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Development of validation rules to support digital lodgement of 3D cadastral plans

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ABSTRACT

Validation is a familiar topic in computing, generally as a mechanism to protect a database from the effects of inappropriate data with the side effect of detecting some errors. As such, the validation rules are determined from the database schema using well understood methodologies. This paper takes a different view by examining digital validation as one of a set of processes that are designed to ensure that the incoming data (in this case, a plan of cadastral survey) is unambiguous and contains sufficient detail to define the legal spatial extents of a property. This is a complex question, especially since the rules and the decisions based on these processes must be defensible (therefore cannot contain arbitrary requirements imposed by a specific database model). Using the jurisdiction of Queensland, Australia, as a case study, this paper discusses the manual submission and lodgement of cadastral survey plans and the current 2D digital process as precursors to the automatic lodgement of all plans of survey. A set of validation rules is proposed for application to single geometric objects, to the relationship of objects on a single survey plan, and to objects that are independently defined on separate plans. It is asserted that, by the nature of the problem, this set is incomplete and will remain so. However, this research has identified a "checklist" of issues to be addressed by jurisdictions hoping to implement digital cadastral survey plan lodgement. The implications of this work in the context of the broader challenges in land administration and within the topic of 3D cadastral data are discussed.

1. Introduction

With the increasing shortage of available land for new developments in our congested urban environments, planners and engineers are looking at opportunities to utilise spaces above and below the ground. Existing land titling and property (cadastral) systems have developed around the concept of a two dimensional (2D) mapping system, however, the actual ownership and rights to individual property parcels extend both below and above the earth's surface, often to unspecified limits. According to Thompson and van Oosterom (2011a), "as the value of land in the urban regions of the world increases, there is a trend towards the subdivision of property rights in 3D [three dimensions]". This implies that instead of simply considering the rights to an area of land in 2D, the rights to a volume of space must be recognised and authorised. As shown by van Oosterom, Stoter, Ploeger, Thompson, and Karki (2011), the legal and technical methods used to effect this change of definition vary from jurisdiction to jurisdiction. For example, Norway and Sweden register different types of constructions provided they are related to a ground level parcel. Network objects are treated as a single object in Sweden while 3D objects are referenced to existing topographic features in Britain. In Australia, the same legal rights apply to 3D cadastral parcels as to 2D parcels, however, the surveying and plan creation requirements differ between 2D and 3D plans as dictated by the registering authorities.

This paper approaches the question of validation from a novel perspective, with the aim of developing a defensible set of rules to ensure an unambiguous and definitive legal and spatial definition of property parcels. Several classes of validation rules required to achieve these proposed rules are investigated and a set of essential decisions to be made prior to implementation of automatic digital acceptance of cadastral survey data is proposed.

The paper firstly examines existing lodgement practices for 2D and 3D cadastral survey data and the associated validation challenges as a precursor to digital validation of 3D survey plans (Section 2). While the topic is relevant to cadastral jurisdictions in general, the jurisdiction of Queensland, Australia is utilised as a case study example. Manual procedures in use in Queensland

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are discussed in Section 3. Section 4 addresses the important subset of rules involving geometric validation, with a wider set of rules being discussed in Section 5. The set of decisions to be made prior to implementation of digital acceptance of plans of survey is proposed in Section 6, and finally in Section 7, the challenges for implementing 3D validation of digitally submitted cadastral data are summarised and future research areas are presented.

2. Background

Australia is a federation of states and territories which operate under a system of government which provides a high degree of autonomy to these jurisdictions. Although all of the states follow a consistent system of land titling known as the Torrens Titling System (Toms, Grant, & Williamson, 1986), the administration of land, including the surveying and subsequent titling, is a state government responsibility (Dalrymple, Williamson, & Wallace, 2003). The land administration system in each Australian jurisdiction has evolved over a long period of time and has been adapted to accommodate changes in society and law. Consequently the state land administration and cadastral systems vary in detail, resulting in differences in semantics and data structures amongst the various states (Cumerford, 2010). To provide consistency to land surveyors and to users of these systems, the Intergovernmental Committee on Surveying and Mapping (ICSM) in 2003 commenced the development of standards to support electronic submission and exchange of cadastral data via the "ePlan" (electronic plan) schema.

2.1. The lodgement process

In the Australian states, the surveying of land and property parcels is not undertaken by the government, but by surveyors who are self employed or employed by private companies. The process of submission and acceptance of the plan of survey by the registering authority (termed "lodgement") is a critical and legally constrained action. A plan, once approved by the local government and duly lodged, becomes a legal document, and part of the documentation by which the government guarantees title to the land. This means that care is needed to ensure that the required standards are maintained and that all necessary information is presented on the submitted documents. "Since the State guarantees title it is only reasonable to expect that it demands certain standards of surveyors who carry out title surveys. Consequently, every State has a system for registering or licensing surveyors and has a set of regulations to control the carrying out of those surveys" (Williamson & Holstein, 1978, p. 36). It is also vital that any decisions by the authorities requiring surveys to be corrected or resubmitted be consistent and justifiable, especially since such actions may incur significant costs to the surveyor.

A simplified schematic of the lodgement process is presented in Fig. 1. The cadastral surveyor creates a survey plan based on the field survey, pre-existing data from the cadastral database and other survey plans. The plan is then submitted to the registering authority. The local government ensures that zoning restrictions such as minimum lot sizes, street frontages, permits for building units, and sub-divisions are observed, and authorises the land configuration. The registering authority accepts lodgement, validates data for previous and current content, and all being well registers the plan, and updates the cadastral databases.

2.2. Digital submission of cadastral plans and data

In recent years, Australia has made significant progress towards the digital submission of cadastral survey plan information through a coordinated and homogenous approach including the development of standards of practice (Cumerford, 2010). The ICSM has been instrumental in drafting the national ePlan guidelines (ICSM, 2010c) including the standardisation of terminology for each jurisdiction. The LandXML (Land Extensible Markup Language) was used to create, interchange and store the cadastral data (ICSM, 2010b).

The ePlan model has significant overlap with the Land Administration Domain Model (LADM) (ISO 19152) (ISO-TC211, 2012) which is a international standard for cadastral information. However, the ePlan development preceded the development of the LADM and has been adapted to Australian conditions, leading to significant differences in semantics and data structure. The LADM is a generic conceptual model providing the concepts and terminology to describe land administration data. Based on this a jurisdictional profile can be developed by using the relevant parts of the LADM and extending this base model with missing attributes, associations, constraints and classes specific for the jurisdiction. This profile can then be used to generate specific exchange formats (XML, LandXML, and CityGML) and if needed also the database schema.

The need for the digital lodgement of cadastral survey data in Australia was identified around 1997 when research was conducted on developing digital submission systems (Falzon & Williamson, 2001). The authors identified issues common to all jurisdictions in Australia, including plan format, data transfer and security. The development of a digital transfer protocol followed in Queensland in 2003, and progressed to the implementation stage of digital submission in 2006 (Cumerford, 2010). The ICSM addressed and standardised most of these issues by creating the ICSM ePlan model (ICSM, 2010a) governing all cadastral jurisdiction of Australia and New Zealand.

In a national land administration structure where there are several independent cadastral jurisdictions, a common digital submission effort must address legal and semantic interoperability issues. Kalantari, Rajabifard, Wallace, & Williamson (2005a, 2005b) identified that "The key to interoperability is data modelling which both recognises and re-engineers existing business processes". The authors also affirmed that digital submission must support business processes such as "electronic conveyancing, digital lodgement of survey plans, and online access to survey plan information" (Kalantari, Rajabifard, Wallace, & Williamson, 2005a, p. 1).

