

**OGC® DOCUMENT: YY-999**

External identifier of this OGC® document: <http://www.opengis.net/doc/WP/geosparql3d>



Open  
Geospatial  
Consortium

# GEOSPARQL 3D WHITE PAPER

---

TECHNICAL PAPER

DRAFT

**Version:** 1.0

**Submission Date:** 2029-03-30

**Approval Date:** 2029-03-30

**Publication Date:** 2029-03-30

**Editor:** Editor One, Editor Two

**Notice:** This document is not an OGC Standard. This document is an OGC Technical Paper and is therefore not an official position of the OGC membership. It is distributed for review and comment. It is subject to change without notice and may not be referred to as an OGC Standard. Further, an OGC Technical Paper should not be referenced as required or mandatory technology in procurements.

### License Agreement

Use of this document is subject to the license agreement at <https://www.ogc.org/license>

### Copyright notice

Copyright © 2025 Open Geospatial Consortium

To obtain additional rights of use, visit <https://www.ogc.org/legal>

### Note

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. The Open Geospatial Consortium shall not be held responsible for identifying any or all such patent rights.

Recipients of this document are requested to submit, with their comments, notification of any relevant patent claims or other intellectual property rights of which they may be aware that might be infringed by any implementation of the standard set forth in this document, and to provide supporting documentation.

# CONTENTS

I. KEYWORDS .....	vii
II. PREFACE .....	viii
III. SECURITY CONSIDERATIONS .....	ix
IV. SUBMITTING ORGANIZATIONS .....	x
V. SUBMITTERS .....	x
1. SCOPE .....	2
2. CONFORMANCE .....	4
3. NORMATIVE REFERENCES .....	6
4. TERMS AND DEFINITIONS .....	8
5. ABSTRACT .....	10
6. KEYWORDS .....	12
7. CONVENTIONS .....	14
8. MOTIVATION .....	16
8.1. Why do we want 3D semantic modeling? .....	16
8.1.1. A geo-spatial 3D specification would support data consumers by: .....	17
8.1.2. A geo-spatial 3D specification would support data providers by: .....	17
9. RELATED WORK .....	19
9.1. CityGML .....	19
9.1.1. CityJSON and CityRDF .....	19
9.2. Medicine & Chemistry .....	20
9.3. 3D data formats and ontologies .....	21
9.3.1. STereoLithography (STL) .....	21
9.3.2. Wavefront OBJ Format (OBJ) .....	21
9.3.3. Polygon File Format (PLY) .....	21
9.3.4. CARARE Metadata Schema .....	22
9.3.5. IIIF 3D .....	22
9.3.6. X3D and X3D Ontology .....	22
9.3.7. Geometry Metadata Ontology (GOM) .....	22

9.3.8. Ontology for Managing Geometry (OMG) .....	22
9.3.9. File Ontology for Geometry Formats (FOG) .....	23
9.4. To consider .....	23
9.5. Cultural Heritage .....	23
9.5.1. Use Cases .....	24
9.5.2. Research applications making use of 3D models in Cultural Heritage .....	24
9.5.2.1. 3D models of cuneiform tablets .....	24
9.6. IFC and BIM .....	25
9.6.1. Industry Foundation Classes (IFC) and BIM .....	25
9.6.1.1. Product model .....	25
9.6.1.2. Evolving views on geometry .....	26
9.6.1.3. Use cases .....	27
9.6.1.4. Implications and questions: .....	27
9.7. Implementations .....	28
9.7.1. CGAL → SFCGAL → PostGIS .....	28
9.7.2. OpenCASCADE .....	28
9.7.2.1. OpenCASCADE-inspired BRep ontology .....	28
9.7.2.2. Topologic .....	28
9.7.3. BRep vs mesh/polyhedron .....	28
<b>10. RELATED WORK .....</b>	<b>31</b>
10.1. CityGML .....	31
10.1.1. CityJSON and CityRDF .....	31
10.2. Medicine & Chemistry .....	32
10.3. 3D data formats and ontologies .....	33
10.3.1. STereoLithography (STL) .....	33
10.3.2. Wavefront OBJ Format (OBJ) .....	33
10.3.3. Polygon File Format (PLY) .....	33
10.3.4. CARARE Metadata Schema .....	34
10.3.5. IIIF 3D .....	34
10.3.6. X3D and X3D Ontology .....	34
10.3.7. Geometry Metadata Ontology (GOM) .....	34
10.3.8. Ontology for Managing Geometry (OMG) .....	34
10.3.9. File Ontology for Geometry Formats (FOG) .....	35
10.4. To consider .....	35
10.5. Cultural Heritage .....	35
10.5.1. Use Cases .....	36
10.5.2. Research applications making use of 3D models in Cultural Heritage .....	36
10.5.2.1. 3D models of cuneiform tablets .....	36
10.6. IFC and BIM .....	37
10.6.1. Industry Foundation Classes (IFC) and BIM .....	37
10.6.1.1. Product model .....	37
10.6.1.2. Evolving views on geometry .....	38
10.6.1.3. Use cases .....	39
10.6.1.4. Implications and questions: .....	39
10.7. Implementations .....	40
10.7.1. CGAL → SFCGAL → PostGIS .....	40

10.7.2. OpenCASCADE .....	40
10.7.2.1. OpenCASCADE-inspired BRep ontology .....	40
10.7.2.2. Topologic .....	40
10.7.3. BRep vs mesh/polyhedron .....	40
<b>11. CURRENT CAPABILITIES .....</b>	<b>43</b>
11.1. GeoSPARQL .....	43
11.1.1. Requirements addressed .....	43
11.1.1.1. Dimensionality .....	43
11.1.1.2. Vocabulary .....	44
11.1.1.3. Core Module .....	44
11.1.1.4. Query functions with 3D support .....	46
11.1.2. Adoption of GeoSPARQL 1.1 .....	47
11.1.2.1. GeoSPARQL Alignments .....	47
11.1.2.2. Geometry Topology Extension .....	91
11.1.2.3. RDFS Entailment Extension .....	91
11.1.2.4. Query Rewrite Extension .....	91
<b>12. REQUIREMENTS FOR GEOSPARQL 3D .....</b>	<b>93</b>
12.1. 5.1 Existing implementation of 3D geometry in GeoSPARQL .....	93
12.1.1. Proposed extensions for GeoSPARQL 3D .....	93
12.1.1.1. Extension 1: 3D representations .....	93
12.1.1.2. Extension 2: Relations of 3D geometries .....	94
12.1.1.3. Extension 3: Appearance of 3D geometries .....	94
12.1.1.4. Extension 4: Multi-component 3D geometries .....	95
12.1.1.5. Extension 5: Positioning of 3D geometries .....	95
12.1.1.6. Extension 6: Alignments of GeoSPARQL 3D .....	96
12.1.1.7. Extension 7: Alignments of Engineering CRS to Geospatial CRS .....	96
12.1.1.8. Extension 8: Geometry Extrusion .....	97
12.1.1.9. Extension 9: Geometry Attributes .....	97
12.1.1.10. Extension 10: Non-topological Query Functions – 3D Extension .....	98
12.2. 5.2 3D Geometry available in IFC .....	98
12.3. 5.3 Vanilla 3D geometry handling in the Semantic Web .....	99
12.4. 5.4 Concluding overview of requirements for 3D geometry in the semantic web .....	99
<b>13. BENEFICIARIES AND BENEFITS .....</b>	<b>101</b>
13.1. Semantic-functional value of 3D-GeoSPARQL .....	101
13.1.1. Meaningful creation and querying of 3D geometry .....	101
13.1.2. Meaningful creation and querying of 3D topological relationships .....	101
13.1.3. Derivation of geometric and topological knowledge .....	102
13.2. Value for user experience, visualization, and application use of 3D-GeoSPARQL .....	102
13.2.1. Visualization .....	102
13.2.2. Calculation and analysis .....	102
13.2.3. Spatial querying .....	102
13.2.4. Machine control .....	103
13.2.5. Modeling, simulation and planning .....	103
13.3. Added value of the 3D-GeoSPARQL for Organisations .....	103

