3D CADASTRAL SURVEY DATA MODEL AND EXCHANGE

FINAL REPORT

Presented by:
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1 Executive Summary

The Cadastre 2034 Strategy of Australia and New Zealand provided a vision of "a cadastral system that enables people to readily and confidently identify the location and extent of all rights, restrictions and responsibilities related to land and real property". The vision noted that, in order to achieve this outcome, property and other interests on land needed to be managed in a federated, integrated, manner based on common standards and enduring principles to preserve the components of the cadastre.

Current cadastral systems are accurate, assured, and authoritative to the extent that they generally support the role of cadastral surveyors to reliably define boundaries. However, as outlined in the Strategy 2034, there are inherent difficulties in consistent technical interpretation of those spatial boundaries. Also, there are rights, restrictions and responsibilities that are not spatially depicted and/or cannot be accessed easily; this is particularly relevant when national reforms are introduced (e.g. Water Act 2007[1] and subsequent amendments).

The 3D Cadastral Survey Data Model and Exchange (3D CSDM) programme of work was established by the Intergovernmental Committee for Survey and Mapping (ICSM) with support from the Spatial Information Council (ANZLIC).

Land Information New Zealand (LINZ) led this programme in partnership with the Department of Environment, Land, Water and Planning (Victoria), the Department of Customer Service (New South Wales), Western Australian Land Information Authority (Landgate), and the Department of Resources (Queensland).

SURROUND New Zealand with McKenzie & Co, OpenWork, Pangaea Innovations and Evolve & Amplify (the Consortium) undertook and developed "a harmonised, open, 3D cadastral survey data model that will enable the transfer of cadastral survey data in all jurisdictions of Australia and New Zealand, and an options analysis of internationally recognised, or widely adopted, transfer formats that could be implemented by major surveying software vendors for encoding/exchanging the cadastral survey data identified in the model."

There were six services prescribed in the proposal and delivered by the Consortium using an incremental AGILE methodology. This method meant that the regular engagement with ICSM product owners determined the agreed scope of the deliverables and any changes that were required could be actioned quickly as blockers arose.

[1] Bureau of Meteorology (2007), *Water Act 2007*, Australian Government, available at http://www.comlaw.gov.au/Series/C2007A00137, last accessed February 2022

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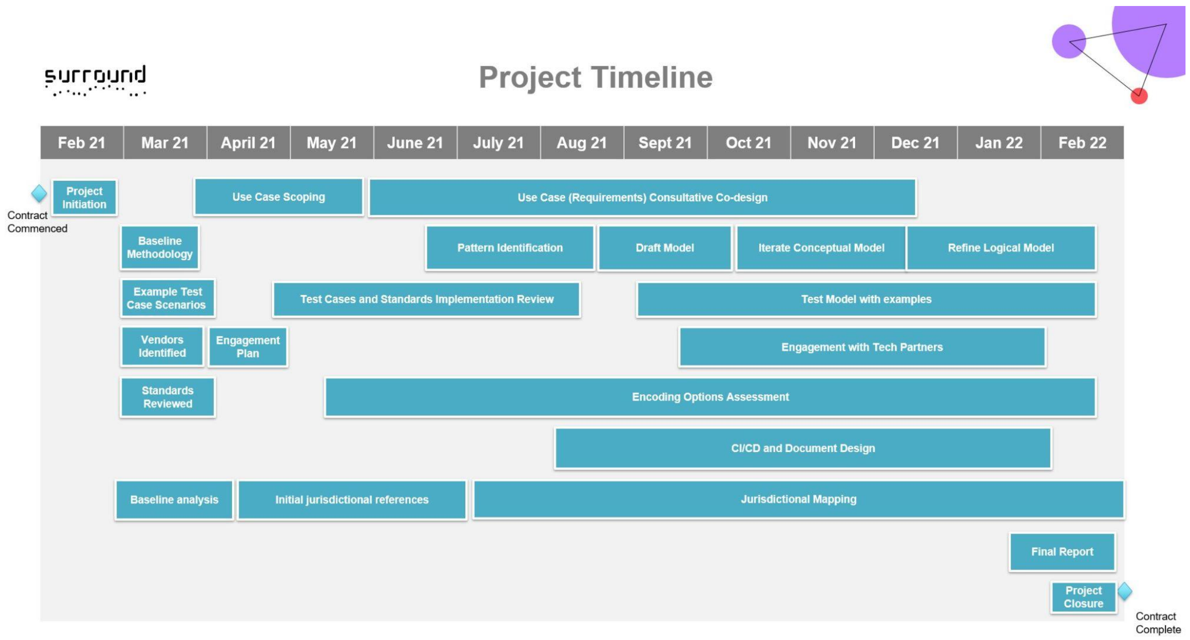

Figure 1: timeline of project activities as undertaken

The services below are fully articulated in the final program report that follows this Executive Summary.

- Project governance and risk management, and stakeholder engagement plan
- Conceptual and Logical data model
- Jurisdictional mappings of data elements to the model
- Data exchange options analysis
- Encoding recommendations
- Final report

In undertaking the work, there were conclusions reached and recommendations have been made that will allow ICSM to use the work of this project to meet the future 3D cadastral needs of Australia and New Zealand. These recommendations also address a range of methodological issues around modelling approaches, management and implementation support that apply generally to the standardisation of similar domain data models. The following section highlights those conclusions and recommendations whilst the supporting technical detail is outlined in the following report.

1.1 Key Conclusions and Recommendations

In undertaking this project a series of key conclusions were reached and recommendations have been made, by the Consortium, which will enable the successful future development of 3D

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Cadastral Survey Data Model and Exchange (3D CSDM) work in Australia and New Zealand. The conclusions are:

- There is a key gap in the standards landscape around common approaches for 3D Feature and Geometry, particularly with respect to basic topology support required. The project establishes a conceptual model for 3D Cadastral Survey Data Modelling which represents a significant improvement on many current practices and reflects emerging good practice internationally.
- The use of UML modelling for 2D (via GML patterns for Simple Features geometry implementations) is not available for effective and concise representations of 3D geometry and topology. Inconsistencies in style and disconnection between Conceptual, Logical, Requirements and other types of model raises overheads and challenges in the use of UML. The collaborative decision to model within a knowledge graph using semantic models, a trend emerging in many large application domains such as the European "Data Spaces" initiatives, has resulted in successful project outcomes.
- Jurisdictional mappings have indicated a gap in the language and regulations used across the ICSM community. Work to standardise and map these data elements within each jurisdiction will be needed to enable programmatic implementation under a common model framework. The "Jurisdictional Mapping" approach pioneered will support mapping *across* jurisdictional and technology usages.
- A governance framework will need to be developed and implemented to support the people, tools and the technology required to support 3D Cadastral Survey Data Modelling. This governance would:
    - ensure that future profile development and implementation of the 3D CSDM across the jurisdictions is managed, maintained and accessible in a sustainable and standardised manner.
    - support changes to jurisdictional regulations to include 3D CSDM requirements. This in turn will drive the requirements to be met by the software vendors and providers of cadastral information. 'Build it and they will come' is not a sufficient driver for change in this community as articulated during the engagement with the software vendors in the course of this project.

1.2 Summary of Recommendations

The following recommendations are made to enable a move from a 2D to a 3D Cadastral Survey Data Model, and to meet outcomes described in Cadastre 2034 Strategy. The justification for these recommendations is explained in the Final Report.

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Methodology

Recommendation Summary:

Recommendation 1: Future work should use an updated methodology that reflects the experiences and lessons learned during the 3D CSDM project.

Recommendation 2: Continued development documenting authoritative jurisdictional cadastral language, and making it available programmatically, will support future model development.

Recommendation 13: Future work on this project should adopt the same 'Co-Design' approach with subject matter experts and business owners to support full engagement for the outcomes required.

Model Management

Recommendation Summary: Treat all aspects of the model as a live knowledge base that is utilised in design and run-time (for at least validation and testing), and can be extended and refined during implementation phases.

Recommendation 4: Consideration be given to establishing and maintaining both design-time validation and on-going automated testing in the model development process.

Recommendation 3: Provision be made to support automation of model-generated documentation past the end of the project.

Recommendation 17: The model and its supporting material continues to be delivered as a coherent, interconnected knowledge base.

Recommendation 18: Centralised governance and maintenance processes established to sustain the model.

3D Geometry Support

Recommendation Summary: Given no "off-the-shelf" option is ready for 3D geometry, and multiple options are emerging around next generation 2D options, develop an interim 2D encoding based on one or more existing options and future proof by starting work immediately on 3D foundational capabilities (spec and reference implementations) to provide feedback ASAP into encoding options to support transition from 2D to 3D.

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Recommendation 7: A functional profile be defined for basic 3D geometry and topology representations as exists for planar (Simple Features) geometry.

Recommendation 8: Encoding patterns for a 3D geometry profile be defined for multiple candidate encoding options such as GML, JSON, OWL, SQLite (Geopackage) and IFC.

Recommendation 9: Reference implementations for test data and software libraries be commissioned to support 3D geometry to support technology capacity "uplift".

Model Encoding Options

Recommendation Summary: Assume encoding using JSON will be the future optimum but unstable in the short term, so start pilots immediately to test options and provide timely feedback to standardisation activities. Note that experience and capabilities to support JSON schema transforms can be leveraged in future integration exercises.

Recommendation 10: Implement a pilot serving existing 2D cadastral data using OGC API and JSON/GeoJSON encoding and using JSON-LD extensions to link data to the machine readable model and validation capabilities.

Recommendation 11: Implement a pilot transformation/validation service using the 3D Cadastral Survey Data Model Canonical Logical model as a target model to take advantage of native and rich validation capabilities.

Recommendation 12: Track international efforts to explore transformation between GIS, CityGML and IFC encodings and determine the potential relevance of emerging capabilities.

Modelling Language

Recommendation Summary: Track and adopt best practices as the wider world learns to integrate UML, schema and semantic modelling approaches, and avoid dead-end and unnecessary choices - choose the most appropriate modelling language for a task and explore tooling to transform as required, based on controlled profiles for consistent usage of ach modelling language.

Recommendation 14: The machine readability and native validation functionality of the SHACL component of the 3D Cadastral Survey Data Model should be exploited to further test model definition, examples and emerging implementations.

Recommendation 15: ICSM should consider options for automated derivation of UML from a semantic model (or synchronisation to preserve diagram layouts) or vice versa (with SHACL).

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Jurisdictions

Recommendation Summary: Start adding jurisdictional details in a common, controlled, scalable fashion and testing model and encoding options, dealing with the extra layer of complexity of finer grained requirements with shared experience and infrastructure rather than divergent documentation forms.

Recommendation 16: Extend the provided semantic model with localised jurisdictional profiles, encoding and transformation details to retain a coherent interconnected knowledge base, tracing capabilities to underlying requirements and to support sharing of experiences around implementation.

Recommendation 19: Jurisdictional profiles are developed with governance in place for future platform implementation. Use is mandated via business rules, derived from surveying regulations, in line with the conceptual model.

Ongoing Governance

Recommendation Summary: Start pilot activities to ensure that clarity about what needs to be governed can be identified, and initiate and test a governance framework early to ensure smooth evolution of capability.

Recommendation 6: Development and agreement of an authoritative governance and maintenance process for community access to registered domain models.

Recommendation 20: ICSM develops a governance framework to support ongoing development, exploitation and implementation of the 3D CSDM.

Recommendation 21: ICSM takes on the role of a central repository for models and code lists. As a central representative organisation, ICSM would be the repository of best practice providing supporting materials and maintenance governance patterns.

Recommendation 22: ICSM to consider hosting the shared implementation services such as documentation generation, testing services, 'playground' and reference (test) data on behalf of the jurisdictions.

Standardisation

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Recommendation Summary: Feed requirements and experiences into active standardisation around modernisation of encoding options of direct relevance to 3D CSDM implementation options. These communities are seeking such experiences in the near future and this provides an active opportunity to engage with technology partners.

Recommendation 5: Development of an agreed roadmap to systematically improve integration, redevelopment, modernisation and transformation between required and related standards.

Recommendation 23: Consideration to be given to international standardisation of a 3D Geometry and Topology profile (Rec 7) and implementation in reusable software libraries and multiple different encoding technologies.

Recommendation 24: Explore standardisation of OGC-API solutions via derivation of JSON-schemas and compatible JSON-LD annotation directly from the canonical logical model. (Note this is an enabler for Rec. 10)

Recommendation 25: Explore derivation of ISO19103 UML profile from canonical logical model to support UML → GML encoding (and possibly future UML → JSON schema approaches). Note this will require a 3D GML profile standardisation to define reusable components for a XML schema encoding.

Recommendation 26: Provide for regular review of standard evolution linked to a model maintenance activity to take advantage of emerging encoding options and reusable resources, with the focus on long term viability of technology vendor support.

1.3 Next Steps as a Roadmap

A 3D Cadastral Survey Data Model has been developed as requested in the form of a Conceptual Model and Canonical Logical Model, with significant additional input around the use of validatable data examples. This is accessible in a machine-readable and human-readable form.

The innovation of data-driven model validation during model development processes is a significant improvement on previous practices - however more work needs to be done to consolidate on this experience and leverage the potential to support encoding specifications, jurisdictional profiles and implementation phases.