2.3. Digital cadastral database

Falzon and Williamson (2001, p. 62) observed, "the purpose of plan lodgement is primarily to support the Government's guarantee of title, although now it is also used for further subdivisional activity, updating of record systems and updating of the State Digital Cadastral Map Base". While this is true for 2D plans and a 2D cadastral database, no Australian state maintains a 3D cadastral database to support this process. This also appears to be the case internationally (van Oosterom et al., 2011).

2.4. Types of 3D cadastral plans and objects

The Queensland Land Title Act (Queensland Government, 1994) provides two methods of defining land in three dimensions:

- *Building Format Plans (BFPs)*: Each lot is defined by the structural elements (walls, floors, etc.) of the building itself. A lot on a Building Format Plan ("Strata Plan" in some jurisdictions) such as that shown in Fig. 2, may consist of several parcels on different floors within an apartment building or buildings. The cadastral database stores the boundary of the base (2D) lot including

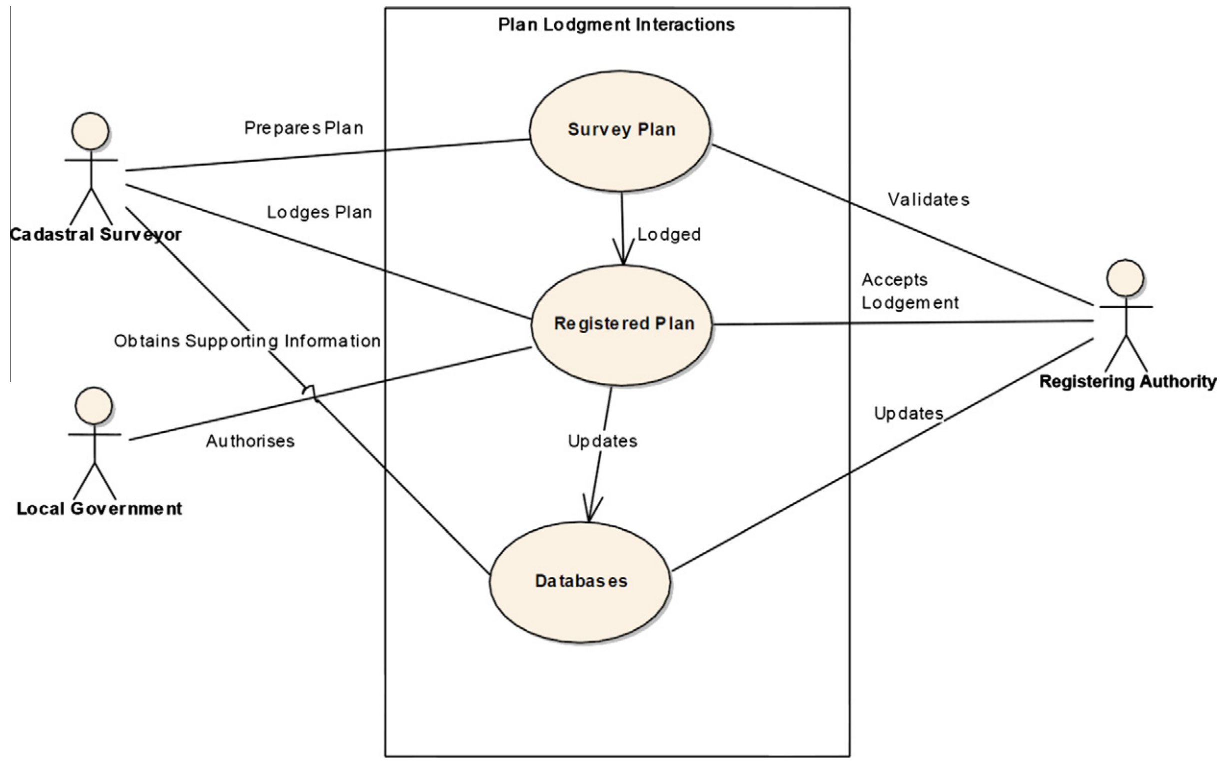

Fig. 1. Schematic of the survey plan lodgement process.

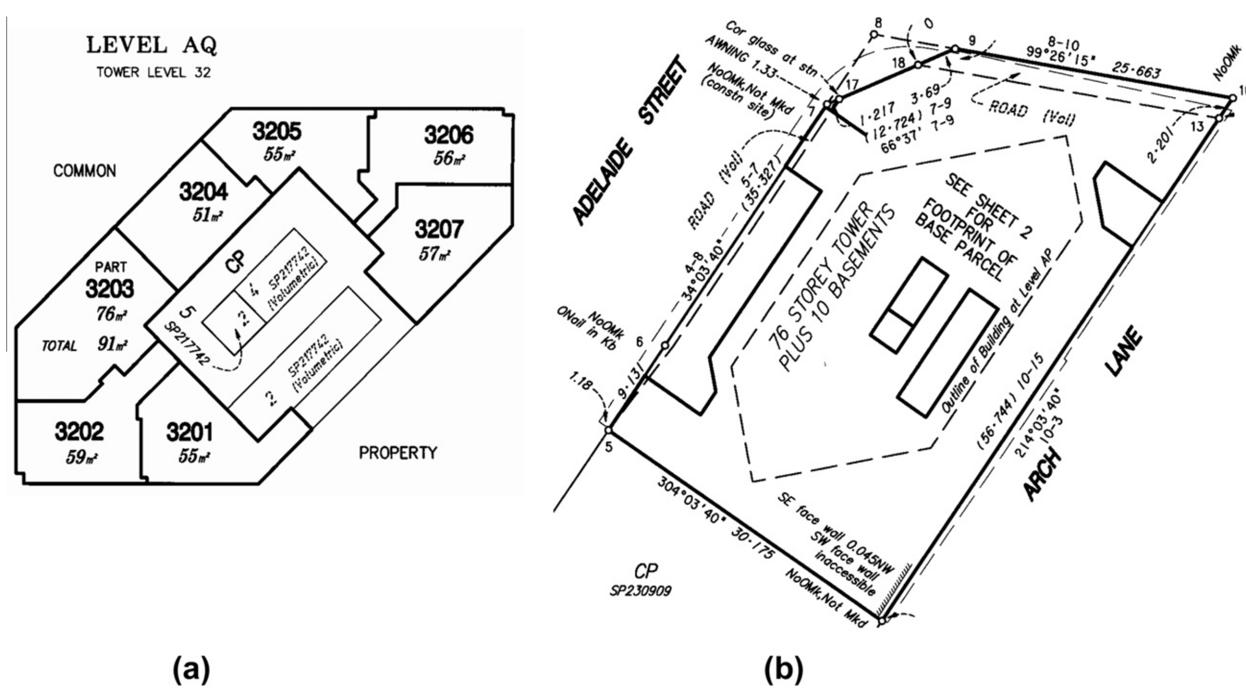

Fig. 2. (a) Building unit footprints for a level of a building in a Building Format Plan (BFP) and (b) outline of building footprint.

the outline of the building footprint(s). The survey plan shows a diagram of the individual apartment units rather than a geometric definition. This is the most common form of 3D spatial unit worldwide, and is often the only form supported.