13.3.1. Brings together different domains (GIS, BIM, CG) .....	103
13.3.2. Enables extension to vocabularies from other domains .....	103
13.3.3. Facilitates better interoperability between knowledge domains with spatial components (geography, aerospace, architecture, product design, (bio)chemistry, IoT, ...) .....	103
14. ANNEX N: N .....	105
15. ANNEX O: HISTORY .....	107
BIBLIOGRAPHY .....	111



## KEYWORDS

---

The following are keywords to be used by search engines and document catalogues.

OGC, GeoSPARQL, 3D



# PREFACE

---

To come...





## SECURITY CONSIDERATIONS

---

The following security considerations apply...

## IV

# SUBMITTING ORGANIZATIONS

The following organizations submitted this Document to the Open Geospatial Consortium (OGC):

- Organization one
- Organization two
- Organization three

## V

# SUBMITTERS

NAME	AFFILIATION	OGC MEMBER
Nicholas J. Car	KurrawongAI	Yes



1

# SCOPE

---



# SCOPE

---

The background is a solid dark blue-grey color. It features several thin, light blue lines that intersect to form a network of triangles and polygons. At each of these intersection points, there is a small, solid light blue dot. The lines and dots are scattered across the page, with a higher concentration in the upper right and lower left areas.

2

# CONFORMANCE

---



## CONFORMANCE

---



3

# NORMATIVE REFERENCES

---

# 3

## NORMATIVE REFERENCES

---

There are no normative references in this document.





# 4

# TERMS AND DEFINITIONS

---

# 4

## TERMS AND DEFINITIONS

---

No terms and definitions are listed in this document.



5

# ABSTRACT

---



## ABSTRACT

---

To come...



6

# KEYWORDS

---



## KEYWORDS

---

To come...



7

# CONVENTIONS

---



## CONVENTIONS

---





8

# MOTIVATION

---

## 8.1. Why do we want 3D semantic modeling?

---

The white paper: “OGC Benefits of Representing Spatial Data Using Semantic and Graph Technologies” describes the beneficiaries and benefits of representing data, including geospatial data, using semantic and graph technologies Abhayaratna2020wp. This section describes the motivation of adding 3D functionality to the GeoSPARQL standard.

While humans can often resolve 3D spatial questions such as “Is cube A inside cylinder B?” — even when the underlying data comes from different systems like GIS and BIM — this typically relies on implicit understanding, conventions, or direct communication between the data creators. For datasets to be meaningfully aligned, the people who created them often need to clarify assumptions, data structures, coordinate systems, or modeling intentions. Without such human-to-human explanation, machines struggle to interpret spatial relationships across heterogeneous sources. A conversion process is required, in which data is made homogeneous for analysis through extraction, transformation, and loading. Based on a homogeneous dataset, conclusions can then be drawn. Performing conversions may result in geometric simplifications, which can limit or even eliminate the functionality of spatial queries Biljecki2019. If one desires digital, automated processing or analysis of 3D spatial questions without requiring conversion, spatial information must be structured in an explicitly machine-readable format. When this is done, initiatives based on federated systems with heterogeneous datasets can obtain computer-generated answers to spatial 3D queries. This requires semantic alignment and standardized geometry processing in machine-driven analysis. In other words, a common vocabulary is needed to semantically define the 3D objects and its 3D spatial function.

Imagine a constructor who wants to use real-time sensor data at a construction site in combination with modelled 3D data and 3D base registration data. By combining this the person wants to visualize the site, perform accurate spatial checks and calculations, and automatically update machine instructions for safe, efficient and autonomous execution”

The system uses 3D GeoSPARQL to integrate the data of the 3D design model, the 3D base registration model and 3D real-time sensor data to:

- Spatially associate sensor data with objects in the design and registration model
- Calculate the permissible tolerances
- Detect the deviations
- Dynamic adjust the design model
- Instruct the machine with the changes
- Visualize the new situation

For both humans and machines, it must be unambiguous what is meant by the queries that are needed to do the job and the resulting answers. It should not matter whether the data is provided in a 3D-GIS, 3D-BIM or 3D-CG standard vocabulary.

#### **8.1.1. A geo-spatial 3D specification would support data consumers by:**

- access and understanding of 3D-geometry and 3D-topology from multiple sources;
- the integration of 3D-data geospatial and non-geospatial;
- data quality evaluation of the given 3D-data;
- Geometric and topological description in natural language.

#### **8.1.2. A geo-spatial 3D specification would support data providers by:**

- Maximizing the use of 3D-geometry and 3D-topology data;
- Defining multiple 3D topology or geometries;
- Assuring the quality of 3D geospatial data.



9

# RELATED WORK

---

This is still just a dump of resources. To be transformed into actual text.

### 9.1. CityGML

---

CityGML [koble2005citygml] is an open standardized data model for the exchange of 3D models of cities and landscapes. Since its standardization by OGC, CityGML has seen a wide variety of proposed extensions and alignments to other data standards.

#### 9.1.1. CityJSON and CityRDF

[27] proposed the extension of the CityGML and its accompanying serialization CityJSON as an ontology model. Currently, the CityRDF standardization group works towards the standardization of this CityGML data model in RDF.

The proposed CityRDF model, even though focused on CityGML and 3D building contents, contains valuable data descriptions which could be generalized in a GeoSPARQL 3D approach. One such element is the description of the appearance of a 3D-modeled building using colors or textures, so-called surface materials. In addition, CityGML includes relations of 3D primitives between each other, which could serve as an inspiration for similiary-named functions or properties in the GeoSPARQL 3D ontology model.

[27] describes the CityGML Ontology, which is an ontology model to formalize the CityGML standard towards a representation in OWL. It shows a workflow of identification, classification and selection of the relevant data points needed to describe 3D city models in OWL as derived from building and city models. In addition, it introduces the concept of Level of Information Need, defining the granularity of the information on the various levels of the building and the types of information retrieval – direct/indirect, i.e. information which is commonly obtained directly from a dataset or using a calculation or reasoning approach. The paper exemplifies the concept in a study case for property unit cost and indoor daylight. The contribution outlined here became the basis of the CityGML ontology which can serve as one broad application area for GeoSPARQL 3D.

Following on this publication [22] presents a system architecture and a set of interfaces that can represent city modeling approaches using dynamic geospatial knowledge graphs. The paper proves the viability of a transition between a SQL based system for 3D building management to a SPARQL based system using a SQL2SPARQL Transformer component. It therefore proves the feasibility of employing linked open data technologies for 3D building data and in particular the CityGML model in practice.

