

A Taxonomy of Spatial Units in a Mixed 2D and 3D Cadastral Database

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Keywords: Cadastral Database, Land Management, ISO LADM, 3D Cadastre

SUMMARY

The aim of this paper is to define the range of objects that may need to be accommodated in the development of a practical cadastral database, to also accommodate 3D spatial units, and permit a range of encodings to coexist.

The level of geometric encoding as defined in the ISO19152 LADM provides a framework of categorization of spatial units recorded in a cadastre, whether formal or informal, historic, current or planned. The levels of encoding range from simple “text based” spatial unit to the “topology based” encoding (in both 2D and 3D). In our proposed categorization, there are two more aspects, in addition to the levels of encoding, which we identify: 1. types of real world spatial unit (according to law/ regulations) and 2. types of geometric descriptions.

The existence of real-world examples of various combinations of 2D and 3D spatial units provide guidelines in the development of a 3D cadastral system. These include, amongst others, spatial units with: open or closed volumes (unspecified top / bottom), faces restricted or not to horizontal or vertical orientation, fixed or moving face(s) (ambulatory), faces (partly) related to physical constructions or not, 3D spatial unit within single surface parcel or crossing many surface parcels (legal space for pipeline), etc.

These are characterizations of the real-world spatial unit, but there are also issues that may become important by virtue of choices made in the database implementation, such as the presence or not of “caves” (dents, holes and trough holes), non 2-manifold boundaries allowed or not, volumes with contiguous or not interiors, boundaries described by planar (flat) or curved primitives, etc.

All three classification aspects, encoding level, real-world spatial unit type, geometric representation are more or less orthogonal (in theory all combinations are possible), but in practice also very much related.

In developing any database, it is vital to have a complete picture of the range of possible objects that need to be modeled, if “surprises” are to be avoided in the implementation and acceptance testing. This paper provides a discussion on the type of classification that is useful for a cadastral jurisdiction and the validation requirements of these classes of objects.

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1. INTRODUCTION

In any modern cadastre there exists a range of different types and formats of spatial units (land parcels). In particular, there is large and accelerating trend towards 3D parcels being defined in urban areas, where land values are high. Van Oosterom *et al* ([van Oosterom et al. 2011](#), [Van Oosterom et al. 2014](#)) have been closely monitoring this trend, and have indicated some of the variety of spatial units that are in use throughout the world.

The level of geometric encoding as defined in the LADM (Land Administration Domain Model - ISO19152) provides a framework of categorisation of spatial units and a detailed range of coverage for registration, where spatial units are recorded in a cadastre, whether formal or informal, current or planned. The levels of encoding defined are:

1. “Text-Based”: The Spatial Unit is defined or partially defined by a textural description. (“Sketch-Based Encoding”, where the spatial unit is described by a diagram which may not have a strict scale or dimensions, is a sub category of Text-Based).
2. “Point-Based”: The Spatial Unit is indicated by a single location point – often intended to be used in conjunction with a geocoded image and with administrative attribute(s) including the size of the area.
3. “Line-Based”: The Cadastre is defined by a collection of line work, with Spatial Units indicated by points within the regions so implied.
4. “Polygon-Based”: Each Spatial Unit is represented as a discrete polygon.
5. “Topology-Based”: A complete coverage of line work is created, with the Spatial Units being defined by faces, edges (and nodes) in the topological structure.

Spatial units might be restricted to a single level of encoding, but in practice it is not uncommon for the legal definition of the spatial unit to impose a restriction on the level of the encoding in the database. For example, a parcel may be defined as bounded on three sides by surveyed lines, but on the fourth by the bank of a river, which may erode or accrete with time. This would be seen as a mixture of text-based encoding with a higher level encoding such as line-based. These are characteristics of the “real world” spatial unit, but there are also issues that may become important by virtue of choices made in the database representation, such as the presence of “caves”, through holes (“donuts”), non-manifold boundaries and volumes with complex forms of contact (e.g. non-contiguous interiors) ([Ying et al. 2011](#))

In developing any database, it is vital to have a complete picture of the range of possible objects that need to be modelled, if “surprises” are to be avoided in the implementation and acceptance testing, as for example, the problematic cases identified in ([van Oosterom et al. 2003](#)). The first use is in the design process, to provide a checklist in monitoring the design

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for completeness. The second is in developing test data for the acceptance testing in the later phases of implementation. Different types of 3D parcels are much easier / harder to encode from source, and some jurisdictions have limitations on the types of 3D objects that can be registered. This paper also provides a method to decide what level of sophistication is needed in the data capture / update processes and resulting representation as stored in the database. It provides a discussion on the type of classification that is useful for a cadastral jurisdiction and the validation requirements of these classes of objects.

The paper is structured as follows: The issues concerning different types of 2D/3D spatial units are identified in section 2, while section 3 discusses the categorisation of “real-world” spatial units (real-estate objects). Section 4 categorises the geometry of spatial units in terms of their complexity, with the practicality and completeness of that categorisation being demonstrated in section 5. Conclusions are presented in section 6.

2. BACKGROUND

For many years now, the presence of 3D real-estate objects in the cadastre has been recognised, but it is only fairly recently these objects have been considered as candidates for inclusion in a cadastral database ([Stoter and van Oosterom 2006](#)). Stoter and van Oosterom (2006) show that polyhedra that are otherwise valid (and could be physically constructed) could be rendered invalid by the database implementation rules (see Figure 1). Bjornsson and Land (2011) have shown that a useful hybrid cadastral database can be implemented which is nevertheless restricted to what we term “Polygonal Slices”. This has proved successful in creating a database in Bahrain ([Ammar and Neeraj 2013](#)). Spain have recorded the 2D definition of “sub parcels”, with an indicator of their floor number, allowing a good representational view of the 3D subdivision ([García et al. 2011](#)).