– *Volumetric Format Plans (VFPs)*: Each lot is defined geometrically by measurements in 3D space. The definition is not dependent on any physical structure, and indeed there may be no structure present. Initially, a 3D lot will consist of 3D parcels restricted within a 2D base parcel (see Fig. 3). If a volumetric spatial unit extends beyond the extent of a 2D parcel such as in the case of a tunnel (see Fig. 6a), it is subdivided, and individual plans are drawn to ensure that each 3D lot is within a 2D base lot. There are no restrictions on the geometric shape that is permitted for a volumetric parcel provided that it can be defined unambiguously. This is a less common form of definition of 3D property rights worldwide.

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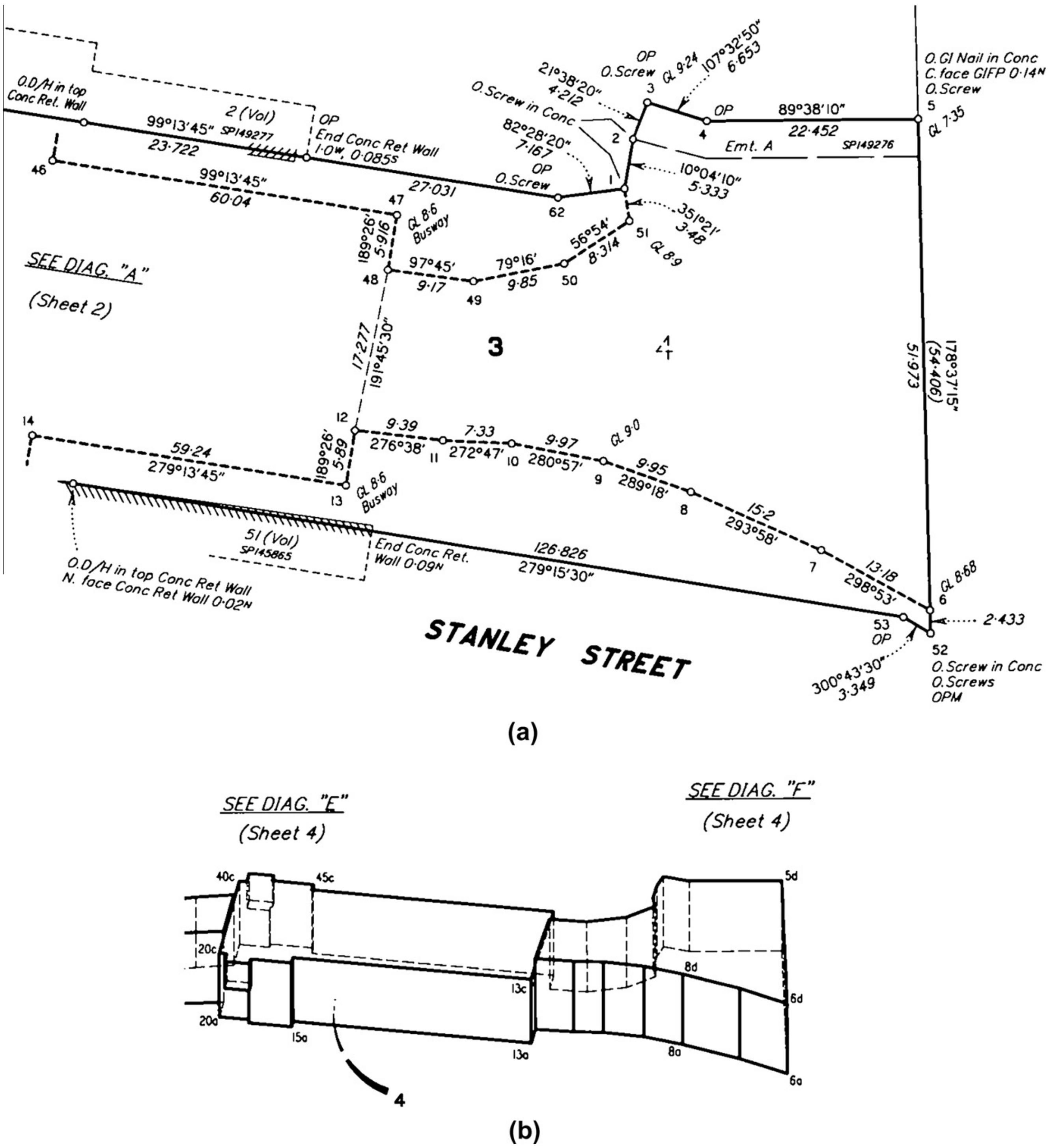
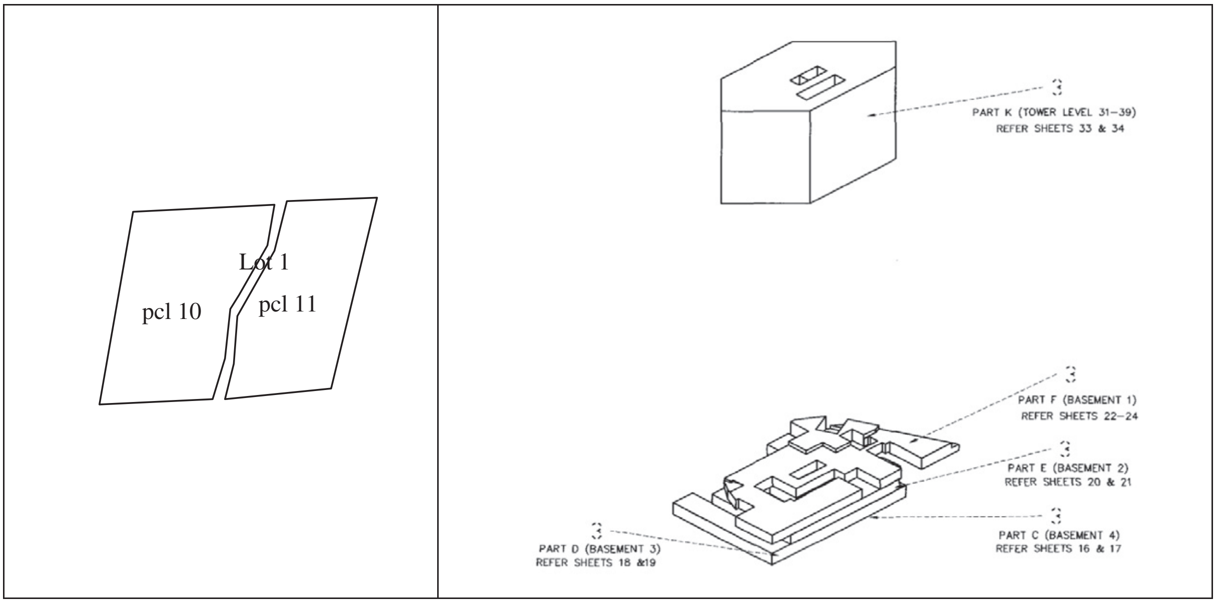


Fig. 3. (a) An example of a volumetric format plan showing the base lot (solid lines), the outline of a volumetric lot (dashed lines) and (b) isometric view of the volumetric lot.

Queensland legislation specifies that a 3D parcel be treated in law exactly as a conventional 2D parcel, and thus it may be traded, mortgaged, leased, etc. in equivalent transactions. However, the cadastral database stores only the 2D outline of volumetric lots (Huitfeldt & Jacoby, 2005).

