Exploring research, development and innovation in the parcel fabric: An LADM-conformant data model for representing, storing and adjusting land boundaries

Keywords: Parcel Fabric; LADM; Innovation; Cadastre; Land Administration;

Abstract

The cadastral market is a highly specialized, diverse, and slower-moving market compared to other IT sectors. While potential shareholders and investors might not be inclined to invest in cadastral markets due to these factors, Esri, a privately held and debt-free company can invest up to 30% of its annual revenue into the research and development of such markets. Esri is the global market leader in geographic information system (GIS) software.

With their research and development efforts, Esri has released its 4th generation parcel fabric solution for the cadastral industry. This solution is designed to meet the business requirements for cadastral markets for the next 15-20 years.

Development of a parcel fabric that caters to a diverse array of cadastral markets requires a group of experienced subject matter experts working together with highly skilled programmers. This paper explores the development of innovative solutions to meet modern business requirements and expectations. These expectations include:

- Accessibility of cadastral data from any client (desktop, web, mobile) as well as editing online and offline
- An LADM (Land Administration Domain Model)-conformant data model
- Multi-user, concurrent editing supported by versioning
- Support for editing and display in 3D and 4D (time)
- Easy migration of data from multiple different sources and in different states
- Easy adoption by inexperienced users
- Localization of the system
- Management of data quality (the system administrator should be able to configure quality checks and apply fix methods)
- Support for parcel lineage display
- Support for cloud deployment and SaaS
- A robust, scalable, and sustainable system
- A system that increases productivity and enhances data quality

This paper will examine the requirements above and introduce new research and development efforts in machine learning, web application, automated interpretation of legal documents and more.

Esri's 4th generation cadastral solution

Esri is the global market leader in Geographic Information System (GIS) software, location intelligence, and mapping. Esri is a privately held and debt-free company and can invest up to 30% of its annual revenue into the research and development of such markets.

With their research and development efforts, Esri has released its 4th generation parcel fabric solution for the cadastral industry. The first generation used ArcInfo workstations and the COGO Coverage model. It was replaced by ArcMap, which supported COGO editing and used geodatabase topology to validate the edits. The third generation used the ArcMap Parcel Fabric, which added additional capabilities but was limited to the desktop.

Each generation of cadastral solution has been built on top of the previous generation, preserving required capabilities and addressing new business requirements and technological advancements. For example, the first 2 generations were designed before the internet age, at a time where GNSS surveying was in its infancy.

In 2019, Esri released the ArcGIS Parcel Fabric©. The new parcel fabric is designed to work across all client types (desktop, web, mobile), on premise or on the cloud. It has been designed to meet the business requirements for cadastral markets for the next 15-20 years.

Figure 1. Esri's evolution of cadastral solutions

Challenges and modern expectations

Cadastral agencies face many challenges. The list below describes some of the common ones:

- Older technology or heavily customized systems. Heavily customized systems are hard to upgrade, expensive to maintain and can be open to cyber security risks.
- Open file formats. Open is not always FAIR. Many agencies have defined their own "open" file formats expecting software vendors to support and maintain them. While these formats are open, they fail to be FAIR (Findability, Accessibility, Interoperability, and Reusability). The industry has moved from using files to web services, three-dimensional data and modern encodings. Open file formats are often two-dimensional, large and slow-to-process XML files.
- Cumbersome processes. While the process of converting manual map drawings to a computer environment can be considered 'digitalization', many agencies have acknowledged that their processes are inefficient and cumbersome. Cumbersome processes make it difficult to consume and perform quality assurance on digital data. Data flow from stakeholders and field surveys is often inefficient and important metadata is lost in the process.
- Resources and staff. Aging workforces, high staff turnover and long learning curves make it difficult for cadastral agencies to meet their goals. Many organizations rely heavily on subcontractors and struggle to grow champions within the organization. Low throughput can have a negative impact on the economy.
- Data. Data is the most important asset of any agency. Data that is not FAIR and does not follow IT best practices (backups, security, etc) is of concern.
- Data quality is unknown. This can pertain to attributes, spatial accuracy, and topological integrity. Stakeholders and the public lose their trust in an organization when data is not current, and quality is unreliable.
- Older integration patterns. Cadastral systems are usually comprised of multiple IT systems integrated with each other. Older integration patterns might use nightly exports of files or direct access to other DBMS systems. This creates dependencies between systems and makes it harder to upgrade one without making changes to the other.
- Security and IT practices (SOA). Often, older cadastral systems are not secure and allow bad actors to take advantage of vulnerabilities. Edits in the system are not tracked for accountability, there is no playback option to view historical data, and 'super-users' can easily modify the records without leaving a trace.
- Meeting modern expectations. Older cadastral systems struggle to meet the following modern expectations:
    - Field workflows –the ability to view and collect field data
    - Web editing – the ability to view and edit data in the web browser
    - Stakeholders and information – the ability to provide stakeholders with capabilities and information products they need.