The transition from 2D to 3D capability needs to be integrated with “future-proofing” around encoding technology choices.

An indicative roadmap of recommended activities required to implement a 3D Cadastral Survey Data Model is illustrated in Figure 2. These take into account the key enablers required for implementation uptake within the wider technology landscape, as well as a progressive

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development of encoding specifications, pilot implementations, supporting infrastructure and ongoing engagement with standards processes and stakeholders.

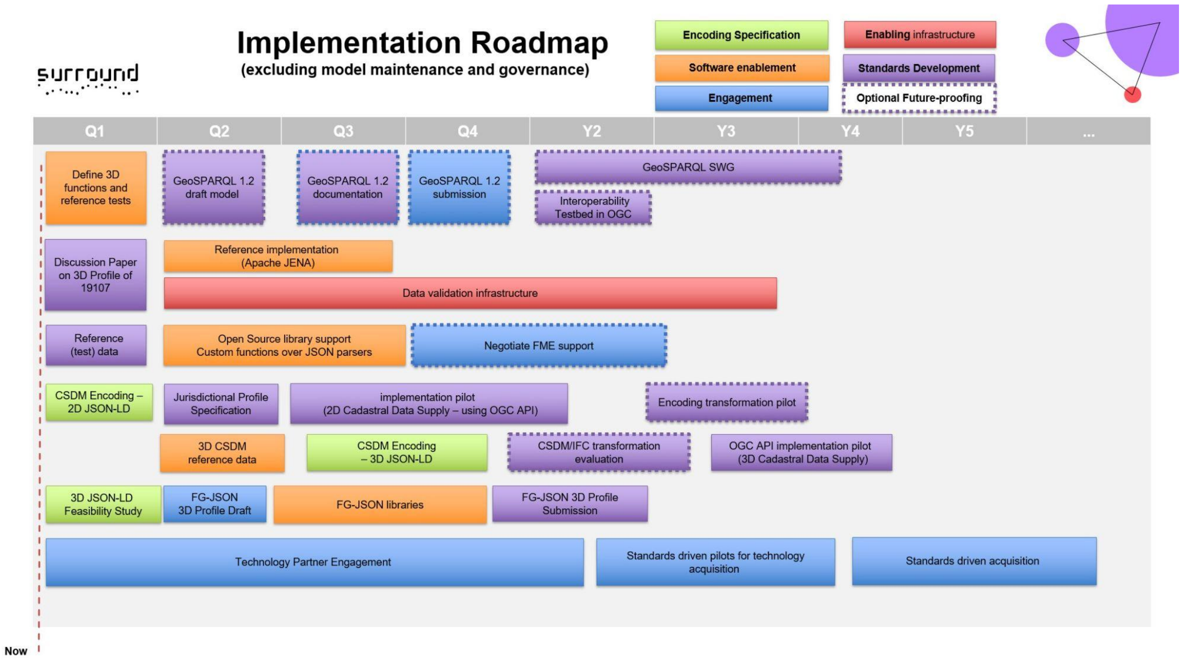

Figure 2: Implementation and standardisation roadmap -

NB: These roadmap elements are scoped against ability to define milestones and they have a general sequential dependency from left to right on the same row, with some cross-dependencies not shown. This sequencing allows for incremental investment in testing the feasibility of emerging technologies whilst providing maximum opportunities for stakeholder engagement on the journey. Each element of the roadmap focuses on minimising risk whilst maximising the number of engaged stakeholders for subsequent steps. Detailed planning will require analysis of implementation activity goals. Optional steps are also identified for engagement with external audiences to increase chances of adoption and future-proof against incompatible standards emerging.

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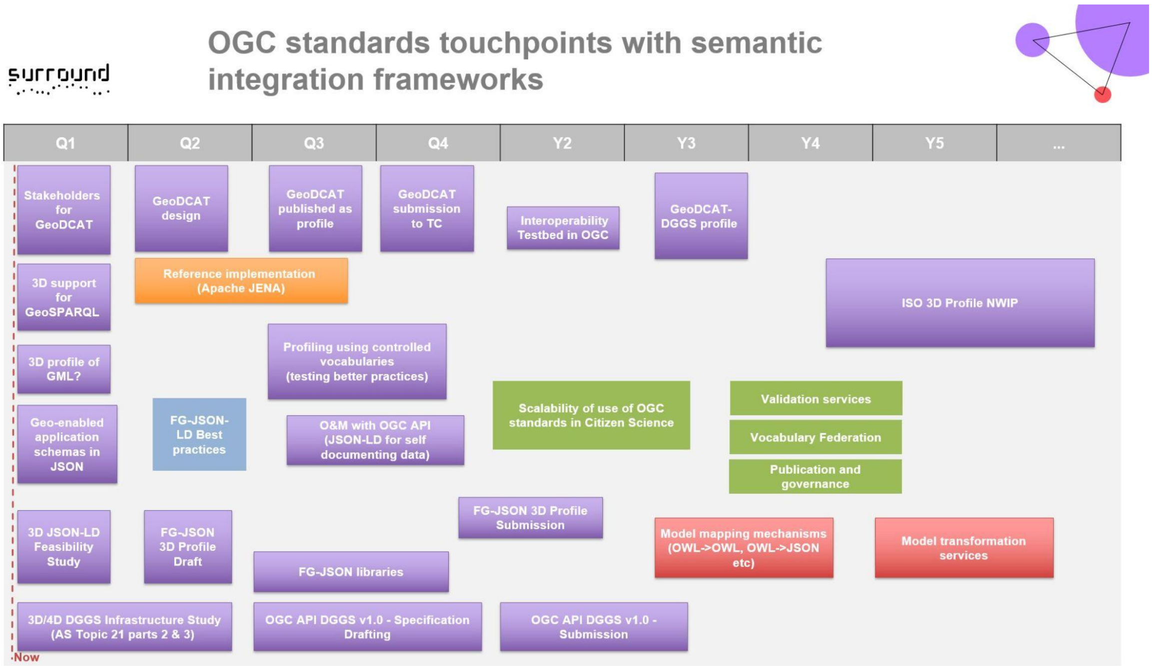

Figure 3: overview of potential overlaps with OGC processes

1.4 Conclusion

The Consortium combined a unique combination of expertise in survey, spatial standards and semantic data technologies to deliver a solution that is both domain-specialised and interoperable. The Consortium is involved in numerous Australian and New Zealand standards bodies, as well as international ones particularly the ISO, W3C, Open Geospatial Consortium & FIG. This involvement is directly related to active standards development efforts by consortia members who are engaged with ISO19152 (LADM Parts 2 and 6), OGC LandInfra (InfraGML), bSI IFC 5, and CityGML 3. Liaison and coordination with these activities will help assure the future success of 3D Cadastral Survey Data Model development.

Our expertise in data model modularity and standards adoption processes allowed us to avoid the inherent inflexibilities that arise when complex, emergent, and loosely-defined domain scopes evolve as single specific encoding without an underlying conceptual framework.

The resulting work has met the requirements of the ICSM 3D CSDM Programme Objective 1 (the harmonised cadastral survey model, including 3D elements), and Objective 2 (options analysis of widely recognised and adopted transfer formats for surveying and other software vendors).

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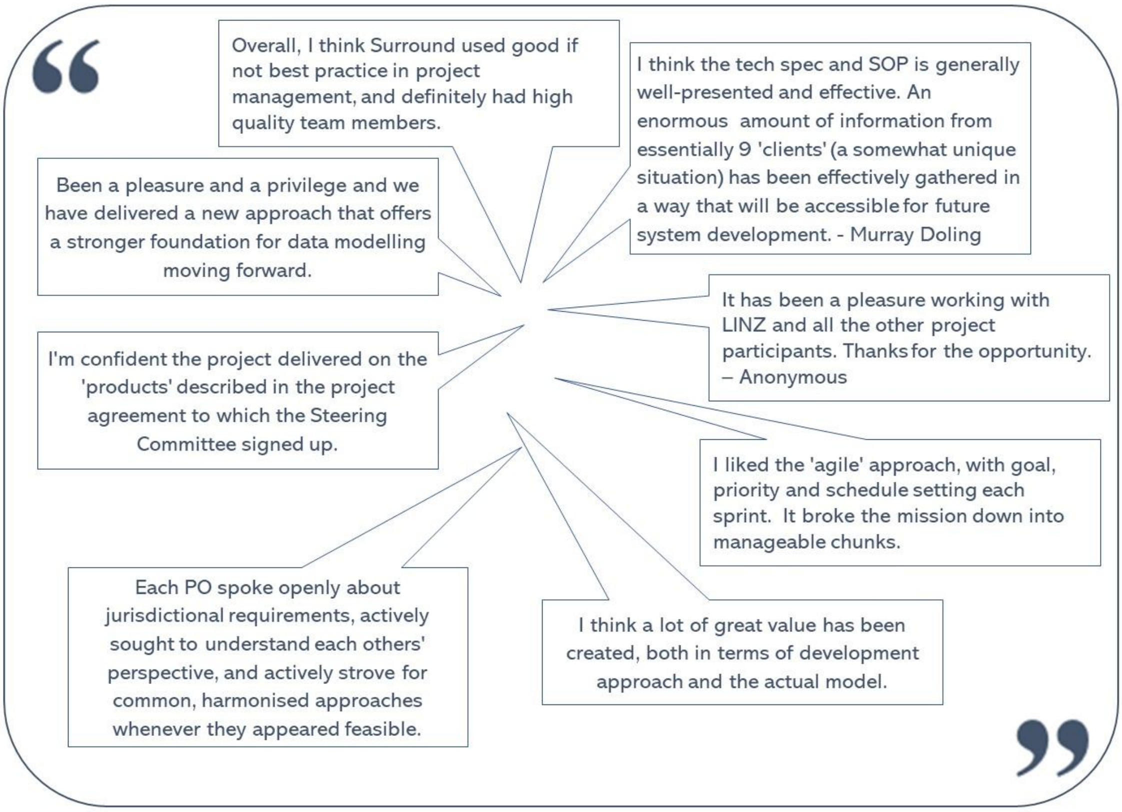
This is a pivotal time in the development of land administration and cadastral data systems worldwide. The ICSM, New Zealand and Australian jurisdictions are commended for taking a leadership role in this space.

The Consortium is grateful and proud to contribute to such a significant initiative.

Project Participant Testimonials



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FINAL PROGRAM REPORT:
3D Cadastral Survey Data Model and Exchange

2 Final Program Report

2.1 Background

The 3D Cadastral Survey Data Model and Exchange programme of work was established by the Intergovernmental Committee for Survey and Mapping (ICSM) with support from the Spatial Information Council (ANZLIC).

Land Information New Zealand (LINZ) led this programme in partnership with Western Australian Land Information Authority (Landgate), the Department of Environment, Land, Water and Planning (Victoria), the Department of Customer Service (New South Wales), and the Department of Natural Resources, Mines, and Energy (Queensland).

In February 2021, LINZ engaged SURROUND New Zealand after an open market procurement process. SURROUND led a Consortium of expert partners including McKenzie & Co, OpenWork, Pangaea Innovations, Evolve & Amplify and SURROUND Australia to deliver the agreed services.

The Consortium combines a unique combination of expertise in survey, spatial standards, and semantic data technologies to deliver a solution that is both domain-specialised and interoperable. The Consortium is involved in numerous A/NZ standards bodies, as well as international ISO, W3C, Open Geospatial Consortium, FIG, and Linked Data standards bodies.

Our expertise in data model modularity and standards adoption processes allowed us to avoid the inherent inefficiencies resulting from attempting complex, emergent, and loosely-defined domain scopes that produce a single, complicated modelling output.

2.2 Approach

The Consortium adopted an Agile Methodology and successfully completed a Co-Design phase with Land Information New Zealand, Western Australian Land Information Authority (Landgate), the Department of Environment, Land, Water, and Planning (Victoria), the Department of Customer Service (New South Wales), and the Department of Natural Resources, Mines, and Energy (Queensland).

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The Co-Design resulted in an agreed engagement model, project plan, milestones, timeframes, stakeholder maps, and a data modelling methodology.

