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Research Article

Technological aspects of a full 3D cadastral registration

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In this paper, we present a new conceptual model for a full 3D cadastral registration system. Two important components are: (1) the 'surface parcel partition' based on a detailed elevation model and (2) the volume parcel and its representation. Technological solutions for both parts are not yet available in commercial Geo-ICT software, and therefore solutions have been investigated, designed and developed (in a Geo-DBMS environment). A number of countries in the world do already have legislation allowing the registration of volume parcels, sometimes even including detailed regulations for 3D survey plans. However, until now, these have not yet been integrated in the cadastral information system. A 3D case from Queensland, Australia is presented, and a prototype is realized based on an integrated 3D cadastral information system: elevation-model-based surface parcels complemented with volume parcels.

Keywords: 3D cadastral information system; 3D models; Integrated height model

1. Introduction

During the last two centuries, the population density has increased considerably, making land use more intense. This trend has increased the importance of land ownership, which has changed the way humans relate to land. This changing relationship necessitated a system in which property to land is clearly and indisputably recorded. In this article, such a system is referred to as a 'cadastre', although many systems with different names are instituted worldwide, which fulfil (more or less) similar tasks, such as cadastral registration, cadastral system, land registry, land registration, land administration, property register and land book.

Individualization of property originally started by subdividing the surface into property units using 2D boundaries. For this reason, the basic entity of current cadastral maps is the 'parcel', which makes the cadastral map a 2D map. To ensure completeness and consistency, 2D parcels may not overlap, and gaps may not occur (forming a surface partition). Although parcels are represented in 2D, someone with a right to a parcel always has in general been entitled to a space in 3D, i.e. a right of ownership on a parcel relates to a space in 3D that can be used by the owner (this includes space above and below the parcel as well) and is not limited to just the surface parcel defined in 2D without any height or depth. If the right of ownership

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only applied to the surface, the use of the property would be impossible. Consequently, from a juridical point of view, cadastral registration always has been 3D. The 2D approach of registration has been adequate for decades to give an insight into traditional property situations, where it is clear which persons are entitled to which parcels (including space above and below the parcel). However, one could question whether traditional cadastral registration, which is based on the concept of a 2D parcel, is also adequate for registering all kinds of situations that occur in the modern world.

Pressure on land in urban areas and especially their business centres has led to overlapping and interlocking constructions. The creation of property rights to match these developments is available within existing legislation, but describing and depicting them in the cadastral registration poses a challenge. The challenge is how to register overlapping and interlocking constructions and how to register the property situations above and below the surface in a cadastral registration that registers information on 2D parcels. Although properties have been located on top of each other for many years, it is only recently that the question has been raised as to whether cadastral registration should be extended into the third dimension. Growing interest for 3D cadastral registration has resulted from a number of factors:

- a considerable increase in (private) property values;
- the number of tunnels, cables and pipelines (water, electricity, sewage, telephone, gas, glass-fibre data cables, coax TV cables), underground parking places, shopping malls, buildings above roads/railways and other cases of multilevel buildings has grown considerably in the last 40 years;
- an upcoming 3D approach in other domains, 3D GIS (Geographical Information Systems), 3D topographic data, 3D data collection (GPS, laser, surveying), and 3D planning, which makes a 3D approach of cadastral registration technologically realizable.

At the TU Delft, the Netherlands research has been carried out to study the needs, possibilities and constraints of a 3D cadastre (Stoter and Ploeger 2003, Stoter and van Oosterom 2003, Stoter 2004). This resulted in several conceptual models for a 3D cadastre, which were translated into prototype implementations. In this article, we present the conceptual model that showed the best potential for the long-term future (section 2). Sections 3 and 4 describe technical aspects on how to translate the proposed conceptual model into prototype implementations. Section 3 details how to represent traditional parcels in 3D space by a height surface of parcels, and section 4 describes a solution for representing volume objects in a Geo-DBMS. Some countries already have a legal framework for the registration of 3D property situations. These solutions are discussed and evaluated in section 5. We will apply our conceptual model to one of these examples, a case study in Queensland, in order to show how our proposed model of the 3D cadastre research can improve 3D cadastral registration. This article ends with conclusions in section 6.

2. Optimal conceptual model of a 3D cadastre

The term '3D cadastre' can be interpreted in many ways ranging from a full 3D cadastre supporting volume parcels, to traditional cadastres in which limited information is maintained on 3D situations. In our research, we have identified three different conceptual models for a 3D cadastre (with several alternatives):

1. Full 3D cadastre, in which persons can explicitly be entitled to volumes:
   - Alternative 1: Combination of (traditional) infinite parcel columns and volume parcels
   - Alternative 2: Only parcels are supported that are bounded in three dimensions (volume parcels)
2. Hybrid cadastre, in which persons are entitled to volumes by giving them rights on the intersecting parcels:
   - Alternative 1: Registration of 2D parcels in all cases of real property registration and additional registration of 3D legal space in the case of 3D property units (within one parcel, using a bottom and top height level of the space to which rights apply)
   - Alternative 2: Registration of 2D parcels in all cases of real property registration and additional registration of physical objects (in 3D space)
3. 3D administrative tags/warnings linked to parcels in current cadastral registration

In our research, the full 3D cadastre was evaluated as the most sustainable solution for 3D registration (Stoter 2004). The last solution (3D administrative tags and warnings) has proven to be a good starting-point (it is current practice in many cadastral registrations). However, a fundamental lack of this approach is that neither spatial nor non-spatial information on the 3D situation is integrated in the cadastral registration: the 3D information is stored in separated files. The hybrid approach has shown to be a good alternative for cadastres that are still very much land (surface)-oriented, i.e. a right to real property can only be established by encumbering the intersecting surface parcels with limited rights and restrictions. Therefore, one basic principle is not addressed. Since the legal status is still registered by means of land parcels, querying the legal status in 3D still means collecting information on the legal status of the intersecting surface parcels.

The FIG Bathurst Declaration (FIG 1999) concluded that 'most land administration systems today are not adequate to cope with the increasingly complex range of rights, restrictions and responsibilities in relation to land'. As in the Netherlands, many other existing cadastres are still based on the paradigm of a land parcel that has its origin centuries ago. This paradigm needs to be reconsidered and adjusted to today's world. Although parcels are traditionally represented in 2D, someone with a right to a parcel has always been entitled to a space in 3D. This led to no disputes as long as only one person was entitled to a land parcel, since the traditional cadastre was capable of reflecting such property situations. However, in recent times, stratified property is common practice, and in many countries multifunctional use of space is official planning policy. Also, the way humans relate to land has changed drastically (the value of private property has increased considerably). Today's cadastral registration should therefore reflect the true principle of property rights that entitle persons to volumes and not to just areas. The ultimate ambition for 3D cadastral registration should therefore be a full 3D cadastre in which it is possible to entitle persons both to unconstrained parcel columns that are defined by boundaries on the surface and to bounded amounts of space (volume parcels).

In a full 3D cadastre, a 3D space (universe) is subdivided into volumes partitioning the 3D space. The legal basis, real-estate transaction protocols and the cadastral registration should support the establishment and conveyance of rights that explicitly entitle persons to volumes (i.e. 3D rights). The 2D cadastral map does not lay down any restrictions on 3D rights: 3D rights are not related to the surface configuration (as is the case in the two other conceptual models of a 3D cadastre). Real-estate objects can be defined in 3D. Rights and restrictions can be related to volumes. Relationships between two volume parcels may be necessary to take care of the accessibility of a volume parcel, for example, which is not directly connected to the surface.

2.1 *Only volume parcels or combination with parcels defined by surface boundaries*

In the full 3D cadastre, alternative 2, the only real-estate object that is recognized by the cadastre is a volume parcel (bounded in all dimensions). These volume parcels form a complete partition of the domain in 3D space. In this solution, it is no longer possible to entitle persons to infinite parcel columns, defined by surface parcel boundaries, but only to well-defined (and totally bounded), surveyed volumes. In this alternative, the cadastral registration of the whole country is converted into 3D. The question can be posed if a full 3D cadastre that only supports volume parcels is realistic for cadastral registrations that have a long history and already contain a large amount of information that is related to 2D parcels which still suffice in many cases. This requires a total renewal of the cadastre, also in 2D situations: traditional 2D situations (parcels with no other owners in the 3D column) also need to be changed. Therefore, in our research, we focused on the more realistic alternative of a full 3D cadastre, which combines volume parcels with parcels that are defined by parcel boundaries on the surface (but which correspond to the infinite parcel columns in 3D space).

