Towards an Implementable Data Schema for 4D/5D Cadastre Including Bi-Temporal Support

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Keywords: Cadastre, Database, 3D, 4D, 5D, bi-temporal, temporal, time-stamping, database history

SUMMARY
Cadastral databases have unique requirements not shared by other spatial databases:

The third spatial dimension must be included, but visualisation using 2D software must also be accommodated. The majority of users of the Cadastre will use 2D software, and should be provided an "instant in time" plan view of the boundaries (with any 3D parcels "flattened"). Some users will have access to and need for fully functioned 3D software, and some to tools with "time sliders" but access to the Cadastre cannot be restricted to such users

A history of the Cadastre must be maintained. It is important that patterns of subdivision and land use can be tracked through the past, and it is highly desirable that planned future activity is included. In addition, a record of the state of knowledge of the database is needed (in case past decisions must be reviewed). That is to say, both the "valid time" and "transaction time" forms of time stamping needs to be accommodated.

The accuracy of the data is constantly being improved (each time a new survey is done), and this action must be reflected within the database as it becomes available. Other parties traditionally use the Cadastral database as a "base map", and accuracy improvements need to be promulgated to these parties.

This paper builds on previous research and development – mixing 2D and 3D cadastre has already been demonstrated, as has Cadastre with transaction time history. This paper considers what is needed to complete the schema. Specifically:

The storage of real-world (valid time) history.
The storage of "tentative time" temporal data for proposed developments.
Database (transaction) time, supported by versioning.
The improvement of accuracy of Cadastral boundaries, both in 2D and 3D spatial units, and of historic spatial units.
2D and 3D views of the data, and 2D update of the data.
Making the data available in scalable services, including access to historic items, and update history.

The novelty of this research is the combination of the full 4D/5D functionality in a single schema that can be implemented in a practical multi-user Cadastral database. This is the first time such a rigorous solution has been presented.

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1. INTRODUCTION

As cities have grown in population, there has been a natural movement towards multi-level subdivision of space, and hence the creation of 3D tenure. This has naturally suggested the inclusion of 3D spatial units within Cadastral Databases. (Aien, Rajabifard et al. 2011, Van Oosterom 2018)

The title of this paper needs some explanation. "4D" has been increasingly used as a shorthand for "three spatial dimensions and time" (van Oosterom, Ploeger et al. 2006). This meaning is used here, but with the extra complexity of two forms of time being involved – the "bi-temporal" model (Snodgrass, Böhlen et al. 1998, van Oosterom , Lemmen et al. 2018), leading to the term "5D". It has been well demonstrated that the database transaction timestamped version of history is compatible with spatial topological encoding (van Oosterom 1997, van Oosterom, Maessen et al. 2002) and concepts for mixing 2D and 3D (Lemmen, Van Oosterom et al. 2010, Thompson and van Oosterom 2010) have likewise been presented. Topological sharing of faces have been suggested in a data transport / plan submission context (Thompson, van Oosterom et al. 2017) while the storage spatial units as polyhedra (Arens, Stoter et al. 2003) has been explored

Visualisation per se is beyond the scope of this paper – "Thus, while 3D visualization systems are mature, research and development activities related to usability and acceptability are missing in the context of cadastre users" (Pouliot, Ellul et al. 2018 page 348).

Section 2 discusses the special features of Cadastral databases, in contrast to other geographical information; Section 3 explores the temporal and boundary packages, and builds a proposed data model. Section 4 investigates the way the data in the database changes over time, and the real-world changes that cause the database changes. Section 5 addresses the maintenance of topology and consistency over two time dimensions, while Section 6 considers proposed cadastral developments and their inclusion in the database. Some subtleties in the third spatial dimension are discussed in Section 7, data access and scalability in Section 8 and conclusions and further research suggested in Sections 9 and 10.

2. POINTS, LINES, SURFACES AND VOLUMES

This section addresses the question: "How is a Cadastral Map different from another map?".

2.1 Fiat[1] Boundaries / Tangible Boundaries

Most mapping involves what Smith (1995) calls bona fide objects – In this paper, the term "tangible" is used. E.g. topographic objects are observed, measured, and marked on the map. By contrast, maps carry markings that do not correspond with real-world physical objects – e.g. the boundary of an Air Traffic Control Zone. Smith calls them "fiat boundaries". In the Cadastral discipline the majority of boundaries are fiat, but not all. For example, a natural

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[1] fiat n. an authoritative decree, sanction or order (Macquarie Dictionary)

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river bank is tangible even if it changes over time, and may be defined as being an "ambulatory boundary".
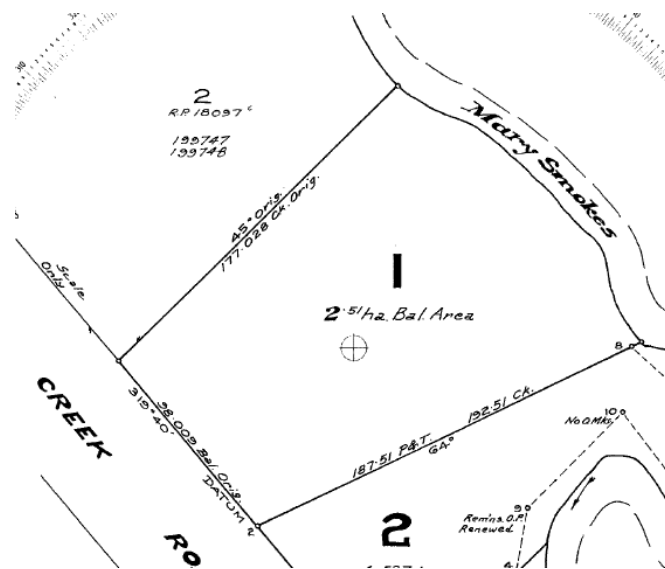

Figure 1 A plan of survey showing fiat and tangible boundaries

For example, in Figure 1 the river boundary line on the map represents the position at a point in time, but the legal property is delimited by the actual bank of river as it exists now (provided the movement has been gradual and natural). By contrast, the other boundaries (attributed by measurements) are fiat, and can be defined by coordinates in a Spatial Reference System (SRS).
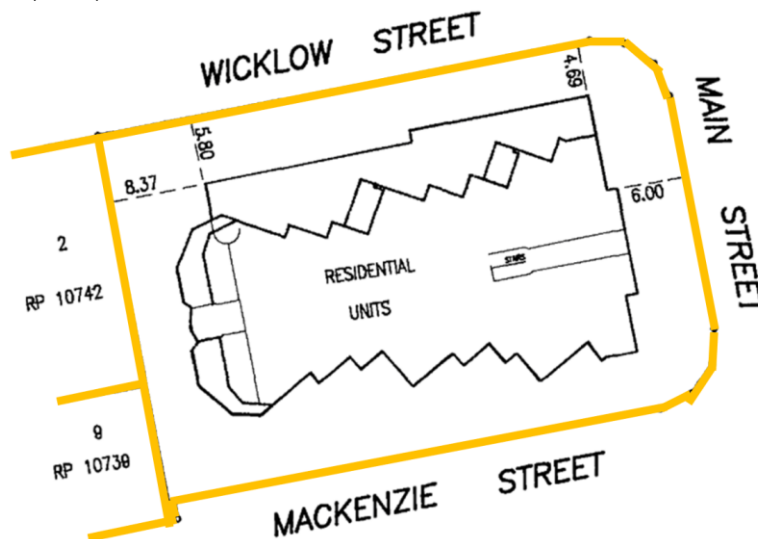

Figure 2 2D Fiat boundaries (yellow) defining a 2D spatial unit on which a 3D subdivision has been built. The unit boundaries within the building are tangible.