The approaches to manage the complexities of this multi-jurisdiction engagement include a series of activities with iterative feedback as illustrated in Figure 4:

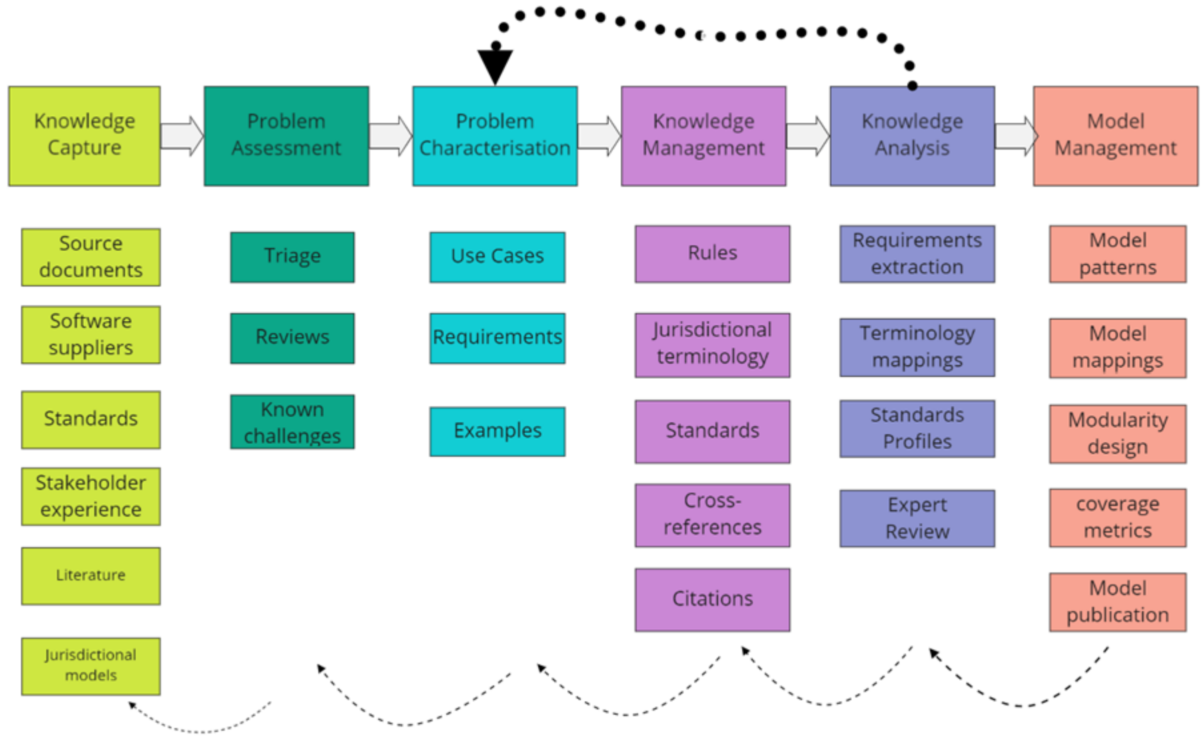

Figure 4: Multi Agency or Jurisdiction Model Methodology Flows

As each element of this process progressed, a comprehensive knowledge base was created through a set of interrelated knowledge graph modules. The resulting knowledge graph can be considered as two main components - the machine-readable model itself consisting of layers starting with standards and common patterns and building out to implementable profiles and the requirements model containing references (rules/clauses) to the underlying business rules of the multiple stakeholder jurisdictions. In addition to informing the model design this knowledge base has multiple uses including generation of the final specification documentation.

Figure 5 shows two approaches to specification generation:

- The top row shows a typical disjointed process where changes to any component require reconciliation across multiple different components - and typically leads to inconsistencies

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being present - often for extended implementation cycles as interoperability failures appear “in the wild”.

- The second shows a fully integrated documentation pipeline supported by a flexible and extensible knowledge base. In this case all normative aspects are generated in multiple forms from the same data. This is a significant improvement in “best practice” introduced as part of the project methodology design.

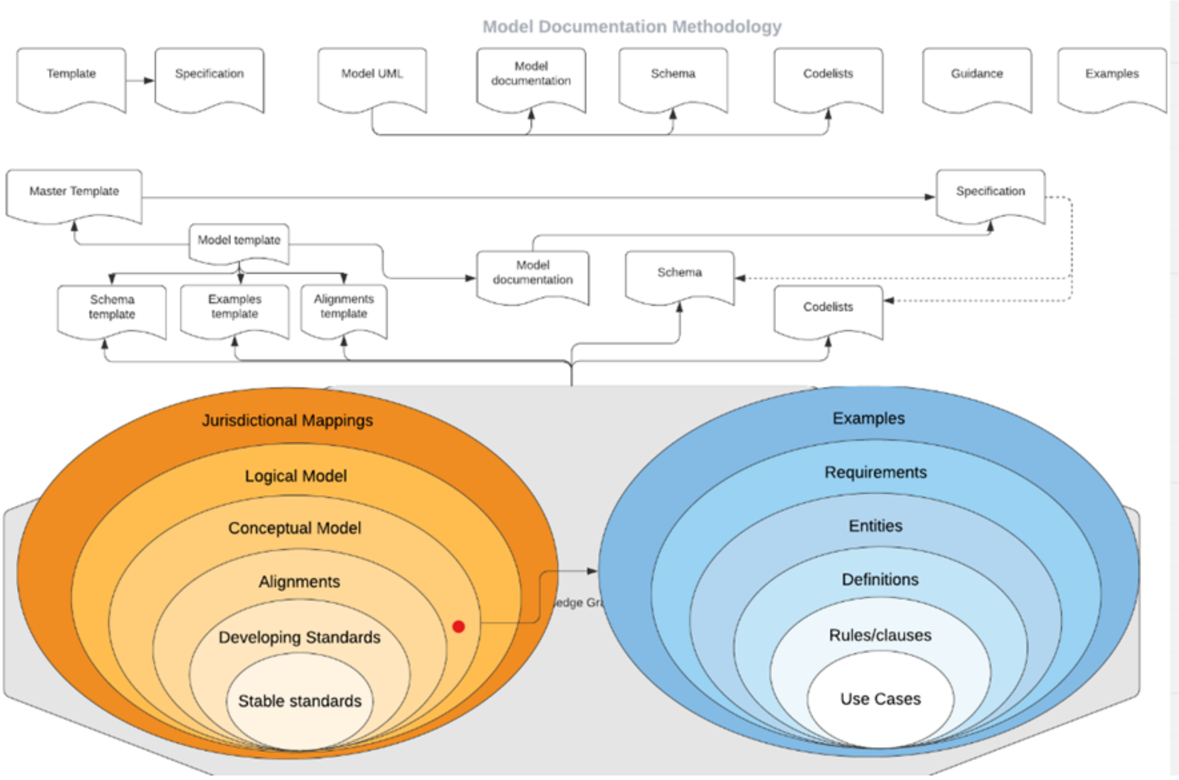

Figure 5: Model Documentation generation - disjointed vs using a knowledge base

This collaborative stakeholder engagement approach increased efficiency and minimised the risks of poor scope and low adoption, based on identification of readiness:

- Availability of relevant data and ability to provide samples and documentation
- Identification of a Use Case demonstrating model to provide business value
- Identification of a problem owner who can validate and guide the development and delivery of outputs to maximise adoption opportunity
- Availability of technical resources to perform validation, testing, and readiness for implementation of specific output components (including technology partner relationships)

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The Consortium used a flexible Semantic Data model profiling approach that balanced the benefits of "custom fit", incorporating each jurisdiction's unique requirements, with Total Cost of Ownership (TCO). The benefits of this TCO and "custom fit" balance include:

- avoidance of technical debt: based on well-supported international standards
- sustainability: ease of maintenance as requirements change over time
- ease of integration with existing tools and systems while being flexible enough to support future capabilities

The Consortium's profiling approach enabled the creation of a conceptual model informed by international standards (e.g., LADM, LandInfra) and vocabularies (e.g., CaLAThe, LandVoc), while allowing the 9 jurisdictions to reflect local needs and requirements in their own language.

This approach provided significant opportunities to create a targeted scope based on a prioritised subset of requirements. Initial analysis undertaken in consultation with key stakeholders, seeking localised solutions, or integration of existing capabilities into the domain model, was used to set a tight scope for an initial core, and demonstrate the process of extending this core to meet emerging needs.

The Consortium's focus on flexibility of encodings of subsets of the model (profiles) rather than a single complex schema, avoids the significant challenges encountered in the past with complex models when implementation is attempted. This allows efficiencies in terms of safe re-use of available standards and software-supported formats, as well as simpler testing for new exchange schemas.

2.3 Audience

The primary audience for the programme is the ICSM, with the nominated stakeholders from Land Information New Zealand, Landgate, the Department of Environment, Land, Water, and Planning (Victoria), the Department of Customer Service (New South Wales), and the Department of Natural Resources, Mines, and Energy (Queensland).

There is significant interest and opportunities from the ICSM 3DCSDM for a broader audience within the Surveying, Infrastructure and Land Administration domains. Figure 6 highlights the finding that the OGC LandInfra model, proposed as a replacement for LandXML, is related in scope but not quite the same as the cadastral domain, but would nevertheless be expected to share a significant common audience.

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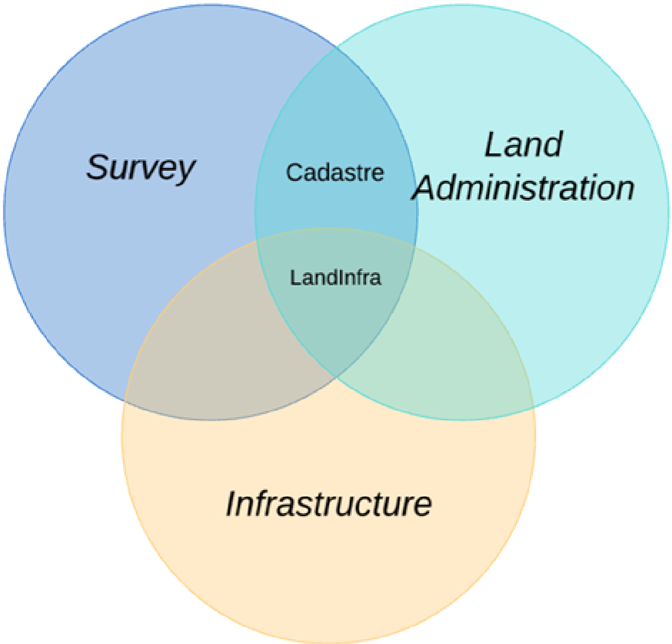

Figure 6: Relationship between cadastral domain and LandInfra standard

2.4 Constraints

- Implementation as an encoding specification and testing was not part of the scope
- Technology shifts and standards development make it challenging to predict the future
- No control over the technology partner (software vendors) uptake and adoption
- Complexities and proliferation of numerous ways of representing 3D objects

2.5 Assumptions

The contractual assumptions are that the following items are out of scope:

1. Implementation of the Data Model.
2. Implementation of the Data Model exchange (transfer) format into surveying software. This will be done by third party survey software providers to enhance their products.
3. Development of a new encoding standard or exchange format (related to Deliverable #3),
4. Activities related to the adoption by international standardisation agencies.
5. Ongoing costs associated with the maintenance and distribution of the Data Model beyond the End Date.

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2.6 Related Documents

- Encoding Recommendations Report [see Annex C in the technical documentation spec.html#_encoding_options]
    - Note this is part of the continual integration allowing systematic update of this as implementation experiences and further external engagement progress.
- Data Exchange Options Analysis
    - This supplements the forward-looking recommendations and is supplied as a separate document.
- System Generated Documentation
    - This is an HTML document and supporting repositories of content, supplied in ZIP format ready for hosting in a suitable infrastructure.

3 Program of Work

Key to the success of this project was the ability to learn along the way and to build on those learnings during the course of the project. Two key supports are required to adopt this approach:

1. High levels of buy-in and collaboration from those who can influence prioritisation of activities
2. Flexibility in the scope of deliverables such that the project is not overwhelmed with contractual overhead for small deviations from initial thinking

Many stakeholders were involved in the project. As well as the multiple parties involved in completion of the work there was also significant contribution from technology partners and jurisdictions. Considered engagement at key points in time were essential to keeping stakeholders informed and engaged throughout the project.

The project was executed using the incremental AGILE methodology. This methodology delivers key benefits of ongoing learning, continuous improvement, high levels of collaboration and enhanced visibility of project outcomes.

13 sprints, each 4 weeks in duration, were planned and executed to deliver the project. Sprints included regular rituals such as:

- Standups to discuss progress, dependencies and blockers as well as to share learnings
- Sprint Planning to prioritise and commit to work
- Showcases to demonstrate progress and gain feedback
- Retrospectives to reflect on how the project is going and support continuous improvement

Key outcomes of the project governance were:

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- Twice-weekly consortium standups
- Risks captured in Jira and reported monthly
- Monthly milestone status reporting
- Regular contract review meetings
- A documented Stakeholder Engagement and Communications Plan

Analysis for this work consisted fundamentally of a needs assessment, being a look at "what is" versus "what should be" from the perspective of jurisdictional cadastral survey systems used to define cadastral boundaries was the primary mechanism adopted to develop the 3D Cadastral Survey Data Model (3D CSDM) Use Cases that the cadastral survey data model has been founded upon.

The objective of the needs assessment was to define the scope of the 3D CSDM and then test their effectiveness with the ICSM jurisdictions and cadastral survey test data to revise/iterate the Use Cases as necessary.

An initial high-level review of jurisdictional documents provided from all jurisdictions was undertaken to define a candidate set of Use Cases for discussion with the Product Owners. Jurisdictional documentation consisted primarily of cadastral survey legislation and associated regulations, cadastral survey directives published by cadastral survey custodians and/or governing authorities, and approved survey plans.

The review identified a set of system components that formed a candidate set of Use Cases. Following review and discussion of the candidate set with the Product Owners (PO) the Use Cases were reduced to a set of four fundamental Use Cases, being Use Case (UC) 3: Survey Observations; UC 4: 3D Cadastral Parcel Surface; UC 5: General 3D Spatial Unit; and UC 7: Cadastral Survey Dataset Details.

Following the reduction of the UC set, a preliminary review of jurisdictional source documents for the PO jurisdictions (NZ, NSW, and WA) was undertaken to develop an initial UC requirement set. Given the jurisdictional source documents focus on requirements for a 2D survey system, the vast majority of the requirements related to UC 3 and UC 7.