2.2 *Full 3D cadastre that combines volume parcels with parcels defined on the surface*

The full 3D cadastre that combines parcels defined on the surface (corresponding to infinite 3D parcel columns) and volume parcels starts with the currently registered parcels (that still suffice in many 2D situations). In addition to the infinite parcel columns, volume parcels are distinguished. In this solution, the real-estate object (the types of objects that are registered) can be:

- parcels, representing either infinite parcel columns, or columns of space from which volume parcels have been subtracted: these parcels are actually defined in 3D (based on the 2D surface representation);
- volume parcels (fully bounded in 3D);
- restriction areas (similar to the traditional parcels, only defined in 2D);
- restriction volumes (fully bounded and defined in 3D).

The UML class diagram of this solution is shown in figure 1 (see also Lemmen *et al*. 2003). The collection of the 2.5D surfaces of parcels (parcels draped over a height surface) explicitly covers the whole surface (without overlaps and gaps), that is, a complete surface partition. This is further examined in section 3. This is a very important concept in cadastral registration in order to avoid inconsistencies. A Parcel implies the whole 3D column above and below the surface or what is left after volume parcels have been subtracted from the parcel column.

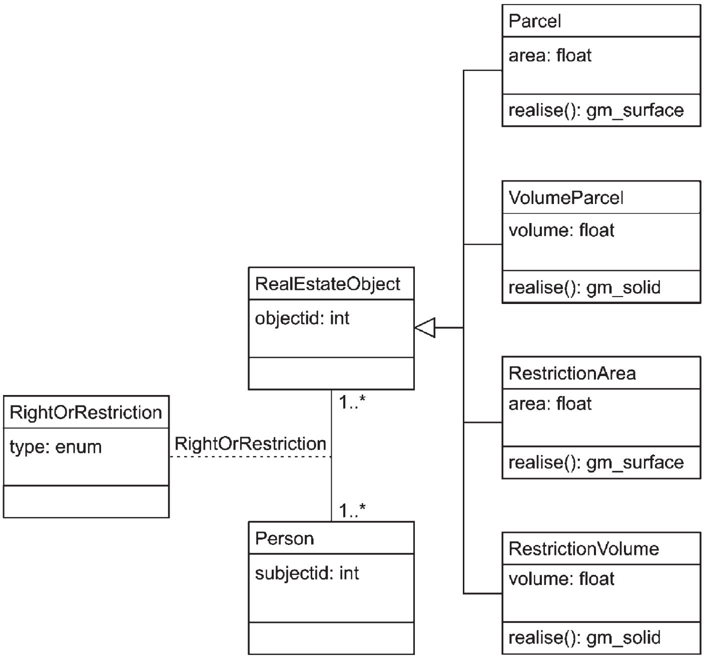

Figure 1. UML class diagram of full 3D cadastre that supports both infinite parcel columns and volume parcels. The parcel objects are part of a 2.5D partition.

The geometry of the VolumeParcel defines a bounded space in 3D (and the possible realization of this is discussed in section 4). Consequently, a complete space partition is defined by the (infinite) Parcel columns and the VolumeParcels. One VolumeParcel can be established crossing several parcels, and several volume parcels can be established above or below one parcel. Important constraints for the full 3D cadastre are:

- projection of Parcels that are defined on the surface should form a full partition of the 2.5D earth surface;
- VolumeParcels may not intersect other VolumeParcels (in 3D).

Because of the different semantic meaning (not related to the ownership right, which may by definition not overlap in space) of RestrictionAreas and Restriction Volumes, RestrictionAreas may intersect other RestrictionAreas (e.g. a forest protection zone may intersect a ground water protection zone), and RestrictionVolumes may intersect other RestrictionVolumes (e.g. a volume that indicates severe soil pollution may intersect with a volume that indicates the presence of a monument imposed by the Law on Monuments).

To be able to register the Parcels, VolumeParcels, RestrictionAreas and RestrictionVolumes in the cadastral registration, all real-estate objects must have a survey document, which should make clear to what space the real-estate object refers. The 3D information in these survey documents can then be integrated in the cadastral geographical data set, which will be a mix of 2.5D objects (surface parcels and restriction areas) and 3D objects. In the remainder of this paper, we will focus on Parcels and VolumeParcels.

3. Elevation-model-based surface parcels

In the 3D cadastre research, the conceptual models of a 3D cadastre, as described in section 2, are translated into prototype implementations. Therefore, the required technology has been studied, and, if necessary, existing technology has been extended with self-implemented extensions (Stoter 2004). The DBMS is considered as the core in the prototype architecture, since DBMS is the fundamental part in the new generation of GIS architecture. In this section, we focus on the first technical aspect of the proposed full 3D cadastral model when combining the volume parcels with elevation-model-based surface parcels: the 2D parcels need to be represented in 2.5D, draped over a height surface. In section 4, another important technical aspect of our model is discussed: how true 3D volume objects can be represented in the DBMS.

For the surface parcels (2.5D representations), we studied the most appropriate data structure. Triangular Irregular Networks (TINs) have proven to be a suitable structure for representing height surfaces. Therefore, we focused our research on representing the height surface of parcels in a TIN structure. For this research, four different types of TINs were generated, all representing surface height models based on point heights obtained from laser altimetry, and of which the last three also include 2D parcels (section 3.2). In all cases, the data are stored in one single DBMS. In the future, a distributed DBMS structure may be possible within the Geo-Information Infrastructure (GII). An integrated view, based on two different databases (as the different data sets are maintained by different organizations in different databases), may be feasible from the technical perspective. This section starts with a short introduction into the background of the problem area (section 3.1) and an introduction of the datasets. In section 3.3, the different TINs are evaluated.

3.1 *Integrated TINs of point heights and parcels*

There is a close relationship between Digital Elevation Models (DEMs, 2.5D), based on raw laser-altimetry point data, for example, and the topographic objects or features embedded in the terrain. Feature-extraction techniques aim to obtain the 2D geometry and heights for certain types of topographic objects such as buildings. There are methods for object recognition in TINs based on point clouds in which the selection of an object (e.g. building roofs, flat terrain between buildings) corresponds to planar surfaces (Gorte 2002). This technique can be used for 3D building reconstruction from laser altimetry. However, this is not the topic of this research. 2D objects from another independent source, such as a cadastral or topographic map, can be incorporated explicitly as part of the TIN structure, which is representing a height surface (Lenk 2001, Stoter and Gorte 2003). In this case, the TIN structure is based on both 2D objects and point heights. The data structure of the surface partition of 2D objects is embedded within the TIN. Within this data structure, the 2D objects are identifiable in the TIN and are obtainable from the TIN, as a selection of triangles which yield 2.5D surfaces of individual 2D objects. For the study described here, the following two data sets have been used (see figure 2).

3.1.1 Terrain height points. For the terrain elevation model, we use a data set representing the DEM. For example, in the Netherlands, AHN (Actueel Hoogtebestand Nederland) is available for this purpose (Van Heerd 2000). The

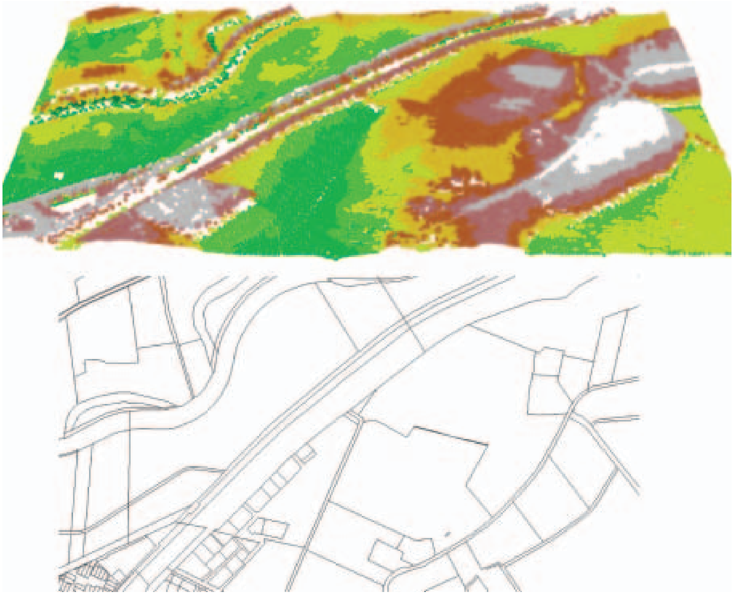

Figure 2. Data sets used in this research; top: elevation (dark: low; light: high); bottom: cadastral parcels. (Colour version available online.)

