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# The Cadastral triangular model

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ABSTRACT

Successful economies rely on effective land administration systems. A key contributor to land administration is the cadastral system and its support for the ongoing definition of boundaries that support secure property rights and effective land management.

Cadastral systems are complex and typically have significant differences in legislation, regulation and survey practices between jurisdictions. And yet the high-level objectives of a cadastral system tend to be essentially the same the world over. Comparisons of cadastral systems in different jurisdictions can easily become focused on the technical, legal, or implementation differences. This can obscure commonalities and opportunities to develop common strategies for the efficient maintenance and development of cadastral systems.

Changes in technology have significantly altered the way that cadastral boundaries can be marked and located in the real world and then represented or visualised on maps or plans and in databases. The rate of take up of these technologies, and the form of that take up, varies between jurisdictions.

A conceptual model to explore the complex relationships between different representations of cadastral boundaries has been developed. This model, which has broad application, is known as the Cadastral Triangular Model (CTM). The CTM is a valuable tool to explore and resolve complex issues facing cadastral systems, for example proposals for the evolution of 3D cadastres. This paper describes the CTM, how it can be used and identifies further applications of this model to address contemporary issues confronting cadastral authorities.

## 1. Introduction to Cadastral systems

"A Cadastre is normally a parcel-based system, where information is geographically referenced to unique, well-defined units of land" (FIG, 1995). The critical role of the Cadastre in support of Land Administration Systems (LAS) is recognised in Dale and McLaughlin (1999) and further unfolded in Williamson et al. (2010).

However, the concept of Cadastre is designed in many different ways in different jurisdictions around the world, depending on the origin, history and cultural development of the region or country. Basically, a Cadastre is a record that identifies the individual land parcels/properties. The purpose of this identification may be taxation (as was the reason for establishing the European cadastres) or it may be security of land rights (as was the case when establishing the Torrens systems in the new world such as Australia). Today, most cadastral registers around the world are linked to both value/taxation of land and securing legal rights in land (Enemark, 2004).

Given many different versions of the cadastral concept, it makes sense to talk about cadastral systems rather than just Cadastre. These systems include the interaction between the identification of land parcels, registration of land rights, valuation and taxation of land and property, and control of present and future use of land. This is shown in Fig. 1 illustrating multipurpose cadastral systems in support of the interrelated functions of land tenure, land value and land use.

The basic cadastral components are the cadastral register identifying the land parcels by number and area, the cadastral map identifying the land parcels geographically, and the cadastral measurements identifying the position of the property boundaries. This identification of land parcels in the cadastral system provides the basic infrastructure for running the interrelated systems within the areas of land tenure, land value and land use. As a result, the traditional surveying, mapping and land registration focus has moved away from being primarily provider-driven to now being clearly user-driven. However, each of those functions includes tasks and processes that impose quite different demands on the cadastral system. The success of a cadastral system is then a function of how well it internalizes these influences and achieves

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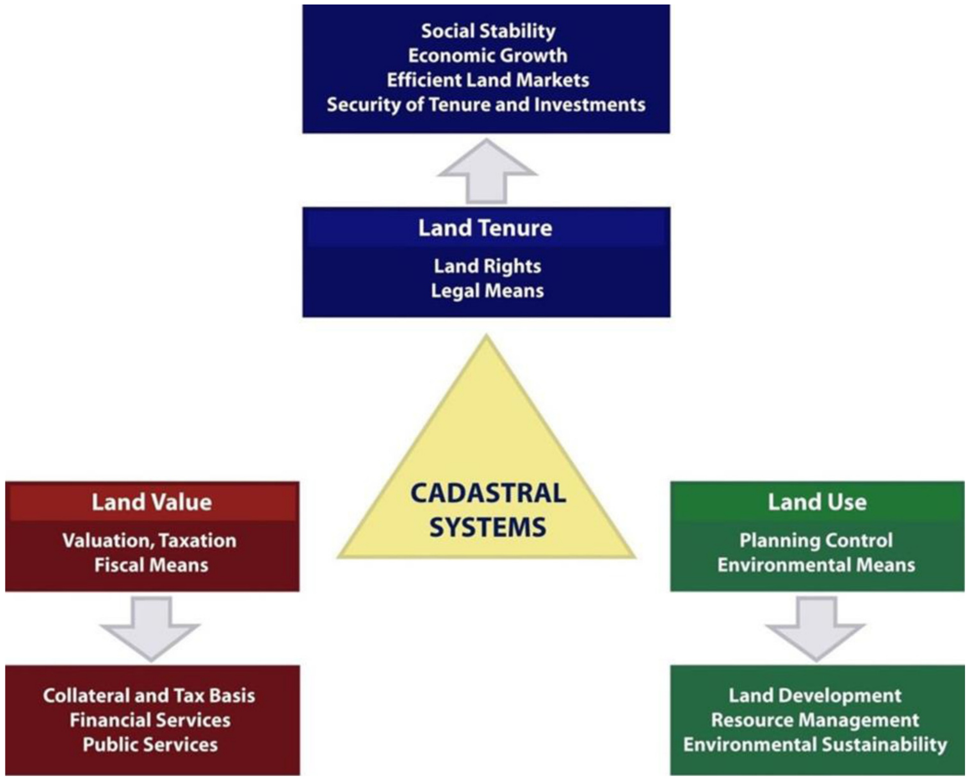


