ROADMAP FOR INTEROPERABLE 3D DATA MODELS IN OGC APIS AND OTHER DATA EXCHANGE APPROACHES

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ABSTRACT:

Many data exchange standards for 3D spatial data applications exist, ranging from the general Geography Markup Language (GML) underpinning CityGML to specific models for business application domains, such as BuildingSMART Industry Foundation Classes (BIM/IFC). There are a number of different approaches to modelling 3D objects, and in general the geometry aspects of these can be readily understood in the context of the visualisation needs of different applications. The topology, or relationships between elements of these objects, on the other hand is either not directly supported by such geometry models or implemented in different ways by different standards. We discuss limitations of existing standards for describing topological relationships in particular. In some cases topology information is embedded in geometry objects using identifiers for vertices, edges and faces, but in general there is scope to develop a standardised model for describing alternatives for topology and 3D geometry representations. A limited set of such models allows for interoperability via transformations between different representations. The ISO 19107 Spatial Schema provides an adequate conceptual model for these concerns, so we present the argument that a profile of this comprehensive model be defined for the limited set of such representation options required for Smart Cities and other similar applications.

1. INTRODUCTION

Interoperability of typical 2D GIS data has been supported through a range of data exchange standards, usually explicitly underpinned by the conceptual framework of the *ISO 19107 - Spatial Schema* standard (ISO, 2019b). Whilst this model is a comprehensive model for multi-dimensional geometry and topology it is rarely, if ever, implemented in full, and many different possible partial representations for 3D geometry and topology are possible. *Geography Markup Language* (GML) (OGC, 2007, ISO, 2020) is a powerful XML encoding standard used for ISO 19107 data which can encode most of it, however, in practice, applications and software rarely support the full range of its possibilities and XML is increasingly being replaced or supplemented by JSON, YAML and "cloud native" binary formats.

For typical 2D spatial applications, the *Simple Features Access* (SFA) (ISO, 2004) profile of ISO 19107 has been created which restricts geometries to "simple features, such as points, lines, and polygons", and is designed to "lower the implementation bar of time and resources required for an organization to commit for developing software that supports GML". This profile is supported by nearly all spatial software, though the extent to which some underlying mechanisms, such as the use of references to reusable geometry elements using XML's *xlink* (W3C, 2001) and the orientation of geometry elements is implemented, varies. Software libraries such as GDAL[1] and Val3dity (Ledoux, 2018) represent a means for applications to cope with these complexities. SFA geometries may use 3D points, but SFA doesn't provide explicit support for solid geometries, shells, nor 3D topology.

Recent trends toward use of JSON (IETF, 2017) as an encoding technology have seen SFA implemented in GeoJSON (Butler et al., 2016), which is content to merely specify "Points Lines and Polygons" without formally referencing an underlying definition for them. The OGC FG-JSON (OGC, 2021) is looking at extended or complementary schemas to support a wider range of capabilities, such as choice of spatial reference system and solid geometries.

We propose a 3D spatial data profile of ISO 19107 (ISO, 2019b) and the specification of functions for 3D data operations. These functions can be implemented in software packages and validated using a test suite. Implementations can be tested against multiple options for encoding, such as JSON & XML. GeoSPARQL (Car et al., 2021) in particular provides the opportunity for the use of JSON-LD (Kellogg et al., 2020) as a bridge between the many emerging JSON schemas and validatable canonical forms with transparent semantics.

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[1] "a translator library for raster and vector geospatial data formats": https://gdal.org/

2. METHODOLOGY

An application domain requiring 3D data exchange standardisation, in this case cadastral parcel definition and survey data exchange, was analysed to identify informational content requirements. These requirements were then compared to various 3D data and exchange models to quantify potential for software support as a key enabler for uptake of any data exchange model.

3D cadastral data includes range of 3D geometries typically found in many 3D spatial domains. Curves (boundary edges) and surfaces (boundary faces) may be planar or parametric, solids (cadastral parcels, easements, etc.) may contain voids where specific property rights are excluded. Survey observations and cadastral parcel boundaries may be described by vectors, or by reference to other spatial objects. Cadastral parcels may also be unlimited in the Z axis. As such, we consider 3D cadastral data geometries and their topological requirements to be representative of a broad range of object-oriented (Worboys, 1995) 3D application domains.

Scenarios were encoded in various candidate spatial data encoding technologies to determine the potential overhead involved and then compared to existing software capabilities. These candidates were drawn from standardisation bodies such as the Open Geospatial Consortium (OGC)[2], buildingSMART[3], the World Wide Web Consortium (W3C)[4], IETF[5] and included both general purpose models (GML (ISO, 2020), GeoJSON[6], GeoSPARQL (Perry and Herring, 2012), etc.) and application domain specific models such as CityGML (Kolbe et al., 2021), IFC[7], etc.