3. Current validation for cadastral plans in Queensland

In Queensland the basic legal unit for recording interests in land is the ‘‘lot’’ (LA_BAUnit in LADM terminology), which may be broken into smaller components known as ‘‘parcels’’ (LA_SpatialUnit in LADM terminology) for the purpose of defining the geometry (see Fig. 4). The lot consists of an integral number of parcels with the same legal interests applying to each. The concept of a ‘‘building unit’’ (for example an apartment or LA_LegalSpaceBuildingUnit in LADM terminology) as a registered interest having its own title, space, definition and rights (Billen & Zlatanova, 2003), has been in use since 1980, as legislated through the *Building Unit and Group Title Act 1980* (*Qld*) and *Body Corporate and Community Management Act 1997* (*Qld*). In this approach, a building unit is itself a lot which may be composed of various parcels (or LA_LegalSpaceBuildingUnit a specialisation of LA_SpatialUnit in the language of the LADM).



(a) (b)

Fig. 4. Dividing a lot (LA_BA_Unit) into multiple parcels (LA_SpatialUnit): (a) in 2D a large rural property is often split by a public road without the ownership details being changed and (b) Lot 3 (a 3D lot in a large building with a single owner) is split into dwellings (part K) and car parks (parts F, E, C and D).

3.1. Validation of paper-based 2D plans

In order to lodge a plan, a registered surveyor carries out a cadastral survey and produces a plan of survey consisting of both spatial and textual data. All survey plans submitted are examined for completeness and correctness using a set of rules compiled from departmental procedures, policies and legislative requirements. It is extremely important in this context that the process is fair, consistent and justifiable, especially given that rejection of a submitted plan may lead to significant extra expense on the part of the surveyor or their client.

In paper-based submission, plans are encoded to create an electronic form of the data for validation and to update the cadastral database.

3.2. Validation of electronically submitted 2D plans

Two dimensional plans go through a partially automated validation process, checking for identification of created and affected lots, adjoining lots, accuracy of other supplied information and compliance to pre-defined plan format and numbering conventions. The validation rules developed have been divided into the following components:

– *Automatic validation checks of the file structure and completeness* – these rules assess the internal consistency of the plan, including dimensions and tolerances.
– *Automatic validation checks of content against existing data* – these rules verify that the new survey is compatible with information already in the departmental databases and that the surveyor performing the survey is registered; e.g. no overlap between two ownership lots.
– *Manual validation checks for items that require subjective assessment and that cannot currently be completed satisfactorily by software* – for example, where natural boundaries are part of a parcel definition.

The rules are subject to periodic review in regard to changes in requirements, and in an attempt to promote checks to an automatic process where possible.

3.3. Validation of paper-based 3D plans

In addition to the usual 2D rules, plans with a 3D component (and which are submitted in digital format according to the rules specified for the building format and volumetric format plans) are currently manually assessed for compliance to administrative and geometrical requirements as detailed in Table 1.

Volumetric format plans require additional checks such as geometric shape including the definition of bounds, faces of a volume, bounding surfaces, vertices, slope or horizontal distances, bounding edges, completeness, flatness (where a tilted face is defined by a polygon with more than three points), verification of lot and part-lot volumes, total volume, location of footprint, the approximate ground level, vertical location, connection to survey marks,

Table 1
Existing 3D validation rules applied to paper based plans in Queensland.

Plan format	Validation group	Compliance to
Building format	Administrative	Parcel creation and existence, plan format requirements, lot/building numbering convention, common property and its location and extent
	Geometric	Manual checking of non-encroachment, verification of total and part-lot areas, of voids, location and spatial extent of footprints. See Fig. 5
Volumetric format	Administrative	Parcel creation and existence, plan format requirements, remainder lots, vertical datum and origin identification and verification
	Geometric	Geometrical shape, volume, location, adjoining geometry

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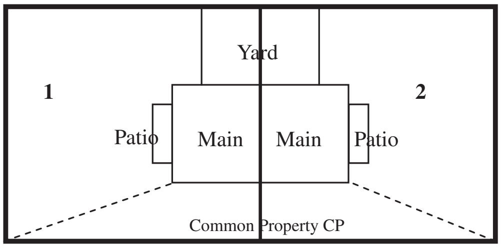

Fig. 5. Verification of component area and volume of a building format plan, e.g. the sum of the areas of the main building, patio, and the yard must add up to Lot 1 or 2, while the sum of Lot 1 and 2 must add up to the parent lot.

adjoining lots (2D or volumetric) on existing plans. Fig. 6 provides an example of the submitted volumetric format plan information including (a) an isometric representation of the lot and (b) the 2D plan of the lot showing the relationships to other boundaries.

In general, complete manual validation of a 3D plan is an almost impossible task. For example, to determine whether a multi-vertex inclined face in 3D is truly planar is beyond what would be expected of a person with a calculator. Fortunately, in Queensland, a convention has been spontaneously developing that:

– Wherever possible, surfaces are horizontal or vertical.
– Other (inclined) surfaces are triangles (see Fig. 6).

These are not official rules, but do assist the surveyors as well as the registering authority, ensuring that the faces are per definition flat and unambiguous (which would not be guaranteed in the case of a polygonal face with more than three vertices). Unfortunately they are not universally observed.

4. Geometrical validity

In a worldwide survey of cadastral jurisdictions, van Oosterom et al. (2011) found that the range of objects registered as 3D cadastral objects varied in different jurisdictions around the world. For example, air-spaces were registered in Canada and Australia, legal spaces around buildings are registered as 3D in Italy and many other countries, legal spaces around networks are registered in Switzerland and Turkey. Tunnels and other underground networks are registered in Victoria, Australia (Aien, Rajabifard, Kalantari, Williamson, & Shojaei, 2011), and infrastructure above and below ground in The Netherlands (Stoter & Salzmann, 2003).

There are several alternative geometric representations that can be utilised for 3D cadastral data. Arens, Stoter, and van Oosterom (2005) identified the polyhedron representation, Bjornsson and Land (2011) considered extruding 2D data to create 3D models, Thompson and van Oosterom (2008, 2011b) have examined regular polytope representations, Stoter and van Oosterom (2005) researched triangulated irregular network based representations whilst Ledoux and Meijers (2009) explored tetrahedron and constructive solid geometry representations. A modified boundary representation based on the concepts of LA_BoundaryFace for 3D objects and LA_BoundaryFaceString for 2D or mixed 2D and 3D objects as presented in the LADM (Lemmen, Van Oosterom, Thompson, Hespanha, & Uitermark, 2010) was designed specifically for cadastral data, and is considered the most promising. It is therefore utilised in this paper.