Some cadastral agencies interpret ‘digitalization’ as switching from drafting on paper to drafting on screen to produce traditional map sheets. Some agencies continue to print and sign PDF documents using scales that are dictated by legacy cabinet drawer sizes. Such an approach is inefficient, introduces data integrity issues and prevents stakeholders from performing analysis.

Technology has transformed modern expectations. Modern expectations include:

- The internet. Use of a web browser on any device to view the status of the cadastral data.
- User friendliness. Maps should be intuitive to the target audience. Black and white cadastral maps that use ‘expert’ symbology can be made accessible by using color, for example.
- Smartphones. Web services allow access to email, bank accounts and map navigation seamlessly on devices such as smartphones. Stakeholders expect to be able to access and edit their data from any device.
- Trustworthiness. Data should be current and accurate for it to be trusted with decision-making processes.
- Security. While data should be viewable by the public, only a subset of named users should be able to modify it. Named users should have to authenticate themselves using the latest authentication technology and their edits should be monitored for accountability.
- Performance and efficiency. Some transactions, like merging parcels, can take a few seconds to perform. Other transactions that require field surveys might take longer. However, once field surveys have been completed, automated quality assurance and efficient data ingestion can reduce processing time from years and months to days and hours.

An LADM Implementation

The Land Administration Domain Model (LADM, ISO 19152) released in 2012 has been used to design and implement parcel fabric. The parcel fabric is an LADM-conformant data model.

There are some differences between the parcel fabric and the LADM worth highlighting:

- LADM is conceptual while the parcel fabric is a physical information model.
- Some LADM terminology is different but can be easily mapped to parcel fabric entities.
- The parcel fabric does not implement the parties package and the 3’R’s (Rights, Restrictions and Responsibilities) as those are usually managed in the land registration and/or CAMA system. However, if desired, these tables and relationships can be implemented as part of the geodatabase model.
- The parcel fabric has many additional capabilities:
    - Explicit parcel lineage and historic parcels.

- Use of the temporal Branch Versioning, which allows one to view data as it was in any historic moment in time.
- Data quality management in the form of quality-based rules. Topology and attribute rules are modeled as part of the information model.
- Use of UUIDs (Global IDs) that guarantee uniqueness across databases and allows one to take the data offline and sync changes.
- All parcel features are tied to their 'source' in the records feature class. The record feature class represents the document that created the parcel features.

Innovation

Innovation requires connections to real world challenges, highly skilled workforces, and supportive cultures and methodologies.

"Necessity is the mother of invention". The parcel fabric team at Esri maintains close connections with customers, aiming to ensure their success with their implementations. As technology and business requirements evolve, connecting with customers introduces new challenges and problems to solve.

The team monitors a parcel fabric ideas board where a community of professionals contribute their ideas and requirements (https://community.esri.com/t5/arcgis-parcel-fabric/ct-p/arcgis-parcel-fabric) where each idea can be voted and promoted.

Esri hires and attracts specialists from around the globe, resulting in software designed by a team of surveyors and cadastral experts. Team members not only bring global experience, but some also have decades of experience working on cadastral software within Esri.

Esri work-culture promotes innovation and collaboration. Each team can work on their own R&D (Research and development) projects, and it is common to see cross-team collaboration between teams. Innovation and breakthroughs can happen when subject matter experts work with new capabilities like machine learning. Agile methodology accelerates development cycles and is focused on delivery of valuable capabilities.

Fit For All

Cadastral organizations, both formal and informal, have a diverse set of business requirements. Using a solution built for formal cadasters on countries with informal cadasters is likely to fail. Furthermore, a solution built for one country might not solve the needs of another country.

