Data validation in 3D cadastre

Sudarshan Karki[13], Rod Thompson[12], Kevin McDougall[3]

[1]Department of Environment and Resource Management, Queensland, Australia, [2]TU Delft, the Netherlands, [3]University of Southern Queensland, Australia

Abstract

In a cadastre, the 2D parcel is nowadays correctly considered to be a special case of the 3D parcel because the rights and restrictions extend beyond the surface itself. Storing, representing and manipulating a true 3D parcel however has not yet been satisfactorily achieved because of constraints in data modeling and software development. Significant research has been done to identify the best ways to represent a 3D solid, with rigorous mathematical testing on the respective merits of alternative approaches. Software companies have come up with their own ways of storing and validating 3D data, mostly as extensions of the 2D concepts. However, validation rules of one software may not be acceptable within another software's validation environment. The validation itself can be specified in great detail but sometimes this leads to redundant, repetitive or unnecessary processing. Because of the high volume of data a typical organization may be expected to handle, it is necessary for the rules to be streamlined and efficient. In this paper, validation is initially approached to answer questions such as: what is validation? why it is necessary to validate?, and how do we validate?. Limiting the scope to the 3D geometry or spatial representation of a 3D cadastre, the paper takes a novel approach in identifying the various aspects of validation of a 3D cadastral parcel and identifies the critical validation factors. It examines the validity within individual parcels and the relationship between adjoining or overlapping parcels in 2D or 3D. Although it is difficult to ensure completeness of rules, critical validation rules are examined for each identified factor.

1. Introduction

The cadastre deals with land and the rights associated to it. It can be considered to be a combination of geometrical and attribute data which is regulated and governed by the country's constitution and other laws for defined purposes. The technical and judicial framework assist in defining the cadastral framework along with other drivers like the land market and present land administration needs. In recent years there has been an increasing trend towards the unbundling of property rights and a demand for more efficient usage of our traditional 2D cadastre through 3D developments. Accommodating and assisting the growth of 3D cadastre as an integral part of the land administration is being largely driven by technology. In many countries, the judicial framework supports a 3D cadastre, while in some others it is yet to be developed. The technical aspects of storing, retrieving, manipulating 3D cadastre is yet to be developed at par with 2D cadastre. Much of the problem lies in defining a data model for 3D cadastre, the interactions with the existing database and data capture methods, and the range of possible shapes and combinations of 3D objects in existence at present and those likely to be in the future. Additionally, support for the subdivision or consolidation of these 3D objects, validation rules for checking the data before, during and after entry into the system, and the optimal validation rules for entry of the data to the system must be considered.

This paper explores the similarities and dissimilarities in the 2D and 3D cadastral data context, focuses on differences between validation of a single object and validation of a set of neighboring objects or partitions of space in the 3D cadastral context, and then narrows down to the optimal validation rules necessary for a 3D cadastre keeping in mind that mixed representations of both 2D and 3D can co-exist in the same dataset or jurisdiction.

1.1 Structure of the paper:

This paper is structured in six main sections: Introduction, Representations based on existing methods, Validation extended from 2D to 3D, Validation in 3D cadastral context, Representations based on ISO19152 LADM, Discussions and further research.

Following a brief introduction to the paper, Section 2 deals with methods of constructing 3D objects from simpler objects such as the tetrahedron, the composite solid object, the extruded object, and their applicability to the 3D cadastre situation in relation to their validation requirements.

Section 3 is a short discussion on validation extending from 2D to the 3D domain. Questions such as what is validation? why do we validate? and when do we validate are discussed briefly to emphasize the need for a validation.

Section 4 of the paper focuses on a 3D cadastral validation situation based on the internal geometry of a 3D parcel, the relationships of 3D parcels to the base parcel, relationships to other parcels, unique geometrical situations that might exist, effects of further processing of 3D geometry and certain entry level validations.

Section 5 deals with the geometrical structures and validation requirements of the newly developed ISO19152 Land Administration Domain Model (LADM).

Section 6 concludes the paper with a Discussion summarizing the paper, with a sub-section on Further Research which proposes work that needs to be extended and studied in depth.

2 Representation of a 3D parcel based on existing methods

Although significant work has been done e.g. (Kazar *et al*) on the validation of generic 3D geospatial objects, cadastral 3D parcels have validation requirements which are more restrictive in some regards (e.g. some 3D parcels may be required to be within base 2D parcels), but may be less restrictive in other regards.

This section deals with the various existing ways of constructing 3D objects, and the validation requirements for them. While the rest of the paper focuses on boundary representations to define a parcel or 3D object, this section discusses other ways of constructing 3D objects, which may provide jurisdictions with options to progress to a 3D cadastre based on their individual circumstances like legal requirements, existing data structure and proposed usage etc.

2.1 Objects constructed using tetrahedrons

The tetrahedron method of generating 3D objects (see Fig 1), has been employed in 3D GIS and extensively studied by Penninga et al (2006) and Rahman and Pilouk (2007). The same principles can be applied to create 3D cadastre using tetrahedrons.

Validation must ensure:

1. Individual tetrahedrons are not degenerate (4 disjoint points)
2. Tetrahedrons used to construct an object do not overlap –

3

The nature of the decomposition ensures that the object is unambiguously defined by a set of tetrahedrons, so the main objective is met, but there are several additional requirements.