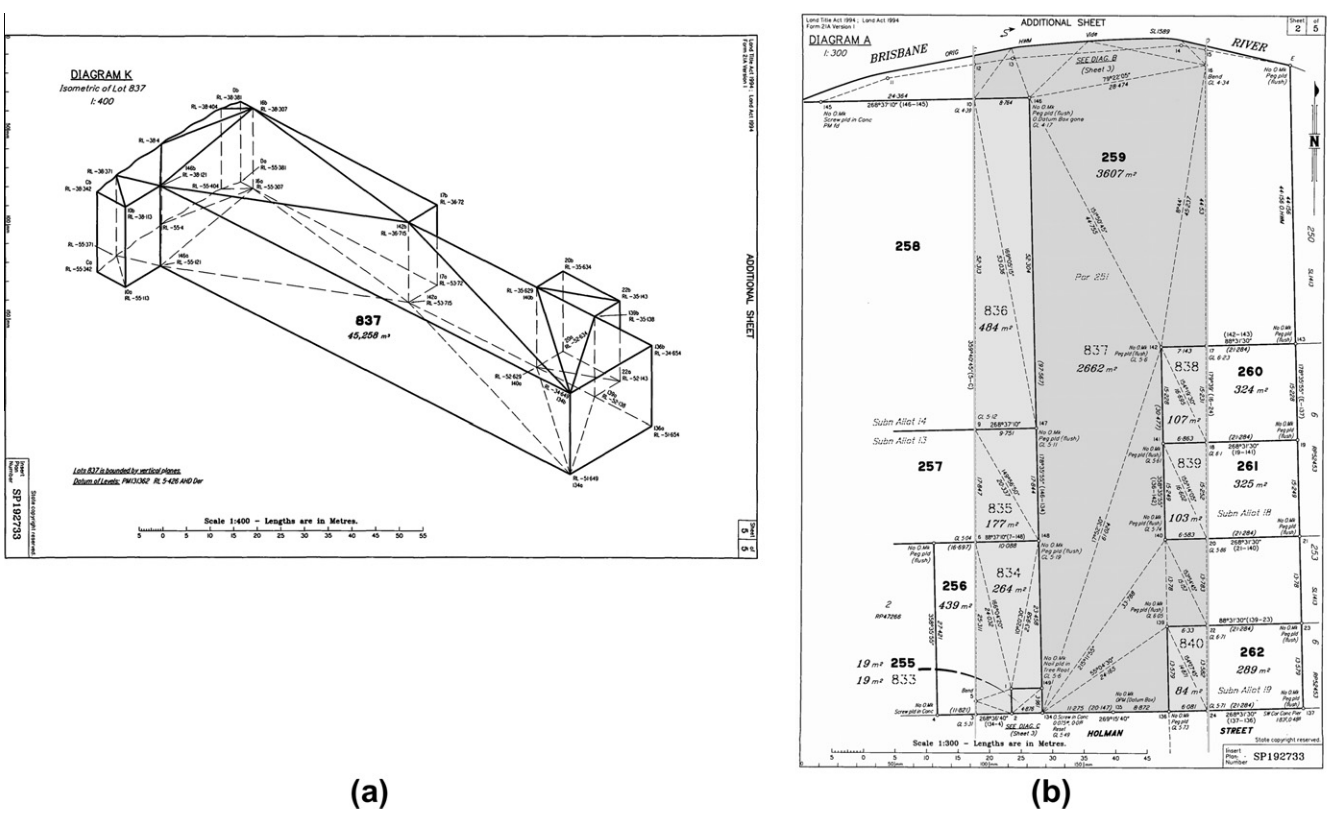

Fig. 6. (a) Isometric view of a below-ground volumetric lot (part of the "Clem 7" tunnel) and (b) outline of that lot (shaded), which is that part of a tunnel that falls within (below) a single standard 2D lot. Note that other parts of the tunnel (light shading) fall within adjoining lots.

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Table 2
Geometrical axioms and their application to validation in this paper, from Thompson and van Oosterom (2011a).

Axiom	Application to 3D validation
A1: No two nodes may be closer than ε apart	Ensures there are no small artefacts (which may be generated by rounding errors, object disturbance or undershoots)
A2: Each node must have at least three incident faces	Prevents unnecessary clutter and over-definition of surfaces. Note – this is optional
A3: The faces incident at a node must not intersect one another except at an edge	Prevents ill-formed objects with interpenetrating surfaces that can have no parallel in the real world
A5[a]: Non-intersecting edges must not approach to within a distance ε of each other	Ensures that there are no very close edges which could mask detection of serious validation failures (which would have been detected had the edges intersected)
A6: Every directed-edge of a face in the shell must belong to a fold[b]	Ensures the ability to distinguish between inner and outer surfaces of a complex object
A7: The directed-edges that delineate a hole in a face must be part of the boundary of other faces	Prevents unnecessary clutter and over-definition of surfaces. Note that this is implied by A2, and only necessary if A2 is omitted. It is also optional
A8: Bounded faces must be planar to a tolerance of ε'	Prevents ambiguity of containment which may have legal consequences due to encroachments
A9: No node may be within ε of a face unless it is part of the definition of that face	As in A5, prevents the masking of serious validation failures (which would have been detected if the nodes were part of the face definition)
A10: No directed-edge may intersect a face except at a node of that edge	Prevents ill-formed objects with edges penetrating surfaces

[a] Axiom A4 appeared in an earlier paper based on this research (Thompson & van Oosterom, 2012), but was later found to be redundant. The numbering has been retained for consistency between papers.
[b] A fold is defined as a pair of faces meeting at anti-equal directed edges with no other faces between them.

To date, research on validation rules for spatial data has been based on the requirement to ensure that the data can be safely loaded into a specific database or format. Contemporary studies on validation have identified rules for the Oracle database management system (Kazar, Kothuri, van Oosterom, & Ravada, 2008), for 3D city models (Gröger & Plümer, 2012a, 2012b), and for a 3D boundary representation (Thompson & van Oosterom, 2011a). The axioms presented by the latter (see Table 2) can be used as validation rules, and provide a foundation for the validation processes required to assess the veracity of the often complex geometry that makes up 3D cadastral parcels.

Note that the decision to enforce A2 and A7 is for the jurisdiction to make. No serious ambiguities of definition result from their omission. Note also that this list of axioms cannot be guaranteed to be exhaustive, and others may be appropriate. In particular, it is likely that a jurisdiction will mandate continuity (internal connectedness) of parcels. Also note that all axioms are needed as it is possible to generate unwanted configurations (invalid representations) for every axiom in which the configuration satisfies all axioms except the current one.

5. Validation rules for digital submission of 3d data

In this section we describe the necessary characteristics of automated processing of 3D data. The establishment of a cadastral parcel, whether it is in 2D or 3D, has significant legal, social and economic implications. In particular, the relationship of the new cadastral parcel with the surrounding parcels is critical to defining the rights, restrictions and responsibilities within the land titling framework. When a volumetric lot is created, it could be considered to be either (1) excised from an existing 3D column (Fig. 7a) or (2) created as 3D lot on an otherwise 2D surface (Fig. 7b).

While the real-world situation is the same in either case, the statement of the validation rules is different. Where a 3D cadastral database is being constructed from survey information, the structure chosen will depend on the view taken in this regard. For the purposes of this paper, the approach taken by LADM (ISO-TC211, 2012) is assumed. That is to say, all 2D parcels are considered to be 3D columns of space above and below the ground surface, but with no defined top or bottom.

5.1. Verifying 3D encroachments using a cadastral database

The location of a 2D base lot is usually defined unambiguously in a digital cadastral database, at least in relation to adjacent lots, but few (if any) 3D cadastral databases exist worldwide. Potentially this makes detection of encroachments between 3D parcels more difficult. The outline of a 3D building can be defined by using surveyed measurements from existing corners (Fig. 8a), and encroachments of the footprint of a building (Fig. 8b) can be detected using simple topological overlay rules. However, in a case like that in Fig. 8c, to detect an upper level (or below ground) encroachment, it is necessary to compare the plan against all existing 3D plans.