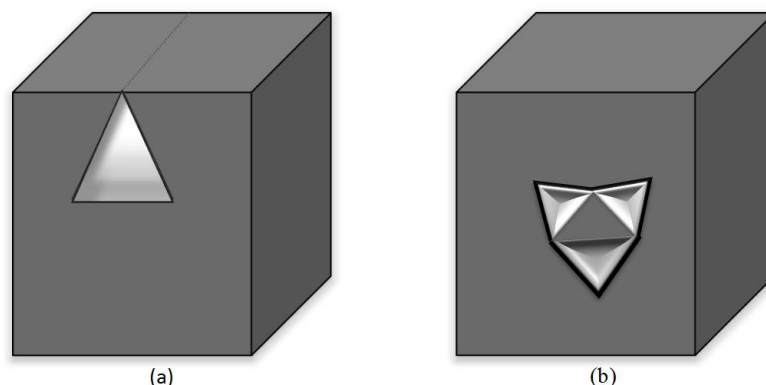


Figure 1 “Valid polyhedra that are determined invalid by the implementation. (a) Edge in the upper face is used four times, (b) front face contains disconnected parts due to tetrahedral dents.” From Stoter and van Oosterom (2006 Page 156)

The majority of jurisdictions that administer a cadastre with 3D parcels, appear to restrict those to the “building format” type of spatial unit ([Acharya 2011](#), [Sørensen 2011](#)) Singapore has identified that the restriction of parcels to “straight walls or flat floors” is not viable ([Khoo 2011 page 516](#)), while the Russian Federation has implemented a pilot database with complex 3D constructs ([Vandysheva et al. 2013](#)).

There is a need to provide a terminology to discuss the complexity of 3D cadastral objects, especially because some simplifications may need to be made to allow them to be represented by a database primitive. For example, complex curved objects may need to be represented by approximations in the form of polygonal slices, if that is all that is allowed in the database.

3. CATEGORISING OF REAL-WORLD SPATIAL UNITS

This section looks at the types of spatial units that are recognised by cadastral authorities in various jurisdictions. First, the more tradition 2D spatial units are discussed in section 3.1, next the 3D spatial units are discussed in section 3.2.

3.1 2D Land Parcels

The majority of boundary lines in a cadastre are what are termed “fiat objects” - that is to say they do not “exist independently of human cognitive acts” ([Smith 1995 Page 3](#)). A minority of boundary lines, by contrast, are defined by natural features (Figure 2). While the shape of 2D cadastral parcels is generally well supported by the “polygon” concept of the OGC Simple Feature specification ([OGC 1999](#)) and ISO19125; given the importance to the property owner of knowing whether a boundary is ambulatory in nature, the simple feature polygon is not advised as a method of representing a cadastral parcel, since it does not provide the necessary attribution of part of the outer boundary linestring¹ (near Albert River). Note that the cadastral parcel does not in general fit the definition of “Feature” as an “abstraction of real world phenomena” ([OGC 1999 Page IX](#)), since there is not necessarily any real-world object demarking the parcel (see Figure 4).

¹ Note, that it is common to record the approximate position of an ambulatory boundary (as a linestring) as it was observed on the most recent survey as though this is the boundary, with an attribute to flag it as “ambulatory”. It is important to remember that the recorded linestring in no way defines the boundary. The real-world feature defines the boundary.

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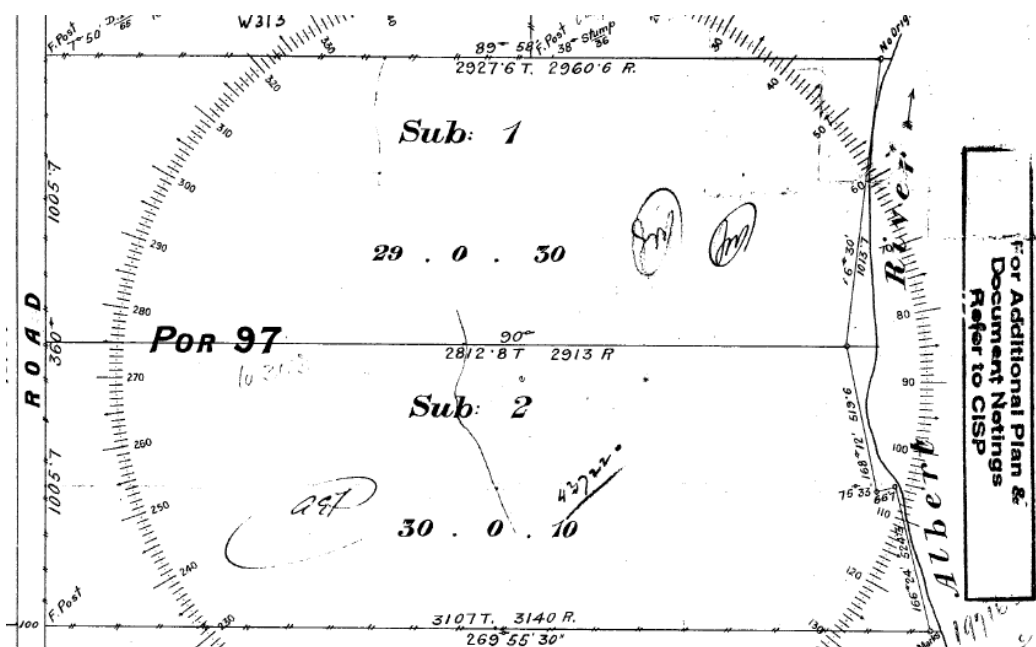
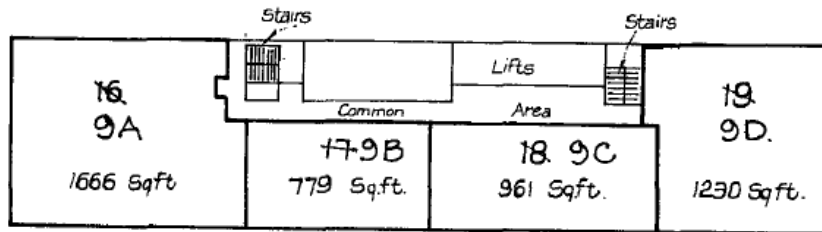