[30] introduces CityGML 3.0 with a newly added Core module including a new space concept and Level Of Detail concept. The given publication sets the standard especially for Level of Detail in 3D buildings, which may be considered for adoption as GeoSPARQL 3D concepts too.

In addition, CityGML 3.0 proposes the addition of 3D point clouds for the representation of 3D geometries of physical spaces and space boundaries. A mapping from IFC to CityGML 3.0 is also proposed by these authors.

CityGML 3.0 therefore represents many of the elements that a GeoSPARQL 3D ontology would need to implement on a more abstract level and can give ideas about future query functions to be implemented in the GeoSPARQL query language.

In addition, a master thesis [hansson2024citygml](#) proved the feasibility of not only converting CityGML to a knowledge graph representation, but also its application in triple stores such as Ontop or 3DCityDB. The mapping of CityGML to the knowledge graph was tested using a set of SPARQL queries retrieving different components of building parts. While the thesis could construct a knowledge graph representation from CityGML, it points out that the incorporation of spatial operations is left to future work and could provide a possible field for GeoSPARQL 3D adoption.

Finally, [21] proposed OntoCityGML, an extension to the CityGML ontology <https://www.sciencedirect.com/science/article/pii/S2666546821000574?via%3Dihub> Semantic 3D City Database – An enabler for a dynamic geospatial knowledge graph

Other details and history of Onto CityGML.

CityRDF working group <https://github.com/ogcincubator/cityrdf>

## 9.2. Medicine & Chemistry

---

The medicine and chemistry domains contain a variety of usecases for 3D applications.

In particular, 3D metadata of microscopy is a common application field, which yielded for instance the [3D Microscopy Metadata Standards \(3D-MMS\)](#) [32] developed by the BRAIN 3D Microscopy Working Group. This standard helps ensuring that a 3D microscopy dataset is sufficiently described to support its re-use by other scientists not involved in data creation. Its adoption will therefore enable investigators willing to share their data to evaluate and decide which data can be combined.

<https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.13083> Ontology-Based Representation and Modelling of Synthetic 3D Content: A State-of-the-Art Review

[24]

A range of approaches have been proposed to permit semantic representation and modelling of synthetic 3D content. These approaches differ in the methodologies and technologies used as well as their scope and application domains. This paper provides a review of the current state of the art in representation and modelling of 3D content based on semantic web ontologies, together with a classification, characterization and discussion of the particular approaches.

<https://www.inderscienceonline.com/doi/abs/10.1504/IJMSO.2017.087702> A novel ontology for 3D semantics: ontology-based 3D model indexing and content-based video retrieval applied to the medical domain

[25]

This paper presents the most comprehensive formally grounded 3D ontology to date that maps the entire XSD-based vocabulary of the industry standard X3D (ISO/IEC 19775-19777) to OWL 2, complemented by fundamental concepts and roles of the 3D modelling industry not covered by X3D.

## 9.3. 3D data formats and ontologies

---

A new GeoSPARQL standard should be compatible with existing approaches to encode 3D data. Semantic technologies should enable users to encode important metadata in the knowledge graph, while retaining the possibility to use already well-known 3D geometry formats either as String literals or file references. [bonduel2019](#) including shows how common widespread geometry formats could be included into knowledge graphs, which could be one starting point to investigate the integration within GeoSPARQL.

### 9.3.1. STereoLithography (STL)

STL files describe only the surface geometry of a three-dimensional object without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations and was invented by the Albert Consulting Group for 3D Systems in 1987. Nowadays it is mainly used for 3D printing purposes, which makes it a plausible candidate for support in GeoSPARQL 3D settings of movable objects such as in cultural heritage. Since the STL format does not contain a geospatial reference, the reference needs to be provided externally if STL files were to be used in a geospatial context. However, STL objects could be used in local CRS contexts as well.

### 9.3.2. Wavefront OBJ Format (OBJ)

The OBJ format is a file format developed by Wavefront Technologies for the Advanced 3D Visualizer animation package. Its roots therefore lie in the world of 3D animation. The format represents vertex coordinates, texture coordinates, as well as vertex normals, parameter space vertices and faces of a 3D model. These are all elements which would need to be considered and supported in an upcoming GeoSPARQL 3D release.

### 9.3.3. Polygon File Format (PLY)

The Polygon File Format is a format which was designed to store 3D data from 3D scanning environments, which makes it especially widespread in the Cultural Heritage application area. The format consists of a vertex list and a faces list with optional parameters per vertex. Like the

OBJ format, supporting PLY would imply including support for vertices and faces of a 3D model and their relationships in a knowledge graph.

### 9.3.4. CARARE Metadata Schema

The CARARE metadata schema [d2013carare](#) is a harvesting schema intended for delivering metadata about an organisation's online collections, heritage assets and their digital resources. The strength of the schema lies with its ability to support the full range of descriptive information about monuments, building, landscape areas and their representations. The CARARE metadata schema builds on existing standards and best practice from a number of different countries in Europe and the rest of the world.

### 9.3.5. IIIF 3D

The International Image Interoperability Framework (IIIF) standard [snydman2015international](#) is currently developing a [specification](#) for the standardization of 3D viewers. The viewer specification includes the visualization of 3D models including lighting positions, a scene graph and annotations in the form of additional 3D objects added to a 3D scene. A GeoSPARQL 3D standard might need to be compatible with, or include a compatibility statement of, converting 3D objects encoded in GeoSPARQL to the IIIF viewer specification. A prototype implementation might be necessary to comply with this specification.

### 9.3.6. X3D and X3D Ontology

The X3D format [feichtenhofer2020x3d](#), [brutzman2010x3d](#), X3DOM [behr2009x3dom](#) and its Ontology version [brutzman2020x3d](#) provide a data format and a blueprint for how 3D data is handled in computer vision approaches. X3D is an interesting format to investigate for 3D components which need to be modeled within a GeoSPARQL 3D specification. It is a likely candidate for a literal format and might be integrated using interlinking approaches to the already existing X3D vocabulary. However, since X3D was invented with computer vision approaches in mind it does not define any geospatial aspects that could be considered by a GeoSPARQL 3D implementation.

### 9.3.7. Geometry Metadata Ontology (GOM)

The [Geometry Metadata Ontology \(GOM\)](#) introduces classes for surfaces which are common in the 3D world, but uncommon for 3D geometries, for instance Meshes or NURBS surfaces. The ontology can serve as an inspiration for extensions in GeoSPARQL 3D and may or may not be fully or partly adopted in the process of standardization.

### 9.3.8. Ontology for Managing Geometry (OMG)

The [Ontology for Managing Geometry \(OMG\)](#) describes states and derivation of geometries which may be useful to the description of data in GeoSPARQL 3D. For example. an extrusion in



3D from a 2D geometry template would have a derivation relation from the 2D geometry which one might want to see modeled in GeoSPARQL 3D.

### 9.3.9. File Ontology for Geometry Formats (FOG)

The File Ontology for Geometry Formats (FOG) provides a bridge between ontology descriptions of geometries and data file descriptions of 3D contents. Since many 3D datasets are of considerable size, their inclusion into the knowledge graph as String literals might hinder the query performance of said knowledge graph. It therefore stands to reason whether to adopt the same or a similar method of geometry access that FOG provides for GeoSPARQL 3D.