AHN is a data set of point heights obtained with laser altimetry with a density of at least one point per 16 m^2, and in forests a density of at least one point per 36 m^2. The point heights are resampled in a regular tessellation at a resolution of 5 m. Owing to availability issues, this regular data set is used, whereas the TIN approach is designed with irregular data in mind. The AHN contains only earth surface points: features such as houses, cars and vegetation have been filtered out of the AHN. The heights in the AHN have a systematic error of, on average, 5 cm and 15 cm RMSE.

3.1.2 Parcel boundaries. The parcels used are from the cadastral database of the Netherlands. In the cadastral database, parcel boundaries are organized in a structure of geometrical primitives (boundaries or edges described by their polylines), and parcels are topologically stored via references to boundaries (Lemmen *et al*. 1998). The typical geometric accuracy is about 10 cm.

3.2 *Generation of TINs*

The triangulation was performed outside the DBMS, since TINs (and triangulation) are not (yet) directly supported within DBMSs. The ideal case would be just storing the point heights and the parcel boundaries in the DBMS, and to generate the TIN of the area of interest on the user's request within the DBMS, without explicitly storing the TIN structure in the DBMS. The representation of the implicit TIN could then be obtained via a view. This is more storage-efficient and less prone to a decrease in quality because no data transfer (and conversion) is needed from DBMS to TIN software and back. However, the on-the-fly triangulation should not take too long; otherwise, generating TIN on request will not work from the usability point of view.

The TINs were generated by means of triangulation software called Triangle (Shewchuk 1996). Triangle was used, since it offers many types of triangulations and control parameters, and in addition it is freeware, written in C. There is a program which can be used directly on the command line. The input and output files are easily accessible, since they are ASCII files. Triangulation software implemented as part of GIS or CAD packages such as Geopak (Bentley 2004) or the 3D Analyst extension of ArcGIS (ESRI 2004) have their own internal data structure, especially for the produced TINs, which makes this triangulation software less flexible. In addition, Triangle supports more types of TINs, e.g. 3D Analyst does not offer support for constrained TINs. This is why these applications were not used in this part of the research. Later on in the Queensland case study in our research (see section 5), 3D Analyst was used, as it has an easy graphical user interface, and it does support the conforming TINs, which is reasonably suitable for the purpose of our research at that stage. CGAL (CGAL 2004), a freeware C++ library with computational geometry functions, does not have the option of building conforming TINs (only unconstrained and constrained TINs are supported), and in addition one still has to create a program (based on the library), which is why CGAL was not used.

3.2.1 Unconstrained TIN. First, a TIN was generated using only the point height data with Delaunay triangulation (Worboys 1995). The Delaunay triangulation results in triangles, which fulfil the 'empty circle criterion'. This means that the circumcircle around every triangle contains no vertices of the triangulation in its interior. In general, this results in good and numerically stable polygons. It should be noted that the Delaunay TINs are computed in 2D and may therefore be suboptimal for true elevation data. The z-value of points is not taken into account in the triangulation process but added afterwards. This is a little strange if one realizes that the TIN is computed for an elevation model in which the z-value is very important; see Verbree and van Oosterom (2003) for a better TIN construction for terrain elevation models. The selection of triangles from the unconstrained TIN (partly) overlapping one parcel surface represents an area larger than the parcel itself, since triangles cross parcel boundaries (figure 3).

3.2.2 Constrained TIN. In order to obtain a more precise parcel surface, a constrained TIN was generated, using the parcel boundaries as constraints. We assigned z-coordinates to the vertices of parcel boundaries by projecting them in the unconstrained TIN. In contrast with the unconstrained TIN, each triangle in the constrained TIN (figure 4) belongs to one parcel only, and therefore the selection of triangles exactly equals the area of a parcel. However, as can also be seen in figure 3, keeping the parcel boundaries (edges) undivided leads to elongated triangles near the location of parcel boundaries (especially in the case of dense laser height data and

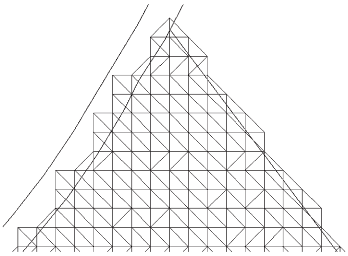

Figure 3. Parcel surface (detail) based on an unconstrained tin (parcel boundaries are shown as well).

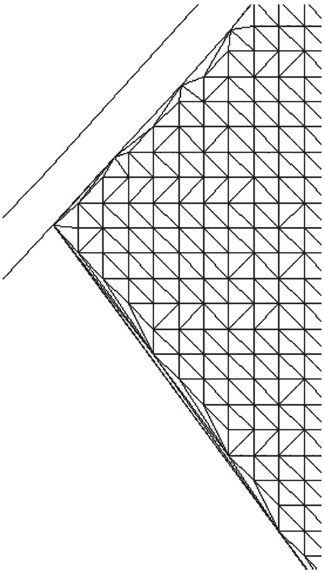

Figure 4. Parcel surface (detail) based on a constrained TIN (parcel boundaries are shown as well).

rural parcels). This has two important drawbacks. First, the very flat elongated triangles may be numerically unstable (not robust, as small changes in the coordinates may cause errors), and the visualization is unpleasant. Second, and maybe even more importantly, a long original parcel boundary will remain a straight line in 3D, even when the terrain is hilly, because there are no intermediate points on the parcel boundaries by which it is not possible to represent height variance across the parcel boundaries.

3.2.3 Conforming TIN. Keeping the original edges in the constrained TIN undivided in the triangulation process leads to elongated triangles if parcel boundaries are much longer than the average distance between DEM points (5 m), which is the case in using parcel boundaries with the AHN data set. An alternative to the constrained TIN may be the conforming TIN. The computation starts with a constrained TIN, but every constrained edge which has a triangle to the left or right not satisfying the empty circle condition is recursively subdivided by adding so-called Steiner points (and locally recomputing the TIN with the two new constrained edges). The recursion stops when all triangles, as well as those with (parts of) the constrained edges, satisfy the empty circumcircle criterion (the Delaunay property). The conforming TIN has both the Delaunay property and the advantage that all constrained edges are present, possibly subdivided in parts, in the resulting TIN. Figure 5 shows a conforming TIN, covering several parcels (different shades of grey). To improve visualization the height has been exaggerated (10 times).

3.2.4 Refined constrained TIN. However, a (normal) conforming TIN also has its drawbacks compared with a constrained TIN. In the case of two very close 'near parallel' constrained edges, a large number of very small triangles are generated while these constrained edges are split in many very small edges (see figure 6). Something similar can happen also when AHN points are very close to the

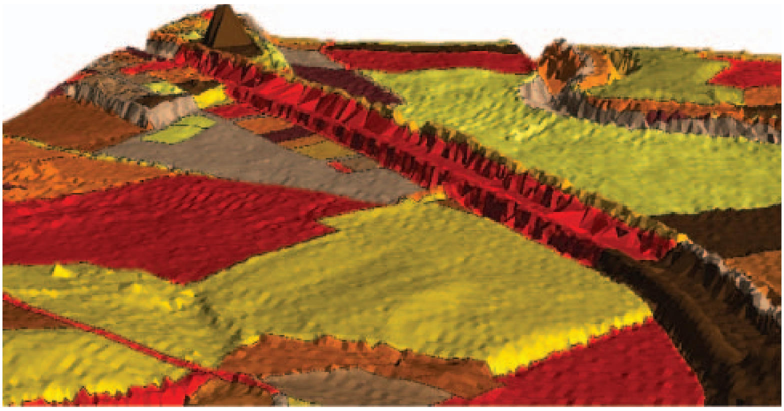

Figure 5. Conforming TIN in which point heights and 2D surface partition of parcels (each with its own shade of grey) are integrated. (Colour version available online.)

constrained edges. These small triangles have no use, as they do not reflect any height differences (at least the height differences cannot be derived from the AHN points), and they also do not contain additional object information.

A solution for this is to split the constrained edges, before inserting them, into parts no larger than two or three times the average distance between neighbour AHN points and then computing the (normal) constrained TIN. Figure 7 shows the refined constrained TIN for one parcel. The edges of the parcel boundaries were split into parts of at most 10 m. These edges were then used as constraints in the triangulation, which resulted in a refined constrained TIN. This improves the shape of triangles considerably (triangles that are too flat and too small are avoided). Moreover, since points are added on the parcel boundaries for which the height has been deduced based on the unconstrained TIN, it is possible to represent more variation in height across a parcel boundary. Also, the problem of many, very small triangles (in case of close ‘near parallel’ constraints and input points close to constraints) in the conformal TIN is avoided.