**Fig. 1.** Multipurpose cadastral systems supporting land tenure, land value and land use, as well as land development (Enemark, 2004; Williamson et al., 2010).

these broad social, economic and environmental objectives.

In modern cadastral systems where the information is captured and managed in digital databases, the spatial component, or digital cadastral map (here referred to as the digital spatial cadastre), is a key layer within the Spatial Data Infrastructure (SDI) which supports and integrates the four land administration functions of land tenure, land value and land use, as well as land development.

Nevertheless, the needs of modern society for sustainable economic development, access to information, and social cohesion can be advanced by alignment of land administrations systems. This alignment is greatly facilitated by spatial alignment of the various land administration datasets.

In order to evaluate the efficiency and effectiveness of LAS in each jurisdiction, and to propose options for further development and improvement, it becomes necessary to look inside the central "Cadastral Systems" triangle in Fig. 1. In particular, given the role played by SDI as an engine of LAS, we need to focus on the spatial component of cadastral systems and analyse how that component interacts with other cadastral system components.

## 2. Cadastral boundaries & Cadastral mapping

### 2.1. Cadastral surveying

Successful economies rely on effective land administration systems and at the core of land administration is the Cadastre (Krelle and Rajabifard, 2010). The cadastral system, through the function of cadastral surveying, provides for reliable determination of the boundaries that delimit rights, restrictions and responsibilities in land. A boundary is where one person's interests in land end, and the neighbour's interests begin (Zevenbergen and Bennett, 2015). A common form of dispute over land concerns the location of the boundary, Landowners and other affected parties need confidence that these boundaries will endure over time in the same position. Together with ensuring the property rights of individuals and corporations that invest in land with confidence that their interests in land are, and will remain theirs (role of land registration), in this way it will be well defined and enduring for their use and for future investment or sale to others. De Soto (2000) describes the role that confidence in property rights plays as being fundamental to the success of capital in countries like Australia and New Zealand.

Therefore, at the heart of cadastral surveying is the determination of cadastral boundaries.

*Cadastral surveying: This is the definition, identification, demarcation, measuring and mapping of new or changed legal parcel boundaries. It usually includes the process of re-establishing lost boundaries and sometimes resolving disputes over boundaries or other interests in real property.* (FIG, 1995)

Surveyors are often engaged broadly in activities that support other functions in LAS such as land development and land management. However, the function of boundary definition is considered so complex and critical to the LAS that this function tends to be reserved in law for those recognised as professional and competent. For example in Australia and New Zealand, these are the licensed or registered surveyors in each jurisdiction (CRSBANZ, 2018).

Each jurisdiction has differences in the processes applied to boundary determination – due mainly to differences in the legislation and regulations applying to cadastral survey. Further changes between jurisdictions have also developed over time due to differing levels of uptake of new technologies in measurement and information technology.

Nevertheless, there are some commonalities in the principles of boundary definition across jurisdictions. A model is developed in this paper that provides a framework for evaluation and comparison of systems of cadastral boundary definition within and between different jurisdictions.

### 2.2. Cadastral boundaries

An interest in a specific parcel of land needs to be separated from interests in other parcels of land. In its simplest form, a boundary is the separation between these two interests in land. In theory, a boundary represents a 'surface' – often depicted on cadastral maps or spatial views by an infinitesimally thin line where this surface intersects the earth's surface (Zevenbergen and Bennett, 2015). This boundary line is often occupied by visible artefacts like hedges, stone walls, ditches, or land use changes.

In a legal sense, Dale (1976) states that in relation to cadastral surveying, a boundary is "either the limit at law of any estate or a physical feature such as a fence erected to mark the limit at law".