2.1 Review of existing approaches

From a standards and interoperability perspective specification of a 3D data model must be designed to be encoding agnostic - and conceivably may be implemented in whole or part with a range of different encoding technologies. Ideally, the conceptual model would be modular with the canonical logical model based on patterns favouring well-known encoding standards that can be reused. For this work, key patterns expected to influence encoding choices include 3D Solid Geometry and Topology of 3D Solids.

A topology pattern, particularly for cadastral data, is expected to strongly influence encoding choices for 3D solids, as cadastral parcels are often required to form a continuous partition of a jurisdictions territory to define exclusive property rights. A frequent requirement of cadastral systems is that there should be no gaps nor overlaps between uniquely owned cadastral parcels; that observation vectors do connect to survey marks found in the field (survey vectors, observations and boundaries, must stop and start at survey points), etc. Additionally, partial rights to property such as easements should be located within one or more cadastral parcels. These relationships are required to ensure data consistency and limit confusion with respect to property rights. More specifically, solid geometry requires an assessment of topology to ensure closure (Stroud, 2006).

Within the geospatial information space topology is recognised as being important particularly for analytical applications (Theobald, 2001). ISO 19107 (ISO, 2019b) and application schema adopting the standard assume a topological primitive approach where objects are deconstructed into their primitive components (nodes, edges, faces,...). Objects are then defined topologically by their bounding primitives (their outer surface). Topological relationships between objects can then be identified by searching for primitives that are shared by the objects (Zlatanova et al., 2004, Zlatanova, 2017). Topology also enables topological primitives *boundary*, *interior* and *exterior* (Egenhofer and Herring, 1990) for describing relationships between spatial objects. This approach has been adopted by the OGC as a basic implementation framework (OGC, 2011).

There are many reasons why a standard encoding of the concepts required to implement a 3D cadastre is not available. Complex and comprehensive standards such as ISO 19107 (ISO, 2019b) may support faithful abstract representations of the underlying theory but are not easy to implement as data exchange standards. Standardised encoding approaches, where available, may also be challenging to use due to the complexity and scope of the standard. It is relatively easy to implement an ad-hoc solution for a narrow application scope, however, these will not be readily interoperable with each other. Many software systems also pre-date suitable encoding standards and may therefore require significant effort to incorporate current standards.

Considering the requirements for topology representation needed for cadastral surveys led us to focus on GIS feature-centric encodings and exclude CAD formats such as DXF and DWG that are object and project centric. However, BIM formats, particularly IFC, can play important roles in sharing 3D cadastre datasets. Existing and potential encoding standards for exchange were reviewed to determine the current state of play. We note that most of the current software used by Cadastral Surveyors fit more naturally in the BIM and CAD world than GIS. However, most land records offices store the cadastral fabric in GIS formats.

2.2 Geometry encodings

Various geometry encodings including Geography Markup Language (GML) (ISO, 2020), Well-known Text (WKT) (ISO, 2016b), GeoSPARQL (Perry and Herring, 2012), FG-JSON[8] and Discrete Global Grid Systems[9] (DGGS) were assessed to determine their ability to describe 3D geometries and topological relationsips. These encodings are frequently adopted for the transport of spatial information.

At a recent OGC workshop focusing on encoding issues and opportunities for LADM (ISO, 2012) data the top five data encodings (most common to least) were DXF (geometry only), GML (ISO, 2020), GeoJSON[6], CityGML(Kolbe et al., 2021) and LandXML[12].

GML is an XML grammar expressing geographical features defined in ISO 19107 (ISO, 2019b). GML serves as a modelling language for geographic systems and an open interchange format for geographic transactions on the Internet. Best practice when developing GML encodings (e.g., CityGML(Kolbe et al., 2021), InfraGML (Scarponcini et al., 2016)) is to create an XML schema (XSD) using the GML schema derived from a UML model based on ISO 19107 (ISO, 2019b). GML covers both geometries and tolopogy. Implementing a "model driven architecture" (MDA) approach to generating GML is well established within the OGC. It does however require consider-

[2] https://www.ogc.org
[3] https://www.buildingsmart.org
[4] https://www.w3.org/
[5] https://www.ietf.org
[6] https://geojson.org/
[7] https://technical.buildingsmart.org/standards/ifc/
[8] https://www.ogc.org/projects/groups/featgeojsonswg
[9] https://docs.ogc.org/as/20-040r3/20-040r3.html

able expertise and tooling support. Regardless of its complexity, GML has been broadly adopted by technology partners, with the caveat that developers have found numerous alternative ways to implement feature geometries resulting in interoperability difficulties. For example, software application A may use a point list to define the exterior of a polygon, whereas software application B requires a LinearRing.