The key to developing a single solution that can meet the needs of different organizations are the following:

- **Configurability**: The solution should be easily configured using out-of-the-box software by subject matter experts without the need for developers. Configurations should persist between software releases and should allow organizations to easily

remain on the most current release of the solution. The configuration should dictate behavior, workflows, cartography, quality assurance, security and more.

- **Extendibility**: The information model should support the addition of relevant parcel types, attributes, domains (code lists), and data quality rules.
- **Scalability:** The solution should be able to scale from a few hundred parcels to millions of parcels, from a single editor to thousands of editors.
- **Security**: The solution should manage privileges and access using groups and roles. Users that can modify the data should have named identities and edits should be tracked. Named users must authenticate and login to the system. The solution should be secured and tested to prevent malicious attacks from 'bad actors'.
- **Flexible Deployment patterns**: It should be possible to deploy cadastral solutions in different architectures, for example, centralized deployments or distributed deployments. Some organizations are moving their IT infrastructure from 'on premise' to commercial or government clouds. Parcel fabrics support both on premise and cloud deployments and soon will support a deployment as Saas on ArcGIS Online.
- **Offline editing**: Organizations with intermittent internet connections should be able to take a portion of the parcel fabric offline and sync their edits when network connectivity is restored. Another trend is to use the web browser for simple and streamlined editing workflows.
- **Adoptability**: Technology should be intuitive, have sufficient documentation and be easy to learn. Esri focuses part of their development efforts on User Experience (UX) and User Interface (UI). ArcGIS Pro has implemented Tasks, which is a configurable framework for designing repeatable workflows. Tasks can be used to reduce the learning curve and make editors more efficient. The parcel fabric also includes extensive documentation that walks administrators and parcel editors through

common workflows.