The Queensland approach to reduce this difficulty is to mandate that all 3D land parcels must exist within the bounds of a base lot. Thus in the case of Fig. 8c, there can be no encroachment of the structure with any adjoining structure provided all plans respect this rule. However, within a single lot, it still has to be checked that the multiple 3D parcels are non-overlapping. This reduces the

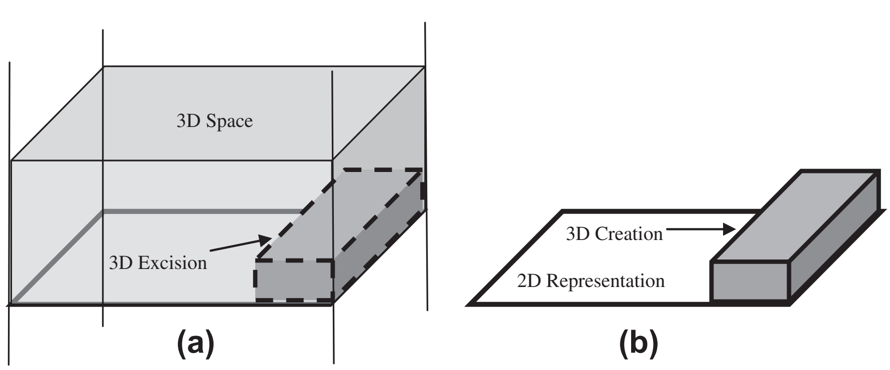
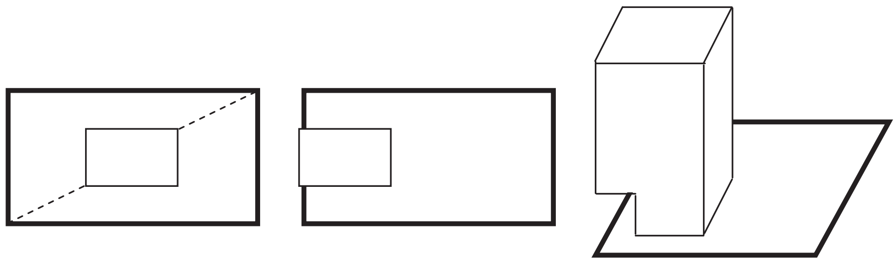
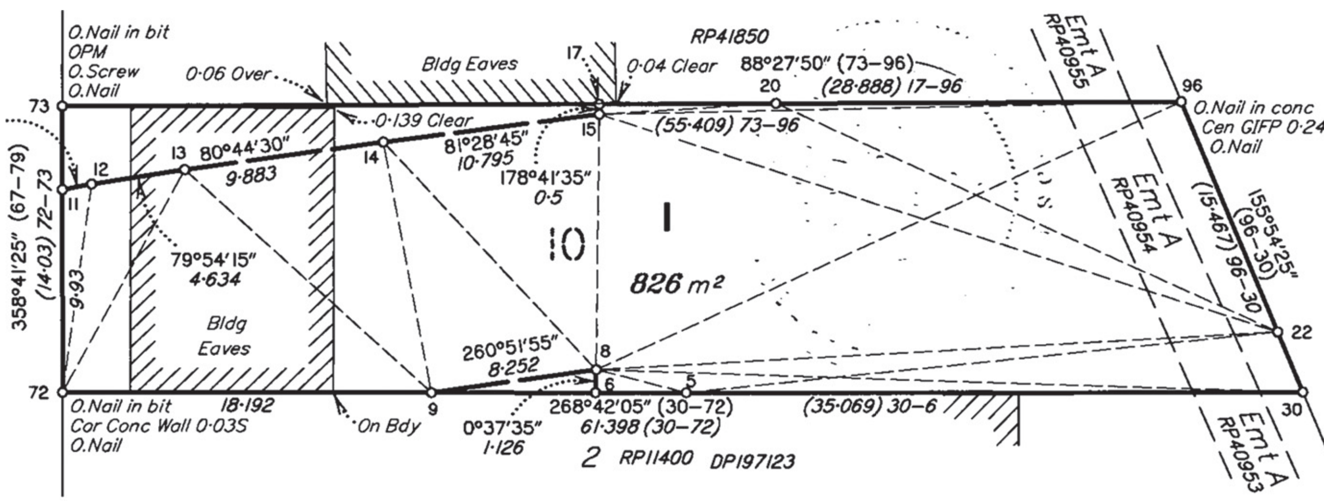


Fig. 7. Excision of volumetric space (a), or creation of volumetric lot (b).

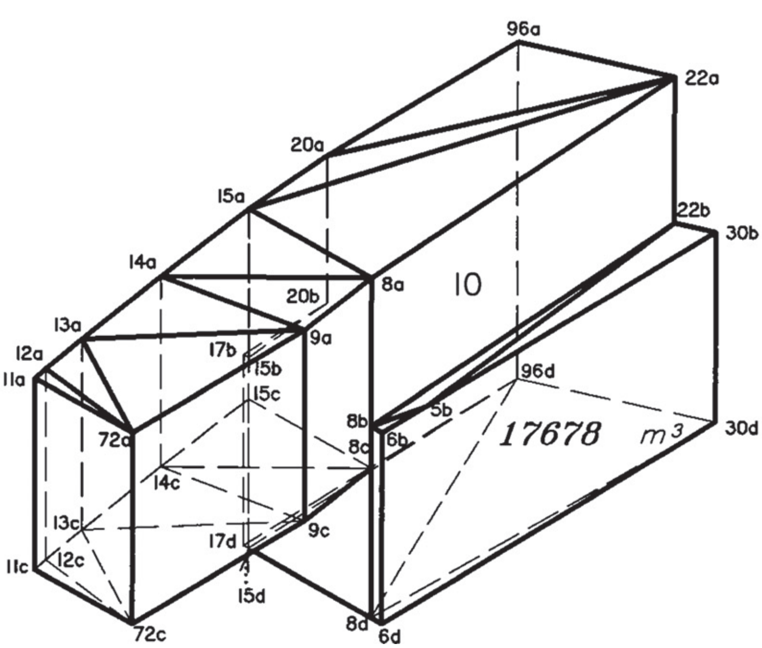


(a) (b) (c)

Fig. 8. Verifying unique location and encroachment of buildings.