Requirements were reviewed and discussed in online workshop sessions with the POs to test for completeness and clarity. During this phase all high-level UCs were subdivided into finer-grained Use Cases to aid clarity during the model design phase. For example, UC 3 was separated into three UCs that focused on Survey Marks, Survey Observations, and Occupation Observations.

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During this reduction phase of the model requirements the SURROUND team transitioned from a traditional paper-based approach to an online knowledge management system, the SOP (Surround Ontology Platform), that ultimately enabled source documents to be linked directly to system requirements. It also enabled a level of transparency with amendments to the 3D CSDM requirements being logged via workflows.

The SOP then formed the basis of workshops with the ICSM jurisdictions to confirm, clarify and or expand use case requirements, and to develop a common understanding of terms fundamental to the 3D CSDM. The online workshop setting enabled the Surround team to garner jurisdictional domain knowledge remotely.

3.1 Initial Methodology Development

The initial methodology proposed (milestone 2 (of 13)) reflected the findings of initial analysis of provided materials and application of best practices around iterative development of complex solutions, applied to the process of design of a modular, maintainable and extensible model as required. Figure 3 (repeated below) shows a graphical representation of the elements of this methodology as well as the feedback loops of the AGILE process - the main iteration around defining the project scope as well as provision for reassessment of assumptions as required throughout the process.

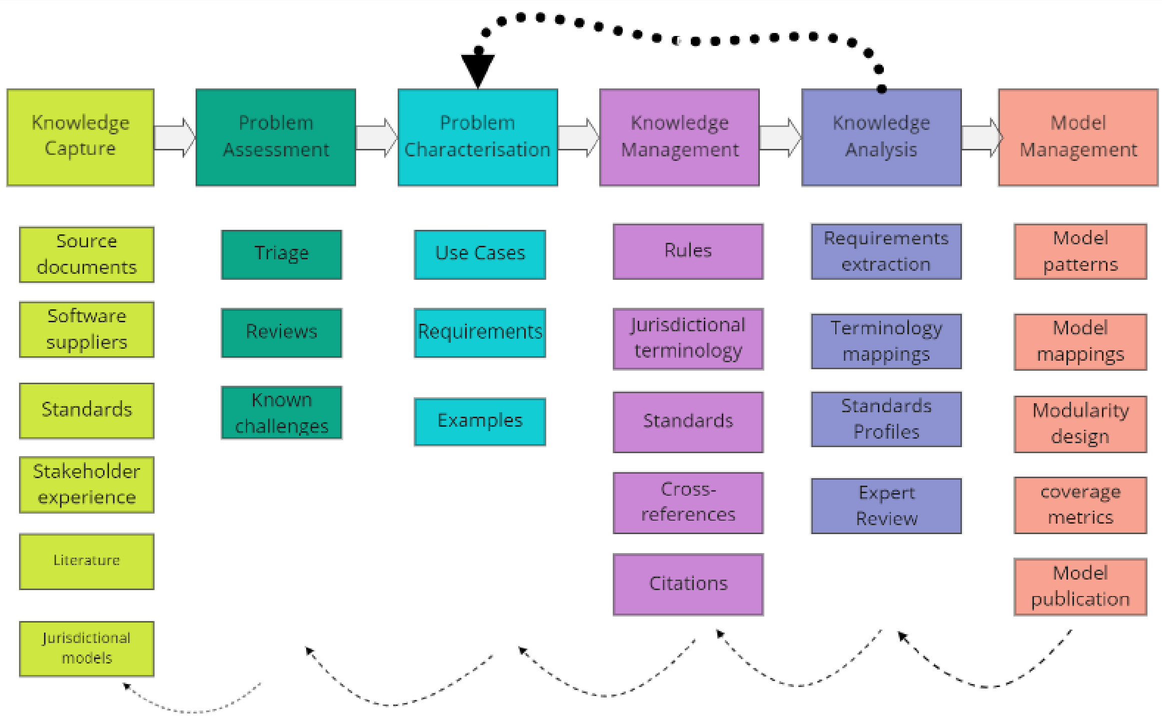

Figure 3: Model Documentation generation using a layered modular knowledge base

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This process methodology was backed by a high-level knowledge architecture to support the modular development and incremental validation of the model outputs.

In practice this methodology proved effective, with the following adjustments:

- The high level of expert stakeholder engagement, coupled with the realisation that the key 3D enablers were not well represented in the jurisdictional practises to date meant that the jurisdictional mapping process was used more to validate the Co-Design outputs than to drive them.
- The emergence of the relative importance of examples to test key conceptual components against implementation feasibility needed to define a logical model, which led to an additional feedback process between examples and the model design itself.

An updated methodology reflecting these experiences would have potential value for further work of a similar nature, including extensions to the scope of this model if required.

Recommendation 1: Future work should use an updated methodology that reflects the experiences and lessons learned during the 3D CSDM project.

3.2 Co-Design Process

The intent of the Co-Design process was to create a shared understanding and shared language between the ICSM participants and the Surround design team. The objective was to gather insight, knowledge, information, and wisdom from the ICSM jurisdictional experts of their jurisdictional cadastral survey systems. This helped the Surround team to build a bridge between the 2D now and a future 3D cadastral world. Surround's role in the Co-Design process was to act primarily as facilitators of participation, and on occasion provocateurs and activists.

The process itself was iterative in that we first commenced working with the ICSM Product Owners (PO) from LINZ, New South Wales (NSW) and Western Australia (WA). Next expertise was brought in from Queensland (QLD) and Victoria (VIC). Finally the remaining jurisdictions, Australian Capital Territory (ACT), Northern Territories (NT), South Australia (SA) and Tasmania (TAS) joined the process. As knowledge was generated with the jurisdictional experts, changes to requirements were tested and further iterated with the PO's and the jurisdictional experts.

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The design process was driven by the Use Case development process. Throughout the project a series of Use Cases were developed to drive requirements. The basis of the Use Cases were jurisdictional requirements driven by cadastral survey legislation and their associated regulations and jurisdictional cadastral survey directions issued by the relevant cadastral survey data custodians.

During the Co-Design process particular attention was paid to extracting and consolidating terminology used to express requirements - the "nouns" defined became the basis for model development and assessment of relevance of related specifications. The cadastral language used across the jurisdictions does vary and work to document and, where possible, harmonise the data dictionaries will enable future model development.

Recommendation 2: Continued development documenting authoritative jurisdictional cadastral language, and making it available programmatically, will support future model development.

3.2.1 Model Development

The model was developed, according to agreement regarding its form, using a source code repository and open standards for model definition (OWL, RDFS, SHACL).

The model was modularised to support potential reuse of relevant parts in different application domains, and to support alignment with emerging standardisation activities for different aspects of the domain. Each module is managed with the following components:

- A conceptual model (described in OWL)
- A logical model (described in SHACL - i.e. as a set of testable constraints)
- A set of examples to explain and test the model
- A "recipe" for loading the model into a knowledge base as a set of named graphs - a technique for preserving modularity whilst establishing comprehensive linkages between different resources.

Established standards are shown in green in Figure 7 . It was necessary to factor out a number of key modules that represent profiles or extensions to available standards for implementation patterns that are not unique to the Cadastral domain (blue in Figure 7). These are modules for which implementation patterns can be standardised independently, supported by reference libraries and used to facilitate uptake of the overall model.

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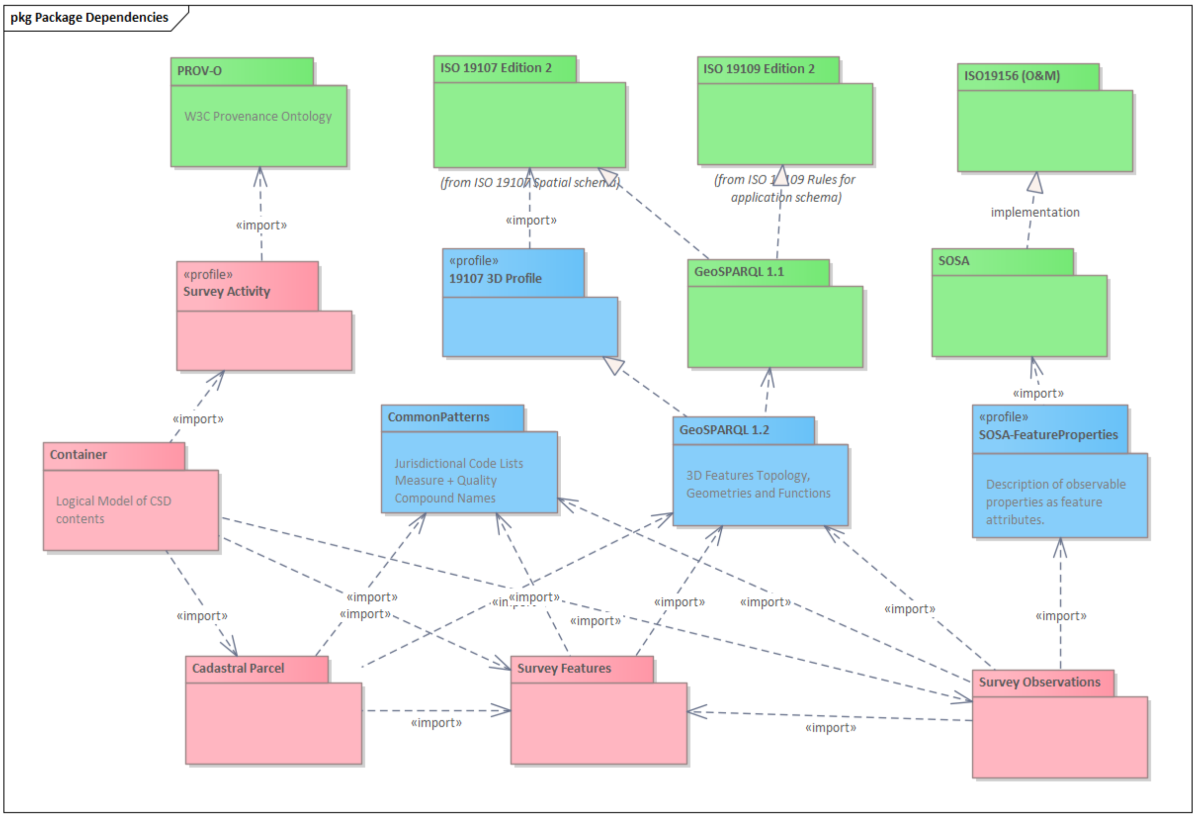

Figure 7: Package Modules of the 3DCSM and applied standards

The 3D Geometry Profile scope addresses the core problem of describing how survey elements relate in a 3D space and allows multiple forms of geometry representation to be used according to system capabilities. For example, solid geometries may be derived from boundary faces that reference survey point locations. The model allows for either reusable geometric elements to be referenced in multiple locations or the collation of geometric elements into alternative representations. This provides flexibility, and validation and visualisation support.

The model is based on the ISO19109 General Feature Model, in that objects with identity have geometry representations. This allows multiple alternative geometry representations to be defined for the same feature, and allows for feature topology to be asserted without complex geometric operations. For example a cadastral parcel may have several possible geometric representations:

1. A typical “2D” footprint
2. A description of extended rights in multiple (geometric) directions
3. A topographic model of the surface (e.g. a TIN)
4. A representative 3D volume (with unbounded extensions truncated for display and calculation purposes)

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5. A DGGS[2] "index" for efficient calculations (see encoding options discussion)

This "meta-model" provides greater flexibility than attempting to define a single "one size fits all" geometry model and attaching object attributes. (Implementations may still create geometry-centric representations, however the underlying conceptual model requires that common object identity is managed across multiple implementations.)
Figure 8 shows a generalised model for features with geometry and topology described in 3D.