3. Composite external faces that are intended to be planar should be planar. (see discussions below)
4. There must be no gaps between tetrahedrons within the objects (this is achieved via a topological representation; e.g referring to nodes via their id and not to repeat the coordinate values)
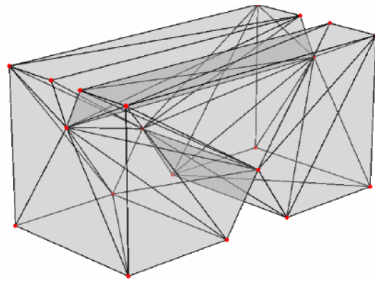

Fig. 1. A solid object created using tetrahedrons (Ledoux 2009)

Discussions:

The validation rules to be considered after Penninga *et al* (2006) and Rahman and Pilouk (2007) are:

- where tetrahedrons are in contact, the contact may be at a single point only, along a line, or on a complete face. No partial contact should be allowed.
- where an object has planar faces, but these are broken into triangles by the tetrahedronization process, checks must be done to determine whether the original planarity is lost due to rounding errors of vertex coordinates.
- it may be considered important that a relationship is maintained between the faces to ensure that they can be kept coplanar (for example, the nearest faces of Fig. 1 clearly should be planar, but there is no indication to validate this).
- where vertices meet, the coordinates must be the same.
- there must be no duplicate vertices, which lead to degenerate tetrahedrons.

2.2 Objects constructed from simpler solids

The composite solid method of generating a 3D block (see Fig 2), can be employed for very low level representations of a 3D object or a 3D city model resembling LoD1 in CityGML (Kolbe 2009). A similar approach can be used to define 3D cadastral parcels.
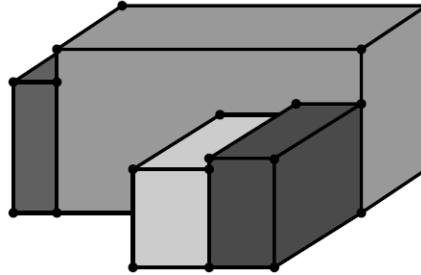

Fig. 2. Solids made from simpler solids (Ledoux 2009)

The simple solids produced would have the advantage of very simple validation constraints as well as quick answers to area and volume queries. It would also be easier to represent in a variable limiting height situation. Complex shapes can be generating by addition of simple volumes or subtraction to eat away from objects.

Where composite shaped volumes are built by eating away surfaces, making sure of the coplanarity. Gaps and intersections may be left during volumes addition or subtraction as well as in contiguous parcels, so that would have to be checked.

2.3 Regular Polytope

A particular example of the construction of objects from simple solids is the "Regular Polytope" (Thompson 2007, Thompson and Van Oosterom 2007). This approach uses as the simple solid a convex region of space, defined as the intersection of half spaces. A Regular Polytope is defined as the union of any number of convex regions (see Fig 2.1). The characteristic of this approach is that any combination of half spaces and convex regions is valid, greatly simplifying the validation process. All that is required is that the size and position of the objects are reasonable, and that continuity constraints are enforced if necessary.
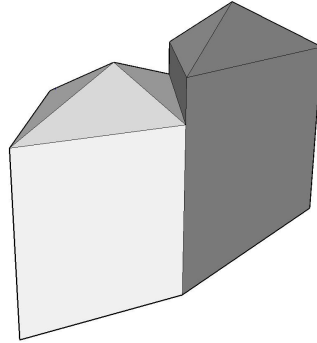
Fig. 2.1. Example of a regular polytope

2.4 Objects constructed by extruding

Three dimensional "objects" can be created using extrusion in many software. This is a convenient way to visualize 3D where variables such as individual object heights, constant heights for objects of same elevations and sometimes even the elevations of the land can be included to generate the 3D view. This may sometimes be the way to generate 3D cadastral views in non-complex situations, where no analytical facilities are required.
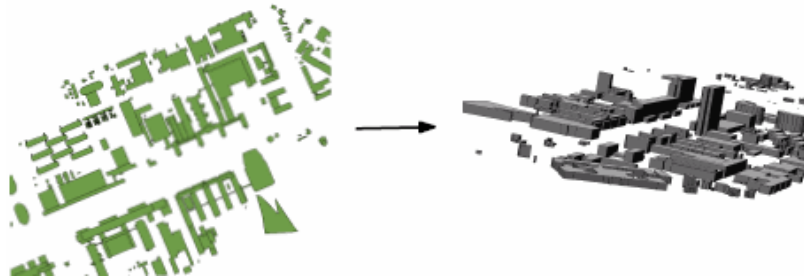

Fig. 3. City model using extrude (Ledoux 2009)

The extrusion method of generating 3D objects (see Fig 3), is fairly simple to build in a commercial software, but since the polyhedra formed are not topologically encoded, checks are limited to the 2D footprint and 3D data extraction is not possible except as a column of height attribute. This method provides a simple way of visualizing 3D cadastral data, but validation is limited to the geometry of the 2D base parcel and the height attribute of the extruded 3D object. However, if validation is required for adjoining objects of differing heights, it becomes more complex as demon-

strated by Ledoux (2009). Also, it is more difficult to integrate 3D volumes with 3D terrain.

3. Validation, extended from 2D to 3D

The object of validation in a 2D/3D cadastral environment is to form a rigorous definition of what is a valid object. This has to be considered in 2D and 3D as well as a mixed representation of both in the cadastre. In the cadastre as well as in other applications, validation needs to be done at various stages of data entry and processing to ensure the integrity of the data and also that future analysis or operations are performed within their intended bounds.

Within the context of validation we need to answer the following:

- What is validation? (Concepts, approaches).
- Why we are validating? (Needs analysis, purpose of validation).
- How we are validating? (Validation rules).
- When should we validate? (At data capture, data entry, post processing etc).

Validation is the process of checking for possible errors in data via pre-defined rules usually before the data is processed or entered into the system. Validation takes on different meanings depending upon the context and circumstances of the application. Validation, for example, to a database administrator would be quite different to that for a web page developer. While the former's validation strategies would be focused on defining integrity checks and business rules, the latter would probably be more concerned about developing strategies to accept or reject entries that users make over the internet and may possibly be malicious. There are lots of common premises for validation as well, for example, data security, logical consistency, data within pre-defined range, format of data, checks for null values etc.