Halsbury's Laws of England 3rd Ed, Vol 3 described a boundary as an imaginary line which divides two contiguous estates. The same source also used the term boundary to describe the "*physical objects by reference to which the line of division is described as well as the line of division itself. In this sense boundaries have been divided into natural and artificial, according as such physical objects have or have not been created by the agency of man.*" (Halsbury's Laws of England, 2020) p354. The concept of a cadastral boundary can usually be understood at this level by the layperson.

In the English literature on cadastral surveying, boundaries can be 'fixed' (where the precise line of the boundary has been agreed and recorded), or 'general' (where the precise line on the ground has not been determined although usually it is represented by a physical feature and shown graphically on a map), or 'natural' (defined by a natural feature such as a river or lake). The 'artificial' boundary mentioned in Halsbury's Laws of England are generally not visible in the field, unless marks have been placed to represent the legal title corners (Zevenbergen and Bennett, 2015).

In the eyes of surveyors, the accuracy with which the corner points have been determined during the cadastral survey is the main factor in describing types of boundaries. In many jurisdictions the regulations that relate to the accuracy requirements of cadastral surveys are developed with fixed boundaries in mind (Zevenbergen and Bennett, 2015)

Cadastral systems document the interests people have in land. To record these interests, we also need to document the boundary location. However, on closer examination the cadastral system that records, manages and re-establishes those boundaries is highly complex. There are many subsystems with complex interactions and dependencies for providing evidence of the location of boundaries and the interpretation of that evidence according to the law. Different experts describing the system may use different terminology for the same concepts or the same terminology for different concepts. This creates the risk that different agents (decision-makers) in different jurisdictions may have differing understandings of how the system operates in practice.

Boundaries are defined and represented in multiple ways within the same cadastral system. For example, hierarchies of evidence allow judgements to be made in the face of conflicting evidence of boundary location. Some of the evidence is readily identified and assessed by landowners (e.g. fences and walls) while other evidence may have greater legal weight and require expert assessment by surveyors. Between jurisdictions, different rules and hierarchies of evidence may apply.

### *2.3. Cadastral mapping*

Cadastral maps introduce an additional concept of what a boundary is – and in this paper we call this the 'spatial' boundary. Large-scale cadastral maps or plans were traditionally paper records. Cadastral maps provide an index for the land register and also for previous cadastral surveys on that land. A cadastral map shows the boundaries of each land parcel and provides a unique identifier for that parcel, and in some cases building locations, geology, soils, and land use. In these traditional paper cadastral maps, the map may be based on individual surveys.

During the latter decades of the 20th century many jurisdictions reengineered these paper-based cadastral maps into digital cadastral maps for use in multi-purpose cadastres (Williamson and Ting, 2001).

Therefore, in discussing boundaries, lawyers, surveyors, landholders and neighbours can all have a slightly different perspective of what the term 'boundary' means to them. This paper considers these differences in more detail and frames the discussion in terms of physical boundaries, documentary boundaries, digital spatial boundaries and legal boundaries.

### *2.4. Impact of technology on Cadastral mapping*

There have been significant changes in technology over the last few decades (Enemark et al., 2016; Lemmen et al., 2015) and further changes are expected that create challenges for how land boundaries are defined, visualised, how information about them is made available to landowners and the public, and understood, even within the relatively coherent cadastral systems across Australia and New Zealand. The technology disruptions that have occurred include:

- The boundaries modelled in the digital spatial cadastral databases allow the Cadastre to be represented by a graphical spatial model or digital cadastral "map" which is then made available by the jurisdictional land agency directly or indirectly to the public, land developers, other government land agencies and surveyors. This provides a very accessible "official" visualisation of boundaries – based on boundary coordinates that are in terms (at some level of accuracy) with a geodetic datum.
- Public access to spatial datasets including the digital spatial cadastre has increased. In the clearest example of this, Google Maps and Google Earth were released in 2005, providing ubiquitous GIS tools for the public (Castelli et al., 2009). A few years later these applications were released on smartphones. The public can now readily use these tools to obtain a representation of boundaries in relation to imagery depicting fences, walls, etc. However, this "official" visualisation is often less spatially accurate than the public may realise.
- Public access to global positioning on handheld devices is ubiquitous (Mannings, 2008). The accuracy on these devices is currently a few metres but is expected to achieve decimetres in the next few years with Satellite Based Augmentation Systems and improved devices. This will enable the public to capture reasonably accurate coordinates and compare these to boundary positions in the digital spatial cadastre.

As a result of these and other changes, many governments have moved towards an e-government model. Digital spatial data is often a key dataset for delivery of e-government services (Holland et al., 2009). The public has come to expect and rely on these services.