3.3 *Conclusions on elevation-based surface parcels models*

Incorporating the surface partition of 2D parcels into a height surface makes it possible to extract the 2.5D surfaces of parcels and to visualize parcels in a 3D environment by using 2.5D representations. As described and discussed in this section, it is not easy and straightforward to create a good integrated elevation and object model. Several alternatives were investigated: unconstrained Delaunay TINs, constrained TINs, conforming TINs, and finally refined constrained TINs. After several analyses, the most promising solution, the refined constrained TIN, was selected and applied successfully to our test case with real-world data: AHN height points and parcel boundaries.

One of the disadvantages of using a dense laser altimetry data set is the resulting data volume and with that the poor performance of the queries. However, because of the ‘sampling’ nature of data obtained with laser altimetry, not all points are needed to generate an accurate elevation model (within epsilon tolerance in the same order of magnitude as the original height model and cadastral data). Therefore, we examined how the number of TIN nodes (and thereby related edges and triangles) can be reduced by removing nodes that are not significant for the TIN, but at the

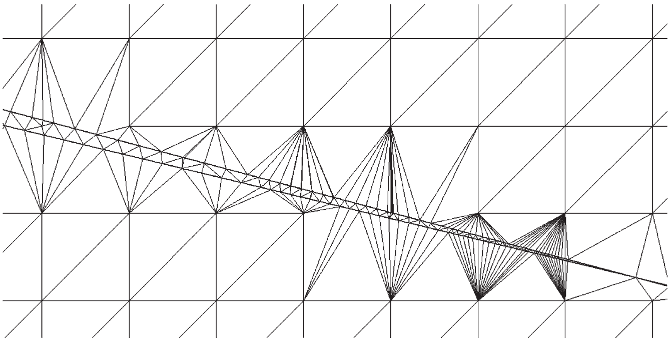

Figure 6. Conforming TIN results in very small triangles in case of two very close near parallel constrained edges or in case AHN points are very close to constrained edges, while no extra information is added.

same time maintaining the constraints of the parcel boundaries. The results of this research are described in Stoter *et al.* (2004).

4. 3D volume objects

The previous section described how to derive and store elevation-model-based surface parcels. This section describes how the second main element of our conceptual model, true 3D volume objects can be supported, including validation and spatial functions in 3D, in a DBMS. The present Geo-DBMSs do not support 3D primitives, but 3D spatial objects can be modelled with 2D primitives such as polygons. This is possible thanks to 3D coordinates, which are supported by the Geo-DBMSs. In this method, several 2D polygons (defined in 3D space) bound a 3D object. These 2D polygons can be stored in one record (multi-polygon) or multiple records (Stoter and Zlatanova 2003).

The absence of a real 3D volume primitive in the Geo-DBMSs, however, creates major problems. Geo-DBMSs do not recognize 3D spatial volume objects, because they do not have a 3D volume primitive to model them. This results in DBMS functions that do not work properly (e.g. there is no validation for the 3D volume object as a whole, and functions only work when these objects are projected, because the third dimension is ignored). When 3D volume objects are stored as one

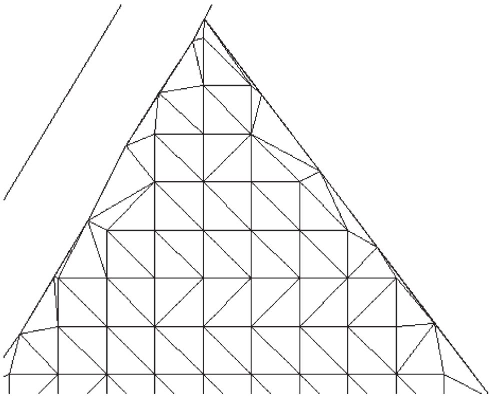

Figure 7. Parcel surface based on a refined constrained tin.

multipolygon or a set of polygons, no relationship exists between the different 2D polygons that define the object. Besides the fact that validation is impossible and that any set of polygons can be inserted, another disadvantage is that the same coordinates are listed several times (causing inconsistency risks), and there is no information about the outer or inner boundaries (shells) of the polyhedron.

Geo-DBMSs were developed for the storage of spatial data according to the OpenGIS 'Simple Feature Specification for SQL' (OGC 1999), because they could guarantee the geometric consistency of the data (in 2D). But now that applications have been built which depend on correct 3D data, new techniques need to be developed to support 3D data as well. The ISO/TC211 spatial schema (ISO 2003) defines 3D geometry primitives in an abstract (mathematical) manner. However, it is outside the scope of this standard to specify the interface of the 3D geometry primitive(s) within the context of a DBMS (SQL). The actual implementation is even further outside the scope. The work presented in this section tries to bridge this gap by offering a solution in the form of a design and an implementation of a real 3D primitive in a DBMS context, including validation functions and several geometric and topological functions that, for example, reflect the volume or the distance in 3D between objects. This section will show how 3D spatial objects can be modelled, i.e. stored, validated and queried, in a Geo-DBMS by using a 3D primitive. Many concepts have been developed in 3D modelling (Molenaar 1990, van Oosterom *et al.* 1994, Pigot 1995, Pilouk 1996, Kofler 1998, Saadi Mesgari 2000, Zlatanova 2000, Coors 2003). In our research, we implemented a 3D model in the DBMS (Arens *et al.* 2003). For the implementation, we extended the geometry model of Oracle Spatial (Oracle 2002). The geometry model of Oracle is (more or less) similar to the OpenGIS model. In the remainder of the section, the implementation will be described. First, an explicit choice for a 3D volume primitive will be made in section 4.1. Then, some implementation aspects, such as the use of internal topology and the syntax of the 3D primitive, are discussed in section 4.2. The validation of 3D primitives is described in more detail in section 4.3. This section ends by listing a number of true 3D functions (in section 4.4), which have been implemented and can be used in querying and analysis of the modelled objects.

4.1 *Choosing a 3D volume primitive*

There are a number of possible 3D volume primitives, which could be used to represent 3D volume objects. In this section, we consider either a polyhedron or a polyhedron with spherical and cylindrical patches. The polyhedron is the equivalent of a polygon, but in 3D. It is made up of several flat faces that enclose a volume. An advantage is that one polyhedron equals one factual object. A polyhedron has exactly one exterior boundary (set of faces). For every internal 'cavity' (hollow), the polyhedron has also exactly one interior boundary. In total, a polyhedron has therefore one or more boundaries (shells). Because a polyhedron can have holes in the exterior and interior boundary (set of faces), it can model many types of objects. A disadvantage is that the buffer operation results in a non-polyhedral object, because this will contain spherical or cylindrical patches, which cannot be represented by the polyhedron primitive. The solution is to approximate the result of the buffer operation (De Vries 2001). An alternative 3D primitive could be the 'Polyhedron combined with spherical and cylindrical patches' (Stoter and van Oosterom 2002). This is the equivalent of the current 2D geometry data model of most Geo-DBMSs (i.e. straight lines and arcs). Thus, 3D objects can be modelled even more realistically. However, again, this primitive is not closed under the buffer operation. In addition, modelling with this primitive is a complex task. The option with spherical and cylindrical patches would fit better into the present 2D geometry data model, but easy creation and implementation favour the polyhedron without spherical and cylindrical patches at first. Hence, the polyhedron was chosen first as the 3D primitive in this research. If needed, spherical and cylindrical patches could be approximated by several flat faces.

4.2 *Implementation*

The 3D primitive is implemented in a geometrical model with internal topology. The polyhedron is realized by storing the vertices explicitly as (x,y,z) and describing the arrangement of these vertices in the faces of the polyhedron. This yields a hierarchical boundary representation (Aguilera 1998, Zlatanova 2000). Note that edges are not stored explicitly in this model. Managing topological structures between objects (e.g. sharing common faces) is not within the scope of the polyhedron primitive. However, internal topology within one object is maintained, since the vertices for one object are stored only once: faces are defined by internal references to nodes, and nodes are shared by faces.

The interpretation code of the faces indicates whether they are part of an outer or inner boundary (of a polyhedron) or part of an outer or inner ring (of a face). Most polyhedra have only an outer boundary (shell), but an inner boundary can, for example, be used to create a hollow object: the inner boundary will then describe this hollow space. Most faces have only an outer ring, but inner rings can be used to create through-holes in polyhedra. These elements already make it possible to model complex objects, e.g. objects with through-holes or objects that are hollow inside.