Figure 2 Cadastral parcels with mix of ambulatory boundaries (Albert River) and fiat object boundaries between 'Sub 1' and 'Sub 2' and the road. Note that in the Queensland Cadastre, road boundaries are fiat boundaries (not determined by the physical road features) unlike the river boundary which is defined by the actual river bank.

3.2 3D Spatial Units

The first major division of 3D spatial units in a cadastre is in terms of the definition. Broadly speaking, there are two types of 3D definition:

1. The "building format" (or more general "construction format") type of spatial unit, which is defined entirely in terms of the construction that surrounds it. For example, a unit which is defined as extending to the middle of the walls of the building (Figure 3).
2. The "pure volume", which is defined geometrically in relation to a geodetic datum, or in relation to known points. In this case, there may be no construction occupying the volume. For example, a communications easement to ensure a microwave link is not obstructed.



Scale:- 30 feet to an inch
Floor Areas are Approximate
Only.

Figure 3 Four individual spatial units defined in terms of the building construction, with no geometric definition beyond a sketch.

In a cadastre containing 3D parcels, the level of encoding may not be the same in the X/Y dimensions as in the Z dimension, as shown in (Thompson 2013). For example, a unit in a building may have its floor plan defined as a polygon with precise positioning, but the height extent may be described merely as “on floor 5”.

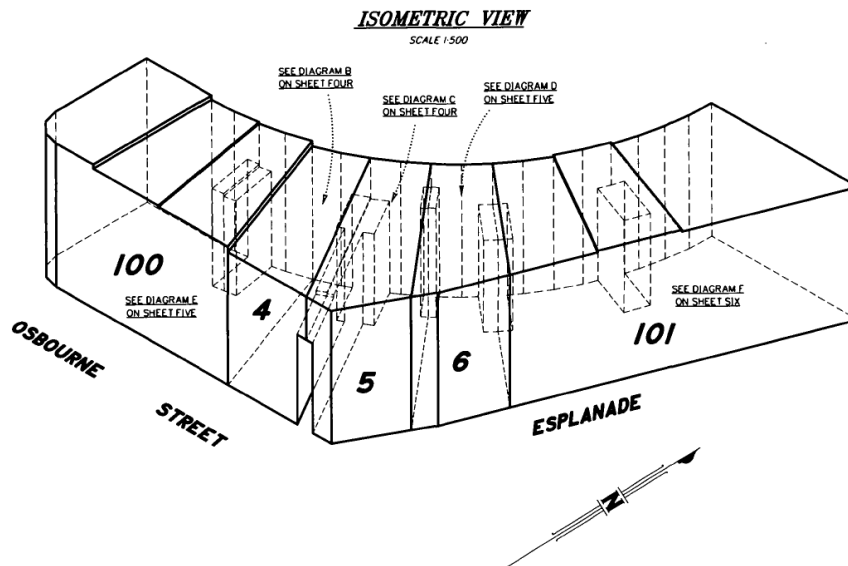


Figure 4 A series of parcels defined geometrically (3D boundaries not coinciding with physical objects).



Figure 5 The buildings in the plan shown in Figure 4. The parcels 4, 5, 6, 100 and 101 are the areas of construction in front of the apartment building. Photo - Google Street View.

By contrast, in the case shown in Figure 4 and Figure 5, the owner has apparently decided to sell space for shops in front of an apartment building. In order to avoid the views from the apartments being obscured, he has limited the height of the shop development by selling only that part of the space below a certain level. The metes and bounds of the spatial units are defined on following pages in the plan. At the time of creation of the spatial units, no building had commenced in the newly created spatial units.

The next major division of 3D spatial units is in terms of the actual shapes. These include real-world spatial units (according to laws and regulations) with:

- unspecified top (to the depth of ...),
- unspecified bottom (below the depth of),
- two horizontal planes defining top and bottom (a “slice”),
- two (potentially non-horizontal) surfaces defining top and bottom,
- faces restricted to horizontal or vertical,
- textually described face(s),
- single valued (for any XY position, only one range of Z permitted),
- presence of caves and/or tunnels,
- moving face(s) (ambulatory),
- non-planar (curved) faces,
- non-contiguous volumes

In order to make sense of this plethora of shapes, the following set of categories is proposed.

4. CATEGORISING THE GEOMETRY OF 3D SPATIAL UNITS

Any finite 3D spatial unit can be represented by a GM_Solid as defined in the GML 3 or ISO19103 specifications ([OGC 2007](#)), since it is the most general form of 3D volumetric object that is useful in defining spatial units. There are various kinds of 3D objects that cannot be represented in this type of representation - e.g. parcels which have undefined tops or bottoms. On the other hand, the vast majority of 3D spatial units in any jurisdiction are much more restricted in complexity, and therefore it is useful in developing a schema and encoding standards to have a set of classes of geometry. For example, in some jurisdictions ([García et al. 2011](#)) the spatial units are defined in terms of the floor plan of the building, with the height defined by the number of floors. It would be unnecessarily time consuming to encode these objects as general volumes. The aim of this paper is to define categories of volumes, to allow the simplest possible form of encoding to be used, and to document the categories of volumes that can be accommodated by a particular data model.