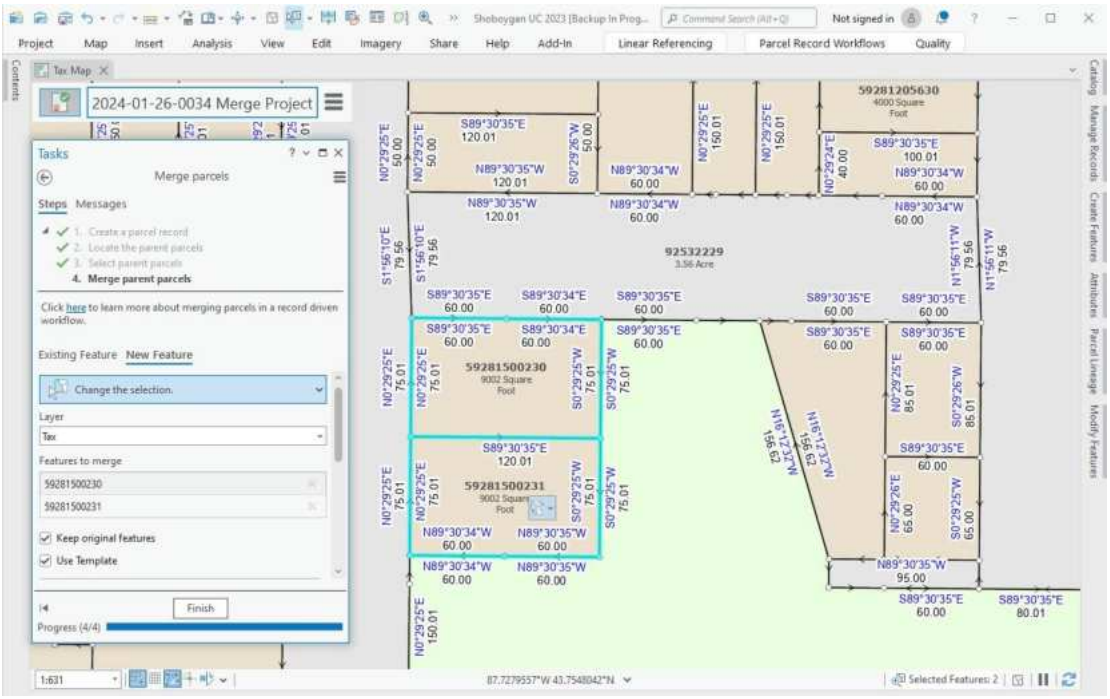

Figure 2. Tasks are used for repeatable workflows

- **Adaptability**: Like LADM, the parcel fabric is designed to work with any type of cadastral system, both formal and informal. It supports the data entry and maintenance of a wide variety of legal descriptions: metes-and-bounds, coordinate based cadastres, area descriptions, boundary resurveys, and more.
- **Support**: The parcel fabric is part of the core ArcGIS Pro software and is fully supported. Customers can contact technical support with "how to..?" questions or report any unexpected software behavior. Many customers also participate in the parcel fabric community https://community.esri.com/t5/arcgis-parcel-fabric/ct-p/arcgis-parcel-fabric where they ask questions, assist each other or inquire how other organizations maintain their workflows.
- **Localization**: Software should be able to be localized to countries of different languages and cultures. This includes translated user interfaces, translated documentation, customized features and appropriate character sets. (source: https://support.esri.com/en-us/gis-dictionary/localization). Using the software in RTL (Right To Left) mode is also supported.

Quality

Data quality is important in any system of record. Cadastral data is used as a foundation layer for many other datasets and processes. For cadastral data to be trusted as a source, it must be of high quality and communicate where data issues might exist.

The ArcGIS Parcel Fabric uses the following configurable frameworks and capabilities to detect and evaluate data quality issues:

1. **Geodatabase Topology**: Use topology rules to define the allowed topological relationships between feature classes. These rules can be validated at any time and checked for any error features. Topology validation can be performed using web services from any client.
2. **Attribute Rules**: Use rules to populate attributes, restrict invalid edits and perform quality assurance checks. Attribute rules enhance the editing experience and improve data integrity. The parcel fabric ships with commonly used attribute rules that can be enabled, configured and validated.
3. **Least Squares Adjustment** (LSA): Use free network and constrained network least-squares adjustments on cadastral data. Free network adjustments check measurement consistency and identify outliers. Constrained, weighted adjustments evaluate and improve the spatial accuracy of parcel corners. The parcel fabric uses the robust DynAdjust least-squares adjustment engine and uses GIS layers for analyzing and displaying adjustment results.

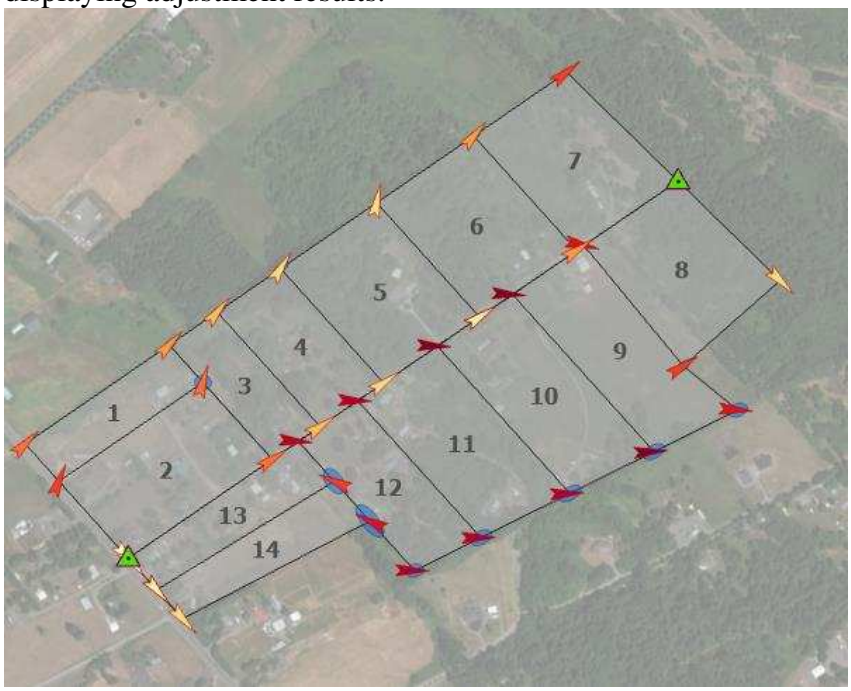

Figure 3. Least-squares adjustment vectors

4. **Quality Layers:** Uses layers to visually review common parcel issues such as boundary lines that are too short, segmented curves (curves that are not true curves) and measurements that do not match the feature geometry.
5. **Dedicated tools:** The parcel fabric includes dedicated tools to detect common issues. One example of such a tool is the Highlight Gaps and Overlaps tool, which allows users to find gaps and overlaps that fall within a specified tolerance.