It is customary in computer graphics to arrange all the vertices of faces in the outer boundaries (outer rings) counter-clockwise, as seen from the outside of an object, and to arrange the vertices of faces in the inner boundaries (outer rings) clockwise (and all inner rings in reverse order). In other words, the normal vector of the face points to the outside of the object. This practice was adopted in the implementation; details and examples can be found in Arens *et al.* (2005). The SQL 'INSERT INTO' command is used to insert a polyhedron (cube) in the table (see figure 8), which shows the syntax when encoding a polyhedron primitive:

```
INSERT INTO polyhedron_table (id, geometry)
VALUES (1,                          -- id of object
mdsys.sdo_geometry(3002,            -- geometry type: 3D line
                                    -- (polyhedron faked for spatial index)
  NULL, NULL,
  mdsys.sdo_elem_info_array(        -- array with triplets: starting offset,
                                    -- element type, interpretation code
    1,2,1,                          -- first triplet is line for spatial
                                    -- indexing, next the six faces
    25,0,1006, 29,0,1006, 33,0,1006, 37,0,1006, 41,0,1006, 45,0,1006),
  mdsys.sdo_ordinate_array(
    1,1,0, 1,3,0, 3,3,0, 3,1,0,     -- coordinates of the nodes 1--4
    1,1,2, 1,3,2, 3,3,2, 3,1,2,     -- coordinates of the nodes 5--8
    1,2,3,4, 8,7,6,5, 1,4,8,5,      -- bottom, top, front face (node references)
    2,6,7,3, 1,5,6,2, 4,3,7,8)      -- back, left, right face (node references)
));
```

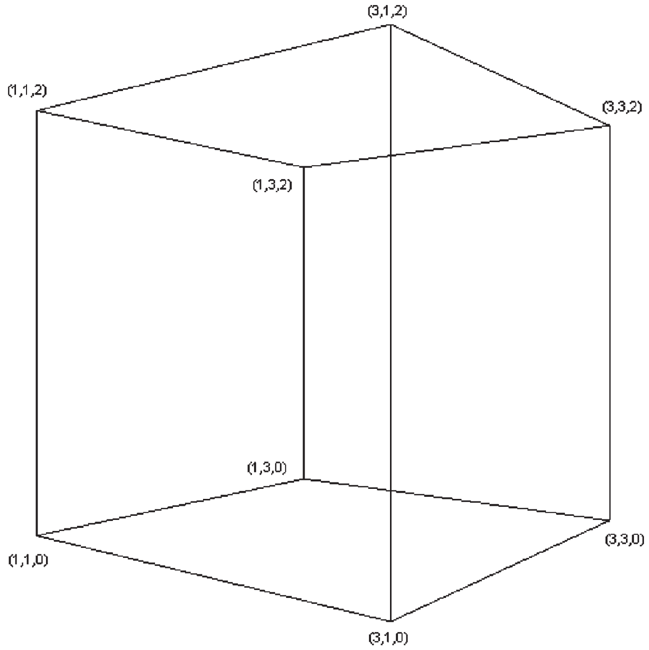

Figure 8. Polyhedron (cube) defined by its six faces.

No new spatial index structure was implemented in this research; instead, the present Oracle spatial index could be used via a small 'trick'. The use of the Oracle spatial index is made possible by storing the 3D polyhedron objects in a special way. As standard Oracle does not yet know the polyhedron data type, the system is 'faked' by using the geometry type of the 3D polyline (geometry type indicated by code 3002). This could be envisaged as a 3D polyline going through all the coordinates of the defined polyhedron. When creating a 3D R-tree (Guttman 1984) in Oracle, a bounding volume is created around this line. This bounding volume equals the bounding volume around the polyhedron. A 3D R-tree can optionally be created (in order to speed up subsequent querying) by the standard Oracle SQL 'CREATE INDEX' statement.

4.3 *Validation*

It is important that the spatial data is checked when they are inserted or changed in the DBMS. Checking the geometry of the spatial objects is called validation. Validation is necessary to ensure that the objects can be correctly manipulated, e.g. it is impossible to compute the volume of a cube when the top face is omitted; this would merely be an open box. Validating may seem fairly easy to humans, but a computer needs a large set of rules to check spatial data. Validation of the values of a data type (such as the polyhedron) is the lowest, most fundamental level of a spatial integrity constraint in the DBMS. To allow for checking the spatial data, it is important to give an accurate definition of the 3D primitive. A polyhedron is a bounded subset of 3D coordinate space, which is enclosed by a finite set of flat polygons in such a way that each edge of a polygon is shared by exactly one other polygon (Aguilera 1998). A valid polyhedron bounds a single volume, which means that from every point (also on the boundary), every other point (also on the boundary) can be reached via the interior.

The implemented validation function and some of the 3D functions have a tolerance value as input parameter. For example, the flat faces of a polyhedron are flat surfaces within a certain tolerance, as the points that make up the polygon can be slightly outside the flat plane, because of the geodetic measuring methods (Teunissen and van Oosterom 1988, Stoter and van Oosterom 2002, Stoter and Salzmann 2003) and the finite representation of coordinates in a digital computer. To solve this problem, a close-to-zero tolerance value was introduced. It is important that this value is not zero, as this would introduce errors in the functions if there were any deviations in floating-point computations. It should not be too large either; otherwise, invalid objects would be accepted as valid. A good value for the tolerance is the standard deviation of the geodetic measurements.

The definition of the polyhedron primitive formed the basis for a set of validation rules, which were implemented to evaluate the validity of stored objects. All the rules together enforce the correctness of the spatial data. First, of all, a check is needed on the storage of the data. Hence, valid interpretation codes need to be used, and node references in the faces need to correspond with existing vertices. Once the spatial object is correctly structured (syntax), the next test can be carried out. The next test evaluates the flatness of the faces. The faces should be flat within a given tolerance. This is tested by estimating a ‘least-squares’ plane through the vertices of the face and then computing the distance from each vertex to this plane. If one of the distances is greater than the tolerance value, the face cannot be flat. At the same time, a test is performed to determine whether the inner boundary of a face is indeed in the same plane as its corresponding outer boundary.

We then ascertain whether the polyhedron bounds a single volume in 3D space (2-manifold polyhedron). This means that the vertices and the edges (2 following vertices) should be 2-manifold, that there should be no intersecting faces and that each polyhedron should be a single connected object. A test to determine whether each edge is used exactly twice (in opposite order) in the polyhedron reveals if the edges are 2-manifold or not (Teunissen and van Oosterom 1988). If the polyhedron is still valid as a whole, the faces have to be checked independently. The faces are checked for their simplicity, which means that they should have an area, they should not be self-intersecting, and the inner boundaries should not intersect (touch is allowed) their corresponding outer boundaries.

The final test in the validation ascertains whether the vertices in the faces are correctly orientated, i.e. counter-clockwise (looking from the outside) for faces in outer boundaries and clockwise for faces in inner boundaries. Only one face of the polyhedron has to be tested, because if the edges are 2-manifold, the whole object is orientated either correctly or incorrectly. It is important as to which face is tested. From the bottom face, we know that the normal vector should be pointing to the negative z-direction. The cross-product of two following edges of a convex part of this bottom face gives the normal vector. The z-component of this normal vector should be negative. If all the criteria in the validation are met, the spatial object is valid.

4.4 *3D functions*

The standard functions in most current Geo-DBMSs (including Oracle Spatial) ignore the third dimension, that is, the 3D spatial objects are projected onto 2D coordinate space. For example, the area of a face that is standing up (vertical face) is zero, because its 2D projection is a line. To offer a realistic functionality, some of the most common functions were implemented in 3D (for 0D up to 3D primitives):

- Unary function/program to insert data: Creating data from 3D multi-polygons and VRML.
- Binary functions that return a Boolean: Point-in-polyhedron and intersection tests.
- Unary functions that return a scalar: Area, perimeter and volume.
- Binary functions that return a scalar: Distance between centroids.
- Unary functions that return a simple geometry: Bounding box, centroid, 2D footprint and transformation functions.
- Binary functions that return a simple geometry: Line segment representing the distance between centroids.

Note that this set of implemented functions is just a small sample of all possible functions. Obvious further implementations would be topology relationship operations in 3D (in the category 'binary functions that return a Boolean') according to the 9-intersection (Egenhofer *et al.* 1993) or to the dimension-extend (Clementini *et al.* 1993) method.

As explained in section 4.2, the 3D polyhedron data type can be indexed with a 3D R-tree. This is very important in case large tables with polyhedrons are used in a query based on one of the above topological relationship functions: the index enables the DBMS to avoid evaluating pairs of polyhedrons, which are not relevant. Functions that return a complex geometry such as tetrahedralization and skeletonization have not been implemented yet, but they are also interesting, because of their analogy with 2D triangulation and generalization (and their possible applications in 3D space).

5. 3D cadastral model compared with current examples of 3D property units

When establishing a 3D cadastral registration, several phases can be distinguished. 3D cadastral registration starts with the possibility to establish 3D property units within the juridical framework. The next step is to provide an insight into the 3D property units, e.g. by drawings included in the land registration (Public Register with the 'source documents' describing the interests in land). Regulations could be laid down, which define how to prepare and structure the 3D information that is required to register 3D property units. In a final phase, this 3D property information should also be included in the cadastral registration (which links the essential information from documents recorded in the land registration to geometry of real-estate objects).