WKT (ISO, 2016b) is a text markup language representing vector geometry objects. WKT overlaps and extends the ISO SFA standard (ISO, 2004). A binary equivalent, Well-Known Binary (WKB), transfers and stores the same information in a more compact form convenient for computer processing but is not human-readable. The formats were initially defined by the OGC and described in their Simple Feature Access.

GeoSPARQL (Perry and Herring, 2012) is an OGC standard that defines a vocabulary for representing geospatial data in RDF and describes an extension to the SPARQL[10] query language for processing geospatial data. It incorporates a topological ontology in RDFS/OWL for representation of GML and WKT geometries, and includes RCC8 (Randell et al., 1992) for spatial reasoning and DE-9IM (Clementini et al., 1993) for assessment of topological relations.

New to the domain of geometry encodings is the OGC Features and Geometries JSON Standards Working Group[8] (JSON-FG SWG). The JSON-FG SWG is building upon the GeoJSON[6] standard to extend essential concepts to the broader geospatial community and the OGC API standard[11]. Initial features include access to a broader range of Coordinate Reference Systems (CRSs), support for ellipsoidal metrics, 3D geometries, and provision of guidance on the representation of feature properties in JSON that are consistent with the General Feature Model (ISO, 2015).

2.3 Application schema encodings

A range of application encodings have been developed for consumption by software applications. Encodings reviewed included Industry Foundation Classes (IFC) (ISO, 2018), LandXML[12] (including regional adaptations ePlan[13] and LandonLine[14]), IETF GeoJSON [15], LADM (ISO, 2012), CityGML (Kolbe et al., 2021), InfraGML (Scarponcini et al., 2016), TopoJSON[16], CityJSON[17], and GeoPackage[18].

LandXML[12] is a specialised XML application encoding used to describe property boundaries, infrastructure features such as roads and underground services, and survey and engineering surveying measurements. The encoding is commonly used in the surveying, land development, and transportation industries. Originally developed to enable data transfer and archiving of data, it is now a standard industry encoding built into many common CAD software packages including 12D, CivilCAD, AutoCAD and Trimble Business Centre. Regarding previous works, we note that various parties have investigated the prospect of basing a 3D cadastre on LandXML based encodings. However, the use of LandXML for 3D is hindered because support for 3D Solid Geometry and Topology is limited. While Z coordinate values are supported, Solids are not, nor is topology. The proliferation of incompatible profiles of LandXML reflect the challenges of emergence of technical standards via non-formal governance processes. LandXML also lacks a conceptual model which was why OGC decided to progress LandInfra rather than adopt LandXML as an OGC endorsed community standard.

Industry Foundation Classes (IFC) (ISO, 2018) is a standard developed for Building Information Model (BIM) data that are a standardised, digital description of the built asset industry. Typically these are implemented using STEP encoding (ISO, 2016a). IFC (ISO, 2018) is an open standard, intended to be vendor-neutral / agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases. IFC geometries and topologies are similar to those defined in ISO 19107 (ISO, 2019b) insofar as ISO 10303-42 (ISO, 2019a) allows for both boundary representations of solids and general sweeping using 2D shapes extruded along curves. ISO 10303-42 (ISO, 2019a) also includes a topological schema that has its basis in boundary representation solid modelling. While not specifically designed for cadastral use cases, IFC does include a number of appropriate classes to describe both cadastral parcels and building occupations. In addition, IFC can provide a useful transfer encoding for 3D geometries that can integrate with existing BIM software used in the Architectural, Engineering and Construction (AEC) industry.

GeoJSON[6] encodes data about geographic features using JavaScript Object Notation (JSON)[19]. GeoJSON provides a means of representing both the properties and spatial extent of features. The central focus of GeoJSON is to simply share spatial data for display in web maps. Much of GeoJSON's popularity derives from its simplicity, making it easy to implement, read, and share. However, it has limits. GeoJSON has no support for 3D geometries, only SFA geometry types. GeoJSON has no construct for topology although TopoJSON[16] can be used to extend GeoJSON to include topology constructs. GeoJSON features have properties encoded using JSON. Properties can use any JSON datatype: numbers, strings, booleans, null, arrays, and objects. However, JSON doesn't support every data type commonly used with spatial data: for instance, date values. GeoJSON doesn't support curves. If you have a LineString representation of a route that you have run, and your GPS watch logged 1,000 different points along that route, including your heart rate, timestamp,etc., there's no clear answer for how to represent that data using GeoJSON. SFA, which directly inspired GeoJSON and most GIS formats, doesn't support linear referenced locations[20]. GeoJSON currently supports a single coordinate reference system, WGS84, except by prior arrangement (with the end user), making it difficult to share data in other coordinates systems.