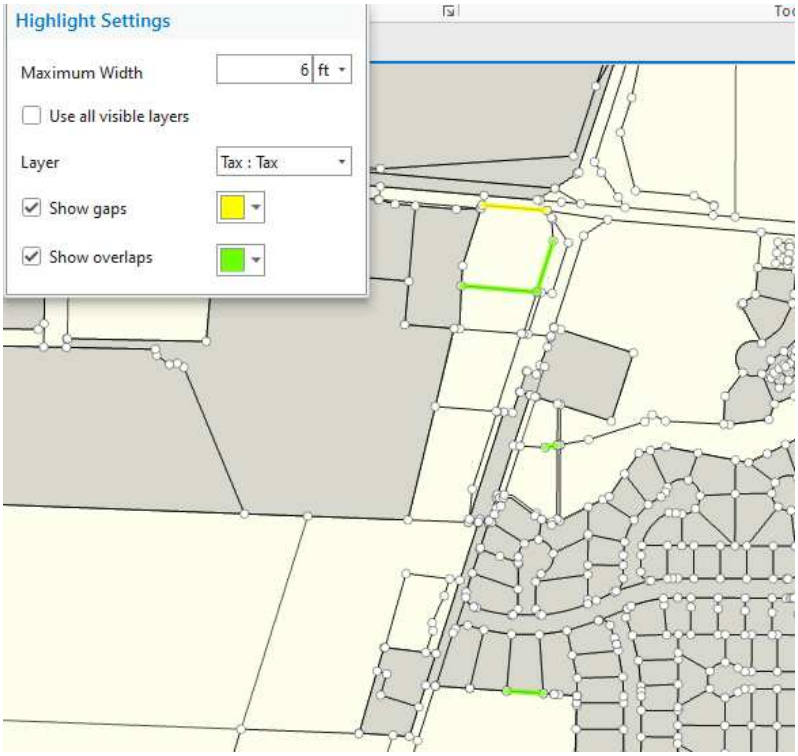

Figure 4. Highlight gaps and overlaps in the map extent

Innovative concepts and capabilities

The parcel fabric introduces innovative concepts and capabilities. Here are some of the highlights:

- **Record-Driven workflows and Quality-Driven workflows:**
  Parcel creation and maintenance workflows can be divided into 2 types of workflows: 'Record-Driven workflows' and 'Quality-Driven workflows'. Record-driven workflows usually involve parcel creation in response to a legal source. Operations such as merging or splitting parcels retire original, parent parcels to create child parcels. Record-driven workflows are limited in their spatial extent and establish parcel lineage. Quality-Driven workflows on the other hand, can be performed at any time and in any spatial extent of the data. Their purpose is to evaluate data quality and improve it. A constrained, weighted least-squares adjustment (LSA) is an example of a quality-driven workflow in which the spatial accuracy is evaluated and improved.

- **Parcel lineage**
  Parcel lineage is established when parcels are retired (parent parcels) to create new, child parcels. These relationships can be visualized using link charts in ArcGIS Pro and explored as part of chain-of-title research in the parcel fabric.