A comparable situation occurs in 3D (Figure 2) – where many 3D spatial units, such as units in a condominium, have primarily tangible boundaries – being defined by walls of a building.

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Other boundaries (shown in yellow) are fiat. In both cases the boundaries have legal status. In Queensland, an ambulatory boundary that is artificially moved loses its status as an ambulatory boundary (Queensland Government 2003); while a building wall which is a unit boundary must not be physically demolished or moved without the submission of a plan of amalgamation.(Queensland Government 1980)
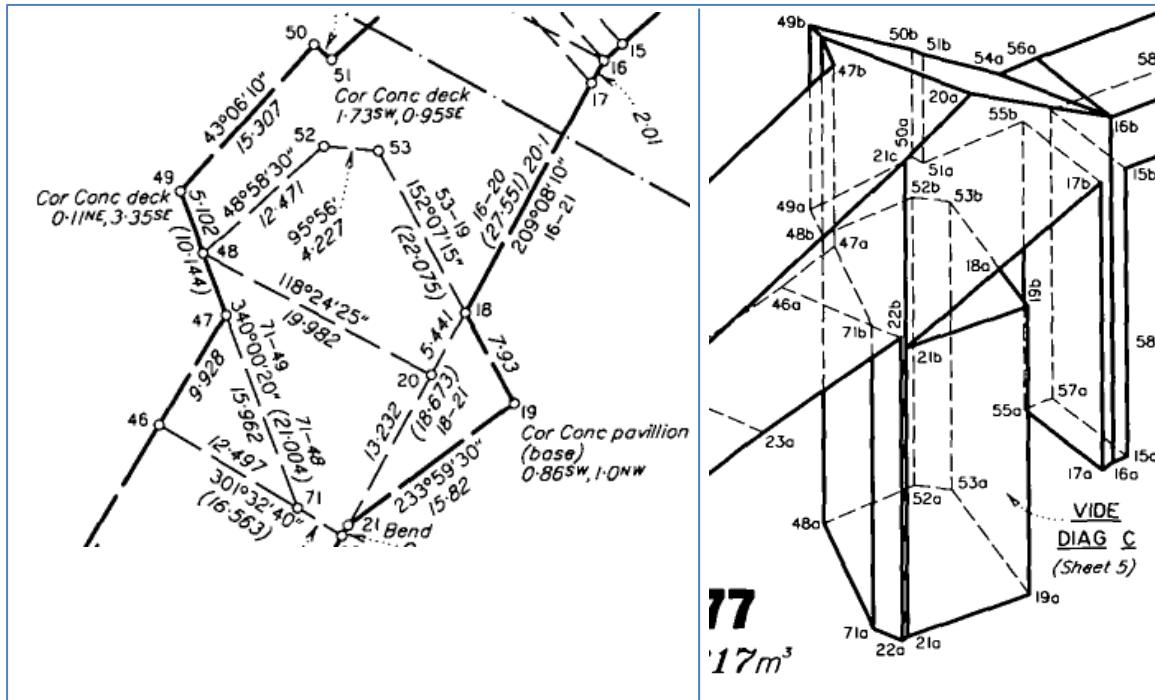

Figure 3 A 3D spatial unit with fiat boundaries

A counter example is shown in Figure 3, which is the space to be occupied by a footbridge. All boundaries here are fiat, and at the time of registration of the plan were unoccupied. Since then, the bridge has been built, but the cadastral space is still defined by the measurements shown, not by the bridge structure. In Queensland (DNRM 2016), this is known as a Volumetric Survey Plan, unlike the case in Figure 2, which is known as a Building Format Plan.

2.2 Control Points

Assume that there exists a set of "control points" which are fixed relative to the earth's surface, and identified (by a permanent OID). Further, assume their coordinates in a given SRS are known as at a point of time. It may be that the points at these locations are occupied by actual markers placed for this purpose by a jurisdiction, or they might be corners of buildings, monuments, or trees. In all cases, they are tangible features. These points are used to calculate positions for cadastral corners and other points of interest to the cadastre. The control points can be "moved" (have their coordinates changed) by a number of events:

1. **Dynamic Datum:** Because the local tectonic plate is moving, the actual position of the control points move constantly relative to the earth's mantle. This may or may not cause

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the coordinates of the control point to change with time (depending on the datum in use – see below).

2. **Correction:** It may be found to have been incorrectly positioned (given incorrect coordinates). If the coordinates are corrected, it must be noted that the actual point has not moved. This invalidates the coordinates of cadastral points connected to it in the past, and required new coordinates to be assigned.

3. **Re-survey:** It may be re-surveyed, and a more accurate position assigned to it. In this case, the real point has not moved, and it may be possible to propagate this correction to cadastral points that use it in their definition.

4. **True Movement:** The marker can actually be moved (accidently or intentionally). If accidental, it may not be known immediately that it is incorrectly placed. If the new position is determined, this correction should not be propagated to cadastral points.

5. **Local Distortion:** The local ground surface may be moving relative to the tectonic plate. (e.g. due to soil creep or local rise or fall of the surface).

6. **Earthquake:** An earthquake or landslide can cause relative movement of the actual points relative to one another, requiring re-evaluation of coordinates of all affected points.

2.3 Cadastral Points

Points which are used in defining the boundary of cadastral spatial units may be tangible or fiat points (Section 2.1). Fiat points are positioned by reference to one or more control points for which coordinates can be determined in some spatial reference system. This reference may be direct or indirect via other cadastral points. "Movement" of cadastral points follow the same events as the control points, but in addition to any of the above events as described for control points another can occur:

7. **Boundary Change**: – for example, a line separating two spatial units is moved a short distance (following an agreement by the owners).

3. A BI-TEMPORAL DATA MODEL

This section describes a data model which can potentially fulfil the requirements of a bi-temporal cadastral database which contains a mixture of 2D and 3D cadastral spatial units. The problem is simplified by observing two factors in a 3D temporal cadastre.