In digital cadastre, the need to validate arises from two simple questions: (i) who owns the particular land or space and (ii) what is the extent of what is owned. Thus, the major reason to validate is the need to provide unambiguous answers to these questions. Where 2D cadastre is in place the extent is generally defined, only limited by the scale of the data capture, the techniques used, the accuracies achieved etc, while the ownership information is tied to the parcel and stored by some means. The 3D cadastral situation is more complex as it gives rise to the primary problem of unambiguously defining the 3D parcel and its extent. Ownership informa-

tion sometimes becomes complex with crossing networks, multiple strata etc.

Although there are similarities as well as dissimilarities in the approaches of the various validation requirements and strategies, the principles generally remain consistent. Generally, an attempt is made to identify all known issues then validation rules are defined against which data are checked before any further processing is undertaken.

This holds true in the 3D cadastral context as well. At this stage it is assumed that there is a 2D cadastre in place, which supports the key elements of storing and retrieving geometrical and attributes data in the system. Thus, storing of attribute information for a 3D parcel can be expected to raise few extra changes. It is the geometrical aspect that is highly complicated to store and validate before any manipulations can be performed.

Geometrical aspects are complicated in the 3D cadastral context because of the variety of shapes and geometries that are possible in a volumetric space. At present there is a general lack of consensus on how best to store or depict the data among the major software dealing with 3D data. For example, using the Oracle database one can define nodes with x, y, z coordinates and use them to construct edges, faces and solid objects.

As in the example in Fig 4, it would be possible to define a polygon from four coordinated points or nodes, and then a solid using the six polygon faces. However, for a truly vertical face, the vertical coordinates would be treated as duplicate points in some software's validation rules, which can disallow entry of the data into the database, thus creating interoperability issues.
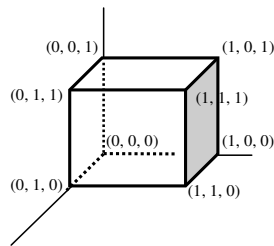

Fig. 4. Defining a volume by enclosing faces

The Open Geospatial Consortium (OGC) and the International Organization for Standardization (ISO) are working together to define a model, for generic 3D spatial information. The OGC (2004) and ISO19107 (2001) are examples of such standardizations.

Of particular interest in the field of cadastral data is the emerging standard ISO19152, the Land Administration Domain Model (LADM). This is an attempt to create an extensible standard that can be used to exchange cadastral information, and that can assist with the implementation of cadastral databases. (Lemmen et al 2009).

As an example of validation, ESRI's specification of ParcelFeatures_Topology (ESRI 2004) shows quite a comprehensive set of rules, tolerances, participating feature classes and the feature to be checked against. Other software have similar rigorous checking in the 2D GIS domain. This kind of checking is as yet to materialise in the 3D cadastre field because there is no agreed standard of validation of the 3D parcel and the ways of defining the rules are justified by the particular situation of the parcel itself (section 4).

Validation can be carried out in various stages during the life of the data. In the 2D or 3D cadastral context, validation can start from the time a surveyor sets foot on the site to the time it is entered to the system and might continue throughout the transaction life of a parcel. Validation strategies depend on the various stages the data goes through, and also in the case of a 3D cadastre the various methods or options of storing the data. In the following section, various options, methods and issues associated with a 3D cadastre are dealt with in further detail.

4. Validation in 3D cadastral context

In this section, situations involving 3D geometry in the cadastral context are listed. These are followed by discussions on the minimum validations rules or specifications that would be required to address these circumstances. In most cases, the 3D volume parcels are within the 2D base parcel, but exceptions may arise in the case of network objects when the 3D network object may extend beyond the base parcel.

The situations described below are classified into various groups based on similarity of conditions. They are based on:

1. Internal validity of 3D parcels.
2. Surface or base parcel.
3. Relationships to other parcels.
4. Unique geometrical situations.
5. Further processing on the geometry.
6. Entry level validations

4.1 Internal validity of 3D parcels

In the same way as it is necessary to ensure that 2D "polygons" have a valid definition, such as the simple feature specification by the Open Geospatial Consortium (OGC 1999), validity checks are necessary to ensure that representations of 3D regions are internally consistent. For example, in a boundary representation, the boundary must be complete, (watertight). Other issues like dealing with coplanarity, internal rings, constructing vertices, etc are equally important. These issues are explored in Kazar *et al*. (2008), to test for Closedness and Connectedness in particular.

4.2 Relationship to surface or base parcel

Unless the entire cadastre is to be represented in 3D, a mixture of 2D and 3D parcels will exist, with the vast majority being 2D. It is the nature of cadastral data that an identifiable set of parcels forms a base layer, which represents the primary interest in the land. In the following discussion, it is assumed that a set of base 2D parcels exists, and forms a non-overlapping partition of the area of the jurisdiction, and that appropriate validation and structural constraints are in place to ensure this. In many cases there will be secondary interests, like easements, represented by 2D parcels. These may form a second complete coverage but usually do not, and may be allowed to overlap.

In this section, the relationship between 3D parcels and the underlying base layer is explored, with reference to the validation tests that may be applicable.

Note that the term "base parcel" should not be taken to mean that it is physically below the "non-base" parcel(s). As noted by Stoter and van Oosterom (2006), the correct interpretation of what is known as a 2D parcel is in fact a column of space from some (possibly unspecified) depth below the earth surface to some (possibly unspecified) height above. What is usually represented as the 2D parcel is the intersection of this column with the surface. However, it must be noted that both bounded and unbounded objects exist in 3D space, for example, objects with open top or bottom.

Requirements

The relationship between the base parcel and the 3D parcels creates validation requirements such as:

1. Whether the 3D parcel is entirely within the base 2D parcel.

2. Checks on the upper and lower bounds of the 3D parcel (which may or may not have bounds on either ends).
3. Variable ground level in relation to the 3D bounds (where there are restrictions on the height above or below the surface to which rights or restrictions are imposed).