ISO 19152:2012 Land Administration Domain Model (LADM) (ISO, 2012), originally an initiative of FIG[21], is a conceptual model that defines an ontology for land administration. LADM has been implemented in many countries, at least 40 (Kalogianni et al., 2021). LADM depends on ISO 19107 (ISO, 2019b) for geometries such as point, curve (line), surface (area), and solid (volume) and topology when required. The main dif-

[10] https://www.w3.org/TR/sparql11-query/
[11] https://ogcapi.ogc.org/
[12] http://landxml.org
[13] https://www.icsm.gov.au/publications/eplan-model-v10
[14] https://www.linz.govt.nz/land/landonline
[15] https://datatracker.ietf.org/doc/html/rfc7946
[16] https://github.com/topojson/topojson
[17] https://www.cityjson.org
[18] https://www.ogc.org/standards/geopackage
[19] https://www.ecma-international.org/publications-and-standards/standards/ecma-404/
[20] Note that GML 3.3 adopts ISO 19148:2021 Geographic information — Linear referencing.
[21] https://www.fig.net/

ference is the terminology that is customary to each application domain is adopted and the grouping of geometries to form more complex features. LADM also includes spatial unit extensions for LocationByText, non-2-manifold and/or unbounded volumes (conventional 2D parcels unbounded in the Z direction). LocationByText allows a spatial unit to be described by a text string, e.g., "that part of Lot 2 south of river", or, "the western 20 m of Lot 5". LADM v2 is currently under development (Lemmen et al., 2020).

The CityGML (Kolbe et al., 2021) standard utilises GML encoding to define a conceptual model and exchange format for the representation, storage and exchange of virtual 3D city models. It facilitates the integration of urban geodata for a variety of applications including Smart Cities and Urban Digital Twins; urban and landscape planning; Building Information Modeling (BIM); mobile telecommunication; disaster management; tourism; vehicle and pedestrian navigation; etc. CityGML 3.0 standardized the underlying information model, and aligned it with ISO so that it can be implemented in a range of technologies. It allows data to be encoded in GML/XML and JSON, or database schemas. Geometries of all CityGML feature types are represented using the geometry classes defined in ISO 19107 (ISO, 2019b). In addition to primitive geometries (points, curves, surfaces, and solids), CityGML makes use of both geometry aggregates (MultiPoint, MultiCurve, MultiSurface, MultiSolid) and composites (CompositeCurve, CompositeSurface, CompositeSolid). The CityGML Conceptual Model does not employ the topology classes from ISO 19107. Topological relations between geometries can be established by sharing geometries (typically parts of the boundary) between different geometric objects via the use of XML's *xlink* (W3C, 2001), hence traversing the topology graph is not bi-directional.

InfraGML (Scarponcini et al., 2016) is an OGC standard with an XML encoding of the OGC Land and Infrastructure Conceptual Model Standard (LandInfra). InfraGML adopts GML 3.3 (ISO, 2020) for geometries and topology. The InfraGML encoding is an implementation-dependent GML encoding of concepts supporting land and civil engineering infrastructure facilities. It is a multi-part standard.

TopoJSON[16] is an extension of GeoJSON that encodes topology. Rather than representing geometries discretely, geometries are stitched together from shared edges. This approach eliminates redundancy, allowing related geometries to be stored efficiently in the same file. However, as with GeoJSON, 3D geometries are not supported and coordinate reference systems are limited to WGS84, except by prior arrangement.

CityJSON[17] is a new standard that encodes a subset of version 3.0.0 of OGC's CityGML conceptual data model (Kolbe et al., 2021). All standard geometries required for solid modelling using boundary representation are included. As is the ability to specify a coordinate reference system, although CityJSON only allows one as opposed to CityGML which allows many in a single dataset. Topological relationships are not supported, nor is there an equivalent to XML's *xlink* (W3C, 2001). Therefore, geometries common to multiple objects must be duplicated. The few CityGML features not currently supported are either because they are seldom used or would over-complicate the JSON encoding. Despite this, bidirectional conversion between CityJSON and CityGML is possible. Like CityGML, CityJSON provides storage of 3D city models built on JSON rather than XML. Limitations inherent in CityJSON are similar to those of JSON and CityGML—a lack of topology and linked data support.