1. The vast majority of boundaries in 3D cadastral spatial units are vertical or horizontal. This allows the aggregation of points which fall along a vertical line (from $-\infty$ to $+\infty$) into what is considered a "2D point". This may be seen as a restrictive special case, because it defines a particular direction as "vertical", but in practice this is not a problem. The usual direction of the vertical in Cadastral definitions is in the direction parallel to the Earths gravity. In most Spatial Reference Systems by this definition, all points on a vertical line have the same Latitude and Longitude or X/Y coordinate values.

2. Many adjustments to the cadastre consist of relatively small corrections to the location of the pre-existing boundaries. An incoming survey is often of higher accuracy than the existing boundaries, and the latter therefore need adjustment. One of the features of this schema is the separation of the coordinates of a point from its function in defining boundaries. Allocating a different coordinate value to a point is here considered a re-measurement action – not a "point movement".

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3.1 The Bi-Temporal Package

Figure 4 shows a schema for a bi-temporal versioning scheme. It is based on LADM (Land Administration Domain Model) (ISO-TC211 2012) LA_VersionedObject and LA_Source classes.

C4_DB_Event - Gives information about an action that affects the database. The major constraint is that Event_Id must be strictly chronological. Very often a DB event is associated with a real-world event, in which case C4_valid_Event.lifeSpanEventId provides the link

C4_Valid_Event - Gives information about a real-world event. It cannot be assumed that sID is chronological. The lifeSpanEventId attribute indicates the DB_Event that introduced this real-world event to the database. In this schema, Valid_Event records do not have creating/destroying DBEvent stamps. If it is allowable to make corrections to the C4_Valid_Event (for example to change the "quality" attribute), corrections will be recorded as though they entered correctly in the first place (from lifeSpanEventId date), Alternatively, DB timestamp attributes can be added: creatingDBEventId and destroyingDBEventId to permit a full database history of this table.

C4_VersionedObject - This supplies the creation and retirement database and real-world events to track the history of an object that may change in real-world attribute(s), and where it is possible to correct the historical record in a bi-temporal model. (Snodgrass, Böhlen et al. 1998).
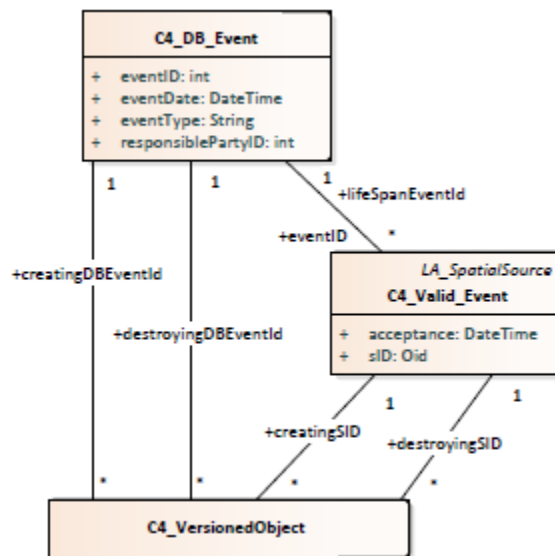

Figure 4 The bi-temporal versioning package

For example, Table 1 records three real-world events, that are entered into the database in two actions. Data operator 14 entered the creation of the permanent mark and the spatial unit in 1/June/2000 even though they were done on dates 4 years apart. The same operator in 2018 entered the details of the subdivision about 1 month after it was registered. The main database tables will use these eventId and sId values – as is described in section 4.4.

Table 1 C4_ValidEvent

sId	acceptance	procedure	source	lifeSpanStamp

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100	1966	Create Permanent Mark	Surveyor 1	200
105	1970	Create Spatial Unit	Surveyor 2	200
260	20/8/2018	Subdivision	Surveyor 3	270

Table 2 C4_Event

eventId	eventDate	eventType	responsibleParty
200	1/6/2000	Data Entry	DP operator 14
270	21/9/2018	Data Entry	DP operator 14

3.2 The Boundary Package

Figure 5 shows a schema for recording the boundaries in 2D and 3D of cadastral spatial units. Connection is made between this and the Bi-Temporal subschema by the fact that many objects are subclasses of C4_VersionedObject.
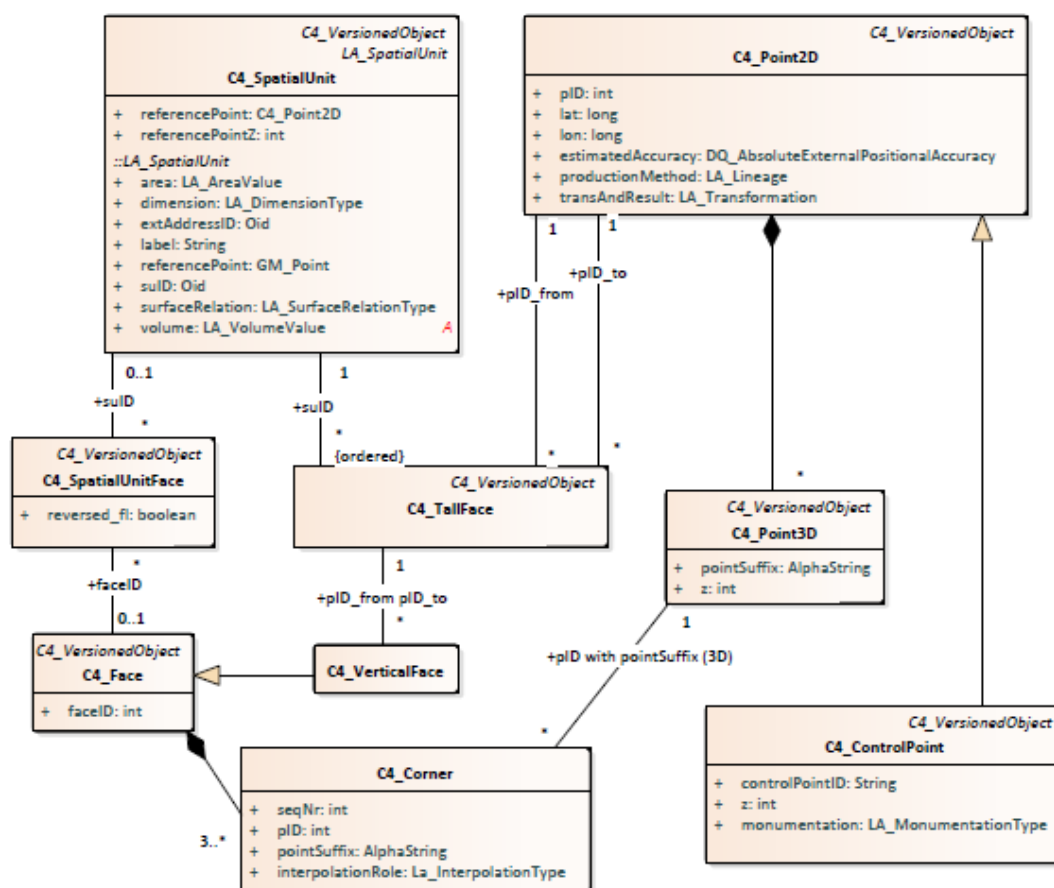

Figure 5 The boundary data package

C4_SpatialUnit – as subclass of the LADM LA_SpatialUnit it contains the geometric and other attributes of a spatial unit. By virtue of its being a subclass of C4_VersionedObject, it records history the spatial unit in real-world (valid time) terms. The transaction time Event

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IDs are created automatically on every database update, and maintain the (transaction time) history of the database representation. For real-world and database history, topology must be maintained throughout time, which is discussed further in Section 3.3 and Section 5.