## 9.4. To consider

---

<https://link.springer.com/article/10.1007/s10845-023-02246-6> Ontology of 3D virtual modeling in digital twin: a review, analysis and thinking

[33]

To help novice engineers understand and scheme 3D virtual modeling in digital twin for future research and applications, this paper reviews 106 digital twin 3D modeling cases with their characteristics, including deployment targets, purposes & roles, collaborative models, data flows, the autonomy of 3D modeling, fidelity, twinning rates, enabling technologies, and enabling tools.

Open standard for particle-mesh data (openPMD)

The openPMD standard, short for open standard for particle-mesh data files is not a file format per se. It provides guidance for meta-data and naming schemes. openPMD provides naming and attribute conventions that allow the exchange of particle and mesh based data from scientific simulations and experiments. Its primary goal is to define a minimal set/kernel of meta information that allows to share and exchange data to achieve portability between various applications and different algorithms, a unified open-access description for scientific data (publishing and archiving), and a unified description for post-processing, visualization and analysis. If outputs from programs, devices (such as cameras), simulations or post-processed data-sets, contain a minimal set of meta information as provided by openPMD, data can be exchanged between those with minimal effort, with the same tools used for visualization.

[19]

## 9.5. Cultural Heritage

---

In the research domain of cultural heritage, 3D models of either cultural heritage artifacts (possibly georeferenced), 3D models of archaeological sites or simply 3D models of ancient buildings are becoming increasingly common.

### 9.5.1. Use Cases

Use Cases in the Cultural Heritage domain include, but are not limited to, the following main interests:

**Visualization:** The visualization of 3D models for the presentation of such 3D models, for example in the context of a museum. 3D models may be styled with a particular set of textures or modeled with a specific set of colours to highlight certain relevant aspects. The visualization of 3D models is currently standardized by the IIIF 3D working group [29], which aims to create viewing parameter descriptions that 3D viewers may implement, similar to the specifications of IIIF 2D for images.

**Object Annotation:** 3D models are seen as the subject of a research question in absence of the original artifact for political, practical or other restrictive reasons. Out of all known methods of the representation of cultural heritage artifacts, 3D models provide the most detail when being delivered as a digital artifact and are therefore very often preferred in a research context. Researchers mark noteworthy aspects of the cultural artifact as 3D annotations [28] which may include surface descriptions, volumes of the 3D model or 3D models which are created and placed adjacent to the to-be-annotated 3D model [20].

**Relation of Objects:** Objects of a specific collections always exist in a spatio-temporal context. It is important to relate these representations via meaningful relations, so that relevant objects of a collection can be retrieved more easily

**AI Applications in Cultural Heritage:** Usage for annotated areas on 3D models or their derivations for machine learning classifications Stotzner\_2023\_ICCV 10.2312/gch.20231157

**Knowledge Graphs as Metadata descriptions:** With the advent of more 3D models being published, the relevance of their creation parameters [31], their contents and their object metadata increases for the usecases of filtering them and also for the possibly automated selection of suitable cultural heritage metadata for e.g. machine learning classifications. Currently, many metadata standards fulfil parts of the description chain and a unified vocabulary to described data types seems to be missing.

### 9.5.2. Research applications making use of 3D models in Cultural Heritage

This section discusses research projects with 3D contents based on the technologies they use as elaborated in the previous section.

#### 9.5.2.1. 3D models of cuneiform tablets

Cuneiform tablets from ancient Iran provide an interesting research area, since they combine a 3D artifact with textual imprints that are of interest to a variety of research communities including Assyriologists, Digital Humanists, Computational Linguists and last but not least Computer Scientists. The creation of 3D models of cuneiform tablets provides the best accessibility to the specificities of the original artifact in its absence and 3D scans have been used by computer scientists as the basis for certain machine learning application tasks, even

though to this day only as a provision for 2D renderings of their surfaces. Interests of the research community include the description of interesting features such as cuneiform signs on cuneiform tablet surfaces and their connection to other text contents or other cuneiform artifacts. Knowledge graphs provide machine learning approaches Stotzner\_2023\_ICCV stotzner2023r with unique opportunities to connect different kinds of data using a unified data format.

To describe 3D meshes, several vocabularies have been developed in the context of the cuneiform studies project:

- MeshSPARQL: A vocabulary to describe essential mesh elements
- Gigamesh Metadata Vocabulary: A vocabulary which describes metadata of a 3D model. The metadata can be generated using the Gigamesh Software Framework
- 3DCAP Vocabularies: An ontology model to describe the creation of a 3D model. It has been applied to different scanning softwares

## 9.6. IFC and BIM

---

### 9.6.1. Industry Foundation Classes (IFC) and BIM

BIM is a paradigm in which object-model definitions — with machine-interpretable semantics — are exchanged, rather than relying on CAD drawings that convey only graphical semantics. The predominant open exchange standard is Industry Foundation Classes (IFC). **IFC is unique in the sense that it allows expressing both geometrical as well as non-geometrical semantics.**

**Non-geometrical: taxonomy of objects (building elements, relational constructs, scheduling information) and related properties**

**Geometrical: approximately 250 constructs related to geometry; even standards with only a geometric focus such as geosparql or collada do not reach that breadth in definitions**

IFC has its idiosyncrasies and challenges, but is **unrivaled in terms of market adoption in a highly fragmented industry.**

#### 9.6.1.1. Product model

In IFC, a construction work is decomposed into a set of products. These products can have **multiple representations**. For example, a wall can be described as a solid body as well as a two-dimensional axis. These representations facilitate different views on the same data: an editable line segment or an easily visualized volume. The Object-relational nature of the IFC EXPRESS schema allows intricate relationships such as a representation context that communicates

additional intent for the representation or presentation styles that can be granularly assigned to individual faces.

At the same time, such a product separates the **placement** (an hierarchical transformation) from the actual geometry definition. The consequence of this is that in spite of its object-relational nature, IFC product representations cannot be used for building-level topological relationships between solids, because even if two solids are touching in 3D, the fact the the placement is externalized out of the geometry definition (or the fact that faces are constructed procedurally and do not exist explicitly), means that the two faces cannot be opposite oriented twins. As such, relational geometric constructs such as space boundaries are provided as additional supplementary geometries. (Identifying faces in procedural geometries is also challenging (topological naming problem), so using geometric semantic overlays to annotate potentially procedural geometries makes sense)

In principle, the IFC schema has been designed in a modular fashion with independent modules for, for example, geometry, materials and meta-data. However in other cases, **semantics and geometry are intertwined** such as tapered extrusions (lofts) where the begin and end profile of a duct carry important semantics.

IFC also allows for **decomposition**, where a whole is aggregated into multiple parts for richer semantics. This allows for example to connect materials and meta-data to the frame and the glazing separately, while still being able to identify the aggregate as a single window. This is not used as frequently, partially due to inability to efficiently instantiate such aggregates as geometry instances.