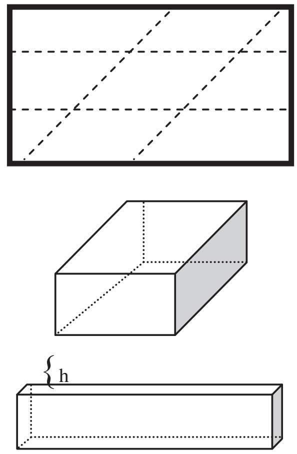


(a) Outline of two volumetric lots in plan view

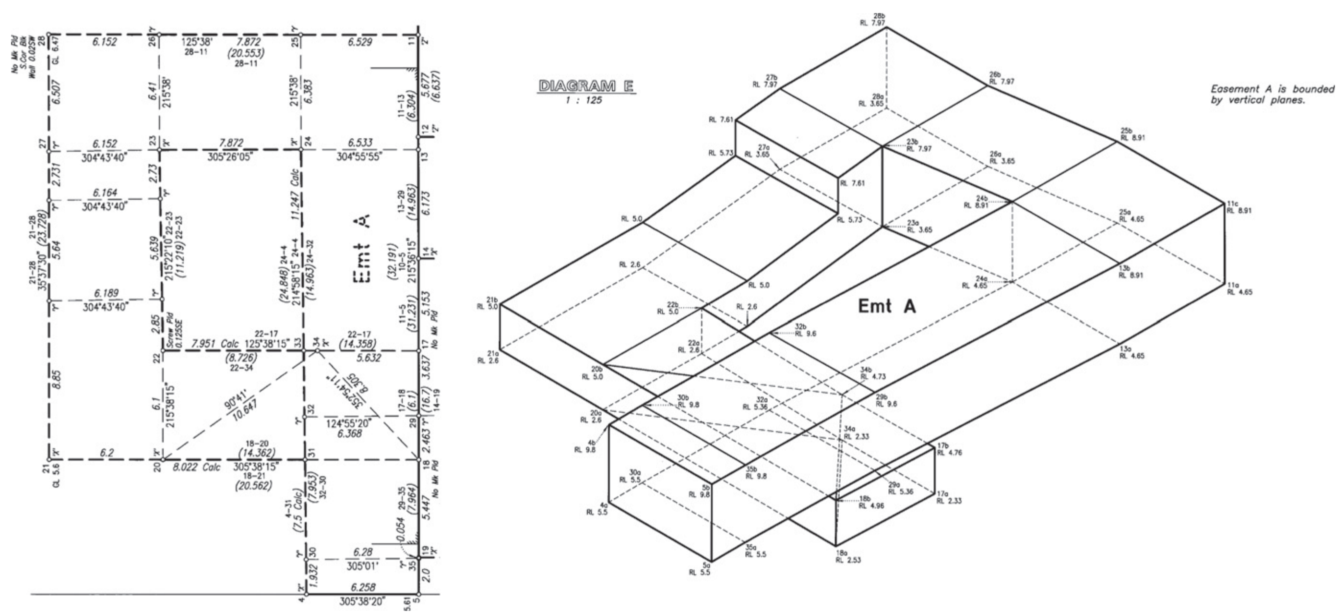


(b) The volumetric lots in isometric view

Fig. 9. Multiple volumetric lots at different levels with similar shape and size are shown on surface plan or 2D cadastral database as a single outline.



(a) Volumetric lots crossing each other and their footprint on the surface plan shown in dashed lines



(b) Volumetric lots with slopes cannot be shown clearly in 2D

Fig. 10. Multi-level volumetric lots and their representation on the surface 2D cadastre.

problem to (a) preventing encroachment of parcels within each individual plan, and (b) preventing encroachment between 2D base parcels. In effect, this rule obviates the need for a 3D cadastral database for validation purposes, but creates other problems. For example, consider the landowners of the surface parcel in Fig. 6b. If they wish to subdivide their property, are they required to re-survey and subdivide the tunnel parcel? The decision in Queensland is "no", and so it cannot be assumed that 3D parcels are constrained within a single base parcel.

Another unfortunate result of the constraining of 3D parcels to be within 2D base parcels is the fragmentation of the 3D networks. For example the parcel shown in Fig. 6 is a part of a cross-city tunnel, which consists of 389 separately defined 3D lots, each of which is defined on a separate plan. This in turn obscures the connectivity of the tunnel network. A further issue is the maintenance of the associated rights and parties, instead of attaching this to a single object, it has now to be attached to all 389 separate parts. This is error prone, perhaps not the first time of registration, but certainly during later updates (without an 'overview plan').

Frequently, two-dimensional cadastral databases store the base lots and plan views of the volumetric lots. In the case of multi-level volumetric lots, the outlines appear either on top of each other (Fig. 9) or crossing each other (Fig. 10).

5.2. Verifying disjoint 3D rights

In a LADM-based implementation of a cadastral database, the standard base lots can remain represented by 2D lots while volumetric parcels are captured as 3D objects. The rights of a standard 2D lot extend both above and below the ground, however, the rights of the 3D building or volumetric lot are limited to the defined extent of the lot. That is to say, some lots are fully bounded in 3D, while others may be open above, below or both. In this regard, individual lots must be disjoint throughout the columns of space defined by the base cadastral fabric (at all possible Z values).

In Fig. 11, the example shows disjoint 3D rights in lots containing private courtyards (PY_1 and PY_2). The face formed by l–g–h–e–n–m–l, is the upper bound of rights for the 3D volume with height

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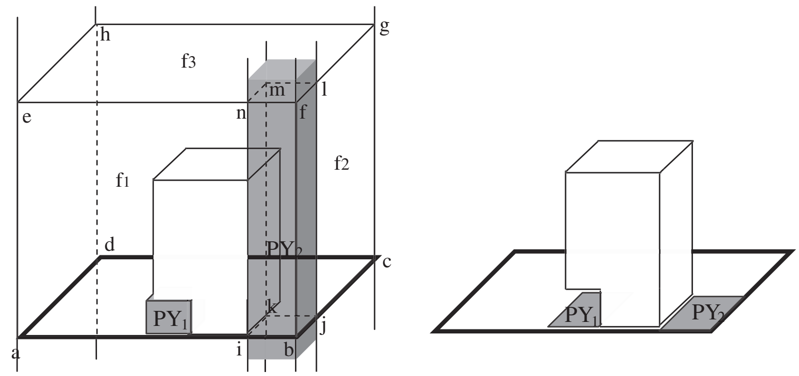

Fig. 11. An example of disjoint 2D–3D rights where part of the same complex is bounded and part is unbounded.

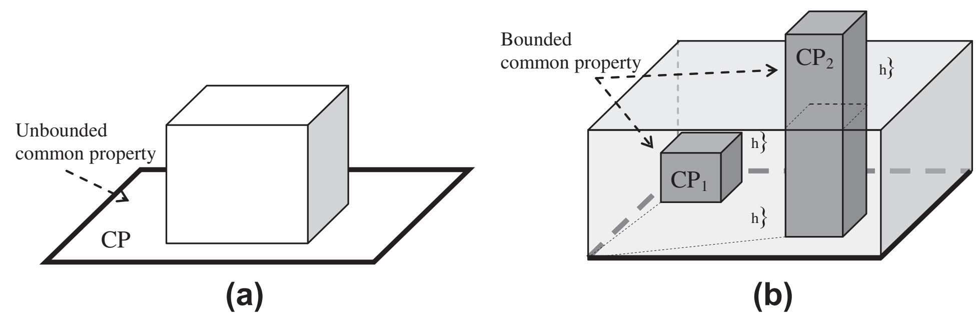

Fig. 12. Common property, external and internal.

a–e. However, the private yard column (PY_2) with footprint i–k–j–b–i is unbounded above and below, while PY_1 is fully bounded.

In earlier times, lots were defined "to the depth of" or "below the depth of" for mining purposes. These are partially open property parcels (unbounded above, and below respectively), and still exist within the cadastre, but are no longer being created except in the case of subdivision of existing partially open property parcels.

5.3. Verifying 3D common property (CP)

In a 3D subdivision, common property is defined in two forms: (1) unbounded or partially unbounded parcel(s) representing the remainder of a 2D lot after the 3D parcels are excised (Fig. 12a), and (2) fully bounded parcels, fully or partially enclosed by other 3D Parcels (Fig. 12b).

In addition to the usual validation rules for parcels within a volumetric lot, there are two additional restrictions. Firstly, any lot that is privately owned or occupied must be connected to the outside world via common property so that it is accessible. Secondly, any common property cannot be completely surrounded by a private parcel. For example, Fig. 12b in which CP1 is invalid, but CP2 is valid. For this kind of check, the exact position of all parcels, including common property must be defined in 3D.

Fig. 13 represents a case where the base lot contains buildings and common property. The common property is the remaining space after the units in the building are excised. As the building is created with unique shape, size and consequently volume for each level, the observations (aa′, cc′, gg′, etc.), which are the means of positioning the internal parcels relative to the outside world, need individual validation for each level. For example, does point c as determined by observation from c' fall correctly on face f_1 as well as f_3?