4.1 Contiguous / Non-Contiguous Volumes

This division is not important to this discussion. The remainder of this section will assume that any basic allocation units (LA_BAUnit) that are non-contiguous are divided into contiguous spatial units (LA_SpatialUnit) (using the nomenclature of the LADM).

4.2 2D Spatial Units

In the parlance of the LADM, a 2D spatial unit is effectively a 3D spatial unit with vertical sides, and with no top or bottom defined. Thus the 2D spatial unit can be seen as the simplest form of 3D spatial unit. It can be defined by a ring of LA_BoundaryFaceString objects delineating the outer boundary, with zero or more rings delineating “holes” in the spatial unit. In this paper, this collection of rings of boundary face string objects will be referred to as a “2D parcel”.

4.3 Above / Below a Depth or Height

This category is the next simplest. It is encoded as a 2D parcel, with definition of a single-valued surface². The spatial unit is defined as occupying the volume above or below that surface. It is commonly used in mining areas to separate the parcel which defines the surface usage of the land from the space below the surface that is subject to mining; see Figure 6.

² In this and other categories, a “single-valued surface” may be described by any function $z = f(x,y)$, which defines a single elevation for any 2D point location within the 2D parcel. It could be defined for example by a TIN. (Triangulated Irregular Network).

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LOT 3 IS TO THE DEPTH OF 30.48 M
 LOT 5 " " " " 21.336 M
 LOT 6 " " " " 15.24 M
 LOTS 13, 15 & 16 ARE BELOW LOTS 3, 5 & 6
 RESPECTIVELY AND ARE BELOW THE DEPTHS OF
 30.48 M, 21.336 M AND 15.24 M RESPECTIVELY.

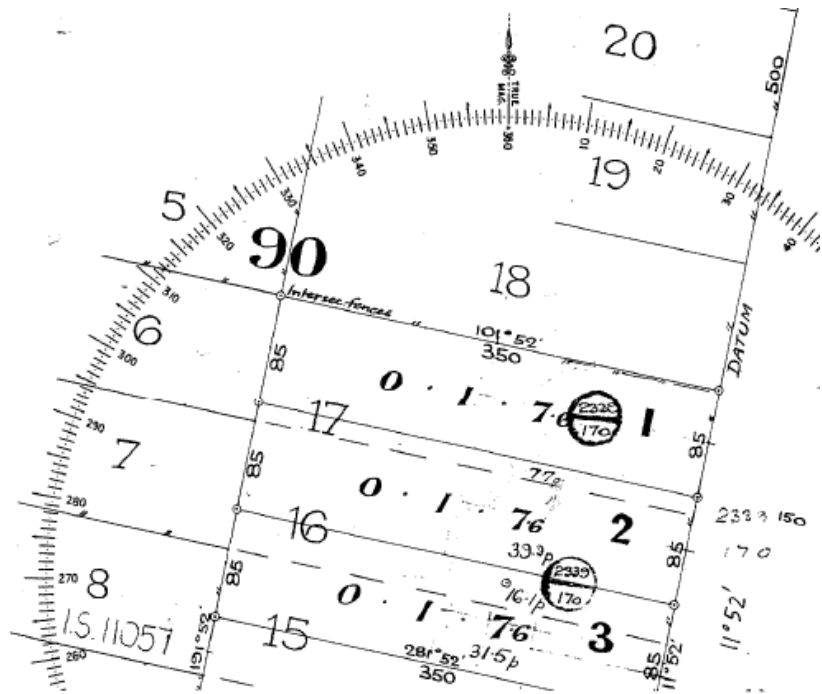


Figure 6 Plan showing Lot 3 to the depth of 30.48m, and Lot 13 directly below it "below the depth of" 30.48m. All other dimensions are presented in a similar form to those of standard 2D format lots.

On an individual spatial unit, the information required is:

1. The extents of the 2D parcel
2. A definition of the surface
3. Whether the spatial unit is above or below the surface

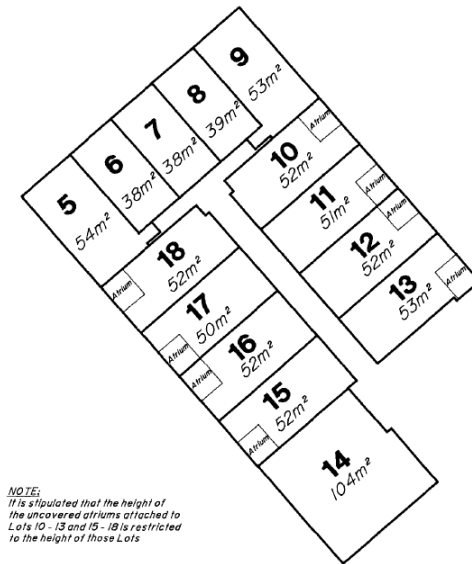
There are three subcategories, depending on the nature of the surface definition:

1. Above/below an elevation: the surface is defined by a horizontal flat plane at a height above/below a datum. (e.g. Australian Height Datum - AHD).
2. Above/below a surface parallel to the local ground surface, and a defined distance above/below it.
3. Above/below an explicit single-valued surface (potentially non-flat).

4.4 Polygonal Slice

This category is encoded as a 2D parcel, restricted to between two single-valued surfaces, which must not intersect or touch (see Figure 12 for a counter example). This type of spatial unit is quite common as a method of defining the volume of a single apartment unit (Figure 7). In many jurisdictions, it is the only form of 3D spatial unit recognised. There are other instances of "slice" spatial units in use in Queensland, not defined by a physical structure (building). See Figure 8 for an example. Note that this spatial unit is more than 10km³ in volume.