### 9.6.1.2. Evolving views on geometry

IFC is heavily influenced by the ISO 10303 (STEP) family of standards, but over time adopted its own geometric paradigms:

- Procedural geometry and boolean operations became less prominent with the adoption of ReferenceView in IFC4. Tessellated geometry definitions were added for more compact exchange.
- **Infrastructure definitions** were added with precise mathematical transition curves and a composition of a horizontal, vertical and cant (inclination) profile.
- IFC5 with an **explicit** (most likely triangulated) geometry schema at the core, with semantic overlays to encode the same procedural semantics as a non-mandatory or use-case specific layer. Heavily inspired by USD with layer-based composition for collaborative exchange.

Especially the handling of **tolerances** means that the standard cannot effectively prescribe a consistent outcome in all cases. Tolerances are needed for BRep model with non-linear underlying geometry and/or fixed precision coordinate values, e.g higher degree nurbs curves are typically intersected with numerical approximation, so a vertex that connects two of such curves needs to have seen as a sphere with the local tolerance as its radius. This tolerance is also applied to boolean operations: an subtraction volume can be slightly inwards of the first operand but is still expected to pierce through the volume and increase surface genus. This contrasts

with the desire of using IFC as a legal basis in contracts. NB Tolerances stand in the way of using existing approaches for SFA geometry predicates such as PostGIS+SFCGAL which is based on arbitrary precision boolean logic as implemented in CGAL without tolerances.

### 9.6.1.3. Use cases

The most successful use case on BIM data is **coordination and visualization** where multiple aspect models are geometrically overlaid in order to find issues, which are then communicated to the authoring software where they are addressed. This approach works, because it respects that individual disciplines all have their own specialistic software.

**Design to design** workflows are much harder to realize, although some Model View Definitions have been developed on top of IFC that enable the transfer of design intent in specific and constrained scenarios, such as precast concrete and structural steel.

**Long-term preservation** of building information is difficult because of the fact that IFC models are difficult to mutate, because they are so explicit and don't contain the vendor-specific design intelligence. Therefore native software cannot always re-import IFC models, but also the native models degrade over time because of the need to migrate to newer editions of the software. Software that can directly operate on IFC to make modifications is still experimental.

**BIM-GIS integration** is challenging because it requires familiarity with both domains on where to draw the line between euclidean and non-euclidean geometries and acceptable error metrics.

**Simulations** on IFC building models are often challenging because the 'bag of individual elements' does not provide a good foundation higher order topological representations required for flow-of-energy type of simulations. For e.g thermal simulation a topological view of space boundaries is required. They have been added as secondary set of ternary relationships, but usage of more specific-purpose and simpler schemas sees still more usage in industry. In general, IFC models are created for a specific purpose and wide-spread usage of those models in neighbouring domains remain challenging because modelling for those neighbouring purposes requires alignment on the worldviews and levels of detail that is often beyond the scope in which such models are procured.

### 9.6.1.4. Implications and questions:

- Euclidean / non-euclidean; is a CRS required?
- Separate representation+placement → enables efficient instantiation, but hinders topological relationships because you require the pair of placement+geometry to locate in space
- Geometry as leaf-values or object-relational model : cannot encapsulate geometry into a single literal, but allows for richer semantics
- BRep model (topology + geometry + orientation + location) vs polyhedral model (e.g halfedge) vs explicit loops of point coordinates
- Procedural vs implicit (e.g constraints) vs explicit (polyhedra)

- Tolerances
- Decomposition inside or outside of the 'geometry ontology'
- Are infra geometries (hor + ver alignment + cant, for positioning and sweeps) in scope?

## 9.7. Implementations

---

### 9.7.1. CGAL → SFCGAL → PostGIS

### 9.7.2. OpenCASCADE

#### 9.7.2.1. OpenCASCADE-inspired BRep ontology

Perzylo, A., Somani, N., Rickert, M., & Knoll, A. (2015, September). An ontology for CAD data and geometric constraints as a link between product models and semantic robot task descriptions. In 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS) (pp. 4197-4203). IEEE.

<https://ieeexplore.ieee.org/abstract/document/7353971>

[23]

#### 9.7.2.2. Topologic

Jabi, W., & Chatzivasileiadi, A. (2021, January). Topologic: exploring spatial reasoning through geometry, topology, and semantics. In Formal Methods in Architecture: Proceedings of the 5th International Symposium on Formal Methods in Architecture (5FMA), Lisbon 2020 (pp. 277-285). Cham: Springer International Publishing.

<https://topologic.app/>

[2]

### 9.7.3. BRep vs mesh/polyhedron

BRep

- Curved surfaces
- Topology: connected components as shells, solids with inner voids, etc.

- Clean APIs due to inheritance: e.g `fn extrude(Topo) → Topo`, for `vertex → edge`; `edge → face`; `face → solid`; `solid → solid`
- Extra indirections: `edge → vertex[] → point`
- Depending on implementation can be inefficient, e.g outer wire of face not explicitly marked need to be checked wrt infinite point
- Data integrity and validation a bit harder

#### Mesh/polyhedron

- Potentially fewer indirections
- Triangle meshes robust and well understood
- Many different data models though, e.g half-edge (only manifold), indexed faceset (no adjacency info), winged/quad/radial edge



10

# RELATED WORK

---



This is still just a dump of resources. To be transformed into actual text.

## 10.1. CityGML ---

CityGML [koble2005citygml] is an open standardized data model for the exchange of 3D models of cities and landscapes. Since its standardization by OGC, CityGML has seen a wide variety of proposed extensions and alignments to other data standards.

### 10.1.1. CityJSON and CityRDF

[27] proposed the extension of the CityGML and its accompanying serialization CityJSON as an ontology model. Currently, the CityRDF standardization group works towards the standardization of this CityGML data model in RDF.

The proposed CityRDF model, even though focused on CityGML and 3D building contents, contains valuable data descriptions which could be generalized in a GeoSPARQL 3D approach. One such element is the description of the appearance of a 3D-modeled building using colors or textures, so-called surface materials. In addition, CityGML includes relations of 3D primitives between each other, which could serve as an inspiration for similar named functions or properties in the GeoSPARQL 3D ontology model.

[27] describes the CityGML Ontology, which is an ontology model to formalize the CityGML standard towards a representation in OWL. It shows a workflow of identification, classification and selection of the relevant data points needed to describe 3D city models in OWL as derived from building and city models. In addition, it introduces the concept of Level of Information Need, defining the granularity of the information on the various levels of the building and the types of information retrieval – direct/indirect, i.e. information which is commonly obtained directly from a dataset or using a calculation or reasoning approach. The paper exemplifies the concept in a study case for property unit cost and indoor daylight. The contribution outlined here became the basis of the CityGML ontology which can serve as one broad application area for GeoSPARQL 3D.

Following on this publication [22] presents a system architecture and a set of interfaces that can represent city modeling approaches using dynamic geospatial knowledge graphs. The paper proves the viability of a transition between a SQL based system for 3D building management to a SPARQL based system using a SQL2SPARQL Transformer component. It therefore proves the feasibility of employing linked open data technologies for 3D building data and in particular the CityGML model in practice.

[30] introduces CityGML 3.0 with a newly added Core module including a new space concept and Level Of Detail concept. The given publication sets the standard especially for Level of Detail in 3D buildings, which may be considered for adoption as GeoSPARQL 3D concepts too.