In a number of different countries, there are (or very soon will be) juridical frameworks facilitating the establishment of 3D property units (Norway, Sweden, Queensland (Australia) and British Columbia (Canada)). This is the first ('juridical') step for establishing a 3D cadastral registration. Section 5.1 will evaluate whether the other steps for a 3D cadastre have been taken in these countries, apart from the juridical step. To illustrate the solutions in more detail, a specific case from Queensland, Australia is presented in section 5.2. Finally, our conceptual model and developed technology is applied to the case of Queensland in order to show the potential of a full 3D cadastre (section 5.3). Some remarks and conclusions based on these experiences are then given in section 5.4.

5.1 *Status and phase of current 3D cadastral registrations*

In our 3D cadastre research, some countries already providing the possibility to establish 3D property units were identified and investigated: 3D construction property in Norway (Onsrud 2002), 3D properties in Sweden (Julstad and Ericsson 2001, Mattsson 2003, Swedish Government 2004), airspace parcels in British Columbia, Canada (British Columbia Government 1996a, 1996b, Gerremo and Hansson 1998) and volumetric parcels in Queensland, Australia (Queensland Government 2003a, 2003b). The ownership of these 3D property units is no longer related to the surface parcels, and the 3D property units are possible within existing juridical frameworks (with some extensions). The requirements to establish a 3D property unit and the 3D details that are maintained differ. For example: the footprints of 3D property units are limited to the 2D surface parcels (British Columbia) or not (Norway, Sweden, Queensland); the 3D property units have to relate to built constructions (Norway, Sweden) or not (British Columbia, Queensland); the 3D property units have to be described in survey plans (British Columbia, Queensland) or not (Norway, Sweden). Despite these differences, it can be rightfully claimed that the juridical step has been solved. The second step is to maintain spatial information in the land registration (document archives), which has also been solved in the described countries. The final step towards a 3D cadastre would be to integrate the 3D information (geometry) of the 3D property units in the cadastral registration (information system), which has been addressed by none of the mentioned countries. Not having a complete solution for 3D cadastral registration has some serious consequences:

- Since the 3D information is laid down on paper (or scanned) drawings (which is a 2D visualization), the 3D information cannot be interactively viewed. This is a weak point because the ability to do so may be very helpful in the case of complex volumetric parcels to interpret the situation correctly (e.g. parcel 103 in the Queensland case; see section 5.2 and figure 10).
- The 3D properties are only described by coordinates and edges on drawings, i.e. no 3D primitive is used. Therefore, it is not possible to check whether a valid 3D property has been established (whether the 3D property is closed, whether the faces are planar, whether there are no crossing edges and faces).
- The 3D information is not integrated with the cadastral map or with other 3D information, e.g. two or more neighbouring parcels cannot be visualized in one view in 3D, and it is also not possible to check how volumetric parcels spatially interact in 3D (overlap, touch, etc.).

These solutions therefore do not address technical issues, such as how to store, query and visualize 3D property objects (in 3D) and how to make sure that 3D properties do not overlap (the condition that 2D parcels may not overlap ensures complete and consistent registration in current cadastres). The basic improvement for 3D registration in those juridical systems that already provide the possibility to establish 3D property units would therefore be to incorporate the information on 3D property units, which is already very well described in survey plans in the land registration, into the cadastral registration.

5.2 *Example from Queensland, Australia*

The cadastral registration in Queensland is used here to illustrate in more detail the characteristics of a land registration that is already able to define parcels with a bounded volume. Queensland was selected from the other countries because for a number of years, it already has detailed regulations for 3D survey plans, and many examples are available from the Public Register (and it also has a complete digital 2D cadastral map). 3D cadastral issues in Queensland have been studied in collaboration with the Queensland Government, Department of Natural Resources, Mines and Energy (NRME).

5.2.1 Volumetric parcels in the registration of Queensland, Autralia. According to the Land Title Act of Queensland (Queensland Government 2003a), a standard parcel (defined in 2D, but implying the 3D column) is a lot (or a collection of lots) which is unlimited in height and depth. Apart from these 'unrestricted' parcels, four parcels with a 3D component are distinguished:

- Building parcels, which are parcels that are generally defined by floors, walls and ceilings;
- Restricted parcels, which are parcels restricted in height or depth by a defined distance below the surface or by a defined plane (restricted easements can also be restricted in height and depth): the boundaries of the restricted parcels coincide necessarily with the boundaries of the surface parcel;
- Volumetric parcels (possible since 1997), which are parcels that are fully limited by bounding surfaces and are therefore independent of the 2D boundaries of the surface parcels;
- Remainder parcels, which are parcels that remain after a volumetric parcel or building parcel has been subdivided from it.

The 'in strata' parcels that were used before 1997 (and are no longer applied) both included the volumetric parcels and the restricted parcels. We focus on volumetric parcels, since these can be compared with the VolumeParcels as defined in our conceptual model.

A volumetric format plan defines land using 3D points to identify the position, shape and dimensions of each bounding surface and is used to reflect volumetric parcels. A volumetric parcel is a parcel which is fully limited by bounding surfaces (which may be other than vertical or horizontal) and are above, below or partly above and partly below the surface of the ground (compare these with restricted parcels and notice the difference). Volumetric parcels have been possible in Queensland under the Land Title Act since 1997. The use and purpose of volumetric parcels (not related per se to constructions, e.g. for viewshed) are determined by the Local Government and other legislation. One volumetric parcel can be established intersecting several parcels. All lines on a volumetric format plan are straight, and all surfaces are flat, unless explicitly stated otherwise; hence, any surface which is mathematically definable (so that an intersection can be calculated) can be registered. The height used to define volumetric parcels cannot refer to above or below a depth from the surface (the height cannot be defined as relative height or depth), since 'this is subject to change and not capable of mathematical definition' (Queensland 2003b). The corners of volumetric parcels should refer to existing structures or marks as much as possible. The vertices of the corners should be given in polar dimensions (and optionally in rectangular co-ordinates) and levels on the

Australian Height Datum. Each volume shall be given an area, which is the area of a footprint, and a volume in cubic metres. The plan should show a 3D representation of the parcel. The 3D descriptions are maintained in titles in the land registration while a footprint of the volumetric parcel is shown on the cadastral map.

The cadastral geographic data set of Queensland has a ‘base layer’, which is a complete non-overlapping coverage, and consists of parcels, road, rail, watercourse and intersection parcels. An intersection parcel is part of a roadway (the intersection of two roads). Volumetric parcels are not part of the non-overlapping coverage, but the footprint of these volume parcels is drawn on the cadastral base layer, and therefore they are overlapping with the base parcels. Also, easements, having their own geometry (and survey plans), are drawn on the base layer and may therefore intersect several parcels (initially, easements are defined on a single base parcel, but the base parcel may get subdivided, leaving the easement whole). Building parcels are not drawn on the cadastral map.

5.2.2 Case study in Queensland. A case study from practice will be used to illustrate the establishment of volumetric parcels in Queensland: the establishment of 3D property units for the Gabba Cricket stadium in Brisbane. This stadium overlaps two streets: Vulture Street in the north and Stanley Street in the south (see figure 9).

Three 3D properties have been established: for the intersection with Vulture Street, a stratum with parcel identifier 100 (established before 1997) and a volumetric parcel with identifier 101; and for the intersection with Stanley Street, a volumetric parcel with identifier 103. The volumetric parcels have been established after 1997. All three parcels are leasehold estates. This means that the holder of the real estate has the right of use and exclusive possession of the property for a specified time, which is comparable to the right of long lease. However, it should be noted that most volumetric parcels in Queensland are related to freehold estates.

The titles establishing the volume parcels contain very detailed 3D information imposed by the regulations: cross-sections are added in case of the strata title, and 3D diagrams are added in the titles for the volumetric parcels (see figure 10 for parcels 101 and 103). All coordinates that are needed to demarcate the 3D property

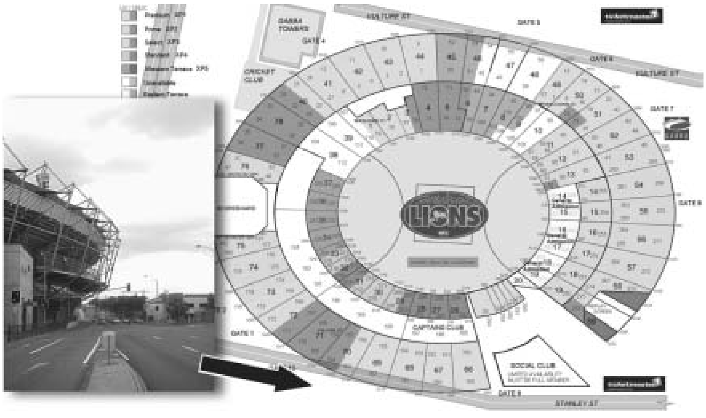

Figure 9. Overview of Gabba Stadium overhanging Stanley Street in the south and Vulture Street in the north, Brisbane, Australia.

are present in the titles in bearing and distances coordinates (and not in rectangular coordinates). The height of all coordinates is defined in the Australian Height Datum.