LEVEL B



NOTE:
It is stipulated that the height of the uncovered atriums attached to Lots 10 - 13 and 15 - 18 is restricted to the height of those Lots

Figure 7 Excerpt from a "Building Format Plan". This defines lots 5-18 in general shape, but without exact dimensions. The heights of the apartments are also undefined. The actual extents of the apartments are defined by the structure of the building.

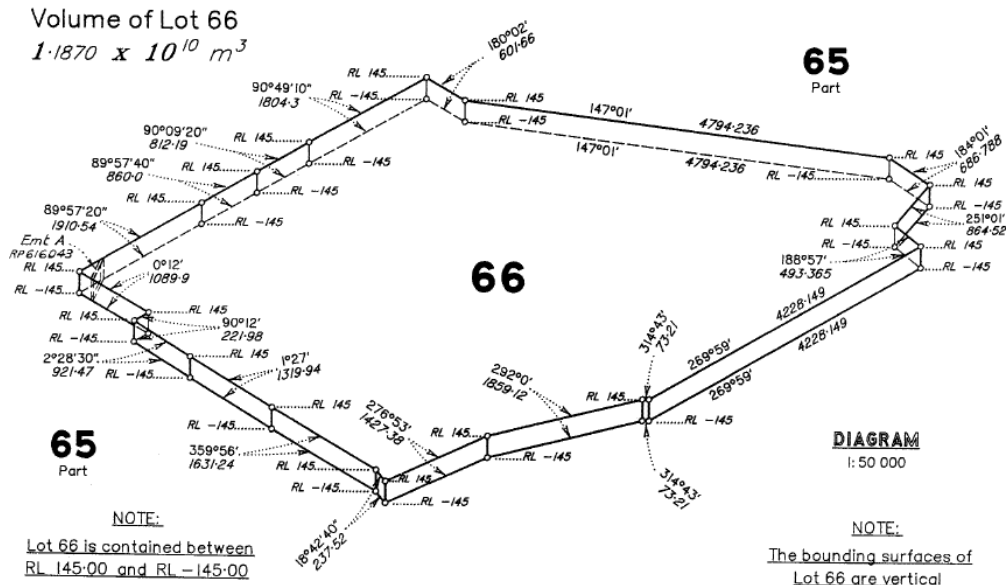


Figure 8 Very large spatial unit defined as a "slice" from RL (Reduced Level) 145m below datum to 145m above datum. Note that the lowest point of the ground surface in this lot is 170m above datum, so that this spatial unit is entirely below ground.

For an individual spatial unit, the only information required is:

1. The extents of the 2D parcel
2. The definition of the top surface
3. The definition of the bottom surface

There are subcategories, depending on the nature of the surface definitions. Each surface may be defined as:

1. Above/below an elevation: the surface is defined by a horizontal flat plane at a height above/below a datum. (e.g. Australian Height Datum - AHD).
2. Above/below a surface parallel to the local ground surface, and a defined distance above/below it.
3. Above/below an explicit single-valued, but potentially not flat surface (Figure 9).

There is also a subcategory where the top and bottom surfaces are defined textually - e.g. "Floor 4" (normally implying a horizontal surface).

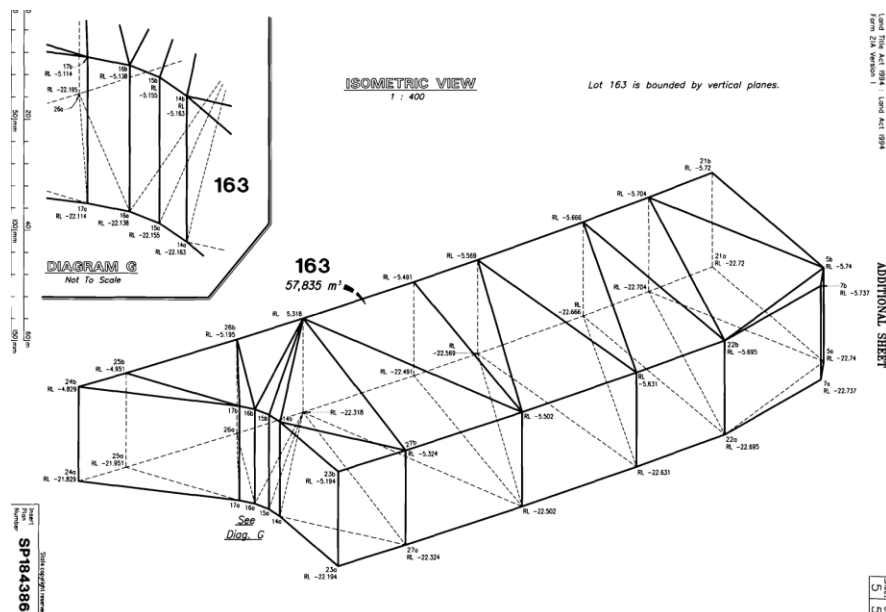


Figure 9 Polygonal Slice. Note that the top and bottom surfaces are not horizontal, but have been triangulated to ensure planarity of faces, and create a single-valued surface.

4.5 Single-Valued Stepped Slice

This is a surprisingly common form of volumetric spatial unit which is usually defined geometrically. It is defined by a set of faces, all of which are either horizontal or vertical. The volume is restricted to being single valued in Z. That is to say, there is no point pair of points in the spatial unit with the same (x,y) coordinates, with a point outside the region between them. This restriction is violated by any volume with a “cave” or “tunnel” in any vertical wall. The reason for this restriction is that the volume can be visualised from above very easily in 2D. Note that caves and tunnels in the top or bottom surfaces are allowed.