C4_Point2D - this records our best knowledge about a 2D location in the real world. It tracks (using the event IDs) the known assignment of geographic coordinate values to the point. A C4_Point2D is, in effect, a vertical line from -∞ to +∞, through the point (lat, lon), and is used to associate any and all C4_Point3D objects that fall on this vertical line (see Figure 6). Note that all changes to the horizontal positioning information of the Cadastre can be done within this class, without updating the other classes in the schema, but there may need to be a re-validation to ensure that topology is not invalidated (see Section 5).

C4_Point3D - this records our best knowledge about a 3D location in the real world. This is the method by which 3D point locations are stored within the database, and as a result any adjustments to the cadastral fabric that result in corrections to point locations (in 2D) are automatically propagated to the 3D boundaries. This is discussed in Sections 4, 5 and 7. A 3D point can only exist within a 2D point location (see Figure 6).

C4_Corner – records the actual corners of a 3D spatial unit or more correctly its faces (Figure 6. In this encoding, all corners of 3D objects are associated with a C4_Point3D object.
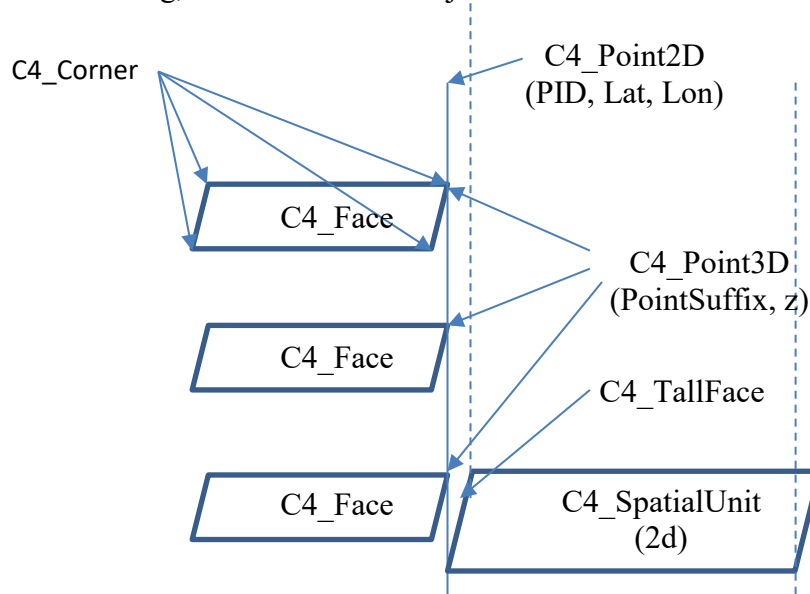

Figure 6 Relationship between Point2D, Point3D and Corner

C4_ControlPoint – a special case of point 2D, which records the 3D position of a physical object at various instants of time. It is identified by a persistent identifier (frequently engraved on the real-world marker).

C4_TallFace – this is a special case of the La_BoundaryFaceString, defined by two 2D points. That is, it is a face which runs from -∞ to +∞, and is planar. It is orientated so that the collection of tall faces join to make an anticlockwise polygon bounding the spatial unit. For the base spatial units that define a single 2D non-overlapping coverage in a topology structure, the tall faces will be in anti-equal pairs (defined by the same two points, but in the reverse order).

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C4_Face – a general 3D boundary face. It associates three or more C4_Corner records. Note this is not used to record the geometry of 2D spatial units (which are recorded as a collection of Tall Faces).

C4_VerticalFace – a special case of a face that lies completely within a tall face. It is an implementation decision whether these are stored or calculated on the fly.

3.3 Constraints

Every TallFace a must be matched with exactly one other TallFace b such that:

a.pID_from = b.pID_to and a.pID_to = b.pID_from

The Each Spatial Unit must be associated with a number of TallFace instances which form closed rings, which in turn define a valid polygon. In effect, a TallFace is a "half" of a 2D line, representing the connection between two 2D points. At the boundary of the domain ("edge of the world"), this constraint should not be applied.

4. DATABASE CHANGE AND EVOLUTION

4.1 Dynamic Datum

To accommodate the plate tectonic movements, one of two approaches are taken – the fixed datum, and the dynamic datum. Traditionally in Australia, a local fixed datum has been used. In this approach, the coordinates of control points do not change during short time intervals because the datum is roughly fixed to the tectonic plate. This works well for mapping within the plate region for a limited time, but a new datum epoch needs to be established on a fairly regular interval (tens of years).

The dynamic datum, by contrast, allows 4D coordinates (x, y, z, t) to be determined, and along with a velocity model, point coordinates can be compared between time ranges. It is assumed that the tectonic movements are predictable, so such events as earthquakes cannot be modelled this way.

If $v(x, y, t) = (v_x(x, y, t), v_y(x, y, t), v_z(x, y, t))$ is a vector function that defines the movement of the plate at location (x, y) at time t, then for point (x, y, z, t), at a later time t' the coordinates will be (x', y', z', t'), where:

$x' = x + (t' - t) \, v_x(x, y, t),$

$x' = y + (t' - t) \, v_y(x, y, t),$

$z' = z + (t' - t) \, v_z(x, y, t)$

For example, to calculate the distance between two points (x_1, y_1, z_1, t_1) and (x_2, y_2, z_2, t_2) with $t_2 > t_1$ it is first necessary to calculate:

$x_1' = x_1 + (t_2 - t_1) \, v_x(x_1, y_1, t_1),$

$x_1' = y_1 + (t_2 - t_1) \, v_y(x_1, y_1, t_1),$

$z_1' = z_1 + (t_2 - t_1) \, v_z(x_1, y_1, t_1)$

then the distance (in 3D) becomes (for short distances, and assuming comparable units):

$$d = \sqrt{(x_1' - x_2)^2 + (y_1' - y_2)^2 + (z_1' - z_2)^2}$$

In practice, since the velocities are quite low, and the velocity function does not vary much over the sort of distances moved in space and time, the function can be approximated as independent of time – i.e. $v(x, y)$. Further the transformation can be reversed to a high degree of accuracy:

$x_1 = x_1' + (t_1 - t_2) \, v_x(x_1', y_1'),$

$x_1 = y_1' + (t_1 - t_2) \, v_y(x_1', y_1'),$

$$z_1 = z_1' + (t_2 - t_1)\, v_z(x_1', y_1')$$

4.2 Determining Dynamic Datum Velocities

The actual measurement of datum velocity is beyond the scope of this paper, but because the tectonic plate is fairly rigid, it is possible to determine the velocities at a restricted number of points and times, using a linear interpolation between them for points observed at different epocs. For example, a vector TIN (Triangulated Irregular Network) (Peucker, Fowler et al. 1978) can be generated from all known velocity measurement points. In the case of a fast-moving but stable plate such as Australia, a small number of measured points will be sufficient. For a more complex, but slower moving landform such as New Zealand, a denser point coverage will be needed.