For the identification of the location of boundaries, previously the public had to rely on expert advice from surveyors or government officials. The move to e-government services, including the digital spatial representation of boundaries – delivered to mobile devices with GPS positioning, creates the impression that members of the public can almost locate boundaries themselves. This aligns with the goals of e-government, that services and authoritative information can be delivered to citizens directly (Holland et al., 2009).

However, the digital spatial boundaries are not sufficiently accurate to serve this new purpose that they were never designed for. They may be fit for the purpose of cadastral mapping but not fit for the purpose of locating boundaries and making decisions about land use and management (Grant et al., 2018)

These developments in cadastral boundaries, cadastral mapping, positioning and digital spatial databases require a new way of thinking about the complexity of various forms of cadastral boundaries and how we identify them. The Cadastral Triangular Model has been developed to help refine and support analysis of this complexity.

## 3. Formulation of the CTM model

The Cadastral Triangular model can be described as an extension of earlier conceptual perspectives. Cadastral boundaries are seen with different perspectives by surveyors and the Courts or legal profession (see 2.1 and esp. 2.2). The legal concept of a boundary can be seen for example at HM Land Registry in the UK which defines the legal boundary as "An imaginary or invisible line dividing one person's property from that of another. It is an exact line having no thickness or width" (HM Land Registry, 2019).

Also noted by Bennett et al. (2012) is the surveyor's perspective of a boundary as being a physical boundary located in space by measurements having some level of stochastic uncertainty. From the surveyor's perspective, the boundary cannot be dimensionless because its location in space has physical and practical limits for its location accuracy or uncertainty. The UK Land Registry defines the physical boundary as "A physical feature that we can see such as a fence, wall or a hedge, which may, coincidentally, also follow the line of a legal boundary" (HM Land Registry, 2019)

Lawyers and judges may have difficulty with the concept that the true location of a boundary in space is not perfectly known and even not perfectly knowable (Bennett et al., 2012). The task of locating a boundary in the world falls to surveyors. The courts can direct a surveyor on how the laws and evidence are to be interpreted. However, the courts generally have neither the expertise, nor the authority, to conduct a cadastral survey to locate, coordinate or mark that boundary. In the Australian and New Zealand jurisdictions, only a licensed / registered surveyor can perform this task.

Another factor in the surveyor's perspective, as well as the limits in their measurements and the consequent uncertainty in boundary location, is consideration of the intensity of land use and the "need-for-accuracy" of the landowners or right-holders.

Thus, two conceptual views can be identified:

the view of lawyers and judges that a boundary is a legal concept –seen as an imaginary line (2D) or surface (3D) with no thickness of width.

the view of surveyors that a boundary is a socio-technical concept – having physical and technical limits to its definition as well as the social limits of how accurately the affected parties (landowners) need it to be defined in space.

Ideally there is close alignment between these concepts of a boundary. In practice this does not always occur. The legal rights may be created by agreement, followed later by survey. However, the survey may never eventuate. Conversely the land parcels may be created by survey first in order to support a future legal transfer of rights – sometimes (but rarely) that legal agreement is not finalised.

These two conceptual views can be depicted as a dichotomy between the survey and the legal perspective of boundaries shown in Fig. 2.

Fig. 2, derived from the description in Bennett et al. (2012) or the guidance notes from the UK Land Registry (HM Land Registry, 2019), can be extended, resulting in Fig. 3, with the recognition that prior to development of digital spatial cadastres, evidence of surveyed boundaries came in two general forms:

- physical boundaries being the tangible evidence and realisation of surveyed boundaries. These are the accepted limits of land use in the physical world – e.g. boundary marks, natural boundaries, fences, walls, a visible line between different types of land use or cultivation, etc.
- documentary boundaries being the documented legal record and evidence of boundaries that had been accepted and agreed at the time of their creation – e.g. survey plans, titles, field notes, supporting documents, transfers, etc.