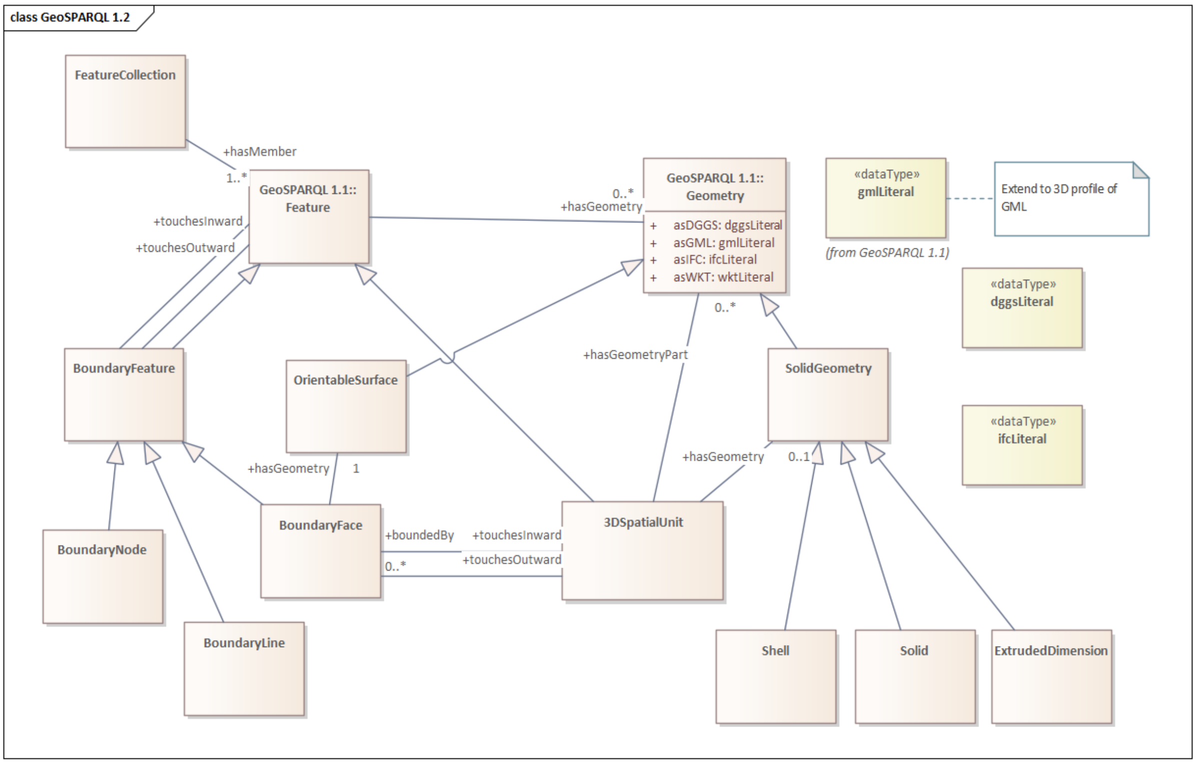

Figure 8: Scope of proposed 3D Geometry Profile

The Cadastral Parcel model is relatively simple extension of this underlying model of 3D objects with some key metadata attributes relevant to the domain:

[2] Discrete Global Grid Systems (DDGS), https://ogcapi.ogc.org/dggs/, last accessed Feb.2022

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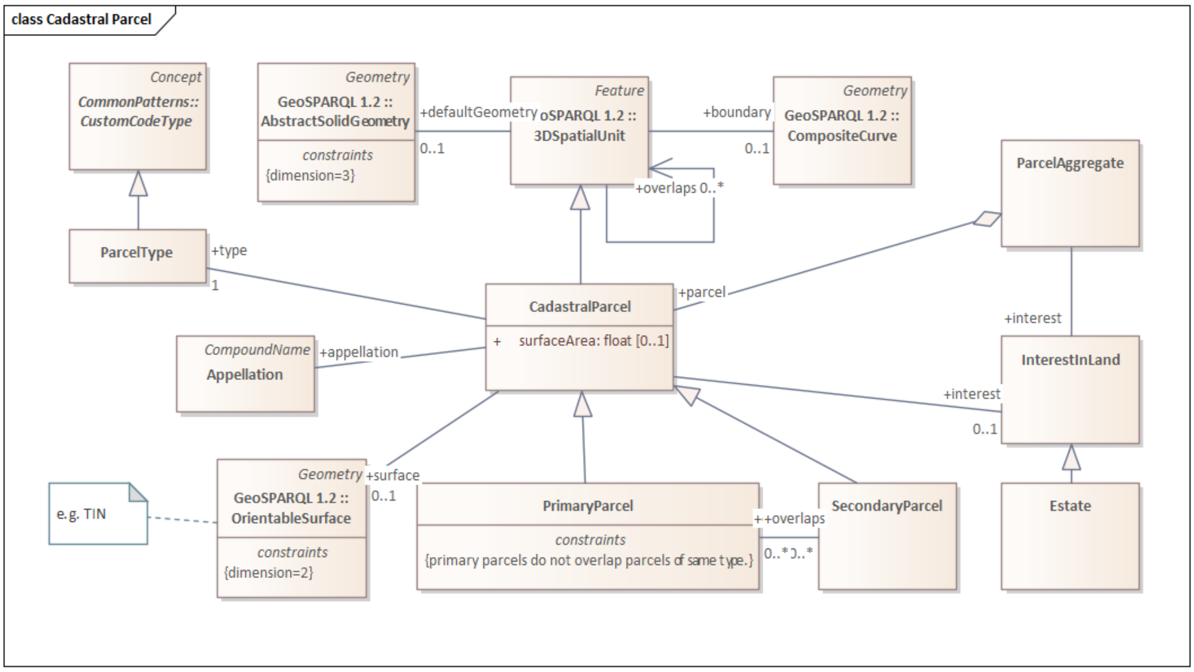

Figure 9: Example model package: Cadastral Parcel

The conceptual model is based on a modular approach around well established flexible patterns. Such patterns may be supported by common interoperable encoding specifications. The domain model specialises and adds specific detail to such patterns as required. These foundation patterns are explained in more detail in Section 9 of the specification documentation https://icsm-au.github.io/3d-csdm-design/2022/spec.html

The core logical model can be best summarised by a "compartment" view of a Cadastral Survey Dataset (CSD) as an exchangeable data object containing multiple elements using flexible standardised implementation patterns:

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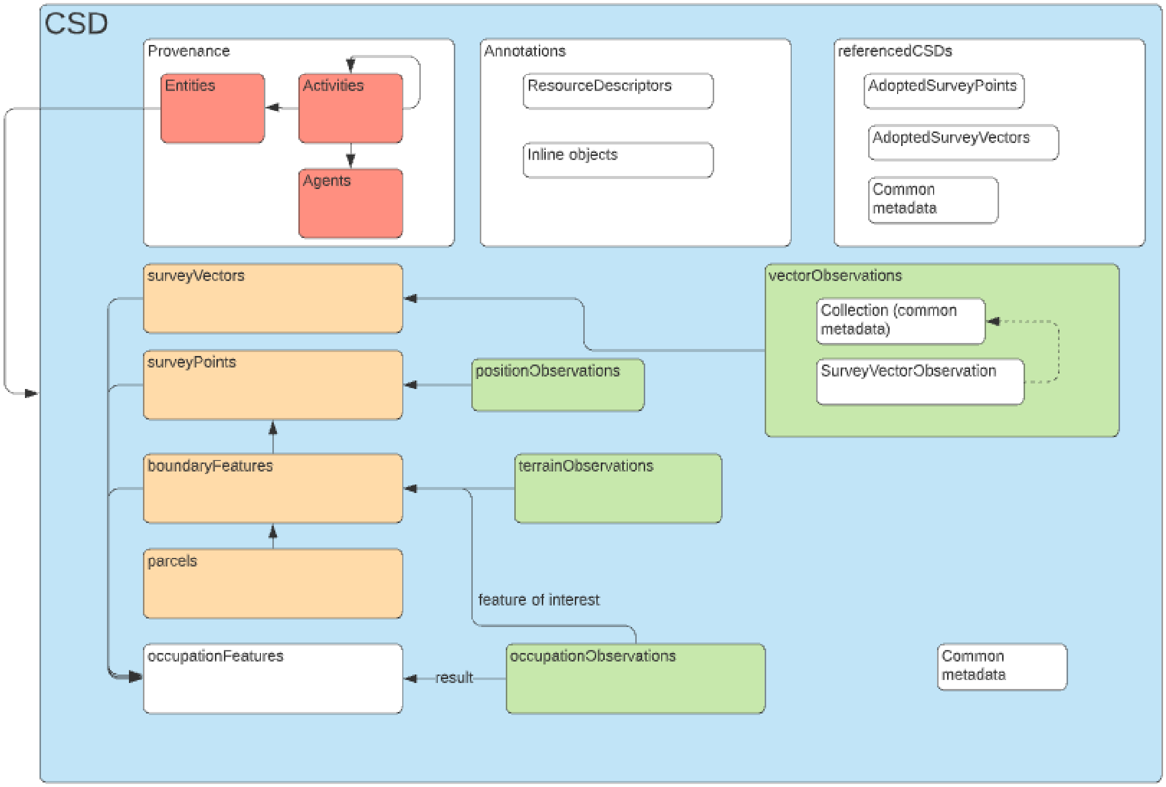

Figure10:Cadastral Survey Dataset model represented as a container

3.3 Specification Documentation

The presentation of the model in a "human readable form" is a necessary adjunct to the model itself, which is a standardised machine-readable representation. In many cases such documents have been created as an additional artefact and have diverged in detail as the model itself is refined or maintained.

Another weakness in current practices highlighted by the model documentation is the inability to locate the latest versions of related materials.

Accordingly the project has extended emerging best practises around deriving documentation directly from a model to include additional aspects such as linkages to key supporting materials:

- Requirements
- Machine readable examples
- Extensible database of implementation examples
- Extensible database of explanatory images
- Live viewer (for 3D concept clarification)

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- Mappings to jurisdictional regulations and terminology
- Feedback mechanisms

We have used an OGC specification template based on the open AsciiDoc standard as a basis for documentation, in accordance with emerging best practices in the OGC specification development process.

In this project we have also applied the principles of Continuous Integration/Continuous Delivery (c.f. https://www.redhat.com/en/topics/devops/what-is-ci-cd) to build a document dynamically from the project knowledge base, including the model source.

This is currently deployed at https://icsm-au.github.io/3d-csdm-design/2022/spec.html

The customised documentation generation tool is available at https://bitbucket.org/surroundbitbucket/mds

This operates on a standard "pipeline" model used in modern code repositories, and can be triggered on a schedule, on commit of updates or manually. This toolset is unencumbered with proprietary technology. It is recommended that provision is made to support this capability on an ongoing basis.

Recommendation 3: Provision be made to support automation of model-generated documentation past the end of the project.

3.4 Standards Review

For a data model to be sustainable and implementable, it must be aligned to existing well-known standards whenever possible. However, when existing standards do not support the requirements, the existing standards may need to be altered or discarded in favour of other standards. Since many consortia members are involved in standards bodies relevant to this work, we understand the suitability, reliability, and influence the development of standards on which the model relies and must interact.

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Standard choices exist in many aspects of this project, from the language in which the data model is written to the encoding standards used by applications supporting the standard. Beyond fitness to requirements, our review included how well governed the standards are and how open they are to participation. At the implementation level, we sought out standards that existing software vendors are familiar with and willing to implement. Where the choice exists, we prefer simple, unambiguous standards to decrease implementation differences.

Our standards review includes a continuing watch of the status of significant standards and future trends. Consortia members are either directly or indirectly involved in these efforts. Active standards development of note include ISO19152 (Land Administration Domain Model Parts 2 and 6), OGC LandInfra (InfraGML), bSI IFC 5, and CityGML 3. Other supporting standards under active development include ISO19157 (Data Quality), ISO19150 (Ontology).

The final model reflects the key findings:

- No standard neatly fits the requirements or can be directly extended or modified
- A range of foundational standards can be used to implement required patterns
- These standards are modelled in different ways - but can be integrated within a semantic modelling framework.
- The enabling “metamodel” of ISO 19107 (Spatial Schema) and ISO 19109 (Application Schema) is a common basis for many standards - and provide key flexibility and future proofing as they form the basis for OGC encoding standards.
- LandInfra could be refactored to allow greater flexibility to meet 3D Cadastre Survey, but this is out of scope and would limit implementation options to InfraGML which would need major revision, and has not received widespread vendor support yet anyway.

The comparison matrix (Table 1) summarises the level of support for different requirements available in existing standards and implementations.

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Table 1: Comparison of support for 3D capabilities

Legend

N/A	Feature Not Applicable
?	Feature implementation details are unknown
Yes	Feature is available and fully supported
Yes ?	Feature is available, but needs further investigation
Partial	Feature is partially implemented or supported
No?	Feature is not available, but needs further investigation
No	Feature is not available

Standard Name	**BSi IFC (IFC4 ISO10303)**	**ISO LADM (ISO19152 :2012)**	**- OGC LandInfra (OGC 15-111r1)**	**LandXML (landxml.org)**	**- ICSM ePlan (ICSM ePlan v10)**	**ISO GML (ISO19136:2020)**	**OGC CityGML (OGC 20-010)**	**GeoJSON (IETF RFC 7946)**	**GeoPackage (OGC 12-128r18)**	**Geographic Information Spatial Schema (ISO19107:2019)**
Primary Users	BIM & AEC	Land Admins	Asset Mgrs, Engineers, Surveyors	Survey Engineering	Cadastral Surveyors	Geographic information modellers	3D City modellers	Web developers	GIS	Geographic information modellers
Project Gov'	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Cadastre Features	Partial	Yes	Yes	Yes	Yes	Yes*	No	No	Yes?	No
Cad. Feat Support	No	?	Yes	Yes	Yes	Yes*	No	?	No	N/A
Cad. Evidence	No	No	Yes	Yes	Yes	Yes*	No	No	Yes	No
Evid. Support	No	?	Yes	Yes	Yes	Yes*	No	No	Yes	N/A
Simple Geom	Yes (ISO10303)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Complex Geom	Yes (ISO10303)	Yes	Yes	Partial	Partial	Yes	Yes	No	Yes	Yes
Complex Geom Sup	Yes (ISO10303)	?	Yes (Leica)	?	?	Yes (FME, GDAL)	?	No	?	N/A
2D Topology	Yes (ISO10303)	?	Yes	Yes?	Yes?	Yes	Yes	No	Yes	Yes
3D Topology	Yes (ISO10303)	?	No	No?	No?	Yes	No	No	No	Yes
2D Topo Support	Yes	?	Yes (Leica)	Yes Limited	Yes Limited	Yes (FME)	Yes (FME)	N/A	Yes	N/A
3D Topo Support	Yes	?	?	No	?	?	?	No	No	N/A

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Code Lists	Enums	Yes *	Yes *	Yes	Yes	Yes *	Yes *	Yes	Yes *	Yes
CRS	Many	Many	Many	Many	Many	Many	Many	1	Many	Many
Metadata	Extensive, inconsistent	ISO 19115	ISO 19115	Basic	Basic	ISO 19115	Basic	STAC, OAPIRec	ISO 19115	N/A
Extensions allowed	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	N/A
Extension Support	Medium	Low	Low	Medium	Low	Medium	Medium	Broad	Low	N/A

3.5 Technology Partner Engagement

The ability of technology partners to implement the data model is a central concern of our work. Early in the process, with the participation of stakeholders, we identified and reached out to all technology partners that are understood to be active in the Cadastral Survey domain within the ICSM jurisdictions.