Discussions:

At least in Queensland, Australia, while the 3D parcels are initially created totally within the 2D parcels, (but this is not universal even in Queensland) this may not be preserved when the surface parcel is subdivided, e.g. a tunnel under a surface parcel does not prevent the owner of the surface parcel from subdividing it, as a result, requirement 1 above may not hold for all time.

The validation rules to make sure that the above conditions were met (if applicable) could include:

- *Ensure that the footprint of the 3D parcel is completely within the 2D parcel.*
If the same horizontal stratum is considered, then it becomes a trivial 2D polygon check, however, as more 3D objects are compared to the base 2D parcel, the situation becomes increasingly complex as in the case of network objects.

- *Ensure that the extrusion above or below the surface by the 3D parcel was completely within the 2D parcel*
If a building is considered to be built enveloping the total base parcel, then the mathematically vertical extrusion in given 3D reference system at right angles to the built surface might be different to the gravity vertical.

- *Ensure that the 3D parcel lies within the legal limits.*
In some countries, there may be a restriction on the above or below ground rights of the 2D parcel. The 2D parcel may or may not be considered to be a special case of 3D as suggested by Stoter (2004), but would vary according to the cadastral interpretation in use for that particular jurisdiction. The LADM (ISO19152 2009) makes this interpretation explicit by defining the boundary of a 2D parcel as a "FaceString", which represents a set of vertical faces, but is actually stored as a 2D linestring (Fig 5)
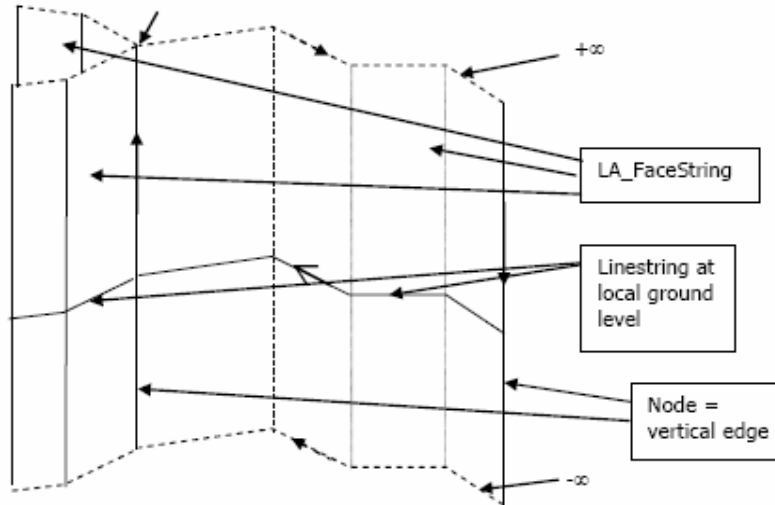
Fig. 5. Face string concepts of a 3D parcel based on 2D Line string at ground level
ISO19152 (2009)

- *Ensure that there are no gaps or overlaps within the individual 3D units that are part of the 2D base parcel*

If the base 2D parcel contains several 3D parcels, as may be the case with buildings on a parcel, then it is just a simple check to see whether there are overlaps or gaps when they are supposed to be touching. However, in the case where network objects are treated as real estate and have defined extents, and surface parcels have defined depths, there might exist a gap between the two strata. This situation may be acceptable from an administrative point of view, but raises the issue of whether the remaining parcel, with the defined 3D parcels excised, is a valid construct (see Fig 6).
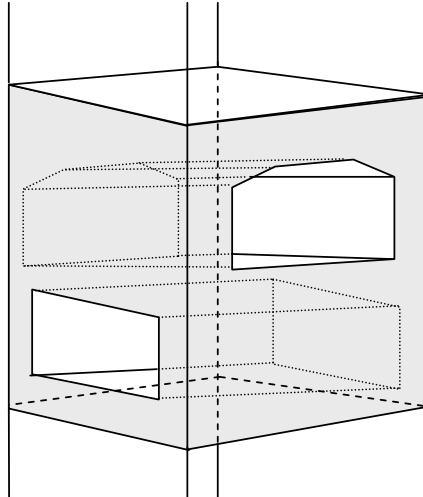
Fig. 6. Complex shape formed when two network parcels cross below, and are excised from a 2D parcel

4.3 Relationships to other parcels

Requirements

Beyond the relationship between 3D parcels and their enclosing base parcels, there is a need to consider the 3D parcels in relation to other parcels, including:

1. Checks on situations where a 3D parcel meets 2D parcels.
2. Checks on the geometry and topology of the 3D parcel and its relationships with neighbouring 3D parcels.

Discussions:

- *Ensure that there are no gaps or overlaps among neighbouring 2D or 3D parcels.*

When considering a simple 2D geometrical network of parcels, the obvious checks would be to find out if there were any (i) self intersections, (ii) overlaps or gaps among other parcels and (iii) partial boundary lines which would not create distinct parcels. In mixed parcels where 2D parcels may coexist with 3D parcels (see Fig 7), a specific form of parcel may be needed, described as "liminal"(see section 5.5), ISO19152 (2009), to allow

what is in reality a 2D parcel to exactly abut a 3D parcel. Unless there is a complete partitioning of space in 3D, the question of gaps or overlaps is difficult to address. Reasonability checking can assist in locating such errors (e.g. finding very acute angles between adjoining surfaces). See section 5.5 for a discussion on topological encoding.
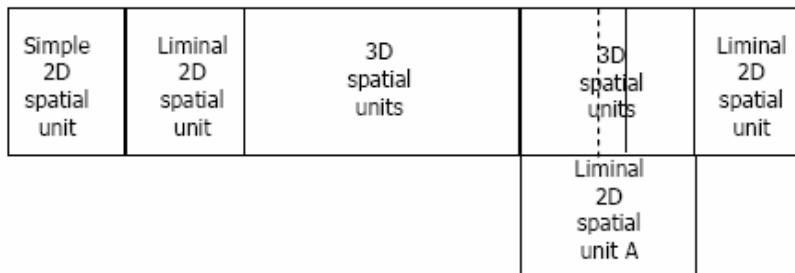

Fig. 7. Top view of mixed 2D and 3D representations ISO19152 (2009)

- *Ensure that the sum of the individual units of 3D floor area per strata was less than or equal to the base 2D parcel.*

This is a trivial and obvious check to verify that the union of all 3D objects per individual strata is totally within the base parcel, where 3D parcel are contained in identifiable strata, such as in a block of units.