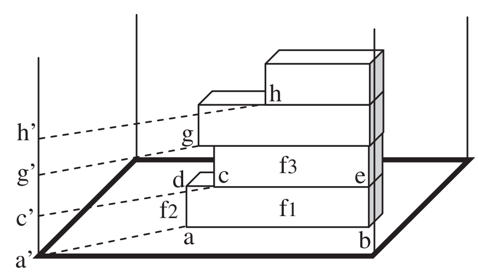

Fig. 13. External common property connection lines.

5.4. Reasonability testing

When the validation of incoming plans is performed manually, there are certain reasonability checks that are done – perhaps unknowingly. In a case such as shown in Fig. 14, a person would notice the conflict in the diagram – two planes meeting at a non-straight line. The automated validation rules may not detect this kind of error because, if the two faces are very close together, they may satisfy axiom A8 (bounded faces must be planar to a tolerance of ε'). The case depicted in Fig. 14 was shown to satisfy all axioms by (Thompson & van Oosterom, 2011a).

5.5. Curved surfaces

Curved surfaces are constructed in the real world and can be measured and represented in a 2D plan as a footprint and an isometric drawing (Fig. 15). In Queensland, any kind of mathematical surface is allowed as long as it can be defined by dimensions (DERM, 2008). Validation processes for curved surfaces are already challenging in the current 2D database environments. However,

Fig. 14. Thin wedge construction from Thompson and van Oosterom (2011a).

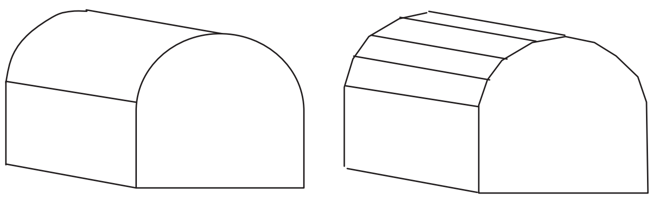

Fig. 15. Curved surface and its corresponding planar polyhedral surface.

with the move towards a 3D cadastral implementation and databases, curved surfaces will remain more complex than most other 3D objects. From a database storage and geometrical validation perspective, curved surfaces can be represented as polyhedral surfaces with planar faces, but this must be recognised as an approximation and not the legal definition. Note that based on curved surfaces it may be very difficult to check if the volume is closed and what the exact shape is; e.g. it has been proven that there may be no mathematical description of the edges between two curved surfaces. The best one could do for such an edge is provide a numerical approximation. Also for this reason in may be more effective to start with polyhedral surfaces anyhow.

5.6. Levels

The LADM permits the use of levels in the cadastre, allowing an independent re-definition of space into more than one coverage. Thus, for example, one level might be used for the land ownership fabric, while another might be used to record mineral resources or mining rights. This is not a requirement in Australian jurisdictions and has not been investigated in detail. The key consideration in this regard is whether one level has "priority" over another, so that the definition of a parcel in a high priority level effectively excises it from any intersecting lower priority level parcel. This may significantly ease the validation and storage requirements, since it is not necessary to generate a partially open parcel when a 3D object is removed from a 2D column of space (for example in Fig. 6 determining the remainder of a base parcel when the tunnel is excised from it). Conversely levels may create new validation issues. For example, it might be invalid for a road tunnel in one level to overlap a mining area in another.

6. Implementation decisions

As a result of the experience gained in the pilot implementation of electronic survey plan lodgement in Australia, and of the research by the authors, it is recommended that the following decisions are required of any jurisdiction intending to follow a similar path for digital submission of 3D parcels.

Geometric issues:

1. What geometric form should the submission use (Boundary Representation, Tetrahedral Decomposition, etc.)? See Section 4.
2. What geometric validation rules are appropriate (e.g. those in Table 2, page 7 with or without A2 and A7)?
3. What will be the contiguity requirements on parcels (i.e. are parcels required to be strongly connected)? See Section 3.
4. Will any other geometric rules be required (e.g. "No parcel may have two faces with the same vertices but opposite sense")?
5. Are curved surfaces to be allowed? If so, what restrictions will be placed on the complexity of the curvature? See Section 5.5.
6. Are "reasonability tests" appropriate (e.g. "No two parcels defining a lot may be more than 1 km apart")? See Section 5.4.
7. What rules apply to the closure of property parcels (e.g. completely bounded in 3D or 2D only)? See Section 5.2.
8. What classes of property parcels exist – for example, private property, common property, public, etc.? See Section 5.3.
9. What accessibility to private property parcels is required (e.g. via common property)? See Section 5.3.
10. What restrictions apply to common property, private property, etc.? See Section 5.3.

Validation against existing data:

11. Will a 3D cadastral database or 2D/3D hybrid database be available to support the validation? See Section 4.
12. What tests are needed to ensure that the relationship of the plan objects to existing parcels is correct (adjacency, encroachment, etc. in 2D and 3D)? (The answer to this clearly depends on point 11 above).
13. Will independent "levels" of cadastre be present? If so, is there a priority of levels? See Section 5.6.
14. If levels are present, are any specific "cross level" checks required? See Section 5.6.
15. Will 3D parcels be restricted to being within a surface 2D parcel's bounds? If so, will this be true for all time, or only at the time of initial parcel creation? See Section 5.1.

Organisational issues

16. Will an LADM, ISO 19152 based country specific profile be developed? (ISO-TC211, 2012).
17. If so, what encoding format should be used for the digital submission, (XML, GML, LandXML, CityGML)?
18. What administrative checks are needed (e.g. "Is the surveyor correctly licensed to submit a plan")? See Section 2.

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19. What comprises a complete plan (e.g. no missing information such as closing bearings and distances)?
20. How is geographic location determined (e.g. is the plan correctly referred to permanent marks, or in other jurisdictions, have coordinates been assigned to all points)?

Careful consideration of these questions is considered essential to the successful implementation of a survey plan electronic lodgement process.

7. Conclusions

The paper has reviewed a specific case study of procedures for the lodgement of cadastral survey data, progressing from the manual checking of 2D plans, to the current hybrid 2D/3D partially automated system, towards the future of highly automated checking of all surveys.

The integrity of any land administration system is dependent on the quality of the data that comprises such a system. Prevention of ambiguity in survey data is essential to the smooth running of a cadastral registry, and the process of validating cadastral data prior to it entering into a cadastral database is an essential quality assurance process. This paper has provided an insight into the validation requirements for both 2D and 3D cadastral information for a particular jurisdiction. A set of validation rules has been proposed for application to single geometric objects, to the relationship of objects on a single survey plan, and to objects that are independently defined on separate plans. By the nature of the problem, this set is incomplete and will remain so, but the research has resulted in a "checklist" of issues to be addressed by jurisdictions hoping to implement digital cadastral survey plan lodgement.

The current absence of a fully 3D cadastral database will continue to limit the integration of legal boundaries into these urban 3D modelling environments, and so development of such a database along the lines of the LADM is a priority. There are a number of research challenges that will continue to demand attention in relation to the validation of cadastral data including: the development of appropriate 3D geometries to represent the wide variety of cadastral objects, further development and refinement of the validation rules and the development of processes to maintain the integrity and quality of 3D cadastral databases. Although the development of 3D databases to support the land administration and property systems is progressing, it is the transition from existing 2D cadastral database systems that will continue to challenge organisations.

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