OGC's GeoPackage[18] data encoding provides an SQLite database implementation of the OGC SF SQL specification (ISO, 2004). GeoPackage is an open, standards-based, platform-independent, portable, self-describing, compact format for transferring geospatial information. A GeoPackage, in essence, is an SQLite container using OGC encoding standards for storing vector features, tile matrix (raster data), non-spatial attribute data, etc. Because GeoPackages are a database implementation and can be normalised basic topology is able to be included. Currently, 3D support is limited. 3D extensions may emerge but are not yet visible at `https://www.geopackage.org/extensions.html`.

2.4 3D solid geometry

Without the capacity to describe cadastral information as solids, the ability to submit 3D cadastral information is limited as it is difficult to test whether the solids are watertight (closed), or validate spatial relationships between cadastral parcels. 2D cadastre parcels (polygon) only require definition in two directions, East (X) and North (Y). Whereas in the 3D space, spatial units (solid) defining the extent of a cadastral parcel requires definition in all directions, X, Y and height (Z). Within the computer modelling domain, the main representations used for the description of solids, spatial units constrained in all directions, include (Stroud, 2006):

- Cell decomposition - division of space, or a cadastral feature, into a set of elements, typically voxels;
- General sweeping - the representation of objects in terms of 2D shapes extruded along general curves, i.e., constructive solid geometry (CSG);
- Set theoretic - a set of primitive shapes or (parametric) surfaces (more correctly half planes) that when combined using Boolean operators form a solid; and
- Boundary Representation - a collection of surface elements that form the skin of a solid.

ISO 19107:2019 (ISO, 2019b) adopted the Boundary Representation (B-Rep) to describe 3D geometries. The skin is composed of a set of adjacent bounded elements called faces; cadastral boundary faces in this context, which define the object's shell. Faces are bounded by a set of edges, or boundary lines, which are curves lying on the surfaces of the faces intersecting the edges. The points where several faces meet are called vertices and, from the perspective of cadastral surveying, represent survey points generally. The data structure can be divided into two primary groups: one responsible for defining the object's structure (the topology) and the form or shape of the object (the geometry).

2.5 Topology of 3D solids

From a cadastral system perspective, topology provides two main functions. First is validating the data according to specific rules, e.g., no overlaps or gaps between primary parcels[22]. Second is the ability to identify and manage shared boundaries and other geometric relationships, e.g., in New Zealand, a Unit Title represents a stratum estate that lies within the base land (subdivided parcel) and is disjoint from the Common Property held by the Body Corporate. Satisfaction of this second requirement assists the implementation of the first because topological models allow geometries to be captured once and referenced many times, significantly reducing data volumes and enhancing

[22] A parcel that may not overlap with other parcels of the same type - they represent exclusive rights.

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data set integrity. Adopting the principles of topology also enables rapid spatial data retrieval, enhanced spatial analysis (Ellul and Haklay, 2006), and enforcement of data integrity rules (Theobald, 2001, Burrough et al., 2015).

Delegation of the enforcement of some topological rules to the application domain may be necessary. Indeed, it is possible, and even common, to delegate all topological concerns to the application. However, embedding topology in the data increases the interoperability of the data by reducing the reliance on particular software components, and also preserves the benefits of data set integrity and reduced file size. Pre-calculation of topological relationships is more efficient, as the relationships are identified once during data creation (typically by domain experts) and then are able to be queried many times (Ellul and Haklay, 2006).

It is long understood that topological relationships are the foundation of spatial reasoning (Dube, 2017). The theory of 2D topological relations has been well studied with Egenhofer and Herring's (Egenhofer and Herring, 1990) 9-intersection model (9IM) and its extension DE-9IM (Clementini et al., 1993) implemented in various software applications. However, neither 9IM or DE-9IM are able to resolve all topological relations between two simple geometries in 3D space.

As noted, topological relations between geometries can be established by sharing geometries (typically parts of the boundary) between different geometric objects. For example, the face between two adjacent 3D cadastral parcels should only be represented by a single geometry (a face) and referenced by all features or more complex geometries defined or bounded by the face. Thus, redundancy can be avoided, and explicit topological relations between parts maintained.

Ideally, the topological graph should be bidirectional, i.e., capable of being navigated up and down the graph. It is common to construct higher dimension geometries from sets of lower geometries, a boundary line is defined by a set of two or more survey points. Construction of geometries in this manner implicitly informs the topology of a spatial unit. However, topology in this sense only allows one-way navigation of the topology graph. Therefore, functions may be required to generate the necessary topology to address specific spatial queries, i.e., which survey points define the solid(s) describing this/these cadastral parcel(s).