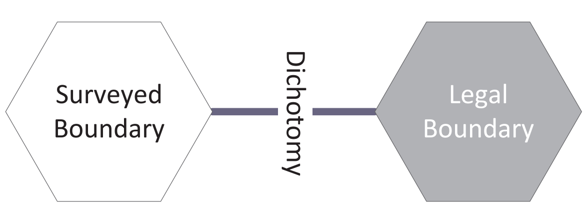

**Fig. 2.** Dichotomy in perspectives of surveyed and legal boundaries.

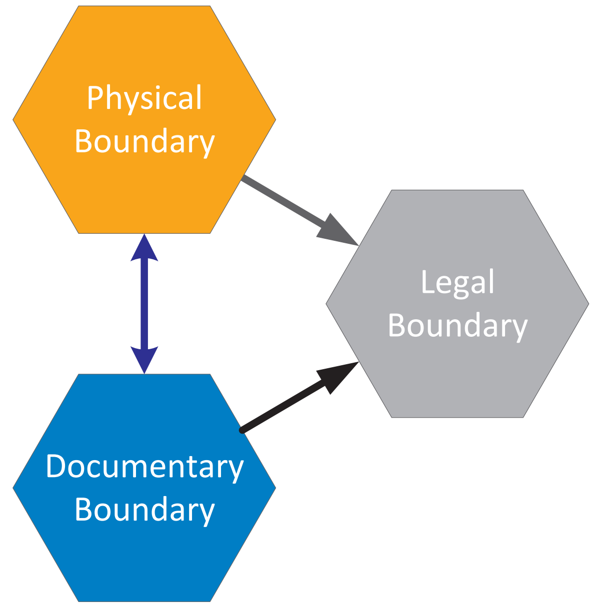

**Fig. 3.** Relationship between Physical, Documentary and Legal Boundary.

Before the digitisation of cadastral records, one form of documentary evidence represented in Fig. 3 was paper cadastral maps covering much of or all of the jurisdiction. These provided guidance as to the location of boundaries, served as indexes to cadastral information and also showed the spatial relativity and connectedness (topology) of all boundary points, lines and parcels in a jurisdiction in terms of their abutting boundary features.

From the 1980′s, many jurisdictions – for example those in Australia and New Zealand – digitised their paper cadastral maps into Digital Cadastral Databases (DCDBs) using Computer Assisted Drafting/Mapping (CAD/CAM) and Land Information System/Geographic Information System (LIS/GIS) software (Williamson and Enemark, 1996; Wilson, 1990). The primary driver for this change was to allow a reduction in the duplication of management and update of different sets of paper maps amongst different agencies responsible for land administration within government (Fig. 4).

Around the same time, the need for a multi-purpose cadastre was identified (McLaughlin, 1975; National Research Council (NRC), 1980). Such a multipurpose system is achieved in practice by sharing the cadastral map as a spatial dataset with other managers of land administration functions (valuation, land use planning, land development, etc). Therefore, while the initial justification for the digital spatial cadastre was to reduce the maintenance cost and duplication of paper cadastral maps (Williamson and Enemark, 1996) its potential value to support a multipurpose cadastre was also recognised – for example in the context of the New Zealand's digital spatial cadastre (Wilson, 1990).

A digital spatial cadastre involves the creation of a spatial representation of the Cadastre which can increasingly be used (rightly or wrongly) as a third form of evidence of boundary location. In addition to the physical representation of boundaries and the documentary representation of boundaries (both aiming to represent legal boundaries), we now have an alternative (and possibly competing) spatial

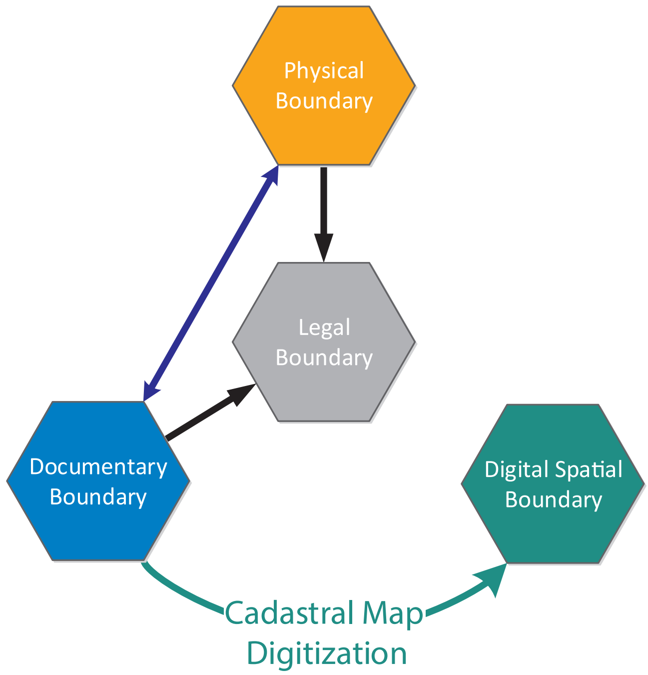


**Fig. 4.** The evolution of the spatial representation of boundaries.

representation of boundaries.

To reflect the development of spatial representations of boundaries and the increasing reliance of government, business and the public on these representations, the above models have been extended to a triangular model of cadastral boundaries as shown in Fig. 5.