We sought to understand their current efforts toward survey observations and 3D Cadastral Survey Data Modelling, and hear their concerns regarding model development on similar projects that they have been involved in. We also engaged with the broader community through formal standards development organisations with whom they participate.

Sustained engagement was difficult in part because the model was still in development during discussions. However, it was important that technology partners and standards organisations be provided an opportunity to contribute early in the development of the 3D CSDM.

The general feedback was that involvement in the development of a conceptual model, while of interest, is not as relevant to them as participation in the development of implementation models. Many of the technical partners expressed some desire to participate in future pilots and testbeds to explore implementation of this conceptual model. In particular, no feedback was received indicating that an “off-the-shelf” option was available for description of cadastral survey data.

3.6 Additional Testing

3.6.1 Model instances

As discussed in the methodology section the provision of explanatory examples was proposed as part of the documentation approach. As the form of the model emerged it became obvious that an

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unplanned opportunity existed to directly apply the logical model constraints as a validation tool to test these examples for consistency in the model.

The project used a proprietary technology suite (SURROUND Ontology Platform - SOP) as a development tool to manage access to the knowledge base during consultation exercises - and to check and validate the model integration before publication. This tool provides inbuilt validation services, so customisation and configuration of SOP to support display also natively supports data validation.

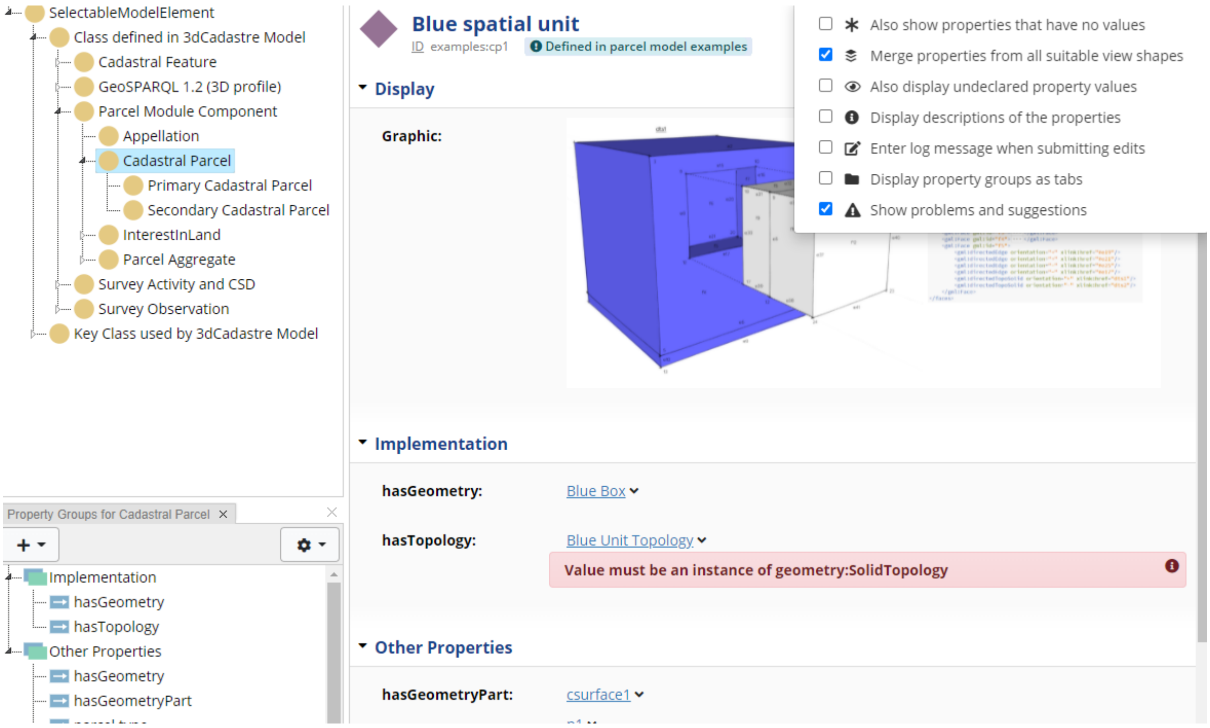

Figure 11: Example of a test data validation report in the SOP User Interface

This level of testing extends the contractual scope but proves extremely valuable in checking the completeness of the model and validity of the examples.
The underlying knowledge base that supports this functionality is all present in the delivered model, and uses directly imported open standards where applicable. It is recommended that consideration be given to establishing and maintaining both design-time validation and automated testing in the CI/CD process. This can be done in multiple ways:

- Editing environment (as per SOP)
- Commit pipeline processing
- Documentation generation (including validation reports)
- Embedded testing tools in the specification document

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- Standalone testing tools
- "Playground" - https://shacl-play.sparna.fr/play/

NB These techniques are in active use in other national federated data integration projects and truly represent an achievable improvement in practice for supporting data exchange standardisation. An example of this approach is the EU Interoperability Testbed SHACL validator. [https://joinup.ec.europa.eu/collection/interoperability-test-bed-repository/solution/interoperability-test-bed] . Similar capabilities are being developed by the SURROUND consortium for other application domains.

Recommendation 4: Consideration be given to establishing and maintaining both design-time validation and on-going automated testing in the model development process.

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4 Discussion and Analysis

4.1 Conclusions / Lessons learned

4.1.1 Standards Landscape

The major conclusion reached is that there is a key gap in the standards landscape around common approaches for 3D Feature and Geometry, particularly with respect to basic topology support required.

For other requirements, standards are available for both conceptual and implementation patterns, however the heterogeneity of the form and nuances around “meta-standardisation” - i.e. the language used to define these models - is sufficiently challenging that available standards are not readily integrated, and hence a range of divergent and incompatible implementations have proliferated.

There are many activities in the immediate past, present and future relating to integration, redevelopment, modernisation and transformation between related standards - however there is no clear or commonly accepted roadmap to systematically improving this situation.

Recommendation 5: Development of an agreed roadmap to systematically improve integration, redevelopment, modernisation and transformation between required, related standards.

The project scope to establish a conceptual model for 3D Cadastral Survey Data Modelling represents a significant improvement on many current practices, and reflects emerging thinking in the OGC to pay greater attention to conceptual modelling. Integration of conceptual models into implementation models remains an active research topic however. (This is a key weakness of UML in the absence of a canonical way to map different model abstractions).

The suite of approaches taken to different aspects of the model development and formalisation represent potential pathways forward to improve the coherence and reusability of published models. The management of domain models is still extremely ad-hoc across different communities of practice and the mechanisms to minimise clashes of scope and incompatibility of implementations are not well defined or supported.

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Recommendation 6: Development and agreement of an authoritative governance and maintenance process for community access to registered domain models.

4.2 Technology Capacity “Uplift”

4.2.1 3D Geometry Support

A key result of the analysis of available standards and the requirements for a 3D Cadastral Survey Data Model is that there is no common expression of the basic 3D geometry and topology requirements of a range of different domain models. In 2D geometry, this is supported through the concept of a “Simple Features Profile” of the underlying geometry theoretical model. This is supported by implementation and testable against software implementations.

We conclude that an equivalent profile for 3D is required, defining both the data models for 3D features with 2D and 3D geometry and topology representations, and supported by a common set of functions that can be used to transform and aggregate geometry primitives into 3D display and analysis ready objects and derive topological relationships.

The definition of such a profile would support development of tools and test suites and provide the basis for a general “uplift” in capabilities of the wider software offerings to meet the requirements of both 3D Cadastral Survey Data Modelling but also related domains such as city and landscape scale models, infrastructure, local and indoor positioning and other related domains, in the same way the Simple Features Profile supports interoperability of multiple implementations of 2D GIS systems.

Recommendation 7: A functional profile be defined for basic 3D geometry and topology representations as exists for planar (Simple Features) geometry.

Recommendation 8: Encoding patterns for a 3D geometry profile be defined for multiple candidate encoding options such as GML, JSON, OWL, SQLite (Geopackage) and IFC.

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Recommendation 9: Reference implementations for test data and software libraries be commissioned to support 3D geometry to support technology capacity “uplift”.

4.2.2 Model Encoding Options

The trend is for a single conceptual model, with multiple platform-independent logical models to generate multiple platform-specific encodings. This provides:

- a reasonable degree of support for relevant legacy capabilities
- A platform-specific pathway to upgrade existing capabilities if desired
- Future-proofed and application specific encoding options

The emergence of JSON as an overwhelmingly popular successor to XML technologies has led to it being the basis of OGC’s strategic roadmap - and hence is regarded as the preferred choice moving forward whilst acknowledging that work on implementation patterns (and hence JSON schema components that can and should be reused) is still emerging.

Direct translation from formal models to implementation via encoding is not yet available for multiple encoding options. UML models designed for deriving XML schemas using GML simple features have not yet been proven to support alternative encoding options becoming more prevalent - in particular JSON encodings. (Work is underway within OGC to explore this - however emergence of best practices might take longer, so recommendations below suggest a proactive approach to test and feed requirements into this process.)

In general it would appear that the survey software industry is adopting a “wait and see” around emerging technologies, hence there may be value in exploring an intermediate phase of testing the implementation challenges around localised profiles, validation and transformation using existing 2D geometry capabilities with multiple encoding options.

Recommendation 10: Implement a pilot serving existing 2D cadastral data using OGC API and JSON encoding and using JSON-LD extensions to link data to the machine readable model and validation capabilities.

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Recommendation 11: Implement a pilot transformation/validation service using the 3D Cadastral Survey Data Model Canonical Logical model as a target model to take advantage of native and rich validation capabilities.

Recommendation 12: Track international efforts to explore transformation between GIS, CityGML and IFC encodings and determine the potential relevance of emerging capabilities.

4.3 Co-Design Experiences

The experience of undertaking a "Co-Design" approach with subject matter experts *and* business (problem) owners has proven to be extremely rewarding to effectively narrow down the tenuous scope implicit in a large number of documents and anecdotal descriptions of shortcomings and challenges into a well understood and document agreed scope.

The systematic application of the AGILE methodology was well supported by both the supplier consortium and the ICSM team, and proved to be a critical framework for allowing steady and incremental progress through a very complex set of concerns.
The final design - of both the underlying scope and requirements and the resulting derived model is quite elegantly simple - reflecting the adage "if I had more time I would have written a shorter letter".

Such a Co-Design approach is a significant investment, however from the perspective of the projects technical lead, a data modeller who has worked with many projects, teams, communities and standards over the decades the project technical lead, this project has been exemplary in both commitment and the ability to relatively "fast-track" both a candidate model and a common understanding of its scope and design in its initial audience. (Similar scoped models have often taken 5 or more years before implementation work can be progressed.)

Recommendation 13: Future work on this project should adopt the same 'Co-Design' approach with subject matter experts and business owners to support full engagement for the outcomes required.

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4.4 Modelling Language - Rationale for Semantic vs UML

The modelling team has significant experience with UML modelling using the ISO 19103/19109 framework and generation of GML application schemas directly from the model. Recent work has included derivation of semantic models from such source material. The key value for this has been the availability of GML patterns for Simple Features geometry implementations. Unfortunately these implementation patterns are not available for 3D geometry and topology, and hence the relative benefit of this approach is lost compared to the overheads and challenges of UML based modelling.

These challenges may be summarised as a lack of consistency in UML models for common practises across the level of abstraction (conceptual vs logical), the UML idiom itself, the management and maintenance of reusable UML models in accessible repositories and the "re-invention of the wheel" for basic implementation patterns in multiple UML models that results from these reusability challenges.

The decision therefore to model within a knowledge graph using semantic models has allowed:

- Reuse of many underlying standard models
- Integration of conceptual, logical, implementation models in a single environment
- Integration of analysis models and underlying reference material
- Cross-referencing the model conceptual and logical views
- Cross-referencing of the model to requirements, related standards and examples
- Integration of example data expressed using the model
- Integration of example data in heterogeneous formats
- Integration of data validation capabilities
- Direct access to the extended knowledge graph to support an integrated and highly extensible specification documentation product exposing multiple different aspects of the model (and potentially future implementations).
- Integration of UML diagrams as model documentation.

Although the consortium faced a range of low-level technical challenges assimilating such a wide range of resources in a novel methodology, ultimately it was proven feasible to manage a knowledge base with all these elements using available "meta standards" and off the shelf tooling (notwithstanding significant customisation effort).