A simple service can be created to return the velocity value for any given 2D point location. This velocity could be recorded as part of the position information of the cadastral points, or can simply be re-calculated in the fly. (This assumes that the datum velocities do not vary appreciably in the time intervals being modelled).

4.3 Fixed Datum

Where a fixed datum is in use, the tectonic movements are ignored on a day-by-day basis, but periodically a correction needs to be applied to all points. This can be accommodated in one of two ways:

> All points in the database can be constrained to be recorded in the same datum – in which case all points have new coordinates applied (in the new datum) at various points of time. This generates a C4_DB_Event for every point. It means that if we look at historic data as we now understand it, it will be referred to the new datum (which may be what we want). If we look at history as we thought it was at the time, it will be in the old datum.
>
> The C4_Point2D record can carry a SRID (Spatial Reference Id)

4.4 Re-Survey

This approach assumes that all points are fixed to the earth surface. Any real change to a point is accomplished by the creation of a new point in the new position. For example, if the control point ID is changed (by engraving a new number on the physical object that marks the point), without any movement of the control point, this is a real world action which does not change the C4_Point2D record. If a point is accidently disturbed by excavation and replaced, it should be given a new identity in its new location. In the following tables, it is assumed that Valid_Event history has never been corrected.

Consider the case illustrated in Figure 7, which shows the case of a simple subdivision. The left figure is the case before, and the right after subdivision. The original spatial unit was created in 1970, and entered into the database on 1/June/2000. The control point S pre-dated the survey, having occured at 1966.

As with many new surveys, accuracy of the coordinates has been improved without moving the points in relation to the earth surface. (In these tables, X, Y coordinates are used instead of lat/lon, to make them more readable).

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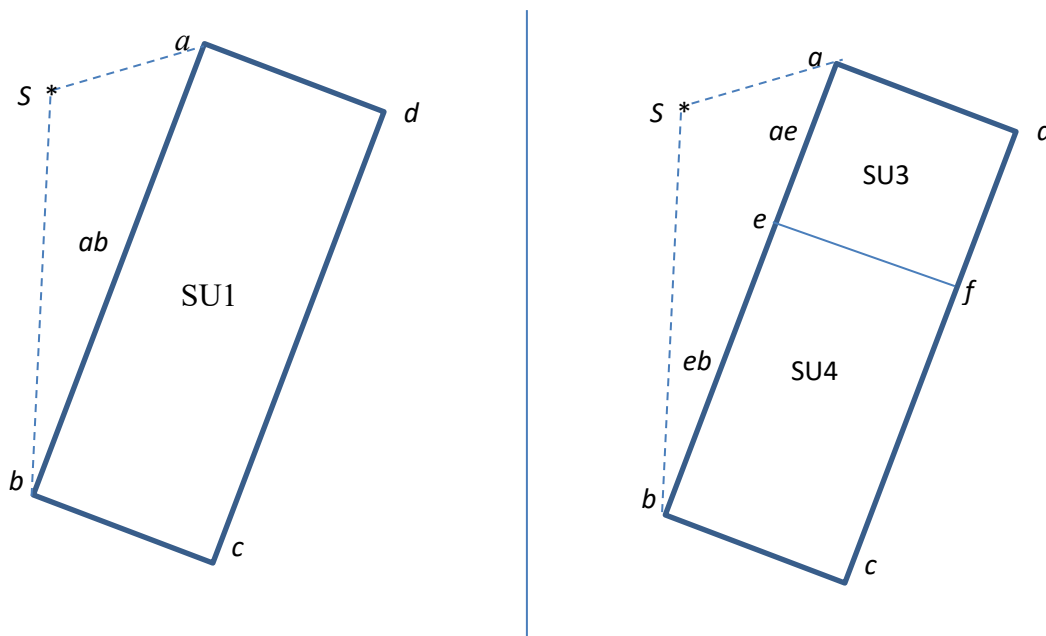Hanoi, Vietnam, April 22–26, 2019

Figure 7 A simple subdivision of a spatial unit – resulting in two spatial units

Table 3 C4_ControlPoint

				Bi-Temporal (Versioned object) Timestamps			
controlPointID	x	y	z	creating SID	destroying SID	creating DBEventID	destroying DBEventID
S	560.123	670.321	25.1	100	∞	200	∞

Table 4 C4_Point2D

			Bi-Temporal (Versioned object) Timestamps			
pID	x	y	creating SID	destroying SID	creating DBEventID	destroying DBEventID
a	570.0	675.0	105	∞	200	∞
b	559.0	650.0	105	∞	200	∞
c	569.0	645.0	105	∞	200	∞
d	580.0	670.0	105	∞	200	∞

Table 5 C4_SpatialUnit

suID	BA_Unit	dimension	area	volume	creating SID	destroying SID	creating DBEventID	destroying DBEventID
SU1	1/RP10000	675.321	252	null	105	∞	200	∞

Table 6 C4_TallFace

suID		pID_from	pID_to	creating SID	destroying SID	creating DBEventID	destroying DBEventID

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SU1	a	b	105	∞	200	∞
SU1	b	c	105	∞	200	∞
SU1	c	d	105	∞	200	∞
SU1	d	a	105	∞	200	∞

Table 7 C4_DB_Event

eventId	eventDate	eventType	responsibleParty
200	1/6/2000	Data Entry	DP operator 14

Table 8 C4_Valid_Event

sId	acceptance	procedure	source	lifeSpanStamp
100	1966	Create Permanent Mark	Surveyor 1	200
105	1970	Create Spatial Unit	Surveyor 2	200

Prior to the update, the database could be as above: Table 3, Table 4 show the points, Table 5 and Table 6 the spatial unit and geometry (C4_TallFace), and Table 7 and Table 8 the history events. So that since 1966, the control point has been present, since 1970, the spatial unit SU1 has also been present, but our knowledge of them in the database only started from DB event 200 in June 2000. Note that this event id (200) is recorded as the event that both valid events were entered into the database (lifeSpanStamp).

More recently, as a result of the survey for subdivision (valid event 260, 28/Aug2018), the control point has not been adjusted, but the cadastral point have been improved in accuracy and the two new points added. The survey was entered a month later into the database at db event 270 21/Sep/2018). The result in the database is shown in Table 9 to Table 14.