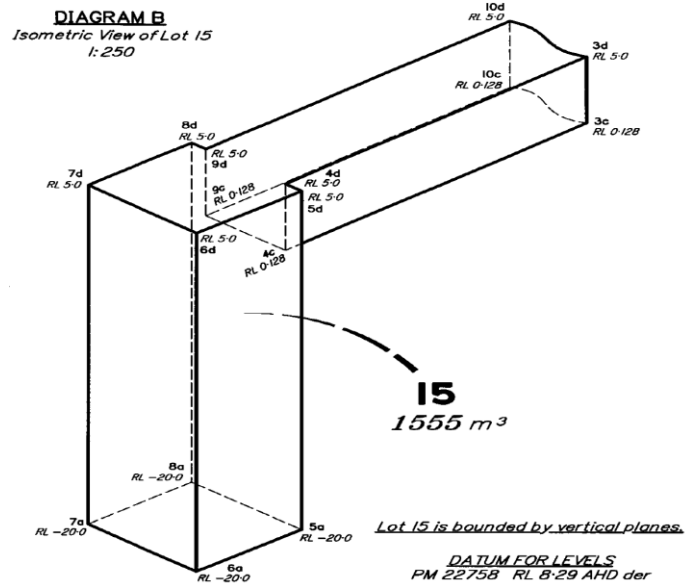


Figure 10 A Single-Valued Stepped Slice spatial unit. Note that the section of boundary from points 10c, 10d, 3d, 3c is an ambulatory natural boundary

4.6 Multi-Valued Stepped Slice

This is defined by a set of faces, all of which are either horizontal or vertical, without the restriction of the volume being single valued in Z. This allows volumes with “caves” or “tunnels” in any wall; see Figure 11. A multi-valued stepped slice can be constructed as the union of a number of slices.

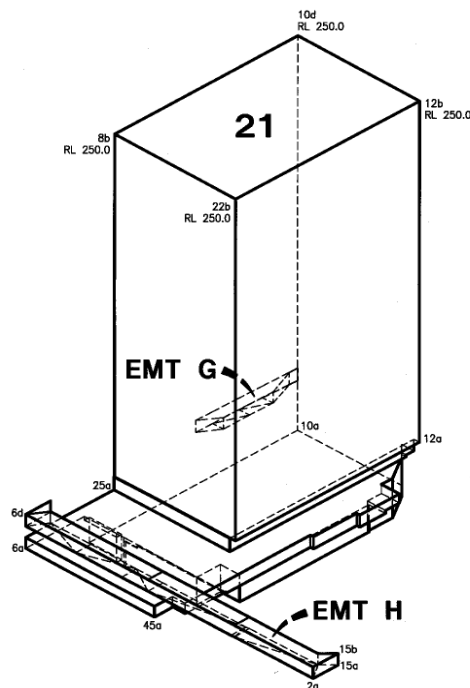


Figure 11 A multi-valued stepped slice. Note that Easement G forms a “cave” in lot 21, thus preventing lot 21 from being single-valued in Z.

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4.7 General 3D Parcels

Parcels not fitting into one of the earlier categories are classified as General 3D parcels (polyhedra); see Figure 12 and Figure 13. This category can be further refined: 2-manifold required or not, open/closed volume, planar/curved boundaries, single/multi-volume, etc.

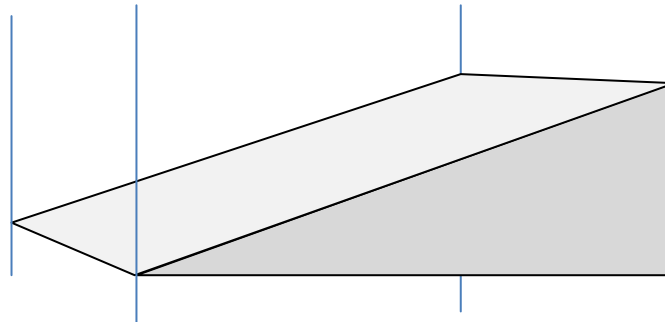


Figure 12 Wedge shaped Spatial Unit. This cannot be defined as a polygonal slice, because the top and bottom surfaces intersect.

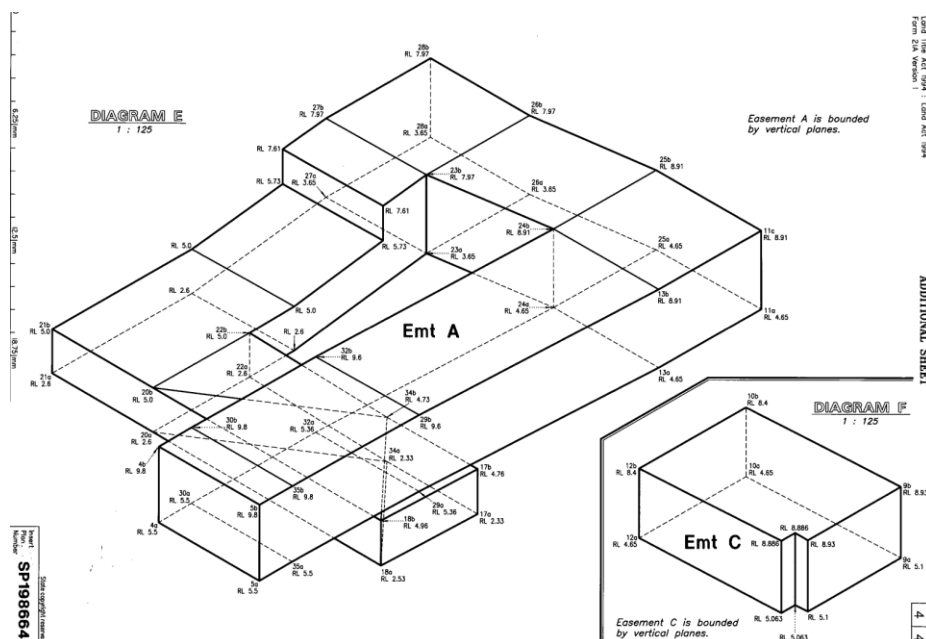


Figure 13 A General 3D spatial unit (Easement A). While the walls are vertical the spatial unit cannot be defined by a polygonal slice, because the defining surfaces are not single-valued in Z. It cannot be a multi-valued stepped slice, because not all surfaces are vertical or horizontal.