This approach reflects the general approach taken by cadastral surveyors when defining cadastral parcel boundaries. Original, reliable monumentation (survey points) defines a cadastral boundary's location. A closed set of cadastral boundary lines defines the cadastral parcel, or a cadastral parcel face in the 3D space.

3D spatial objects may consist of points or vertices, Lines being an edge defined by two vertices, Faces described by a closed set of three or more lines, and Solids consisting of a closed set of four or more faces. Given these spatial objects, the 9IM model has been extended to a 25 Intersection Model (25IM) by subdividing a boundary into face, edge and vertex components (Zhou and Guan, 2019). Hence the five topological components are the exterior (3D), interior (3D), face (2D), edge (1D), and vertex (0D). This results in ten groups of topological relations, solid/solid, solid/face, solid line, solid/point, face/face, face/line, face/point, line/line, line/point and point/point. 25IM adopts the same spatial relationships as 9IM, being disjoint, contain, equal, meet, cover, and overlap. While 9IM has 512 (2^9) possible relations to account for 25IM has 33.5M in theory (2^{25}). However, in the real world these reduce to 2,651 topological relations (Zhou and Guan, 2019). This is still a large number that will take some computational effort to assess, particularly if data sets are large.

The following figures (1 and 2) depict two possible relationships, Solid/Solid Overlap and Cover.

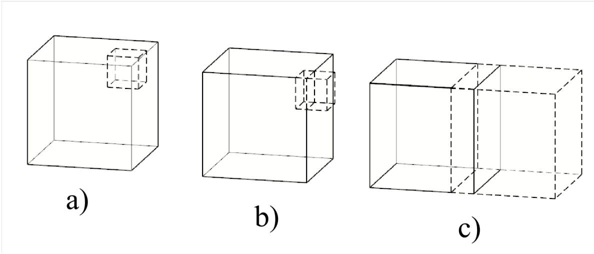

Figure 1. Solid/Solid Overlap: **a)** A's edges are disjoint from B's and a vertex of B is covered by A; **b)** A and B have faces that touch and a vertex of B is covered by A ; **c)** A and B have faces that touch and B has a face covered by A.

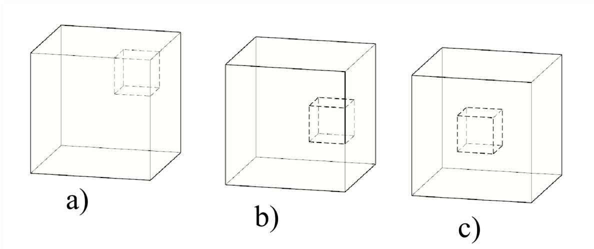

Figure 2. Solid/Solid cover at face: B is covered by A and **a)** has a common vertex and edges; **b)** has a common edge; **c)** and has a common face.

An ideal representation keeps geometry and topology separate, allowing greater flexibility but at the risk of ambiguity when created with conflicting information. This approach is implemented in GML (OGC, 2007) where the `<gml:Solid>` element describes the geometry, and the `<gml:topoSolid>` element describes the topology.

```
<gml:Solid gml:id="s1">
    <gml:name>Blue box above ground</gml:name>
    <gml:exterior>
        <gml:Shell>
            ...
        </gml:Shell>
    </gml:exterior>
</gml:Solid>
<gml:topoSolid gml:id="ts1">
        ...
</gml:topoSolid>
</gml:solidMember>
```

When a cadastral spatial units geometric representation is implemented using a strict B-Rep approach, then in instances where two or more spatial units intersect, e.g., an easement passing through a cadastral parcel, each spatial unit is split into discrete solids at parcel boundaries. The cadastral parcel would be split into the portion of the cadastral parcel outside the easement, volume **A** in Figure 3, and the portion inside the easement, volume **B** in Figure 3. The easement would also be split at the cadastral parcel boundaries, volumes **B** and **C** in Figure

3. These would then be aggregated to form each specific spatial unit. The easement portion inside the cadastral parcel, common to the cadastral parcel and the easement, is only created once but referenced in the definition of each spatial unit. All intersections between the cadastral unit and the easement are explicitly defined in this approach.