In this model the exterior double-headed arrows and the interior single-direction arrows serve distinctly different functions (Fig. 6).

The exterior double-headed arrows forming the triangle, represent the actions to convert or transform boundary information from one conceptual form to another. For example, the transformation from boundary marks and their spatial relationships into the documented bearings and distances between those marks as recorded in field notes and survey plans. Or the conversion of documented survey information in the form of bearings and distances between new and existing boundaries, together with coordinates of geodetic control marks, to

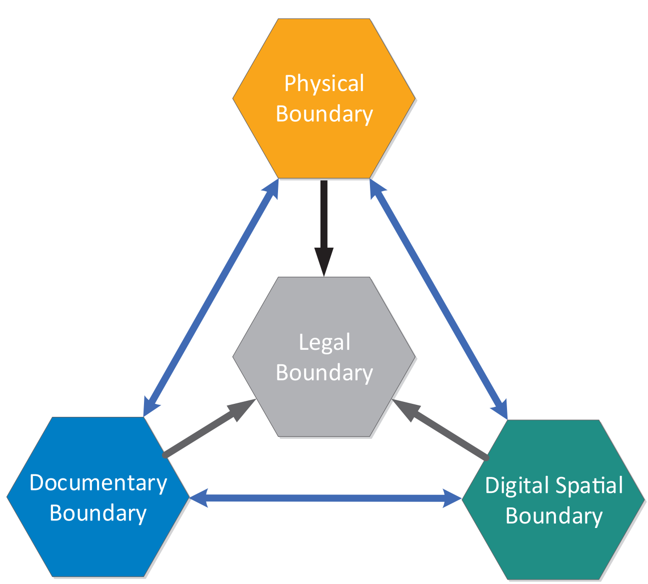


**Fig. 5.** Cadastral Triangular Model showing the interrelationship between Physical, Documentary, Spatial and Legal Boundaries.

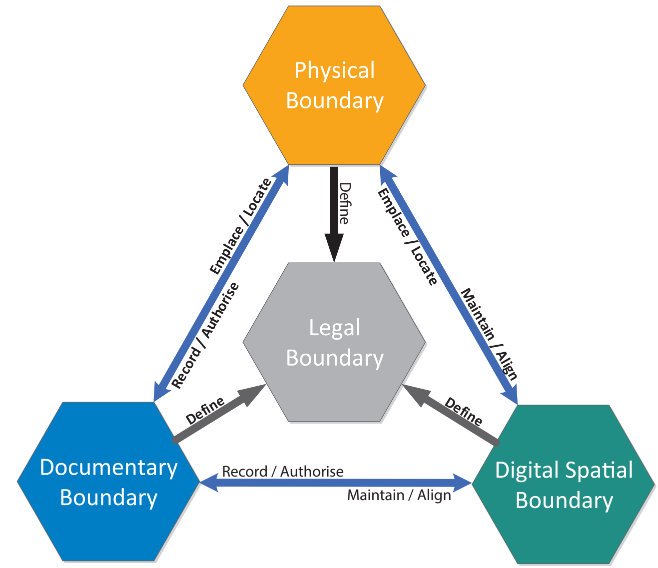


**Fig. 6.** Cadastral Triangular Model – detailed relationships.

align and maintain the coordinates and topological relationships that are encapsulated in spatial objects. Or, to complete that anti-clockwise loop around the model, the potential role for information from the digital spatial cadastral database to be used to emplace new physical boundary marks or locate other physical features related to boundaries.

The interior inward pointing arrows do not represent transfer of information – they represent the role of boundary information to define and provide evidence for the location of the legal boundary.

## 4. The elements of the CTM

In this section, each of the elements on the Cadastral Triangular Model (CTM) are described to clarify the application of the model for analysing cadastral systems.

### 4.1. Physical boundary

Physical boundaries are representations or evidence of a boundary in the real physical world. The physical features can take many different forms and serve different roles. Some examples are:

Natural features including moveable boundaries, (e.g. riverbanks);

Artificial boundary features (e.g. walls, fences) that are visible on imagery;

Emplaced boundary or survey marks with a relationship to the boundary (may be partly visible on imagery).

#### 4.1.1. Arrows pointing to physical boundary

The arrows pointing to Physical Boundary represent the use of information in either the documentary record (such as survey plans and titles) or the digital spatial cadastre (coordinated points and lines in the spatial model) to either:

- emplace boundary marks at boundary positions; or
- locate existing physical features that represent boundaries (marks, fences, walls, natural water boundaries).