- *Ensure that the faces between parcels are complete, so that distinct parcels are formed.*

This situation can arise in 2D when the line dividing two parcels does not connect to the opposite boundary, so that two apparently separate parcels cannot be distinguished (see Fig 7.1). The parcel itself would appear complete, but neighborhood operations within the two intended subdivided parcels would be erroneous. This is a trivial case for a 2D parcel which is treated by most GIS or CAD software, but for a 3D parcel, it becomes a lot more complex to ensure that the faces connect exactly.
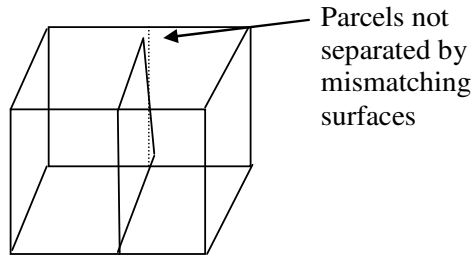
Fig. 7.1. 3D representation of an incomplete subdivision

- *Ensure that self intersections or loops do not create new unintended parcels.*

Again this is not difficult for a 2D parcel and these are already dealt with by most software; however, for a 3D parcel, it is more difficult to ensure that there are no unintended slivers (or shells in 3D), as well as to ensure that once this is resolved, the corrected surfaces remain coplanar (see Fig 7.2).
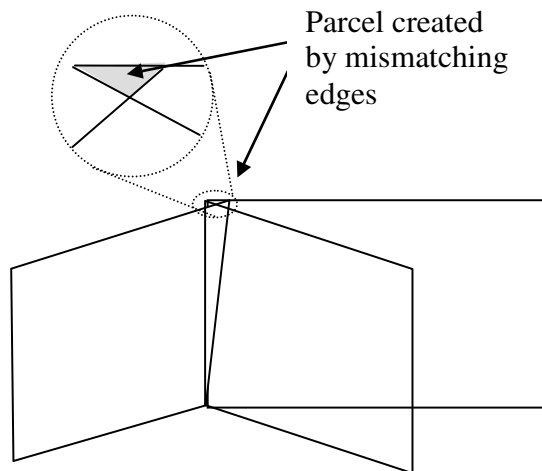

Fig. 7.2. 3D representation of self-intersections creating spurious parcels

4.4 Unique geometrical situations

In this section, unique situations that involve utility networks, or different strata being owned by different parties, existing and officially allowed encroachments or "hanging" parcels creating their own problems have been discussed.

Discussions:

- **Utility Network**. The main complexity of 3D network is its relationship to the base surface parcels (Fig 8). Several issues arise, like:
  - does the network subdivide when surface parcels are subdivided?
  - recording the network when the surface parcel is not mapped in cadastre (e.g. roads, rivers, reserves etc)
  - representing and recording the objects when the networks cross (e.g. tunnels and underground busways),
  - dealing with a situation when the network emerges to the surface,
  - dealing with variable and irregular shapes and sizes etc.
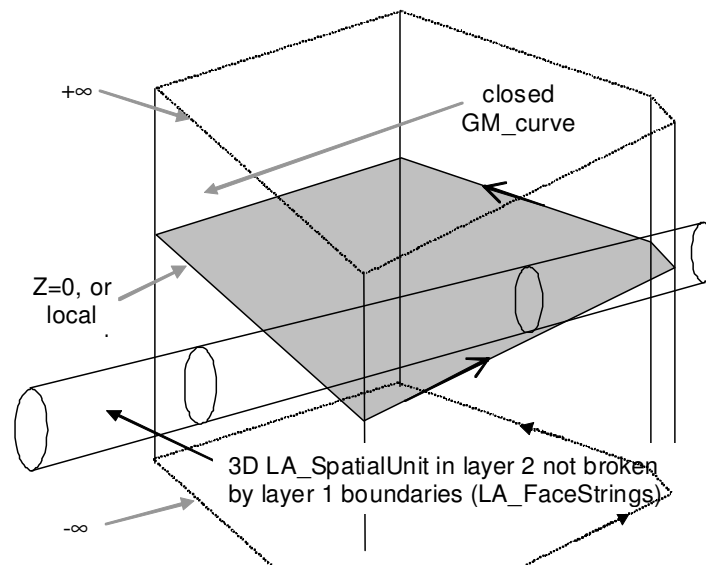

Fig. 8. Utility network object spanning surface parcels (ISO 19152 2009)