Table 9 C4_ControlPoint

controlPointID	x	y	z	creating EventID	destroying EventID	creating DBEventID	destroying DBEventID
S	560.123	670.321	25.1	100	∞	200	∞

Table 10 C4_Point2D

PID	X	y	creating SID	destroying SID	Creating DBEventID	Destroying DBEventID	Note
a	570.0	675.0	105	260	200	270	
a	570.123	675.321	260	∞	270	∞	*
b	559.0	650.0	105	260	200	270	
b	559.178	650.317	260	∞	270	∞	*
c	569.0	645.0	105	260	200	270	
c	569.216	645.022	260	∞	270	∞	*
d	580.0	670.0	105	260	200	270	
d	580.1	670.103	260	∞	270	∞	*
e	566.012	667.321	260	∞	270	∞	*
f	576.192	662.416	260	∞	270	∞	*

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Note * – in Table 10, the new values of these point locations were entered at DB event 270 (21/Sep/2018), as a result of the survey at valid event 260 one month earlier.

Table 11 C4_Event

eventId	eventDate	eventType	responsibleParty
200	1/6/2000	Data Entry	DP operator 14
270	21/9/2018	Data Entry	DP operator 14

Table 12 C4_ValidEvent

sId	acceptance	procedure	source	lifeSpanStamp
100	1966	Create Permanent Mark	Surveyor 1	200
105	1970	Create Spatial Unit	Surveyor 2	200
260	20/8/2018	Subdivision	Surveyor 3	270

The remainder of the tables are affected as follows:

Table 13 C4_SpatialUnit

suID	BA_Unit	dimension	area	volume	creating SID	destroying SID	creating DBEventID	destroying DBEventID
SU1	1/RP10000	2	252	null	105	260	200	270
SU3	19/RP2000	2	55	null	260	∞	270	∞
SU4	20/RP2000	2	197	null	260	∞	270	∞

Table 14 C4_TallFace

suID	pID_from	pID_to	creating SID	destroying SID	creating DBEventID	destroying DBEventID
SU1	a	b	105	260	200	270
SU3	a	e	260	∞	270	∞
SU4	e	b	260	∞	270	∞
SU1	b	c	105	∞	200	∞
SU1	c	d	105	260	200	270
SU4	c	f	260	∞	270	∞
SU3	f	d	260	∞	270	∞
SU1	d	a	105	∞	200	∞

To see the currently accepted database view of the cadastre as it now exists, include these clauses for all tables (x) being accessed

    AND x.destroyingDBEventID = ∞
    AND x.destroyingSID = ∞

So that in accessing, for example, a join between the tall face and spatial unit would be

    SELECT … from C4_TallFace f, C4_SpatialUnit u WHERE <selection predicate>
    AND f.destroyingDBEventID = ∞ AND u.destroyingDBEventID = ∞
    AND f.destroyingSID = ∞ AND u.destroyingSID = ∞

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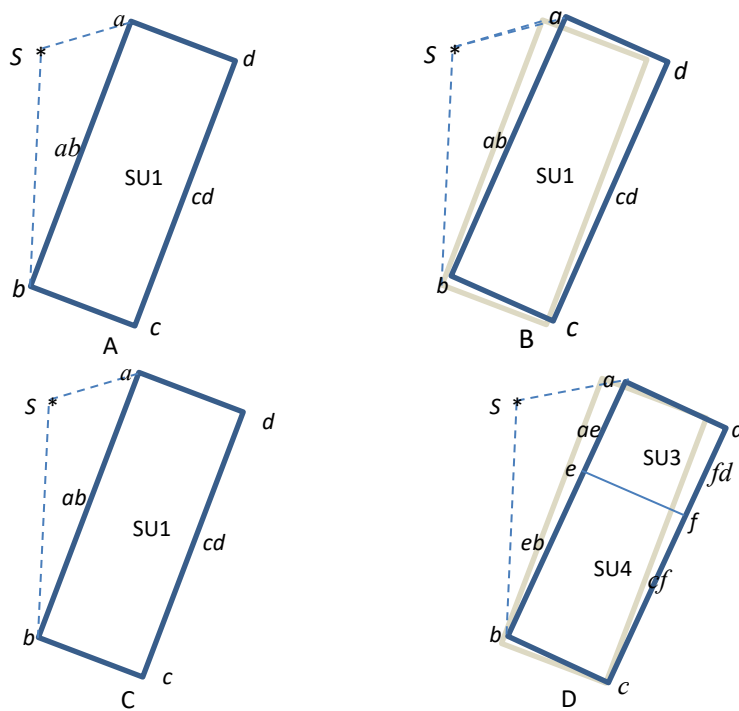Hanoi, Vietnam, April 22–26, 2019

Figure 8 A. the database as it was in 1970 (or viewed today as at 1970). B. the spatial unit in 1970, as we now believe it was positioned (with original data in grey behind – coordinate adjustment exaggerated). This improved position was the result of the 2018 survey. C. The database view as at 1/9/18 – the SU1 has been subdivided, but data entry was not yet completed. D. The spatial units as they were on 1/9/18, now that the plan has been entered into the system.

To view what we now believe the cadastre to have been at time stamp T (see Figure 8), the clauses "AND x.destroyingSID = ∞" are replaced by "AND x.creatingSID <= T AND x.destroyingSID > T". To obtain the value of T from the actual dateTime t, it is first necessary to query the DB_Event table:

Select eventID as T from C4_Event where eventDate <= t and eventDate > t.

To view what we believed at time stamp T that the situation was at dateTime u, (we may have better information now, but want to see why a decision was made):

SELECT … from C4_SpatialUnit su, C4_ValidEvent v1, C4_ValidEvent v2 …
WHERE <join predicate> AND <selection predicate>
AND su.CreatingDBEventID <= T AND su.DestroyingDBEventID > T
and v1.acceptance <= u and v2. acceptance > u
and v1.sID = u.creatingSID
and v2.sID = u.destroyingSID

There may be points in the vicinity that are no longer current cadastral points (e.g. old subdivision corners removed by amalgamation). These should also be allocated new coordinates. A simple linear interpolation (e.g. using a vector TIN based on the known current cadastral point adjustments) should be used to adjust the old points).

4.5 Correction

This is the case where a point has been recorded in the database with incorrect or inaccurate coordinates. The current point record is retired, and a new record created, using DB event id

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timestamps and the same PID. Because the real-world point has not moved at the time of discovering the error, the same creating and destroying SID values should be used on the new point record. Thus all spatial units (even ones no longer current) will be corrected.

4.6 True Movement

Where a cadastrally interesting point is actually moved (e.g. by distortion of the earth surface due to construction work), when the movement is discovered, it is a real world change as at the time the movement happened (if known), and with today's DB time stamp. If the movement is discovered as part of a new survey, care is needed, because the point's "old position" should also be corrected in line with undisturbed points that are being improved by the survey.