The successful project execution and final deliverable reflects the viability of this choice. It is a modular knowledge base expressed using open standards that can be used by a range of available

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technologies - albeit with some customisation expected to support the particular different types of information elegantly.

Recommendation 14: The machine readability and native validation functionality of the SHACL component of the 3D Cadastral Survey Data Model should be exploited to further test model definition, examples and emerging implementations.

Recommendation 15: ICSM should consider options for automated derivation of UML from a semantic model (or synchronisation to preserve diagram layouts) or vice versa (with SHACL).

4.5 Jurisdictional Mapping

The exact scope of the "Jurisdictional Mapping" reflects the Co-Design engagement through analysis and modelling phases. It became clear that many of the key requirements around 3D representations were not explicitly covered in either the regulatory material nor existing implementation examples - there simply was not a set of existing practices to map to or to drive harmonisation of the model.

What was evident however was the diversity of terminology used across different jurisdictions and subtle differences in process and metadata requirements. The eventual approach to Jurisdictional Mapping was thus a combination of related aspects:

1. To explicitly map model requirements to a knowledge base derived from legislation and regulations.
2. To explicitly map agreed terminology (from the Co-Design process) to specific terminology from jurisdictions. (*This approach has been catered for but not executed within this phase - each jurisdiction should attempt to harmonise its own internal terminology during the development of jurisdictional profiles, at which point the model itself is available as a candidate source of terminology for adoption where appropriate).*
3. To include references to jurisdictional perspectives in the generated documentation - with the option to generate specific versions of the document for a given jurisdiction.
4. To model a flexible pattern of customisation via an extensible set of "Jurisdictional Code List" types at a conceptual level, and instances of such code lists at a logical model level.
5. To create examples of a logical model of Jurisdictional Code Lists using a standard vocabulary model with multiple possible implementation encodings available.

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6. To allow further customisation of the logical model for jurisdictional scope using the same flexible constraints languages incorporated into the logical model (a combination of SHACL - shapes constraints language and easily integrated semantic models of any jurisdictional specific business rules and extended metadata requirements).

A summary of the gamut and facets of the mapping completed are outlined below:

- 49 Jurisdictional documents were ingested into the platform and mapped by jurisdictions
- The general spread of mapped Pre-Conditions per each Use Case is shown in Table 2.

Table 2: Summary of Mapped Pre-Conditions by Use Case

Use Case	Count of Mapped Pre-Conditions
Use Case 03 - Survey Observations	73
Use Case 03.1 - Survey Points and Marks	278
Use Case 03.2 - Per Observation	171
Use Case 03.3 - Occupation	94
Use Case 04 - 3D Cadastral (Primary) Parcel Surface	201
Use Case 04.1 - 3D Cadastral (non-primary) Parcel Surface	53
Use Case 05 - General 3D Spatial Unit	18
Use Case 05.1 - Parcel Requirements	31
Use Case 07 - Cadastral Survey Dataset Details	274
Use Case 07.1 Cadastral Survey Documentation	114
Use Case 07.2 - Equipment Description	41
Use Case 07.3 - CSD Datums	101

- From a total of 91 Pre-Conditions developed in the Use Case model, only 14 were not mapped by any Jurisdictions. At the time of writing, these were:
  - Geometries to be Referenced
  - Parsimony - avoid duplication of information

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    - Compatibility with encodings available for related systems
    - Have a GML geometry encoding that preserves topology information
    - Convenience of form for most important cases.
    - State Solid Volume
    - Explicit Semantics of encoded elements
    - Features with observable, optional geometries
    - Tool support
    - Future-proofing
    - Requires a Terrain Intersection Curve
    - Be information-complete w.r.t. topology
    - Solid Geometry Requires Topology
    - Encoding Requirement
- The reasons for this may include:
    - At a higher level of abstraction (about modelling) than regulatory requirements.
    - No suitable jurisdictional document parts that are relevant to the Pre-Condition
    - Knowledge discovery issues due to the relative complexity communicated by users of navigating the array of Pre-Conditions
    - Potential data issues which prevented users from finding the Pre-Condition

Recommendation 16: Extend the provided semantic model with localised jurisdictional profiles, encoding and transformation details to retain a coherent interconnected knowledge base, tracing capabilities to underlying requirements and to support sharing of experiences around implementation.

4.6 Model Testing

A key methodological advance implemented in this project was to introduce systematic model testing capabilities. This reflects an innovative application of a more general technology best practice around software development through test design. The use of a knowledge graph framework allows for test cases to be implemented as data instances directly against the conceptual model, and validation for completeness against the logical model using standardised approaches (SHACL). In the knowledge management platform SHACL validation of examples can be performed by the user.

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It would be possible (and is highly recommended) to incorporate automation of SHACL validation against implementation examples by testing transformation of implementation encodings to the canonical logical model and executing these tests. This allows one set of tests to be used both to help maintain the reference specification and reference test data sets, but also to test individual implementation options, including both encoding formats and implementing software.

The same logical model components and transformation utilities can then also be directly used at run-time in implementing systems to validate data.

4.7 Knowledge Graph Driven Document Generation

Another key innovation introduced in this project is the application of the technique of the Continuous Integration/Continuous Development (CI/CD) process - in this case automated regeneration on a regular basis of the specification documentation from the knowledge base, including model, examples, cross-references, jurisdiction mapping summaries and other aspects as required.

The documentation template was built on a standard OGC pattern and uses the same underlying open and free documentation generation tools, customised to access the knowledge base.

Significant further customisation was introduced to include the example data aspects, including integration of a dynamic viewer component that performs both the function of user orientation around example data, but also testing the ability to transform elements of the 3D Cadastral Survey Data Model to equivalent elements using the buildingSmart IFC encoding.

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5 Detailed Findings

5.1 Model Usage

The model is delivered as a coherent, interconnected knowledge base. This knowledge base is used by the specification publication process, but can be extended as a repository of implementation resources.

The model is ready to derive implementation (encoding) specifications - however it is worth noting that this typically involves constraints around technology support. Derivation of encoding standards tends to be a hybrid approach based on model translation and predefined libraries of implementation patterns for some concepts. (For example, typical Application Schema in UML based on ISO19103 uses the ISO19107 geometry model - however implementations are expected to capture references to ISO19107 and directly convert to data structures supported by implementations - usually GML Simple Features- as opposed to direct translation of the model.)

Thus the recommendation is that the model is used to define implementation patterns for target technologies (XML, JSON, IFc) for a reusable 3D geometry module, and then use these as part of a direct derivation process from the model to implementation schemas.

It is recommended that the model is used to directly drive implementation testing in a CI/CD/CT approach supported by “playground” utilities and reference test data.

It is recommended that the model is aligned with available and emerging implementations through updating the knowledge base and exploiting in particular CT (testing) part of CI/CD/CT.

It is also recommended that the model be further tested and used directly to support publication of jurisdictional implementation profiles - it provides the data model for local customisation through code lists. The standard model for these code lists can be extended using the existing modelling framework to include local business rules relating to processes and co-existence of components - for example a requirement that a cadastral parcel appellation includes a particular form of reference to a previous survey or an estate title.

It is recommended that the model is used to drive transformations to support interoperability between different systems - for example to derive CityGML views or IFC views for integration into landscape or design scale applications. The model supports modular transformation mappings as a design pattern, however standardisation of transformation specifications is an active and emerging capability in the open standards environment.

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Recommendation 17: The model and its supporting material continues to be delivered as a coherent, interconnected knowledge base.

5.2 Model Maintenance

It is recommended that the facility to maintain the model as an extensible knowledge graph is maintained and the CI/CD specification generation capability is deployed for ongoing use.

It is recommended that implementation exercises act as further tests of the model and model governance and maintenance processes are established to support rapid and shared access to model updates. This phase should be regarded as an extension of the Co-Design approach, albeit with an updated set of stakeholders.

It is recommended that a stable version of the model is published when at least one implementation is proven viable, at which stage model governance processes can evolve to more formal change management and publication support preservation of previous versions as required.

Recommendation 18: Centralised governance and maintenance processes established to sustain the model.

5.3 Jurisdictional Profiling

It is recommended that Jurisdictional Profiles be described both conceptually and using specific implementation platforms relevant to jurisdictional systems.

This involves:

- Extended models to capture local business rules (if applicable)
- Publication of localised codelists as per provided patterns.
- Publication of SHACL constraints to use local customisations against the “canonical logical model”
- Publication of technology-native constraints

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Note that "technology-native constraints" may be limited in scope - for example XML schemas can validate structure, and Schematron can perform some limited content validation but more advanced business rules need customised code to check.

Recommendation 19: Jurisdictional profiles are developed with governance in place for future platform implementation. Use is mandated via business rules, derived from surveying regulations, in line with the conceptual model.

5.4 Ongoing Governance and ICSM roles

The possible role of ICSM in exploitation and implementation of this model will potentially be mirrored across multiple domains. This project represents an evolution of best practice, particularly around the systematic provisioning of models with supporting materials for both technical implementation and regulatory response.

It is recommended that ICSM be considered a potential "jurisdiction" for the purposes of defining interoperability profiles of potentially internationally standardised models, and supports further specialisation by jurisdictions and related application domains using the same mechanisms. These mechanisms include model management, vocabulary (code list management) and maintenance governance patterns.

It is also recommended that ICSM consider hosting or governance of shared implementation services such as documentation generation, testing services, "playground" and reference (test) data. Such services can be developed and tested in pilots at a jurisdictional level and adopted by ICSM when proven to meet operational requirements.

These recommendations are consistent with the objectives of the Cadastre 2034 and would be part of a governance framework where ICSM would provide leadership, accountability, transparency, openness, integrity and efficiency. The framework would also outline how the jurisdictions would interact within a federated environment.

Recommendation 20: ICSM develops a governance framework to support ongoing development, exploitation and implementation of the 3D CSDM.

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Recommendation 21: ICSM takes on the role of a central repository for models and code lists. As a central representative organisation, ICSM would be the repository of best practice providing supporting materials and maintenance governance patterns.

Recommendation 22: ICSM to consider hosting the shared implementation services such as documentation generation, testing services, 'playground' and reference (test) data on behalf of the jurisdictions.

5.5 Standardisation

The 3D CSD model is based on the most appropriate available standards. Such standards do offer interoperable implementations, such as GML for ISO1907, however it is clear that the range of implementation options are not consistent across different standard models and the evolutionary nature of encoding options. Nevertheless, "filling in the gaps" with implementations of key patterns as required is preferable to the proliferation of ad-hoc approaches in different domains. Standardisation pathways for these enablers can be sought to future-proof implementations.

Alignment with other standards should be undertaken at the time implementation and encoding specifications are developed. This is because many such standards are only available at implementation level of detail (schemas), and implementations will require testing in detail using example data to validate semantic interpretations and alignments.

Consideration should be given to the international standardisation of a 3D Geometry and Topology profile that can be implemented in reusable software libraries and multiple different encoding technologies. We recommend that a priority is given to defining a 3D profile of ISO 19107 with accompanying encodings in a subset of GML and the planned FG-JSON (Feature-Geometry) encoding standard.

In parallel, investigation of JSON-LD encodings for *Observations & Measurements* (ISO 19156)-based models compatible with emerging OGC API and GeoPackage solutions in particular should be explored as a basis for encoding technology modernization, using existing 2D cadastral data to validate the process of deriving alternative physical models from the canonical logical model.

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Recommendation 23: Consideration to be given to international standardisation of a 3D Geometry and Topology profile (Recommendation 7) and implementation in reusable software libraries and multiple different encoding technologies.

Recommendation 24: Explore standardisation of OGC-API solutions via derivation of JSON-schemas and compatible JSON-LD annotation directly from the canonical logical model. (Note this is an enabler for Recommendation 10).

Recommendation 25: Explore derivation of ISO19103 UML profile from canonical logical model to support UML → GML encoding (and possibly future UML → JSON schema approaches). Note this will require a 3D GML profile standardisation to define reusable components for a XML schema encoding.

Recommendation 26: Provide for regular review of standard evolution linked to a model maintenance activity to take advantage of emerging encoding options and reusable resources, with the focus on long term viability of technology vendor support.

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6 Next Steps

6.1 Options for Implementation

6.1.1 Development of Physical Models

The “canonical logical model” provides one form of physical model that can be immediately implemented, as illustrated by the examples - however it is expected that the unfamiliarity of semantic models is likely to be a significant barrier to progress and hence this form is more useful as an intermediate model to support transformations and validations of multiple physical encoding models.

Our standards and technology review indicates no suitable “off-the-shelf” encoding for 3D topology exist, it is therefore recommended that attention be paid to developing:

- a equivalent JSON-LD encoding suitable for use with the new generation of OGC API specifications; and
- consideration of an extension of GeoPackage specification to support 3D.

See the section on *Schema derivation approaches* for more information on the development of physical models.

6.1.2 Technology Partner Engagement

Implementation requires a pathway to software support. As has been noted in discussions throughout the project, the most likely scenario is for one or more jurisdictions to test a suitable encoding for extraction and acceptance of submissions and then seek vendor implementations in a procurement process.