It is generally less common to use digital spatial boundary coordinates for this purpose but in some jurisdictions they can be used where other evidence is less reliable or absent, or for lesser interests such as licenses, easements, etc.

### 4.2. Documentary boundary

Documentary boundaries are representations or evidence of a boundary recorded on documents – most commonly created under a legally supported and regulated process such as cadastral survey or land registration. The types of information recorded in documents include:

survey measurements including measurements to boundary marks, offsets to fences & natural features, reference marks etc.

Calculated boundary dimensions, offsets between boundary marks or boundary positions such as road widths, etc.

Plans and diagrams showing the relationships between boundaries, marks and other physical features.

References to other relevant legal documents such as titles, survey plans, field notes, statutes, approvals of interested parties, etc.

#### 4.2.1. Arrows pointing to documentary boundary

The arrows pointing to Documentary Boundary represents the recording and potentially authorisation of documentation of boundaries - for example, survey field notes, calculation sheets, reports, and survey plans derived from survey observations of marks or other physical features. In some cases, cadastral boundary documents can be generated and authorised that were derived, fully or in part, from the digital spatial cadastre - for example, a plan of amalgamation of parcels or a license which has been generated without an actual field survey.

### 4.3. Digital spatial boundary

A Digital Spatial Boundary is the representation of a boundary recorded within a digital spatial database. There is a potential for these to also serve as evidence of boundary location. The most common way of representing data in this database is in the form of a digital map view. (Historical paper-based cadastral index maps of boundaries are classified here as documentary boundaries rather than Digital Spatial Boundaries.)

The points, lines and polygons (potentially surfaces and polyhedrons also in a 3D digital spatial cadastre) are defined as spatial objects which have coordinates in terms of an official coordinate reference frame as well as the topology defining the connectedness of the spatial objects.

The spatial database incorporating digital spatial boundary information will often have a great deal of other attribute data as well as other spatial datasets (e.g. geo-referenced imagery). However, the focus of this paper is the spatial representation of boundaries.

#### 4.3.1. Arrows pointing to digital spatial boundary

The arrows pointing to Digital Spatial Boundary represents the use of documented boundary information (survey plans, etc) or information on physical boundary feature locations (coordinates) to:

- maintain the spatial objects in the digital spatial cadastral database by adding new boundaries following subdivision, etc, or
- use improved measurement of physical boundaries or connections to geodetic control to update and align the digital spatial boundaries with their correct positions.

### 4.4. Legal boundary

The Legal Boundary represents the position where the boundary is located in accordance with correct application of the law. This is an idealised construct – an accepted convention which provides a framework for the application of the law relating to the extents of rights, restrictions and responsibilities in land.

The Legal Boundary itself does not exist in the physical world. It is an imaginary line having no thickness (for example HM Land Registry, 2019). However, in order to have any practical effect, the legal boundary must be "realised" – it must be given expression in the world where rights are exercised. This occurs by the cadastral surveyor applying their judgement to all of the evidence available to make a determination of the location of the Legal Boundary.

Cadastral surveyors weigh up this evidence in accordance with correct legal principles. In cases of conflict or ambiguity, the definitive decisions on the application of the law could be made in a court of law and then implemented by a surveyor in accordance with those decisions.

The Legal Boundary is conceptual. It is realised, documented, and/or evidenced in the form of the Physical Boundary, Documentary Boundary and the Digital Spatial Boundary.

#### 4.4.1. Arrows pointing to legal boundary

The three arrows pointing inwards from Physical Boundary, Documentary Boundary and Digital Spatial Boundary to Legal Boundary represent the evidential role of either physical, documentary or digital spatial information to define the correct legal determination of a boundary position.

The fact that there are multiple forms of information and representation of the same thing – a legal boundary – is one of the central responsibilities and difficulties facing cadastral surveyors.

## 5. Applications of the CTM to analysis of cadastral systems and boundary information

This model can be used to gather information on the complex interrelationships of boundary information in the cadastral system and how these interact with the legal aspects of boundary definition. This information may be drawn from a wide range of cadastral decision-makers, stakeholders and users – each with their own expectations and ways of describing those parts of the overall system that are most important to them.

The language that is used by these different agents in the cadastral system can often vary – especially between jurisdictions but even within jurisdictions. Cadastral surveyors, land agency officials, geospatial data users, lawyers, Council planning officers, utility managers, landowners, etc – these groups all depend on the system but bring their own perspectives and sometimes language to their descriptions of it.