4.7 Local Distortion

This is a collection of true movements, and has to be handled as a set of real-world events as at the time of the distortion if known. If the distortion is steady and slow, it may be modelled in the same way as a datum change (using a linear interpolation between points of known velocity).

4.8 Earthquake and Landslides

In an extreme example of a local distortion, in which the earth surface movements may not be continuous, Control points need to be re-established (as a new real-world position). Cadastral corners need to be re-established, and the event should not adjust historic positions of any points in the region of distortion.

4.9 Boundary Change

Where cadastral boundaries are actually moved – for example in the accretion of a river bank, erosion of a coastline … the points that define them should not be moved – new points should be created. However, if a survey is carried out, there may be improvements in positions of existing points that are carried through.

4.10 Chronological Sequence of Database Events

It is fairly simple to ensure that the database event IDs maintain a chronological sequence – so that the C4_DB_Event table carries the constraints:

$a.EventID > b.EventID \Rightarrow a.EventDate \geq b.EventDate$

$a.EventID = b.EventID \Rightarrow a.EventDate = b.EventDate$

$a.EventDate > b.EventDate \Rightarrow a.EventID > b.EventID$

and further for any versioned object v:

$v.destroyingEventID > v.creatingEventID$

and for two versions of the same object (v, w) with the same ID:

$v.destroyingEventID \leq w.creatingEventID$ OR

$w.destroyingEventID \leq v.creatingEventID$

4.11 Valid Events out of Chronological Sequence

By contrast, it is entirely reasonable that in a large database some real-world updates are entered to the database in a more timely fashion than others. For example, in an area of high development, there may be more priority given to keeping the database up to date than in less progressive regions. Thus is it not reasonable to use a "serial" field for the primary key (sID) of the C4_Valid_Event table (as may be done with C4_DB_Event.eventID). Thus it cannot be assumed that for events a, and b:

$a.sID > b.sID \Rightarrow a.acceptance \geq b.acceptance$

$$a.sID = b.sID \Rightarrow a.\ acceptance = b.\ acceptance$$
$$\text{and } a.\ acceptance > b.\ acceptance \Rightarrow a.sID > b.sID$$

A further effect of this is that a situation arises that a real-world event may cause disruption of what was seen as a valid, but later date, event. For example If a spatial unit has its external address changed, but the label is unchanged, If then an earlier change is applied to the database changing the label field, there is a danger that the label will revert to its original value after the address change.

It seems reasonable to mandate that on an individual spatial unit, the updates are to be entered and validated in a chronological order, but there is still the issue of neighbouring spatial units. If neighbours are permitted to be updated out of sequence, the topological rules need to be enforced before and after any out-of-sequence operations.

5. RE-VALIDATION

When new data is added to the database, it is validated in reference to a set of rules including topologic requirements. This is a general principle of database maintenance. But in addition, whenever an adjustment of the coordinates of a point or points is carried out, there may be need for a re-validation. For example, if there are close points/lines in the database, rounding or calculation effects may cause them to cross or merge. In the 3D case, if a face is not horizontal or vertical, adjustment may cause it to no longer be planar (to the required tolerance). This could be a time and resource heavy operation – which needs to be done for every spatial unit with one or more adjusted point coordinates. Fortunately, there are ways of shortcutting this process, or releasing the on-line transaction while a background activity "tidies up".

5.1 Robustness Parameter

As suggested in (Thompson and van Oosterom 2006a), when the validation is done on initial load, a "robustness parameter" can be calculated for each spatial unit. This is a measure of how much distortion can be accepted in the data before any validation failure for that spatial unit is possible. In practice, this calculation does not add to the difficulty of the validation. As a simple approach, where a number of point coordinates are adjusted, if the maximum adjustment plus the required tolerance is less than the robustness of all affected spatial units, re-validation is not needed for acceptance the update. The robustness of all affected parcels should be reduced by the maximum adjustment value. This leaves the database in a valid and consistent state.

The only problem with this approach is that after the update, robustness parameters have been set to pessimistic values, so it would be advisable to initiate a background job to re-calculate them for all affected spatial units. Failure to run this job does not compromise the integrity of the database, but may cause a future update to trigger an unnecessary rejection of an update.

5.2 Flatness Flag

It is a fact in many 3D cadastres that the majority of faces are either horizontal (as the floors in buildings), vertical (as the walls are), or triangulated. If a spatial unit is flagged as "well behaved" when all faces follow this pattern, the re-validation is unnecessary, unless flagged by the robustness issues as above.

6. TENTATIVE TIME

Where planning approvals and other planned activities with dates in the future are to be included in the Cadastral database, two basic problems arise.

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1. The planned activity may never happen – the proposed acceptance date may come and go without anything being done. The activity could be delayed or abandoned.
2. More than one activity can be planned for the same geographic area These can be compatible proposals, alternatives of which a maximum of one is to be realised, or inconsistent proposals by different parties (see Figure 9).
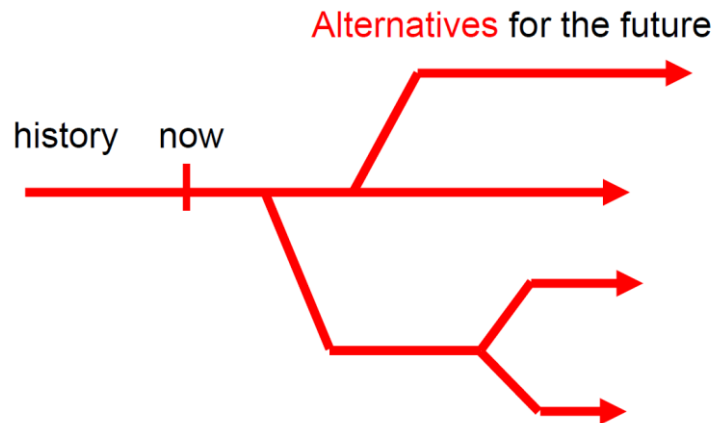

Figure 9 When dealing with planned activities, alternative timelines become a real possibility

It has been identified by many jurisdictions that such planned activities should be stored in a fashion that makes them readily accessible in conjunction with more conventional Cadastral data. An obvious way of doing this is to include such activities in the Cadastral database. The events associated with a planned action may include:

- Submission of the proposed plan (of survey) for the action
- Approval of the plan
- Registration of the plan
- Cancellation of the proposed plan
- Resubmission

It is also to be recognised that the same issues apply to the RRR (Rights, Restrictions and Responsibilities) (ISO-TC211 2012) part of the database, but the details are outside the scope of this paper (see Section 10).

From an event point of view, it is quite possible to use C4_Valid_Event to record a proposed event, with an acceptance date in the future, but this must be marked as "tentative" and excluded from all current cadastral enquiries – perhaps by imposing a separate range of sID values. An exception should then be raised if the proposed acceptance date is passed without action having been completed (it must not be permitted to slide into a current status by the acceptance date having been reached without action being taken).