- **Multiple strata**. An ideal approach would be to allow multiple owners to rights and restrictions on multiple strata independent of each other,

but since most cadastres are based on surface parcels, it becomes complex to maintain a relationship between them. This is highlighted in the case of network objects (see Fig 8) where they will need update operations such as extensions, excisions, splits and merges etc; but as a way around the complexity of maintaining the relationship between the surface and the network object, easements have sometimes been created as subsets of the surface parcels and amalgamated to match the network object. However, if multiple strata titles are allowed (see Figs 8 and 9), constraints must be considered in both the horizontal and vertical direction. In the horizontal direction, the network object would more often than not fall within many surface parcels, which would make it difficult to have a condition where the 3D object lies within the base parcel. In the vertical direction, objects such as crossing networks or tunnels would not encroach in 3D but would in 2D.
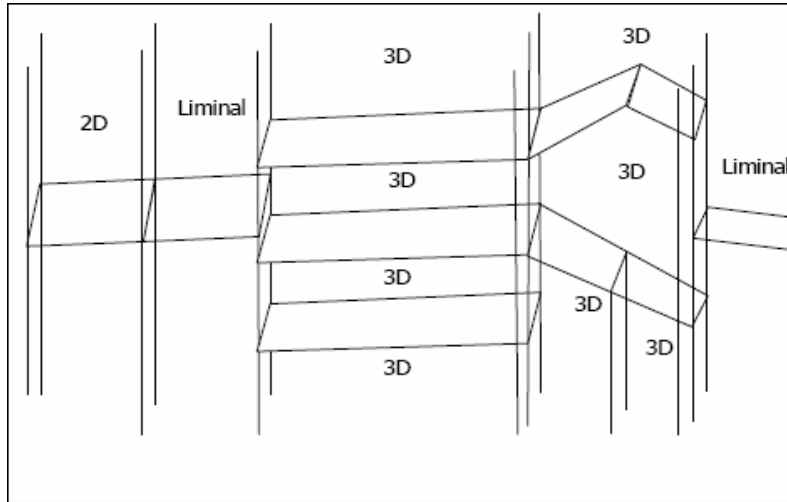

Fig. 9. Mixed use of face string and face to define both bounded and unbounded volumes (ISO 19152 2009). Liminal parcels are 2D parcels which directly adjoin the faces of 3D parcels.

- **Existing encroachment**. If the encroachment is in both the horizontal and vertical directions (2D and 3D), and if 3D volume parcels were created (see Figs 10 and 11), then making sure that the specification allows such parcels to be recorded as legal objects, is quite complex. In such a situation, the validation rules must be able to handle such exceptions as part of the validation process.

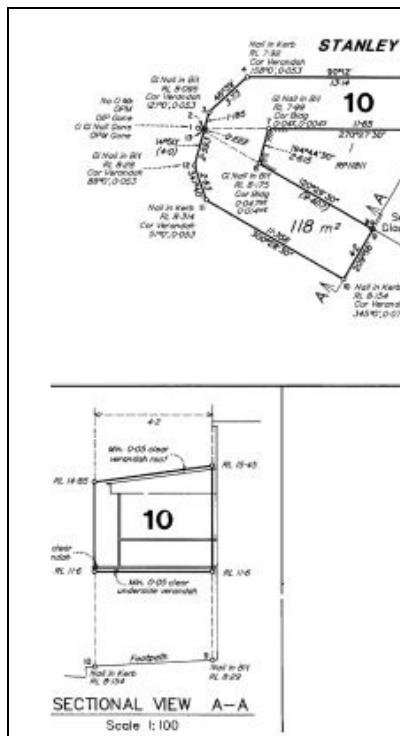**Fig. 10.** The Gabba Stadium overhanging Stanley Street in Brisbane, Australia

Fig. 11. (Left) 3D parcel number 10 of the Thai Rose, (Right) the restaurant over-hanging the footpath on the corner of Stanley Street and Main Street in Brisbane

- **"Hanging" title.** Titles that have no base parcel (see Fig 12), as in the case of the Story Bridge over Brisbane River where one part of the bridge is leased out to permit the lease operators to run a "bridge climb" tour for a fee. This title does not have a base parcel as the bridge is not mapped as a cadastral object, however rights have been created. This creates a complexity in storing and validating such objects as they are not tied to any surface cadastral object.

Fig. 12. The Story Bridge over Brisbane River (Google Earth)

4.5 Further processing of the geometry

Requirements:

1. Effect of subdivision of the 2D base parcel on the 3D parcel and vice versa
2. Consolidation of contiguous or non-contiguous 3D parcels
3. Creating a total/partial reserve/easement on the 3D parcel
4. Limiting of vertical extent of certain 3D parcels by legislation (e.g. in mining areas, owner's rights to the land underground for a group of parcels may be more restricted in depth than other parcels in surrounding areas)

Discussions:

- **Effect of subdivision**

  If the 2D parcel is subdivided, it affects the above ground and below ground objects differently. The above ground object such as buildings are also subdivided and it would be just a simple check to see that the 3D object is subdivided proportionately and that the split object is vertical. However, for below ground objects, such as network objects which might extend beyond the parcel, it will be difficult to adapt to circumstances where they might or might not be subdivided. A further complexity is added, if there are two crossing networks below the subdivided parcel or above ground cables with legal space around them for protection, with each network behaving differently as far as subdivision is concerned.

- **Consolidation of 3D parcels**

  Consolidation would be the opposite of subdivision (where the rights, restrictions and responsibilities of two parcels are identical), similar constraints would apply.

- **Creating easements**

  Creating an easement on a 2D base parcel would be similar to subdivision, but if the easement was meant to match a 3D network object and the surface parcel amalgamated, then additional steps would be required to validate the 2D-3D compliance

- **Vertical extents**

  Some areas of the same city, like Ipswich city near Brisbane, can have variable limits to the underground extent based on depth below surface to which owners can exercise their rights, so a reduced level of the ground surface needs to be recorded with the cadastre, so that checks can be made on the extent of the limiting depth.

- **Non Planar Surfaces**

  These greatly increase the complexity of the situation, particularly where curved surfaces intersect, which may result in 3D curved edges with no simple mathematical definition. For this reason, they are usually approximated by a number of planar faces.

4.6 Entry Level Validations

In addition to the above mentioned situations, there may be other circumstances involving geometry which needs to be mentioned for the sake of completeness.

Continuity of parcel.