In addition, CityGML 3.0 proposes the addition of 3D point clouds for the representation of 3D geometries of physical spaces and space boundaries. A mapping from IFC to CityGML 3.0 is also proposed by these authors.

CityGML 3.0 therefore represents many of the elements that a GeoSPARQL 3D ontology would need to implement on a more abstract level and can give ideas about future query functions to be implemented in the GeoSPARQL query language.

In addition, a master thesis [hansson2024citygml](#) proved the feasibility of not only converting CityGML to a knowledge graph representation, but also its application in triple stores such as Ontop or 3DCityDB. The mapping of CityGML to the knowledge graph was tested using a set of SPARQL queries retrieving different components of building parts. While the thesis could construct a knowledge graph representation from CityGML, it points out that the incorporation of spatial operations is left to future work and could provide a possible field for GeoSPARQL 3D adoption.

Finally, [21] proposed OntoCityGML, an extension to the CityGML ontology <https://www.sciencedirect.com/science/article/pii/S2666546821000574?via%3Dihub> Semantic 3D City Database – An enabler for a dynamic geospatial knowledge graph

Other details and history of Onto CityGML.

CityRDF working group <https://github.com/ogcincubator/cityrdf>

## 10.2. Medicine & Chemistry

---

The medicine and chemistry domains contain a variety of usecases for 3D applications.

In particular, 3D metadata of microscopy is a common application field, which yielded for instance the [3D Microscopy Metadata Standards \(3D-MMS\)](#) [32] developed by the BRAIN 3D Microscopy Working Group. This standard helps ensuring that a 3D microscopy dataset is sufficiently described to support its re-use by other scientists not involved in data creation. Its adoption will therefore enable investigators willing to share their data to evaluate and decide which data can be combined.

<https://onlinelibrary.wiley.com/doi/abs/10.1111/cgf.13083> Ontology-Based Representation and Modelling of Synthetic 3D Content: A State-of-the-Art Review

[24]

A range of approaches have been proposed to permit semantic representation and modelling of synthetic 3D content. These approaches differ in the methodologies and technologies used as well as their scope and application domains. This paper provides a review of the current state of the art in representation and modelling of 3D content based on semantic web ontologies, together with a classification, characterization and discussion of the particular approaches.

<https://www.inderscienceonline.com/doi/abs/10.1504/IJMSO.2017.087702> A novel ontology for 3D semantics: ontology-based 3D model indexing and content-based video retrieval applied to the medical domain

[25]

This paper presents the most comprehensive formally grounded 3D ontology to date that maps the entire XSD-based vocabulary of the industry standard X3D (ISO/IEC 19775-19777) to OWL 2, complemented by fundamental concepts and roles of the 3D modelling industry not covered by X3D.

## 10.3. 3D data formats and ontologies

---

A new GeoSPARQL standard should be compatible with existing approaches to encode 3D data. Semantic technologies should enable users to encode important metadata in the knowledge graph, while retaining the possibility to use already well-known 3D geometry formats either as String literals or file references. [bonduel2019](#) including shows how common widespread geometry formats could be included into knowledge graphs, which could be one starting point to investigate the integration within GeoSPARQL.

### 10.3.1. STereoLithography (STL)

STL files describe only the surface geometry of a three-dimensional object without any representation of color, texture or other common CAD model attributes. The STL format specifies both ASCII and binary representations and was invented by the Albert Consulting Group for 3D Systems in 1987. Nowadays it is mainly used for 3D printing purposes, which makes it a plausible candidate for support in GeoSPARQL 3D settings of movable objects such as in cultural heritage. Since the STL format does not contain a geospatial reference, the reference needs to be provided externally if STL files were to be used in a geospatial context. However, STL objects could be used in local CRS contexts as well.

### 10.3.2. Wavefront OBJ Format (OBJ)

The OBJ format is a file format developed by Wavefront Technologies for the Advanced 3D Visualizer animation package. Its roots therefore lie in the world of 3D animation. The format represents vertex coordinates, texture coordinates, as well as vertex normals, parameter space vertices and faces of a 3D model. These are all elements which would need to be considered and supported in an upcoming GeoSPARQL 3D release.

### 10.3.3. Polygon File Format (PLY)

The Polygon File Format is a format which was designed to store 3D data from 3D scanning environments, which makes it especially widespread in the Cultural Heritage application area. The format consists of a vertex list and a faces list with optional parameters per vertex. Like the

OBJ format, supporting PLY would imply including support for vertices and faces of a 3D model and their relationships in a knowledge graph.

#### 10.3.4. CARARE Metadata Schema

The CARARE metadata schema d2013carare is a harvesting schema intended for delivering metadata about an organisation's online collections, heritage assets and their digital resources. The strength of the schema lies with its ability to support the full range of descriptive information about monuments, building, landscape areas and their representations. The CARARE metadata schema builds on existing standards and best practice from a number of different countries in Europe and the rest of the world.

#### 10.3.5. IIIF 3D

The International Image Interoperability Framework (IIIF) standard snydman2015international is currently developing a specification for the standardization of 3D viewers. The viewer specification includes the visualization of 3D models including lighting positions, a scene graph and annotations in the form of additional 3D objects added to a 3D scene. A GeoSPARQL 3D standard might need to be compatible with, or include a compatibility statement of, converting 3D objects encoded in GeoSPARQL to the IIIF viewer specification. A prototype implementation might be necessary to comply with this specification.

#### 10.3.6. X3D and X3D Ontology

The X3D format feichtenhofer2020x3d, brutzman2010x3d, X3DOM behr2009x3dom and its Ontology version brutzman2020x3d provide a data format and a blueprint for how 3D data is handled in computer vision approaches. X3D is an interesting format to investigate for 3D components which need to be modeled within a GeoSPARQL 3D specification. It is a likely candidate for a literal format and might be integrated using interlinking approaches to the already existing X3D vocabulary. However, since X3D was invented with computer vision approaches in mind it does not define any geospatial aspects that could be considered by a GeoSPARQL 3D implementation.

#### 10.3.7. Geometry Metadata Ontology (GOM)

The Geometry Metadata Ontology (GOM) introduces classes for surfaces which are common in the 3D world, but uncommon for 3D geometries, for instance Meshes or NURBS surfaces. The ontology can serve as an inspiration for extensions in GeoSPARQL 3D and may or may not be fully or partly adopted in the process of standardization.

#### 10.3.8. Ontology for Managing Geometry (OMG)

The Ontology for Managing Geometry (OMG) describes states and derivation of geometries which may be useful to the description of data in GeoSPARQL 3D. For example. an extrusion in

3D from a 2D geometry template would have a derivation relation from the 2D geometry which one might want to see modeled in GeoSPARQL 3D.

### 10.3.9. File Ontology for Geometry Formats (FOG)

The File Ontology for Geometry Formats (FOG) provides a bridge between ontology descriptions of geometries and data file descriptions of 3D contents. Since many 3D datasets are of considerable size, their inclusion into the knowledge graph as String literals might hinder the query performance of said knowledge graph. It therefore stands to reason whether to adopt the same or a similar method of geometry access that FOG provides for GeoSPARQL 3D.