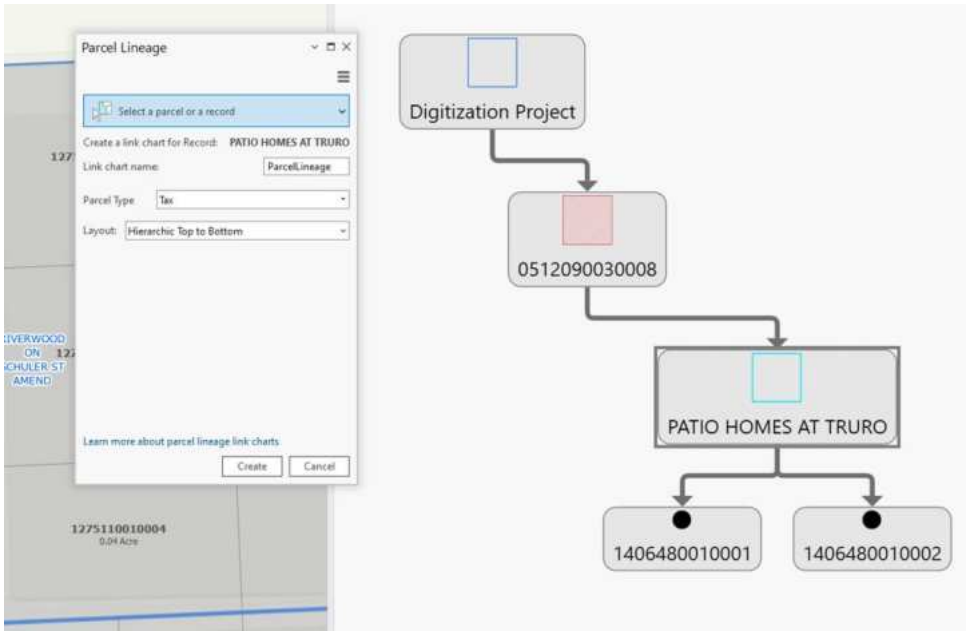

Figure 5. Parcel lineage in the parcel fabric

- **Four dimensions (4D):**
  Parcel fabric features are Z-enabled (x, y, z coordinates) and time-aware. By leveraging the geodatabase and using branch versioning, users can get historic views of the data at any moment in time.

- **Offline editing:**
  The parcel fabric supports offline editing. Users can zoom to a desired map extent and extract all the parcels in that extent while maintaining their topological integrity. The extracted data is stored locally in a mobile geodatabase (SQLite) and a version is created for the offline replica. Offline data is useful when the internet connection is not reliable, or work needs to be performed in the field. In this scenario, users can sync their edits at any time to their editing version, which will pull and push any deltas to their offline replica.

- **Web Services and Service Oriented Architecture (SOA):**
  The parcel fabric enterprise deployment uses web services and capabilities that are exposed though REST API (JSON). SOA reduces ETL (Extract, Transfer, Load) – instead of copying the data for different stakeholders and purposes, the administrator can decide what to publish and which privileges to assign. For example, the 'public' user only has the privileges to view the data (read-only). Other SOA advantages include viewing data in real-time on web browsers, leveraging server resources and the use of "thin clients" (reduces the chattiness" between the client and the server.

- **Versioning:**

In an enterprise deployment, the parcel fabric uses multi-user branch versioning. Multi-user editing occurs on versions, which are reconciled with the default version after editing is complete. Branch versioning has enhanced editor tracking where every edit is tracked by date and time. Users can view historical states of the data at any moment in time.

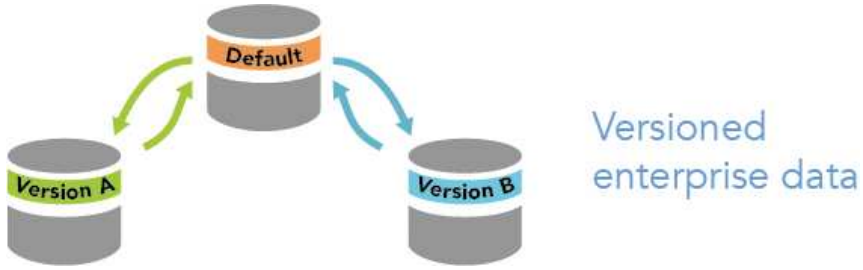

Figure 6. Multi-user editing is supported by versioning

- **Duality between the legal world and the physical world:**
  The parcel fabric can store both the legal representation (COGO measurements, legal dates, legal areas) and the physical representation (shape geometry) of parcels. The physical representation of the parcel geometry can be improved over time, for example, using least-squares adjustments to improve spatial accuracy. Storing both the physical and legal representation helps improve data quality. For example, comparing the legal areas of parcels to their shape area geometries can identify mismatches and possible data quality issues.

- **Strata parcels:**
  The parcel fabric supports the storage and display of strata parcels above and below the ground. For example, strata parcels can be used to model condominiums, flats or apartment units. Tools are available for improved data entry of floor plans and users can use map exploration tools to display floors in three dimensions (3D). The parcel fabric uses an attribute-driven approach (AKA 2.5D), which is efficient and has the advantage of always displaying data relative to the most recent elevation surface model.