A group of parcels in a cadastral map may be intersected by, for instance, a road due to development. This will lead to two possible choices: firstly, to maintain each intersected parcels as multi-polygons because they have the same owner and share the same history as the other split part, or, secondly, to create a new record-set for both the divided parcels since the road is an enduring structure, which will permanently divide the parcels and which might even facilitate land transactions for the discrete lots. Both of the cases can be handled by cadastral software, but the choice depends on the predicted practical use of the subsequent data. Validation in such a situation would be limited to a consistent logical approach rather than a rule based method, especially if there is an underground network through the parcel.

Reasonability.

Sometimes when entering data that has been collected in the field or compiled from various sources into the system, due to operator level error, the identification number of two different plans may be incorrectly recorded as the same. This can only be distinguished from the case discussed above if the distance between the parcels exceeds a reasonable value.

Spatio-Temporal.

Although strictly not geometrical, the temporal aspects of cadastre need to be validated as more cadastres round the world are shifting towards a 4D cadastre. Most of the validation in the time dimension will be descriptive and subjective with the spatio-temporal validations being performed at event time itself and thus governed by any of the situations and rules above. In some problem domains it is preferable to treat this as four equivalent as 4D primitives, however, in the cadastral domain the simplifying assumption of changes as atomic events is usually acceptable.

5 Representations of a 3D cadastral parcel as allowed by the ISO 19152 LADM

The ISO19152 LADM, as it is being defined at present, has 5 ways of defining parcels (known in the standard as LA_SpatialUnit). These are:

1. point spatial unit (section 5.1)
2. text spatial unit (section 5.2)
3. line spatial unit (section 5.3)
4. polygon spatial unit (section 5.4)
5. topological spatial unit (section 5.5)

An excerpt of the LADM documentation is included – see Fig 13. Parts of this diagram are used to illustrate the encodings (Figs 14 -19). These encodings are not exclusive and may be mixed within a single database. It is even possible to combine encodings within the definition of the same parcel, e.g. a parcel may be defined by lines on 3 sides but be completed by text.

All of these encodings are applicable in 2D or 3D, and different levels of validation are possible in each case. In general, these are in order of increasing sophistication, but also in order of increasing validation requirements as validation rules will differ for the geometrical/topological primitives and thus the features based on the primitives.

Thus, it can be expected that point based spatial units may be applicable where little detailed knowledge of the cadastre is available because of limited resources. While limited in its analytical functions, this encoding could be used to indicate the location of land parcels against a photographic background.

At the other extreme, the topological encoding allows analytical use of the data, calculation of areas, volumes, determining overlap with other coverages, etc. The cost is that much more stringent validation is needed before data can be included in the database. Correction of these validation errors can be beyond the resources of some authorities. The LADM uses the term "Spatial Unit" for what has been referred to as a parcel. In this section, "Spatial Unit" is used to refer to a parcel.

Fig. 13. Classes LA_FaceString, LA_Face, LA_SourcePoint and
LA_SpatialSourceDocument from the ISO 19152 LADM being developed

5.1 Point based encodings

Very little validation is possible – except to ensure that the points don't co-
incide (see Fig 14), and fall within the required jurisdiction

```
┌─────────────────────────────────────┐
│         LA_SpatialUnit              │
├─────────────────────────────────────┤
│  referencePoint: GM_Point           │
│                                     │
│                                     │
└─────────────────────────────────────┘
```
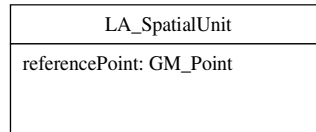
Fig. 14. Usage for Point based spatial units

5.2 Text based encodings

These spatial units are described textually, with the option of a reference point. While the description can be clear and unambiguous, very little formal validation is possible (see Fig 15). However, consistency in data collected and stored can be achieved by using standard forms during collection and storage, such that gross or negligent errors can be immediately visible.
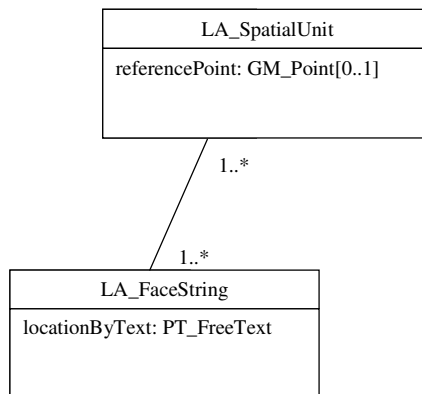
```
┌─────────────────────────────────────┐
│         LA_SpatialUnit              │
├─────────────────────────────────────┤
│  referencePoint: GM_Point[0..1]     │
│                                     │
└─────────────────────────────────────┘
                   \
                    \   1..*
                     \
                 1..* \
         ┌─────────────────────────────┐
         │      LA_FaceString          │
         ├─────────────────────────────┤
         │  locationByText: PT_FreeText │
         │                             │
         └─────────────────────────────┘
```

Fig. 15. Usage for Text based spatial units

5.3 Line based encodings

The characteristic of the line-based encoding (otherwise described as 'spaghetti') is that, while validation can be carried out to the same degree as any of the more highly structured approaches; the encoding is capable of interchanging and storing data that contains significant ambiguities, inconsistencies and topological breakdowns. It is suited to the situation where

data exists, in a basic and "un-processed" form, but being the best available, must be made available (see Fig 16).
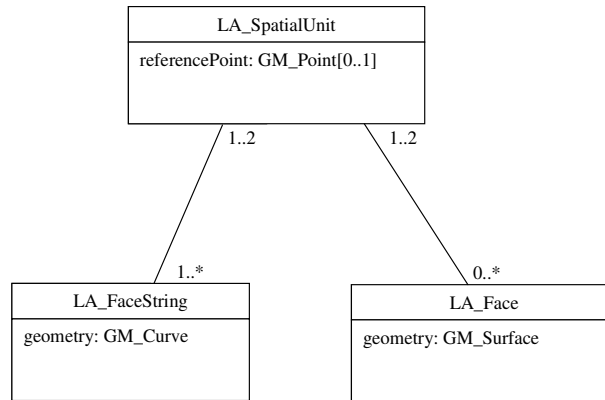