4.8 Balance of Parcels

Several parcels are defined as a 2D spatial unit with a 3D region defined within it. The inner 3D region could be of any complexity as described in section 3.2, but there are two variants of what this construct means:

1. The volume may be a primary interest excised from the 2D spatial unit.
2. The volume may define a secondary interest (e.g. lease; see Figure 14), therefore leaving the base spatial unit as a standard 2D parcel.

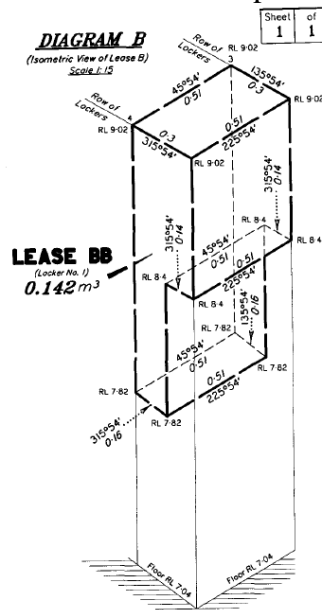


Figure 14 A General 3D spatial unit which is excised from what would otherwise be a simple 2D spatial unit.

5. COMPLETENESS OF THE CATEGORISATION

In order to ensure that the categories are complete and non-ambiguous, a set of questions are posed in the order shown in Figure 15. Provided these questions are well defined, the categorisation is definitive. As indicated in section 4.7, the General 3D Parcel can be further refined: 2-manifold required or not, open/closed volume, planar/curved boundaries, single/multi-volume, etc.

This decision tree is intended to capture the intrinsic geometry of the spatial unit, and does not consider any modifications that might be necessary to represent that geometry computationally. For example, if it is necessary to force the closure of a volume by adding a “top” polygon to an “above the depth of” parcel, or to introduce construction lines to force the manifold boundary surfaces, this may introduce additional categories within the computational representation.