The other issue is where multiple activities are planned in the same geographic area. This can invalidate the topological constraint that ensures a complete partition of space. This can be accommodated in the proposed schema by relaxing some constraints. For example – normally a tall face must be matched by exactly one anti-equal tall face. If tentative objects are being recorded, a tentative tall face may lie exactly along a real one, or not be paired at all. It must also be recognised that new Point2D, and Point3D instances may be created that never

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become part of the current Cadastre. They must be kept even if the proposed action is cancelled.

7. THE THIRD SPATIAL DIMENSION

The third spatial dimension – commonly designated as Z, is rather a special case. The positive Z direction is usually designated as being in the negative direction of the Earth's gravity, and is commonly referred to a local datum height, which in many cases is based on the level of the oceans. In a similar way to the X,Y coordinates of a point, the value of the Z coordinate of a real-world object will change due to the same sort of effects – e.g. tectonic rises or falls of the Earth's crust, re-measurement, etc. The practice is that these changes are often de-coupled from the X,Y coordinate changes, because they are independently determined, and are subject to different physical processes and time scales. In addition, even though lines of latitude and longitude diverge from the grid lines of a projection, the Z direction is theoretically the same in any projection and in the real world.
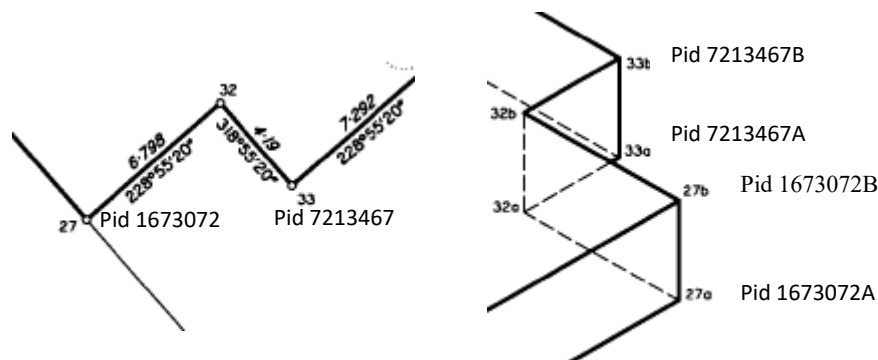

Figure 10 Left: part of a plan showing the 2D positioning of points, Right part of the same plan showing the 3D points along the "poles" defined by the 2D points. Note the relationship between the pids of the 2D and 3D points. (It is common prcatice that where horizontal planes are present, the alphabetic suffixes are the same, but this cannot be relied upon, Conversely, planes which are not horizontal frequently do use the same alpha suffix)

The suggestion here is that a C4_Point2D is seen to represent a "pole" with the same 2D coordinates, and therefore parallel to the direction of gravity but in the reverse direction. All 3D points on this pole are represented as C4_point3D records, and are referenced to the C4_Point2D. This reflects the approach taken in the Qld survey procedures – where locally on a survey plan, the 2D point positions are fixed and given numeric identifiers, while the 3D points are identified by the point number and an alphabetic suffix. Permanent point identifiers in Qld are numeric for the 2D point, with an alpha suffix for the 3D points (Figure 10).

8. ACCESS

So far, the main subject of this paper has been the database structure, however a database is not useful without viewing and update mechanisms, so this section briefly discusses these issues.

8.1 2D and 3D viewing and Update of the data

In most jurisdictions, the majority of spatial units are 2D in nature, so it would be unreasonable to require all access to the cadastral database to use 3D viewing and update tools. Powerful tools are available for general 3D data manipulation, and these have value in 3D cadastre, but with significant work still to be done (Cemellini, Thompson et al. 2018, Pouliot, Ellul et al. 2018), but it is clear that a service will need to be created to provide the linkage between the database and the 3D manipulation software.

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A significant amount of useful visualisation and update can potentially be done using 2D GIS-type software, including positional adjustment and correction. The fact that this schema separates the point coordinate values from the property boundary records means that a GIS which expects all geometric tables to include a simple feature geometry column (with the coordinates embedded) cannot directly access the data. Thus, in this case as well, a service, or possibly a database view will need to be created. In either case, the logic is very simple – every spatial unit has a defined set of TallFace records, which together define a polygon, so that access to 2D and 3D spatial units can use the same logic. The 2D software will by default see the 3D spatial units as polygons (in a different colour/theme) overlapping the base units and each other.

8.2 Access to historic items, and update history

The versioned object pattern has proven its worth in production databases, and shown to be compatible with sophisticated data schemas (van Oosterom 1997). The bi-temporal extends this, and may even permit corrections to the history, with later review of those corrections. It provides an audit trail of the database updates in combination with a true history of the cadastre. A corollary of this is that the user interface will need to be well designed. An enquiry such as "What did we in 2018 believe were the adjoining spatial units to the one at 29 Main St. on 1st July 2000" is easily implemented in this schema, but provides a challenge for the user to formulate. Further complex enquiries are possible such as "What changes have been made to the update that subdivided SU127 since it was entered to the database, and who made those changes?". Suffice it to say, the user interface must be carefully designed.

8.3 Making the data available in scalable services

There is a lot of abstraction within the schema, and the complete separation of point locations from the actual geometry and topology may make implementation a challenge in terms of scalability. It is to be expected that the vast bulk of enquiries will require current data, using the most up-to-date available (i.e. most recent valid events and DB events). It may prove worthwhile to generate a redundant view or copy of the current view of the database in simple feature geometry form for 2D access, and polyhedron form for 3D.

9. CONCLUSIONS

A schema has been proposed which supports 3D spatial units in the same database as 2D spatial units. It has been argued that this permits access to the data using software that is intended for 2D only, as well as by fully featured 3D visualisation software (although more work is needed in the area of visualisation). It has also been indicated that what is basically a 2D operation – correcting the coordinates of cadastral boundaries can automatically apply to the 3D objects.

The schema is bi-temporal in nature, including the "Valid date" and "Database Event" timestamping. And suggestions have been advanced on methods to ensure topological validity of the data in "5D" (so that topology is preserved through three dimensions of space and two of time).

10. FURTHER RESEARCH

Non-planar faces exist in Cadastral Databases (Thompson, van Oosterom et al. 2017), but have not been directly addressed in this paper. There are difficulties involving generating the curve of intersection of non-planar faces that need further investigation.

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Other sections of the cadastre in its broader sense – such as the Party and the Administrative packages (ISO-TC211 2012) need to be explored in the same way from a bi-temporal perspective.

While a datum velocity in the X,Y directions has been discussed, no Z velocity has been considered in this paper.

The effects of finite accuracy arithmetic (Franklin 1984) become more significant in 3D calculation. For true corporate database technology, a rigorously verified algebra is necessary.

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