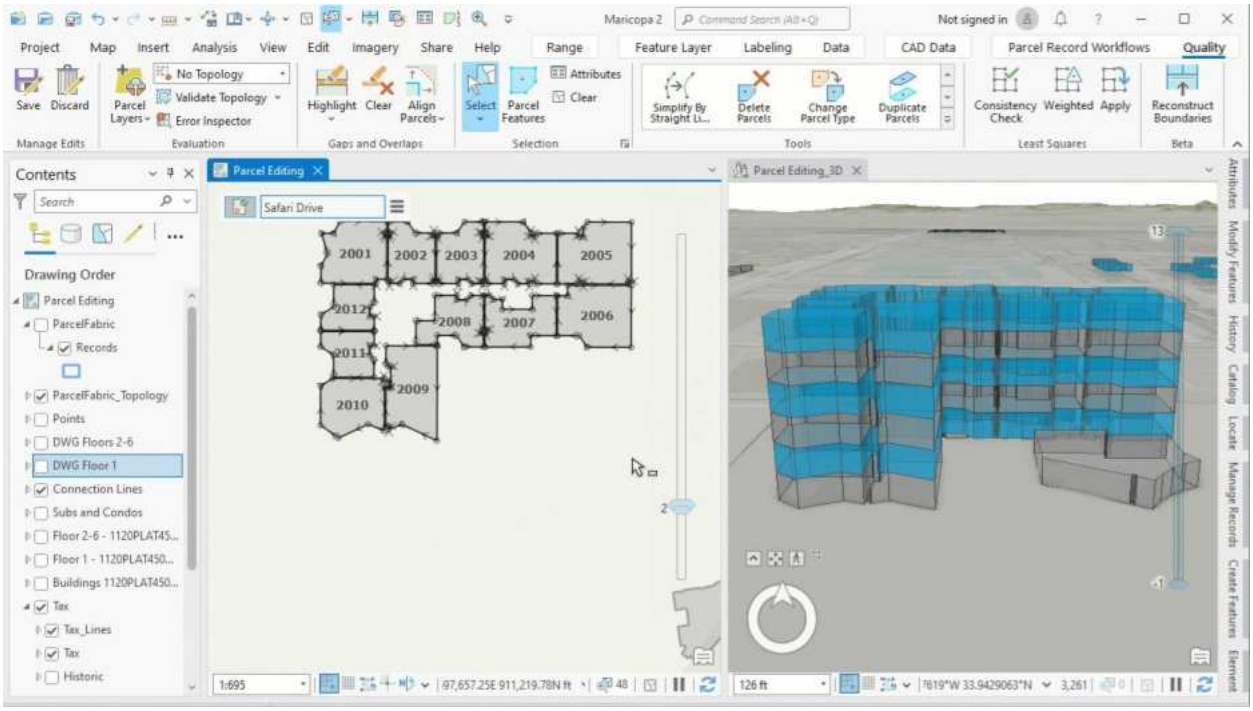

Figure 7. 2D and 3D map showing strata parcels imported from CAD files

- **Title map creation:**
  Many countries include a parcel map as part of their legal registration documents. The parcel map depicts a single parcel with a listed sequence of points and/or lines. A title map can be easily created using a geoprocessing tool called Export Sequenced Parcel Features. The dynamic elements in the map layout refresh to represent each exported

parcel and can be saved out to a PDF file.