## 10.4. To consider

---

<https://link.springer.com/article/10.1007/s10845-023-02246-6> Ontology of 3D virtual modeling in digital twin: a review, analysis and thinking

[33]

To help novice engineers understand and scheme 3D virtual modeling in digital twin for future research and applications, this paper reviews 106 digital twin 3D modeling cases with their characteristics, including deployment targets, purposes & roles, collaborative models, data flows, the autonomy of 3D modeling, fidelity, twinning rates, enabling technologies, and enabling tools.

Open standard for particle-mesh data (openPMD)

The openPMD standard, short for open standard for particle-mesh data files is not a file format per se. It provides guidance for meta-data and naming schemes. openPMD provides naming and attribute conventions that allow the exchange of particle and mesh based data from scientific simulations and experiments. Its primary goal is to define a minimal set/kernel of meta information that allows to share and exchange data to achieve portability between various applications and different algorithms, a unified open-access description for scientific data (publishing and archiving), and a unified description for post-processing, visualization and analysis. If outputs from programs, devices (such as cameras), simulations or post-processed data-sets, contain a minimal set of meta information as provided by openPMD, data can be exchanged between those with minimal effort, with the same tools used for visualization.

[19]

## 10.5. Cultural Heritage

---

In the research domain of cultural heritage, 3D models of either cultural heritage artifacts (possibly georeferenced), 3D models of archaeological sites or simply 3D models of ancient buildings are becoming increasingly common.

### 10.5.1. Use Cases

Use Cases in the Cultural Heritage domain include, but are not limited to, the following main interests:

**Visualization:** The visualization of 3D models for the presentation of such 3D models, for example in the context of a museum. 3D models may be styled with a particular set of textures or modeled with a specific set of colours to highlight certain relevant aspects. The visualization of 3D models is currently standardized by the IIIF 3D working group [29], which aims to create viewing parameter descriptions that 3D viewers may implement, similar to the specifications of IIIF 2D for images.

**Object Annotation:** 3D models are seen as the subject of a research question in absence of the original artifact for political, practical or other restrictive reasons. Out of all known methods of the representation of cultural heritage artifacts, 3D models provide the most detail when being delivered as a digital artifact and are therefore very often preferred in a research context. Researchers mark noteworthy aspects of the cultural artifact as 3D annotations [28] which may include surface descriptions, volumes of the 3D model or 3D models which are created and placed adjacent to the to-be-annotated 3D model [20].

**Relation of Objects:** Objects of a specific collections always exist in a spatio-temporal context. It is important to relate these representations via meaningful relations, so that relevant objects of a collection can be retrieved more easily

**AI Applications in Cultural Heritage:** Usage for annotated areas on 3D models or their derivations for machine learning classifications Stotzner\_2023\_ICCV 10.2312/gch.20231157

**Knowledge Graphs as Metadata descriptions:** With the advent of more 3D models being published, the relevance of their creation parameters [31], their contents and their object metadata increases for the usecases of filtering them and also for the possibly automated selection of suitable cultural heritage metadata for e.g. machine learning classifications. Currently, many metadata standards fulfil parts of the description chain and a unified vocabulary to described data types seems to be missing.

### 10.5.2. Research applications making use of 3D models in Cultural Heritage

This section discusses research projects with 3D contents based on the technologies they use as elaborated in the previous section.

#### 10.5.2.1. 3D models of cuneiform tablets

Cuneiform tablets from ancient Iran provide an interesting research area, since they combine a 3D artifact with textual imprints that are of interest to a variety of research communities including Assyriologists, Digital Humanists, Computational Linguists and last but not least Computer Scientists. The creation of 3D models of cuneiform tablets provides the best accessibility to the specificities of the original artifact in its absence and 3D scans have been

used by computer scientists as the basis for certain machine learning application tasks, even though to this day only as a provision for 2D renderings of their surfaces. Interests of the research community include the description of interesting features such as cuneiform signs on cuneiform tablet surfaces and their connection to other text contents or other cuneiform artifacts. Knowledge graphs provide machine learning approaches Stotzner\_2023\_ICCV stotzner2023r with unique opportunities to connect different kinds of data using a unified data format.

To describe 3D meshes, several vocabularies have been developed in the context of the cuneiform studies project:

- MeshSPARQL: A vocabulary to describe essential mesh elements
- Gigamesh Metadata Vocabulary: A vocabulary which describes metadata of a 3D model. The metadata can be generated using the Gigamesh Software Framework
- 3DCAP Vocabularies: An ontology model to describe the creation of a 3D model. It has been applied to different scanning softwares

## 10.6. IFC and BIM

---

### 10.6.1. Industry Foundation Classes (IFC) and BIM

BIM is a paradigm in which object-model definitions — with machine-interpretable semantics — are exchanged, rather than relying on CAD drawings that convey only graphical semantics. The predominant open exchange standard is Industry Foundation Classes (IFC). **IFC is unique in the sense that it allows expressing both geometrical as well as non-geometrical semantics.**

**Non-geometrical: taxonomy of objects (building elements, relational constructs, scheduling information) and related properties**

**Geometrical: approximately 250 constructs related to geometry; even standards with only a geometric focus such as geosparql or collada do not reach that breadth in definitions**

IFC has its idiosyncrasies and challenges, but is **unrivaled in terms of market adoption in a highly fragmented industry.**

#### 10.6.1.1. Product model

In IFC, a construction work is decomposed into a set of products. These products can have **multiple representations**. For example, a wall can be described as a solid body as well as a two-dimensional axis. These representations facilitate different views on the same data: an editable line segment or an easily visualized volume. The Object-relational nature of the IFC EXPRESS schema allows intricate relationships such as a representation context that communicates



additional intent for the representation or presentation styles that can be granularly assigned to individual faces.

At the same time, such a product separates the **placement** (an hierarchical transformation) from the actual geometry definition. The consequence of this is that in spite of its object-relational nature, IFC product representations cannot be used for building-level topological relationships between solids, because even if two solids are touching in 3D, the fact the the placement is externalized out of the geometry definition (or the fact that faces are constructed procedurally and do not exist explicitly), means that the two faces cannot be opposite oriented twins. As such, relational geometric constructs such as space boundaries are provided as additional supplementary geometries. (Identifying faces in procedural geometries is also challenging (topological naming problem), so using geometric semantic overlays to annotate potentially procedural geometries makes sense)

In principle, the IFC schema has been designed in a modular fashion with independent modules for, for example, geometry, materials and meta-data. However in other cases, **semantics and geometry are intertwined** such as tapered extrusions (lofts) where the begin and end profile of a duct carry important semantics.

IFC also allows for **decomposition**, where a whole is aggregated into multiple parts for richer semantics. This allows for example to connect materials and meta-data to the frame and the glazing separately, while still being able to identify the aggregate as a single window. This is not used as frequently, partially due to inability to efficiently instantiate such aggregates as geometry instances.

### 10.6.1.2. Evolving views on geometry

IFC is heavily influenced by the ISO 10303 (STEP) family of standards, but over time adopted its own geometric paradigms:

- Procedural geometry and boolean operations became less prominent with the adoption of ReferenceView in IFC4. Tessellated geometry definitions were added for more compact exchange.
- **Infrastructure definitions** were added with precise mathematical transition curves and a composition of a horizontal, vertical and cant (inclination) profile.
- IFC5 with an **explicit** (most likely triangulated) geometry schema at the core, with semantic overlays to encode the same procedural semantics as a non-mandatory or use-case specific layer. Heavily inspired by USD with layer-based composition for collaborative exchange.