It is proposed that a short cut to the process could be achieved by focussing on the standardisation of a core 3D capability independent of specific application usage and the details of the model. Engaging technology partners in a limited collaborative process to develop this as a potential standard can be achieved using OGC innovation program processes, such as Testbeds, Pilots or Interoperability Experiments.

Implementation pilots that support candidate encodings, provide access to existing survey data using these and provide validation tools and reference data to allow compliance to be shown are the recommended engagement strategy in the short term. This allows an opt-in approach for vendors to examine encoding specifications in practice, understand local profile customisation requirements and evidence the standard is practical. A validation infrastructure provides a

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long-term framework to support future vendor engagement, validate compliance and support future evolutions of this and related data exchange models.

6.1.3 Standardisation

The GeoSPARQL Standards Working Group of OGC would be an ideal starting point for initial development of a 3D profile specification and reference implementation and testing. This is due to plans to formalise this specification as a joint ISO standard.

A set of specific activities could be defined to scope this development activity:

1. Specification of requirements for 3D representation options
2. Specification of functions required to transform 3D geometry forms to meet different requirements from different initial geometry representations
3. Support for JSON encoding for geometries
4. Support for JSON-LD to link application feature models to ISO19107 conceptual model via GeoSPARQL logical model.
5. Support for GML geometry for 3D
6. Support for GML topology
7. Support for IFC encoded geometries.

A range of activities and projects are also underway to investigate the relationships between CityGML and BIM/IFC. Future work would include investigating the potential role of a common 3D profile with these two specifications, as well as encoding options.

6.1.4 Development of a Reference Implementation

The model is machine-readable, and can potentially be used to derive implementation schemas using different encoding technologies. To conform to the direction of the wider community it is recommended that a JSON-LD encoding be developed as an implementation option consistent with the use of OGC API directions, and this is aligned with current activity within the OGC on a canonical JSON schema for the Feature/Geometry metamodel used by ISO models, GML and others.

It is recommended that JSON-LD be a key priority for encoding as it natively encodes the provided canonical logical model and can be directly validated using the model constraints. There is flexibility however in how JSON schema patterns can be enforced for interoperability amongst JSON environments that cannot process the additional semantic information.

Encodings should reuse standardised patterns for common data types - in the case of a 3D Cadastral Survey Data Model the most important pattern is support for reusable geometry elements within topologically explicit 3D feature representations. It is recommended that

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implementation of this specific module be undertaken first. The first step would be to define the necessary functions required to transform different geometry representations to test completeness and efficiency of the model encoding. A reference implementation (not necessarily optimised for performance) of the necessary functions can be developed in concert with a suite of test cases. This reference implementation can then be used to drive a validation suite for software implementations (to confirm their outputs can be used to derive the full set of geometric and topological information necessary for use of submitted data.

These 3D profile requirements should be submitted as an extension of the GeoSPARQL semantic standard in its planned evolution as a joint ISO/OGC/W3C standard. A supporting reference implementation using the Apache Jena open source toolkit could support native RDF approaches, but does not preclude more survey industry-oriented software library support - such as GeoPackage, GML or other encoding options in tools such as FME and open source libraries such as GDAL, GeoAPI, Leaflet (https://leafletjs.com/) etc.

6.1.5 Schema Derivation Approaches

For the full 3D Cadastral Survey Data Model a subsequent implementation approach can be based on either derivation of schemas from the model. Such technologies are feasible but not yet established; some research is required to determine availability of candidates and current activities in this space. Note this is an active area and will change quite rapidly in the near future. An ontology for describing JSON schema elements is already in development, which would support a standardised expression of the mapping from the logical model to a JSON-schema encoding: https://www.w3.org/2019/wot/json-schema. With this in place, it is relatively trivial to imagine software to perform this derivation.

An open source solution for a related problem (of establishing how published specialised profiles relate to underlying standards) has been developed as part of OGC research activities that generates JSON-schemas has been trialled and provides confidence that this approach is readily achievable given target JSON schema implementation patterns.

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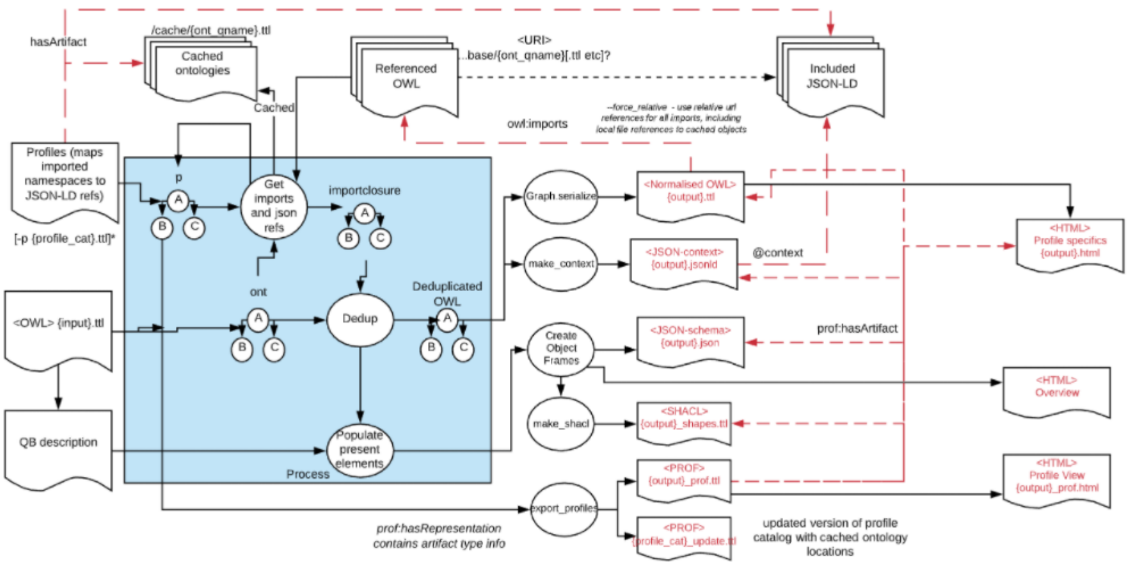

Figure 12: *Profilewiz* experimental tool for identifying overlaps between semantic models and generating minimal schemas

Other schema derivation tools and options may also become available and should be explored in a review process prior to committing to a trial of their capability. These include “shapechange” (https://shapechange.net/app-schemas/) used in various trials in OGC processes for UML models. Native schema generation for JSON may potentially be supported by semantic technologies as well as UML toolsets.
The suggested roadmap allows for experimentation of model->encoding derivation options for a 2D implementation pending availability of encoding options for 3D aspects being finalised.

6.1.6 Interoperability Through Validation of Transformations

It is also recommended that 2-way transformations between the canonical encoding (RDF) and each implementation is developed and shared as part of the extended knowledge base for the model (and hence accessible via model documentation).

The use of SHACL (Shapes Constraint Language) to refine the Conceptual Model to specify a Canonical Logical Model provides for native validation capabilities against multiple valid RDF encoding options (XML, TTL, JSON-LD). SHACL provides a much richer validation option than typical schema validation capabilities native to some encoding formats. Furthermore, this approach can be further extended to define specific and alternative Logical Models to meet specific encoding patterns, and the definition of Jurisdictional profiles determining allowable code lists and additional business rules.

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This provides for a single option for testing interoperability of encoding options and implementations in a flexible platform. Not only is the basis for validation using SHACL native to the delivered form of the logical model, it is richly powerful and extensible with plug-in functions as required. (Some complex business rules may require software development for specific functions - not the proposal to develop reference functions for 3D geometry manipulation and validation) . .

6.1.7 Regulatory Review

The update of regulations to support a full 3D digital submission process is an expected follow-on activity. The project has delivered a structured knowledge base of *current* regulations and relation to the 3D Cadastral Survey Data Model.

The opportunity this presents is to perform systematic gap analysis and collaborative development of new regulations to meet this expectation, through extension of the knowledge base and online collaboration tools.

6.2 Other Options for Exploitation of Knowledge Base

In addition to the direct implementation pathways of encoding design, interoperability validation and regulation development, the knowledge base provides for future integration of the 3D Cadastral Survey Data Model into a broader context.

This includes:

- Mapping of the model to existing and emerging implementation options
- Mapping of the model to existing and emerging standardised domain models
- Reuse of model components in larger system scopes, such as Digital Twin activities.
- Mapping of the model to related application domain models
- Development of implementation profiles to simplify usage for specific applications
- Semantically enhanced search functions across regulation and related documentation.

Each of these opportunities will require some analysis of the current and emerging context and underlying business requirements to choose the most effective approach, however model modularity and extensibility, coupled with use of powerful general purpose model patterns means that such activities can be easily assimilated with minimal impact on the core implementation processes.

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7 Annex 1 - Glossary

Term	Definition
Apache Jena	A free and open source Java framework for building Semantic Web and Linked Data applications based on RDF.
BIM/IFC	Building Information Model IFC is a standardised, digital description of the built asset industry. It is an open, international standard (ISO 16739-1:2018) and promotes vendor-neutral, or agnostic, and usable capabilities across a wide range of hardware devices, software platforms, and interfaces for many different use cases.
CityGML	The OGC CityGML standard defines a conceptual model and exchange format for the representation, storage and exchange of virtual 3D city models.
CI/CD/CT process	Continuous integration, continuous delivery, continuous testing and continuous deployment is a method to frequently deliver applications to customers by automating stages of the application development process. .
FME	Feature Manipulation Engine is a data integration platform with built-in support for hundreds of formats and applications and transformation tools. It allows users to build and automate custom integration workflows.
Geo-API	The W3C Geolocation API returns a location and accuracy radius based on information about cell towers and WiFi nodes that the mobile client can detect.
GDAL	The Geospatial Data Abstraction Library is a computer software library for reading and writing raster and vector geospatial data formats.
GeoPackage	A GeoPackage is an open, non-proprietary, platform-independent and standards-based data format for a geographic information system implemented as a SQLite database container.
GeoSPARQL	OpenGIS® standard for SPARQL (RDF Query Language) extensions and an ontology for geospatial data
GML	OpenGIS® Geography Markup Language (GML) Encoding Standard. The standard is also published by ISO as ISO 19136:2007.
IFC	Industry Foundation Classes (IFC), is a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an

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	open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases. Multiple encoding standards for IFC exist and are being actively developed, including xml (ISO 10303-28:2016), json, hdf (ISO 10303-26:2011) and ifcOwl formats; with the STEP physical encoding format (ISO 10303-21:2016) currently being the most commonly used file format.
ISO	International Standardization Organization, www.iso.org ISO is an independent, non-governmental international organisation with a membership of 167 national standards bodies. Through its members, it brings together experts to share knowledge and develop voluntary, consensus-based, market relevant International Standards that support innovation and provide solutions to global challenges. (Standards Australia is the Australian national standards body represented on ISO www.standards.org.au)
JSON	JavaScript Object Notation is a lightweight, standardised, data-interchange format.
FG-JSON	JSON for Feature Geometry - this is a method of encoding geospatial feature data using JSON.
JSON-LD	JSON for Linked Data - a W3C standard for encoding linked data using JSON.
Leaflet	https://leafletjs.com/
OGC	Open Geospatial Consortium, www.opengeospatial.org The Open Geospatial Consortium (OGC) is an international consortium of more than 500 businesses, government agencies, research organisations, and universities driven to make geospatial (location) information and services FAIR - Findable, Accessible, Interoperable, and Reusable.
OGC-API	The OGC API family of standards are being developed to make it easy for anyone to provide geospatial data to the web.
Ontology	Ontologies are frameworks for representing shareable and reusable knowledge across a domain. They describe relationships and connections making them useful for modelling high-quality, linked and coherent data.
RDF	Resource Descriptor Framework - the W3C standard for describing knowledge as graphs of logical (subject,predicate,object) assertions (triples).

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SHACL	Shapes Constraint Language is a W3C standard language for describing RDF graphs. It is designed to enhance the semantic and technical interoperability layers of ontologies expressed as RDF graphs.
UML	Unified Modelling Language is a modelling language used in the field of software engineering to provide a standard way to visualise the design of a system.
W3C	The World Wide Web Consortium (W3C) is an international community that develops open standards to ensure the long-term growth of the Web. www.w3.org

This glossary tries not to repeat the cadastral terms provided by ICSM on their website:

- "Cadastre definitions - Glossary" - https://icsm.gov.au/sites/default/files/Cadastre%20definitions%20glossary-v1.0.pdf
- "Cadastral boundary system concepts and terminology" - https://icsm.gov.au/what-we-do/cadastre

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8 Annex 2 - Acknowledgements

Sincere thanks go to the many people who have contributed to the success of this project. Those listed below are specifically acknowledged for their significant contributions, however thanks and appreciation are also extended to those members of your teams and networks not specifically named.

Name	**Role**
Anselm Haanen	Steering Committee Chair
Jeff Needham	Steering Committee member, Product Owner (NZ) and Contract Manager
Genevieve Abrey and Toni Hill	NZ Subject Matter Experts
Jennifer Lai	Project Manager
Eric Sharpman	Steering Committee member (NSW)
Adrian White	Steering Committee member and Product Owner (NSW)
Prudence Lawrence and Simon Hine	NSW Subject Matter Experts
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Mark Briffa and John Gallagher	Steering Committee member (VIC) and Subject Matter Experts
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