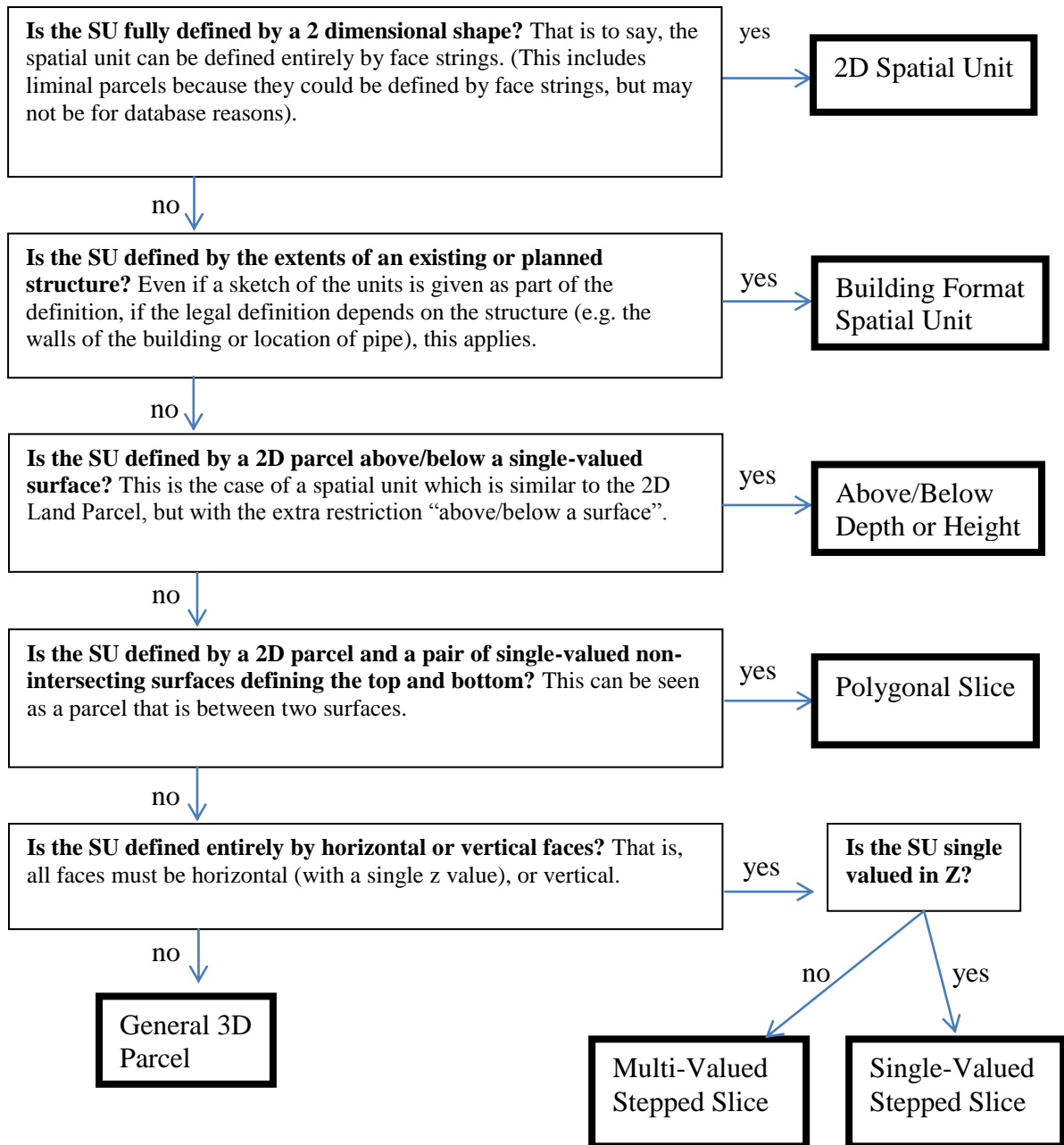


Figure 15 Flowchart to determine the category of a spatial unit

5.1 Indicative Population Sizes of Geometry Categories

This section contains data from a mixture of sources, primarily taken from the Queensland Cadastre. Because the finer details of interpretation of the older paper survey plans is not necessarily easy, in order to estimate populations of 3D geometry types, only plans covering a section of the Brisbane CBD were obtained, and counted. Thus the following tables 1 and 2 are subject to errors: 1) Because of the small sample size (97 plans), 2) Because the area of Brisbane may not be representative of patterns throughout Queensland or the world, 3) Due to

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errors in interpreting the paper plans. Thus the figures should not be used as reliable estimates, but only to give an initial idea of whether particular types of geometry are common or relatively rare. Note on Table 1: The building format lots and volumetric lots as a percentage of the state are inaccurate because it is impossible to determine from the database whether the areas overlap. Thus some areas are counted more than once in calculating the total.

Table 1: Types of spatial units in the current Queensland DCDB (as at December 2014)

| | Count | Total Area (m ²) | Average area (m ²) | % of state by number of parcels | % of state by area |
|----------------------------|-----------|------------------------------|--------------------------------|---------------------------------|--------------------|
| Total current base parcels | 2,759,230 | 1.903×10 ¹² | 689,705 | 100% | 100% |
| Base 2D property parcels | 2,224,119 | 1.689×10 ¹² | 759,524 | 81% | 89% |
| Easements | 237,371 | 1.68×10 ⁹ | 7,104 | 8% | 0.1% |
| Building format lots | 291,916 | 2.5×10 ⁷ | 121 | 8% | 0.001% |
| Volumetric parcels | 2,899 | 7.41×10 ⁷ | 25,571 | 0.1% | 0.004% |

Table 2: Estimates of frequency of Geometry Types (Spatial Units) (as at December 2014)

| | Plans in sample area | Spatial Units in sample area | Plans in state | Estimated Spatial Units in state |
|-----------------------------|----------------------|------------------------------|----------------|----------------------------------|
| 2D shapes | About 600 | About 600 | 484,139 | 2,224,119 |
| Building format | 40 | 2,463 | 39,738 | 291,916 |
| Above/below depth of | 2 | 2 | 815 | 4,056 |
| Polygonal Slice | 21 | 655 | 800 | 8,000 |
| Single-Valued Stepped Slice | 14 | 20 | 500 | 600 |
| Multi-Valued Stepped Slice | 3 | 3 | 120 | 150 |
| General Polyhedron | 17 | 23 | 700 | 700 |

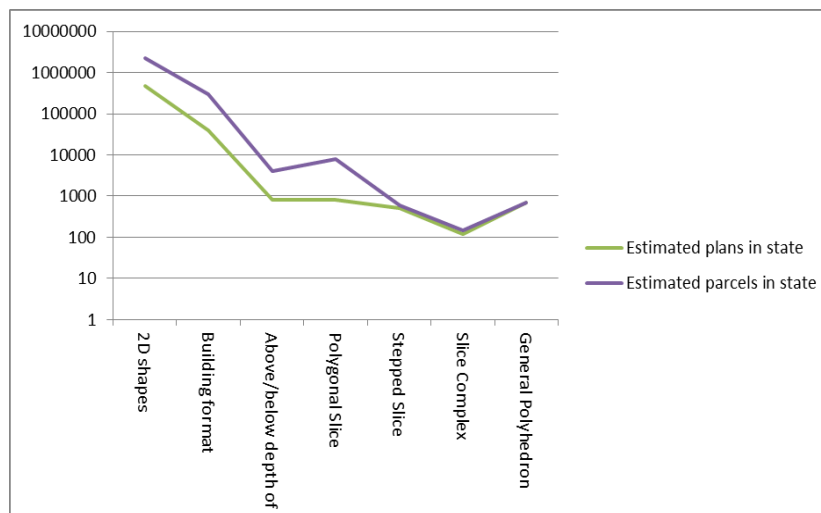


Figure 16 Estimates of frequency of Geometry Types. The general trend is predictable - as the spatial unit complexity increases, the number of instances tends to decrease.

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Note on Table 2 and Figure 16: The numbers of 2D parcels and plans, in the sample area are a rough estimate, while the numbers in the whole state are a reliable count of the plans and property parcels (excluding road parcels). By contrast, the 3D parcel and plant counts in the sample area are fairly reliable (subject to the three comments above), while the numbers in the state are scaled, and should not be considered more than a general guide.

6. CONCLUSIONS

A categorisation of cadastral parcels has been presented, which is potentially useful in discussing the requirements of a Cadastral Database. Where a jurisdiction is able to determine for example that no 3D objects more complex than a polygonal slice (or above/below height of) exist in their cadastre, a wider range of commercial software will be available to them. By making the categorisation definitive and verifiable - in that any parcel can be placed in one and only one category, any confusion is prevented: that is to say a standard terminology is created. As stated in section 4.7, the classification can be further refined: 2-manifold required or not, open/closed volume, planar/curved boundaries, single/multi-volume, etc.

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