Fig. 16. Usage for Line based spatial units

5.4 Polygon based encodings

The polygon-based encoding stores 2D spatial units as simple polygons, while 3D spatial units are stored as polyhedra. Each FaceString represents one ring, and there should be at least one outer ring and zero or more inner rings. There is no intrinsic constraint that ensures that spatial units do not overlap, or that there are no gaps between them (see Fig 17).
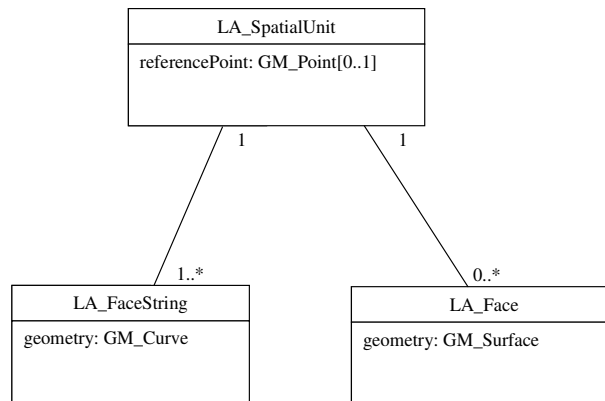

Fig. 17. For polygon-based spatial units

5.5 Topology based encodings

The topologically encoded form of spatial units is similar to the traditional topological encoding, and requires that each faceString, and each face is stored once only, with links to the left and the right spatial units (Figs. 16 and 18). As such, there is an in-built constraint that prevents certain kinds of invalid data from being represented, and is particularly suited to the situation where a complete non-overlapping partition of space is to be defined.
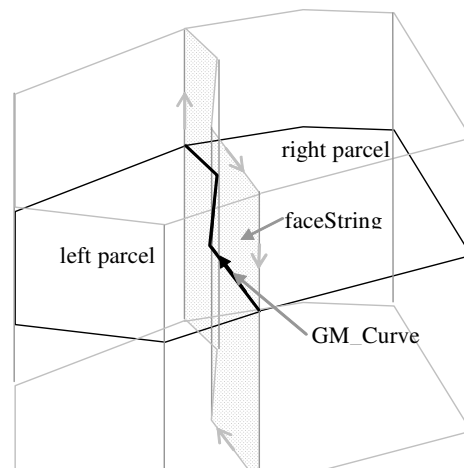

Fig. 18. Topologically encoded 2D spatial units (with common faceString shaded) (ISO19152 2009)

The combinations of 2D and 3D spatial units that adjoin, create an extra complexity for the topological encoding form (see Fig 19). Because a 2D spatial unit may directly adjoin a 2D spatial unit, an additional type of spatial unit (described as "liminal") is needed. This parcel is intrinsically a 2D parcel, but has to be represented with faces in its boundary. (ISO19152 2009).
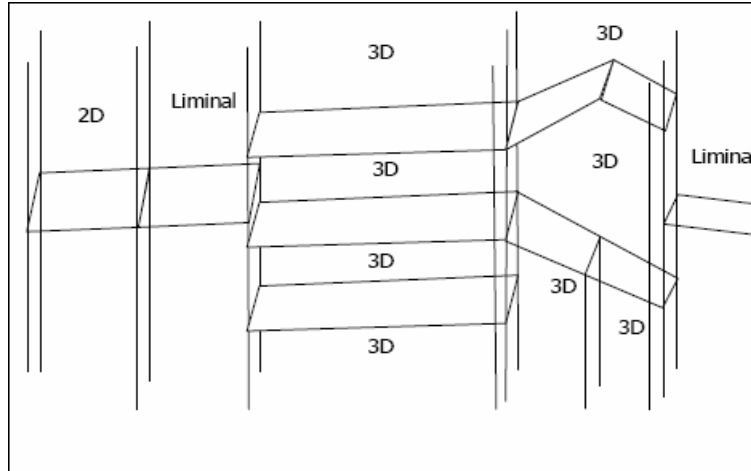
Fig. 19. Reprint of Fig 9, showing topological encoding of the junction of 2D and 3D spatial units, side view of Fig 7 (ISO19152 2009)

6. Discussion and future work

The amount and completeness of the validation that needs to be applied to cadastral data varies according to the level of maturity and sophistication of the databases and applications involved. For that reason, ISO19152 defines alternative encoding strategies to ensure that for whatever level of validation is achievable, the data can still be represented.

The decision as to what validation rules are to be applied by a particular registering authority will be made by that authority, and should be enabled by technology. This philosophy will ensure that authorities are not inhibited from developing a cadastral database by the high cost of ensuring pristine data.

As an example, a cadastre may begin life with a mixture of point and text based spatial units, gradually being upgraded to a line-based encoding. This form can be shown to be useful for certain applications, in spite of topological failings. Further effort could then result in a fully topological cadastral database.

It is significant that all five levels of maturity that are accommodated by ISO19152 can be applied in 2D and 3D, and even more importantly, to a combination of 2D and 3D parcels.

6.1. Further Research

This paper provides a preliminary investigation of the issues concerned with validation. It raises questions and identifies problems that need to be resolved to ensure a functional 3D cadastral system. As a generic study, in-depth analysis and investigations can be carried out on each aspect of the validation requirements during the stages of data collection, storage and processing. As specific requirements will differ, and not all of the issues raised in this paper are relevant to all 3D cadastres, user specific validation requirements need to be studied to suit individual circumstances.

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