The footprints of the 3D properties are part of the cadastral geographical data set. Figure 11(*a*) shows the cadastral map with the footprints of the volume parcels, and figure 11(*b*) shows the cadastral map without the footprints of parcels 100, 101 and 103 (and without the geometry of easements). This shows that volume parcels are not part of the base parcel map and that volumetric parcels (and traditional strata parcels) exist separately from the base map and may therefore intersect parcels of the base parcel map. For example, the 3D stratum title of parcel 100 crosses two parcels on the base map.

5.3 *Conceptual 3D cadastral model applied to a case study in Queensland*

To evaluate the proposed conceptual model of a full 3D cadastre (see section 2) and to show the potentials of the solutions that were found in the selected countries, our conceptual model of the full 3D cadastre is translated into prototype implementations using technology as explored in this research (see sections 3 and 4). For the implementation in the DBMS Oracle Spatial is used, to access the information

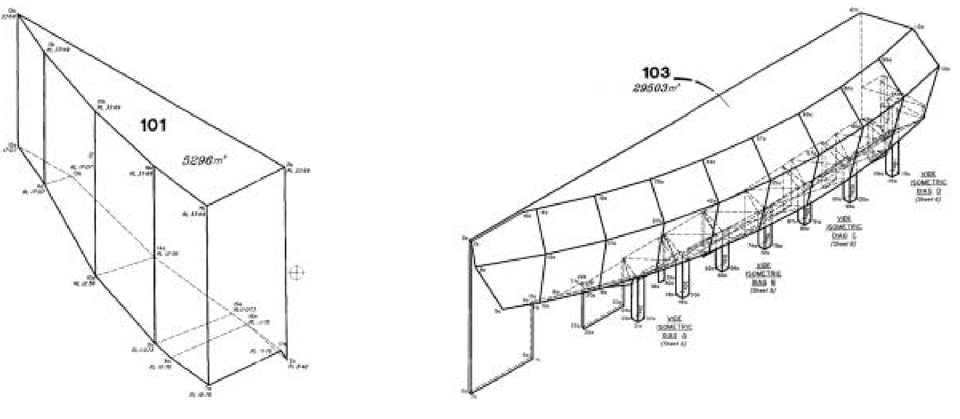

Figure 10. Examples of 3D diagrams added to volumetric titles (parcel 101 and 103).

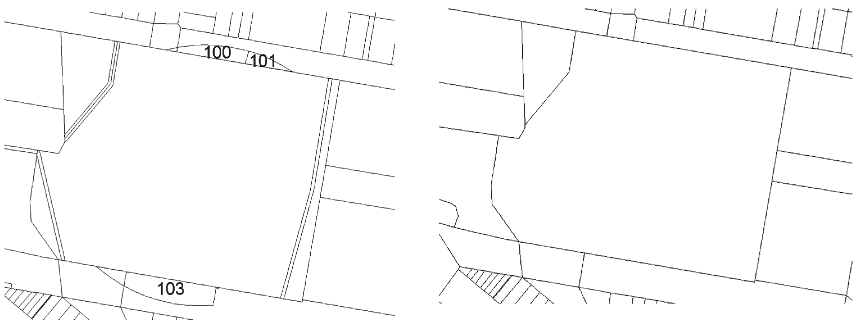

Figure 11. Cadastral map with (and without) footprint of volume parcels (100, 101 and 103) (and easements; these are the 'narrow paths' present in the map on the left-hand side).

MicroStation Geographics (Bentley) is used, and ArcView 3D Analyst is used to generate the integrated height and parcel model.

We applied the full 3D cadastre concept to the described case study in Queensland, the Gabba Stadium in Brisbane at the location of Vulture Street (in the north), i.e. parcel 100 (stratum parcel) and parcel 101 (volumetric parcel). The following steps were followed to convert the spatial information on the (scanned) 3D survey plans into the geometrical primitive in the DBMS:

1. The field measurements, as indicated on the survey plan by distances and bearings betweens the successive points, were adjusted by traverse adjustment for each parcel in a local coordinate system.
2. The local rectangular coordinates were fitted to the (global) map coordinates by an over-determined conformal (Helmert) transformation using three connections points in both coordinate systems.
3. The faces were constructed with references to nodes.
4. This information was inserted in a topological model and a self-implemented 3D geometrical primitive in the DBMS (see Stoter and van Oosterom 2002, Arens *et al.* 2003), by which the 3D geometry could be (spatially) queried.

After these steps, the 3D geometries could be visualized and queried in one integrated view (see figure 12), which offers major improvements. It is now possible to see if and how the 3D geometries interact and to view the 3D situation interactively.

The neighbouring polygons as defined do not match face to face; comparison of the common boundary between parcel 100 and 101 reveals a difference of about 30 cm (see figure 13). This may indicate an error, but in this case it is correct. The

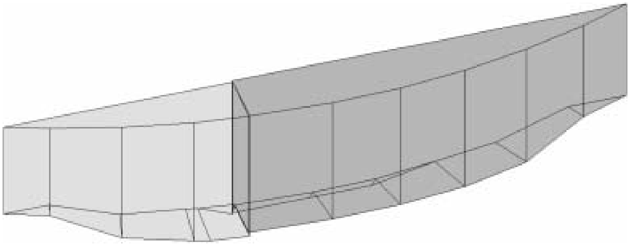

Figure 12. Visualization of 3D geometries of volumetric parcels, stored in DBMS.

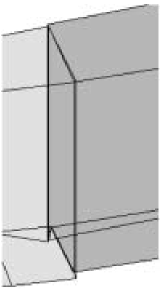

Figure 13. Zoom-in on figure 12 showing that shared faces do not coincide.

two parts were determined at different times, and parcel 101 allows more space around the structure. The measurements define the space while there is no real object to mark the limits of the parcels. Therefore, the geometry of the volume parcels must by definition be correct. In the 2D map (figure 11), there is no such error; the reason is that in the 2D map, some topology processing (based on a certain tolerance) is performed during the update process. Small input errors are cleaned in 2D, but in 3D, no topology processing is performed.

In order to validate the volumetric objects and to perform 3D functions on the objects, the geometry of the 3D objects was stored using the self-implemented 3D geometrical primitive (Arens *et al.* 2003; see section 4). Therefore, we were able to query the 3D objects in an integrated DBMS environment:

```
/* validate 3D geometries */
select bid, validate_polyhedron(return_polyhedron(shape), 0.5)
validate
from qld_3Dgeom;

BID   VALIDATE
---- ----------
100   True
101   True


/* calculate volumes of 3D geometries
select bid, volume(return_polyhedron(shape)) volume
from qld_3Dgeom;

BID   VOLUME
---- -----------
100   12725.1989
101   5329.18583


/* check if two geometries intersect (1=TRUE and 0=FALSE) */
SELECT d1.bid, d2.bid
FROM robject3dql d1, robject3dql d2
WHERE
intersection(return_polyhedron(d1.shape),
return_polyhedron(d2.shape),0.01)=1
AND d1.bid < d2.bid;

BID  BID
--- -----
100  101
```

The 3D geometries can be incorporated in a cadastral geographical dataset that contains surface parcels represented in 2.5D in order to obtain a 3D overview of the complete situation. For this purpose, a conforming TIN was generated (using ESRI software), which incorporated the surface partition of the cadastral base map (see section 3). The result is shown in figure 14.