Allowing land professionals in the cadastral domain to communicate with a shared ontology was outlined as a goal for the Core Cadastral Domain Model (CCDM) (van Oosterom et al., 2006) which subsequently evolved into the Land Administration Domain Model (LADM) (Lemmen et al., 2015). The CTM can be considered as a further tool to assist with this goal.

For the research project within which the model was developed (Grant et al., 2018), it was found that these different groups of stakeholders and decision-makers were able to recognise and understand the model as presented and therefore able to make consistent contributions of their needs and expectations.

Given the importance of land use, land management and land ownership to the economy and environment in any jurisdiction, a critical aspect of the cadastral system is the mechanisms for identifying and resolving conflicts in boundary determination. The CTM assists with identifying these.

The closed external loop of the triangle should ideally ensure that all representations of a boundary are consistent with each other – at least within the accuracy limits of the applicable regulations for cadastral survey. In practice, differences exist for many reasons ranging from human error, poor historical practices (by modern standards), through to changes in the physical environment (including earth deformation) and legacy databases that were created for one purpose but subsequently used for other purposes.

The three inward pointing arrows will often result in different solutions for the location of the legal boundary. The rules and conventions in the hierarchy of evidence provide mechanisms for resolving these differences. Information management systems represented by the three external double-headed arrows around the triangle describe systems for data maintenance, transformation and resolving conflicts where they are identified.

The CTM provides a mechanism for consistently describing and evaluating these potential conflicts and the mechanisms for resolving them.

Referring back now to Fig. 1 above from Enemark (2004) and Williamson et al. (2010), we can also see the Cadastral Triangular Model as a framework for assessing the boundary information aspects of the central triangle (Cadastral System) of that diagram as it supports the land administration functions of land tenure, land value, land use, and land development.

### 5.1. Applications to digital spatial cadastre

Grant et al. (2018) used an initial form of this model to assist with the analysis of the optimal positional uncertainty of the digital spatial boundaries across Australian jurisdictions and New Zealand, including the role that the digital spatial boundaries do, or should, play in boundary determinations. This research resulted from initiatives to improve the coordinate accuracy of digital spatial boundaries in these jurisdictions.

Following the philosophy of "Fit for Purpose Land Administration" (Enemark et al., 2016) – albeit in advanced rather than developing cadastral systems – the optimal (or fit-for-purpose) positional uncertainty for boundaries should be dependent on the purposes served by the boundary information.

To collect the data & information flows within each of the cadastral systems, interviews were held with all land administration agencies across Australia and New Zealand (i.e. Offices of the Surveyors General) and key users of the digital spatial representations of boundaries. The CTM assisted by providing a framework for common understanding of the data flows, dependencies and purposes served.

### 5.2. Potential future applications of CTM

There are other challenges facing cadastral systems and authorities, including a trend towards developing 3D cadastres. Increased prevalence of elevated and tunnelled roadways etc, add to existing interest in the representation of 3D land tenure and property rights for traditional high-rise units and office buildings. The CTM could be used as an analysis framework in this area by helping to clarify the extent to which cadastral systems are already managed as 3D boundaries as well as the data & information exchanges required with 3D digital spatial boundaries that must remain consistent with other forms of boundary information.

Other potential applications may include development of fit-for-purpose cadastral systems in developing countries (Enemark et al., 2016), i.e. identifying how low cost aerial images or GPS mapping can be applicable in determination of boundaries that are consistent with physical features and long-standing community agreements. Furthermore, the question of how these initial lower cost solutions can lead to upgrade pathways for continuous improvement of cadastres, can be addressed by applying the CTM. This also relates to modern approaches to the application of geospatial and survey data to land administration (Lemmen et al., 2020) where the CTM may be useful as an analytical framework.

## 6. Conclusion

Cadastres, other land administration agencies and practitioners are faced with ongoing challenges. Many of these challenges emanate from technological advances in recent years, public access to information and corresponding changes in public expectations. For land administration agencies and researchers to respond to these issues a conceptual model was developed – the Cadastral Triangular Model (CTM).

The CTM is a graphical model which can be used as a framework for collecting and analysing different forms of evidence for boundary determination and the interrelationship between physical, documentary and digital spatial boundary representations. The CTM is a communication tool which can assist analysis of specific flows of data & information between different aspects of the complex cadastral system. The CTM was specifically designed for research into the optimal positional uncertainty of the digital spatial cadastres across Australian and New Zealand jurisdictions. However, the CTM also has potential to assist analysing other issues facing land administration agencies. e.g. 3D cadastres, the role of coordinates in boundary definition, or implementation options for fit-for-purpose cadastres in developing countries.

## Author statement

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## Declaration of competing interest

None.

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## Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.104758.

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