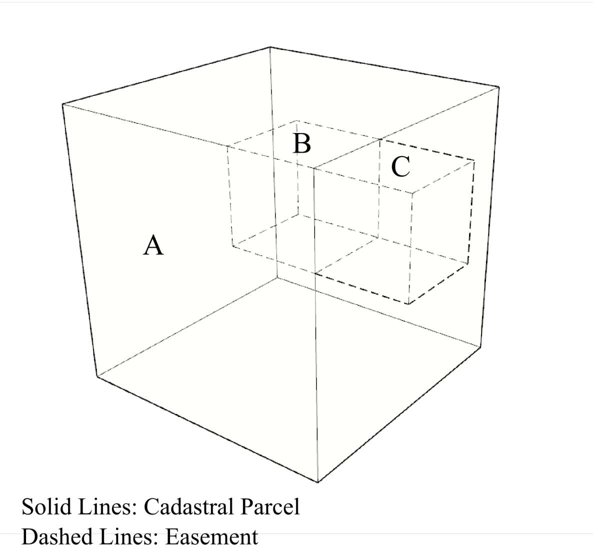

Figure 3. 3D geometry depicting two overlapping geometries

A simplified approach might model the cadastral parcel and the easement independently of each other. There is no explicit definition of the relationship between the two spatial units in this instance. If such an approach is adopted, from a cadastral surveying perspective, it is recommended that an intersection curve, similar to CityGML's terrain intersection curve, be defined to describe explicitly where the two solids meet.

3. RESULTS

Analysis of requirements identified that the topology of features in 3D was not easily addressed with pure geometry elements. A case in point is where a boundary between adjacent 3D objects may have a complex geometry and require explicit information pertaining to its state - such as its area, or its "occupation". In other words: observations about real world phenomena are located on or near such a boundary.

In a 2D world it is not particularly challenging to either duplicate sections of geometry for shared boundaries or to calculate the shared boundary extents as required. In 3D this is made significantly more complex for multiple reasons, including computational overhead but also the potential for different forms of representations including "extruded geometries", triangular irregular networks (TINs) and other polyhedral surfaces, etc. Simply put: the number of combinations of geometry type and element re-use by reference in a 3D world is much greater than for 2D and the complexity of operations is higher, so the support of convenient software libraries is vital. The challenge is that many required elements, such as extrusion parameters, the relationships between features and boundaries and even topology and re-use of geometry elements, are not standardised. Making software work for the many possible *ad hoc* solutions that lack of standardisation leads to is not feasible.

It was ascertained that many of the available encoding options simply provided no support for encoding of 3D geometries and topology, and the most powerful candidate, GML, was complex and verbose. The current state of implementations of ISO 19107 across a range of different profiles and encoding options illustrates the gap between advanced 3D support in ISO 19107 and existing encodings.

Examining the various encodings of the spatial standards has lead to the conclusion that the implementations tend to adopt subsets of more general conceptual models. They are sometimes identified explicitly as profiles and sometimes implicitly via commentary in documents. Our experience has also shown that the existing encodings provide poor support for the management of 3D information.

We note that OGCs SWG for FG-JSON (OGC, 2021) is expecting to extend GeoJSON to support 3D geometries through polyhedron geometry objects or other encodings (base surface plus height, support for circles, more compact coordinate encodings). Of particular interest is the the GeoSPARQL specification which defines a semantic model for feature and geometry expressed in RDF[23]. GeoSPARQL defines not only data elements (properties) for relationships based on topological and spatial relationships, but also functions that can be invoked to calculate these. It allows use of a number of geometry encodings, as of GeoSPARQL 1.1, WKT, GML, KML, GeoJSON and DGGS.

GeoSPARQL is currently under active development and 1.1 is close to finalised. GeoSPARL 1.2 is planned following 1.1 release and the scoping for that version is underway with a number of proposed extensions, including 3D geometries described here, see the GeoSPARQL Standards Working Group's Issue Tracker[24].

4. DISCUSSION

In the same way that SFA forms the basis of most 2D geospatial data software libraries, a 3D profile of ISO 19107 (ISO, 2019b) could be used to provide a convenient scope for key capabilities needed for a wide range of 3D applications, crucially for interoperability & transformations between geometry and topology representations, which is critical for robust validation strategies.

Given the current state of implementations of ISO 19107 (ISO, 2019b) across a range of different profiles and encodings illustrates the gap between advanced 3D support in ISO 19107 (ISO, 2019b) and existing encodings. We recommend development of a 3D spatial data profile of ISO 19107 (ISO, 2019b) similar in nature to GDAL. To minimise long-term risks it is proposed to develop an implementation strategy predicated on alignment with wider community trends towards JSON (developers) and IFC (Digital Twins), emerging developments coming out of the OGC SWGs driving FG-JSON and OGC APIS, and development of GeoSPARQL 1.2.

Figure 4 illustrates the potential for providing 3D support in both geometry and topological relationships between features, anchored by GeoSPARQL (Perry and Herring, 2012) as a functional standard that allows for multiple geometry encodings.