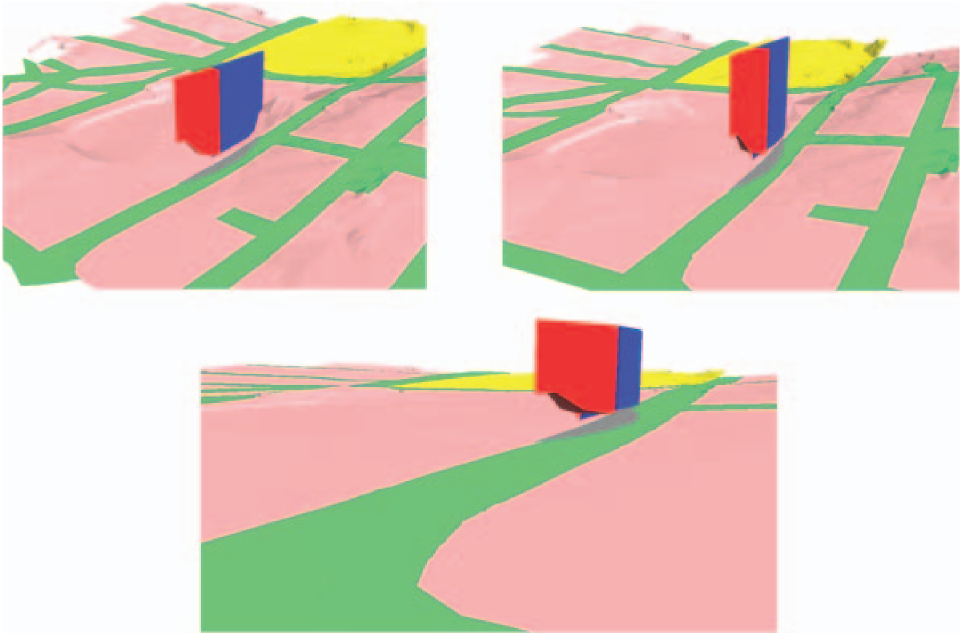

Figure 14. Visualization of 3D geometries of volumetric parcels together with the 2.5D cadastral base map. (Colour version available online.)

5.4 *Evaluation of the full 3D cadastral model*

As can be concluded from this case study, the full 3D cadastre offers many improvements over traditional cadastral registrations:

- The real situation is no longer projected on the surface, i.e. volumetric parcels are not dominated by the parcel pattern on the surface.
- Persons can be entitled to space in a transparent way instead of establishing property rights on intersecting parcels to establish the legal status above and below the surface.
- The space is precisely described in a 3D survey document, which offers a uniform way of defining 3D property units.

The full 3D cadastre also offers improvements in countries and states that have already established 3D property units unrelated to the surface:

- The information from the 3D survey document can be used to insert the volume parcels in a topological structure and in geometrical primitives in the DBMS.
- The volume parcels can be viewed interactively.
- The geometry of volume parcels can be checked, for example, to see whether the faces are planar, whether the volume is closed, or whether there are any self-intersections.
- The 3D situation can be (spatially) queried in the DBMS (e.g. do volume parcels intersect?).
- The volume parcels can be visualized in an integrated view with a 2.5D representation of the parcels that are defined by parcel boundaries on the surface.

- The volume parcels and the 2.5D surface parcels can be queried in the DBMS, e.g. is the volume parcel located above or below the surface, or does it intersect the surface?

The advantage of having the 3D property unit in the same environment as the 2D parcels clearly offers great potential. However, even starting from one of the more advanced environments (Queensland, where both the legal aspects and the 3D survey documents are satisfactorily dealt with), quite a number of important issues still need to be addressed:

- In the survey plans, both the 3D points and edges are specified (as required), but there is no explicit listing of faces and the polyhedron itself. It is important to reconstruct the faces, and it is possibly ambiguous, especially in more complex cases (such as parcel 103).
- The validation of the polyhedron is important (especially if it consists of faces other than horizontal, vertical or triangular faces). Is the volume completely closed? Is the orientation correct? Are holes or cavities modelled correctly? Are all the faces planar within a certain tolerance? (The points that make up the faces (defined in 3D) can be slightly out of the flat plane because of the geodetic measuring methods and the finite representation of coordinates in a digital computer. Therefore, the faces of a polyhedron are flat within a given tolerance.)
- The (footprints of the) 3D objects do not fit perfectly in the cadastral map: a straightforward conversion from the local coordinates to global coordinates (rotate, translate) resulted in a mismatch of about 60 cm: additional field measurements are required to solve these differences.
- The Queensland regulations also allow non-polyhedral 3D objects, such as (rotated) ellipsoids or cylindrical patches (see figure 15). Should these be converted to polyhedra (approximation within given tolerance) to be modelled in the DBMS, or should the DBMS be extended with complex 3D data types?
- Attention should focus on how to make sure that two polyhedra do not overlap in 3D space (but at most touch in a common node, edge or face) and on how to make sure that there is no 3D sliver between two polyhedra that are supposed to be touching neighbours.

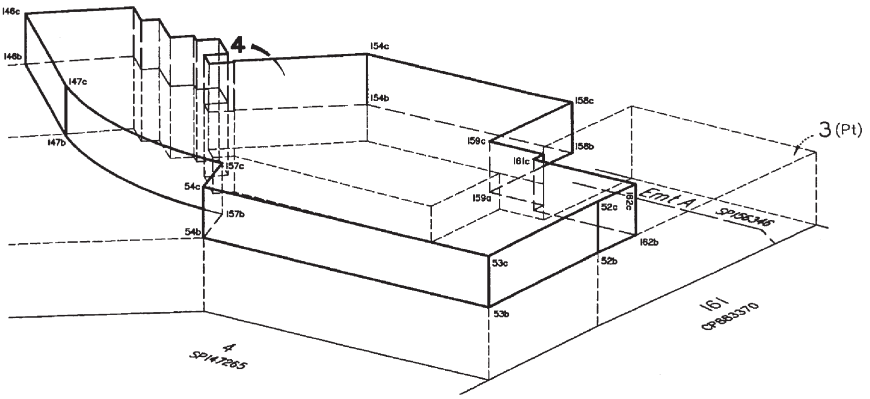

Figure 15. Volumetric parcel defined with more complex geometry than polyhedron (note the cylindrical patch).

- The cadastral registration should be organized in a uniform manner. In the case study (with only three 3D objects all related to the same construction), some differences are noticeable:
  - Neighbour parcels 100 and 101 are both on the same side of the stadium, but parcel 100 is related to a stratum parcel, since it was established before 1997, and parcel 101 is related to a volumetric parcel, which is only possible after 1997. Therefore, the available information for the parcels differs.
  - Parcels 101 and 103 are both volumetric parcels, while parcel 101 is relatively rough. It seems that parcel 103 is defined quite tightly around the construction (making this object quite complex).
  - Trivial registration errors should be avoided, such as the recording of the volume. It turned out that the recorded volume of parcel 101 in the cadastral registration was not correct (10,000 times too large), probably due to some typing error (because the survey plan was correct).

In areas with a high density of volume parcels, a true space partitioning might be needed (defined in a full topological model).

6. Conclusions

In this article, we have presented the 3D cadastre model that showed the best potential for the long-term future based on the requirements for cadastral registration: a full 3D cadastre that supports both infinite parcel columns defined by 2D surface parcels and volume parcels. The advantage of this model is that it has a strong link to the current 2D registration (parcels represented with parcel boundaries are still supported), while it is also possible to establish volume parcels which are no longer related to the surface. For the representation of parcels in this model, a height surface of parcels is needed. The integrated model of parcels and point heights was also described in this article. Several TINs were created and evaluated. The refined constrained TIN showed the best potential. In the future, the representation of the integrated TIN should be implemented as an integrated view (in the DBMS sense) on the two data sets maintained as independent and distributed sources, and not as a physical permanent integration. The second technological development was the selection, design and realization of a 3D volume primitive within the geo-DBMS, a polyhedron data type, which is used to represent the (completely bounded) volume parcel. The implementation of a full 3D primitive was also shown in this article.

The full 3D cadastre model was evaluated by comparing it with the cadastral registration in Queensland, Australia (and a number of other countries/states: Norway, Sweden and British Columbia, Canada). Although these are examples of more advanced registrations with respect to providing a legal framework for 3D properties, the 3D properties are not incorporated into cadastral base maps (at best as footprints). It can be concluded therefore that, although the countries have several remarkable differences, they can all be supported by a cadastral registration based on our full 3D cadastre model.

In our 3D cadastre prototype environment (based on a 3D polyhedron extended version of the ORACLE Spatial DBMS and ESRI and Bentley GIS/CAD software), the 3D property survey plans of a case study in Queensland were converted into a representation in the DBMS, and the surface parcels were successfully merged with a terrain elevation model and also loaded in the DBMS. This environment offers the possibility to query, analyse and visualize the true 3D situation of the properties. Roughly stated, this article showed that both the legal, organizational and technical aspects of a 3D cadastre have been solved. It is therefore expected that in the near future, more countries and states (including the Netherlands' Kadaster) will implement (further) steps in the direction of the full 3D cadastre model as described in this article. It should also be noted that there are important aspects (in the conversion and use of a 3D cadastre) which require further attention.

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