Important directions include the integration of 2D and 3D data models and the development of dimension-independent topological and geometric data models. These data models should be uniformly usable for both 2D and 3D worlds. If these spatial data integration challenges are not solved and incorporated into current geo-data standards, we expect the development of many separate 2D and 3D solutions in the future. Such solutions would avoid seamless data integration. Thus, challenges for future research include spatial data integration, new user interfaces for geo-databases, development of 3D/4D geo-information systems, and geo-sensor databases. Two scenarios in the fields of early warning against natural hazards and emergency response demonstrate the application of some of the concepts presented in this article.

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