The specification of cadastral survey data using a 3D profile of ISO 19107 provides an opportunity to test a mechanism to take advantage of additional ISO and OGC standards for both

[23] Resource Description Framework: https://www.w3.org/RDF/

[24] GeoSPARQL Standards Working group correspondence is public: https://github.com/opengeospatial/ogc-geosparql/projects/4

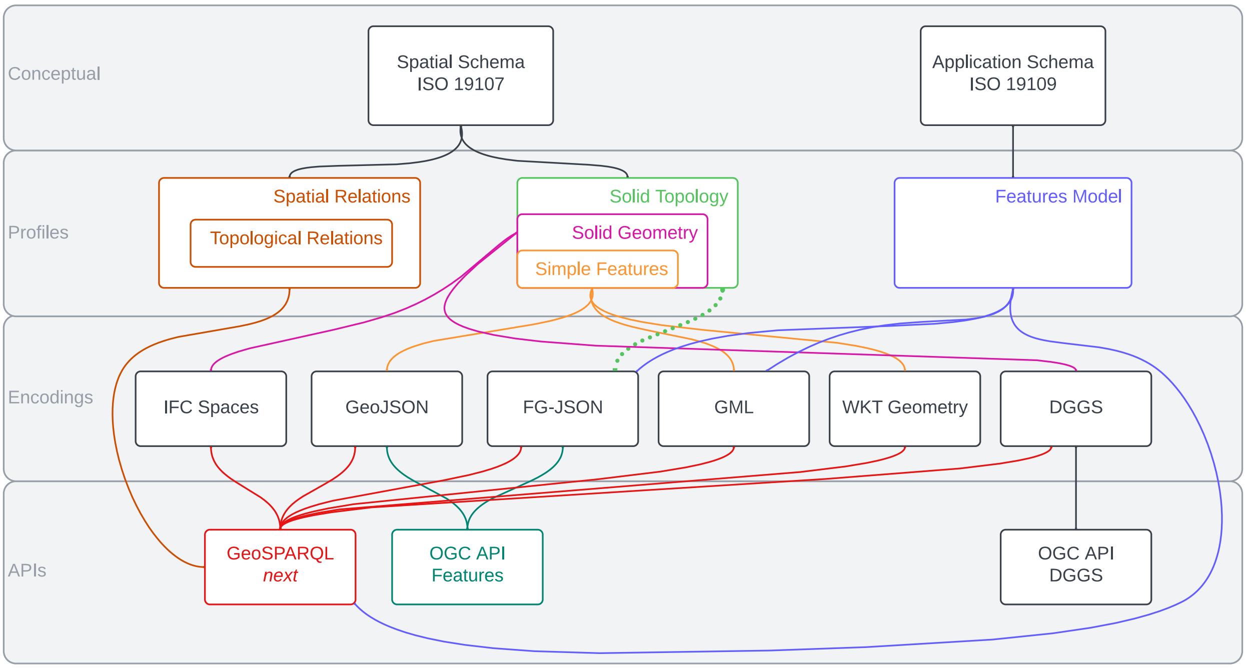

Figure 4. Proposed support for 3D within existing spatial standards

spatial encoding and data sharing. Thus, reducing the requirement to implement *ad hoc* spatial encoding and querying functions in order to deal with the increased complexity of 3D objects. One example is the ability to leverage DGGS technologies via ISO 19170-1 (ISO, 2021)/OGC Abstract Specification Topic 21 (Gibb(Ed.), 2021). DGGS infrastructures (particularly volumetric [3D/4D] DGGS) provide a way to reduce the complexity of spatial queries on objects because both the topology and geometry of DGGS infrastructures are simplified, common throughout the entire infrastructure and consistent with both 9IM and 25IM. While a conventional 25IM spatial query of two, or more, 3D objects is standardised (at the algorithm level), its implementation usually results in a significant computation burden every time that particular query operation is run. By 'mapping' or 'tagging' these objects to the zones of a DGGS infrastructure this same 25IM query can be performed repeatedly with much more simplicity and very minimal computation overhead. This is because a 9IM/25IM query (and all 9IM/25IM queries for that matter) can be reduced to a simple database index lookup operation rather than a spatial query operation.

5. CONCLUSION

As we have shown there are many alternative implementations of 3D data models consistent with a common underlying theory, but varying in how topology in particular is captured relative to geometry primitives. In the interests of interoperability between these and minimisation of proliferation of still more data exchange patterns here exists a case to define a formal 3D profile of ISO 19107 for the subset of 3D operations needed to handle existing uses of 3D data in standardised application models. This profile would form the basis of a series of functional capabilities that are implemented in reusable software libraries, simplifying declaration of interoperability and allowing transformations between different data representations, for different needs.

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