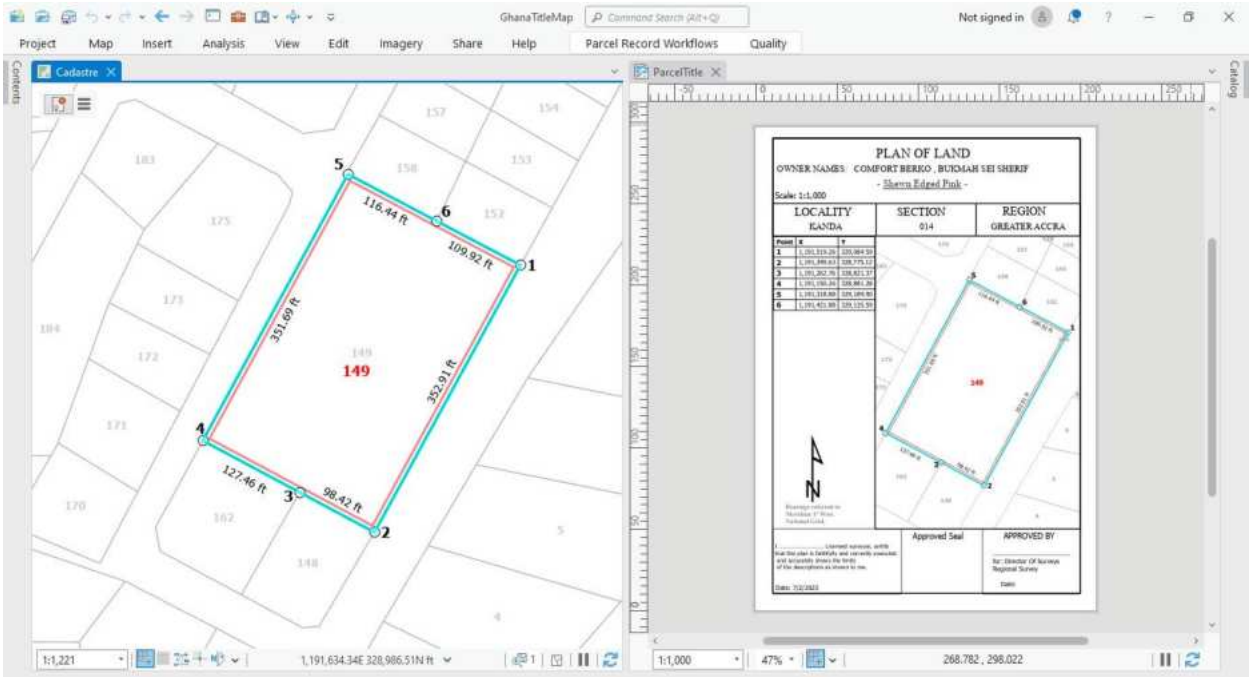

Figure 8. An example of a title map that can be automated and exported to a PDF file

Current R&D projects

- **SaaS – Parcel Fabric on ArcGIS Online**
  ArcGIS Online is a complete mapping and analysis solution offered as SaaS (Software as a Service). ArcGIS Online runs on esri-administered infrastructure and allows organizations to create their own self-administered portals. Publishing a parcel fabric to ArcGIS Online is as easy as uploading it as a file geodatabase item. This new type of deployment, scheduled for a 2024 release, will make it easier for NGOs and under-resourced organizations to deploy an LADM conformant parcel fabric.

- **Mobile workflows**
  Organizations such as the Dutch Kadaster International and Cadasta have proven that ArcGIS Field Maps (formally known as ArcGIS Collector) can be used to collect parcel data using a Fit-For-Purpose methodology. ArcGIS Field Maps offers new field collection capabilities for parcel fabric. The collected data will not go stale and once collected it can be properly maintained to support common transactions.

- **OCR Deeds into the traverse tool**
  Typically, parcel editors enter parcels from deeds that start at a commencement point,

go to a ‘point-of-beginning’ (POB) and then form a closed loop. With OCR (Optical Character Recognition) technology, scanned documents can be automatically processed in the parcel fabric. In this scenario, a parcel traverse can be automatically created from a scanned deed instead of the manual data entry of dimensions. This will greatly improve the rate at which new parcel data can be added to the parcel fabric.

Conclusions

Esri invests up to 30% of its annual revenue into research and development. The latest parcel fabric represents the 4th generation cadastral solution and has been designed for the next 15-20 years.

The parcel fabric is developed by a group of experienced professional surveyors and subject matter experts.

The parcel fabric provides a comprehensive framework for managing, editing, and sharing parcel data. Using web services, the data can be accessed in real time from any type of client: desktop, web and mobile.

The parcel fabric is a physical implementation of LADM. It can be extended and configured to meet specific country profiles as needed. It is robust and can support millions of parcels with hundreds of concurrent editors.

The parcel fabric supports all types of legal descriptions and can be deployed in any country. It supports boundary-based descriptions (metes-and-bounds) as well as coordinate-based cadastres. It supports 2D, 3D and even 4D (time).

As technology and business requirements continue to evolve, esri continues to work closely with experts and customers to develop new and innovative capabilities that improve efficiency and quality of cadastral records.