Especially the handling of **tolerances** means that the standard cannot effectively prescribe a consistent outcome in all cases. Tolerances are needed for BRep model with non-linear underlying geometry and/or fixed precision coordinate values, e.g higher degree nurbs curves are typically intersected with numerical approximation, so a vertex that connects two of such curves needs to have seen as a sphere with the local tolerance as its radius. This tolerance is also applied to boolean operations: an subtraction volume can be slightly inwards of the first operand but is still expected to pierce through the volume and increase surface genus. This contrasts



with the desire of using IFC as a legal basis in contracts. NB Tolerances stand in the way of using existing approaches for SFA geometry predicates such as PostGIS+SFCGAL which is based on arbitrary precision boolean logic as implemented in CGAL without tolerances.

### 10.6.1.3. Use cases

The most successful use case on BIM data is **coordination and visualization** where multiple aspect models are geometrically overlaid in order to find issues, which are then communicated to the authoring software where they are addressed. This approach works, because it respects that individual disciplines all have their own specialistic software.

**Design to design** workflows are much harder to realize, although some Model View Definitions have been developed on top of IFC that enable the transfer of design intent in specific and constrained scenarios, such as precast concrete and structural steel.

**Long-term preservation** of building information is difficult because of the fact that IFC models are difficult to mutate, because they are so explicit and don't contain the vendor-specific design intelligence. Therefore native software cannot always re-import IFC models, but also the native models degrade over time because of the need to migrate to newer editions of the software. Software that can directly operate on IFC to make modifications is still experimental.

**BIM-GIS integration** is challenging because it requires familiarity with both domains on where to draw the line between euclidean and non-euclidean geometries and acceptable error metrics.

**Simulations** on IFC building models are often challenging because the 'bag of individual elements' does not provide a good foundation higher order topological representations required for flow-of-energy type of simulations. For e.g thermal simulation a topological view of space boundaries is required. They have been added as secondary set of ternary relationships, but usage of more specific-purpose and simpler schemas sees still more usage in industry. In general, IFC models are created for a specific purpose and wide-spread usage of those models in neighbouring domains remain challenging because modelling for those neighbouring purposes requires alignment on the worldviews and levels of detail that is often beyond the scope in which such models are procured.

### 10.6.1.4. Implications and questions:

- Euclidean / non-euclidean; is a CRS required?
- Separate representation+placement → enables efficient instantiation, but hinders topological relationships because you require the pair of placement+geometry to locate in space
- Geometry as leaf-values or object-relational model : cannot encapsulate geometry into a single literal, but allows for richer semantics
- BRep model (topology + geometry + orientation + location) vs polyhedral model (e.g halfedge) vs explicit loops of point coordinates
- Procedural vs implicit (e.g constraints) vs explicit (polyhedra)

- Tolerances
- Decomposition inside or outside of the 'geometry ontology'
- Are infra geometries (hor + ver alignment + cant, for positioning and sweeps) in scope?

## 10.7. Implementations

---

### 10.7.1. CGAL → SFCGAL → PostGIS

### 10.7.2. OpenCASCADE

#### 10.7.2.1. OpenCASCADE-inspired BRep ontology

Perzylo, A., Somani, N., Rickert, M., & Knoll, A. (2015, September). An ontology for CAD data and geometric constraints as a link between product models and semantic robot task descriptions. In 2015 IEEE/RSJ international conference on intelligent robots and systems (IROS) (pp. 4197-4203). IEEE.

<https://ieeexplore.ieee.org/abstract/document/7353971>

[23]

#### 10.7.2.2. Topologic

Jabi, W., & Chatzivasileiadi, A. (2021, January). Topologic: exploring spatial reasoning through geometry, topology, and semantics. In Formal Methods in Architecture: Proceedings of the 5th International Symposium on Formal Methods in Architecture (5FMA), Lisbon 2020 (pp. 277-285). Cham: Springer International Publishing.

<https://topologic.app/>

[2]

### 10.7.3. BRep vs mesh/polyhedron

BRep

- Curved surfaces
- Topology: connected components as shells, solids with inner voids, etc.

- Clean APIs due to inheritance: e.g `fn extrude(Topo) → Topo`, for `vertex → edge`; `edge → face`; `face → solid`; `solid → solid`
- Extra indirections: `edge → vertex[] → point`
- Depending on implementation can be inefficient, e.g outer wire of face not explicitly marked need to be checked wrt infinite point
- Data integrity and validation a bit harder

#### Mesh/polyhedron

- Potentially fewer indirections
- Triangle meshes robust and well understood
- Many different data models though, e.g half-edge (only manifold), indexed faceset (no adjacency info), winged/quad/radial edge



11

# CURRENT CAPABILITIES

---

## 11.1. GeoSPARQL

---

GeoSPARQL is the most common geospatial extension of SPARQL. It was accepted as an OGC standard in 2012 and revised as GeoSPARQL 1.1 in 2024.

According to the standard document, “The OGC GeoSPARQL standard supports representing and querying geospatial data on the Semantic Web. GeoSPARQL defines a vocabulary for representing geospatial data in RDF, and it defines an extension to the SPARQL query language for processing geospatial data”.

### 11.1.1. Requirements addressed

In order to define which capabilities GeoSPARQL needs to adopt for full 3D compatibility, we first take a look at GeoSPARQL 1.1 current capabilities with regards to 3D.

#### 11.1.1.1. Dimensionality

In this white paper, when we discuss three dimensional data, we mean three dimensional geometries; instances of the class `geo:Geometry`. GeoSPARQL 1.1 defines three different properties for geometry that have to do with dimensionality:

1. `geo:dimension`, or *topological dimension*: This is the number of perpendicular directions in which a geometry extends. A point, for example, extends in no direction, so its topological dimension is 0. A line has a length, but no width or height. Its topological dimension is 1. A cube has a topological dimension of 3.
2. `geo:coordinateDimension`: In the geometric model that GeoSPARQL uses, points are the basic building blocks of geometry. A point geometry can have a different number of coordinates, depending on the space in which it is placed. A point on a flat map, or on the surface of a sphere, needs two coordinates. The *coordinate dimension* is the number of coordinates in the points that define a Geometry.
3. `geo:spatialDimension`: In order to support linear referencing, geometries in GeoSPARQL can have a measure value. This is a relative position along a line or a curve, and does not extend the Geometry in space. The *spatial dimension*, therefore, can be used to denote the number of coordinates in a point, excluding the measurement value.

The extended capabilities for GeoSPARQL discussed in this white paper concern the cases where the *spatial dimension* (which can be expressed with property `geo:spatialDimension`) of geometry has the value 3.

The table below shows the values of the three dimension properties for some Geometries (expressed as Well Known Text (WKT)).

Table 1

GEOMETRY (WKT)	GEO:DIMENSION	GEO:COORDINATEDIMENSION	GEO:SPATIALDIMENSION
point (4 15)	0	2	2
point Z (4 15 3)	0	3	3
linestring (4 15, 13 2)	1	2	2
point M (4 15 60)	0	3	2
point ZM (4 15 3 60)	0	4	3

#### 11.1.1.2. Vocabulary

GeoSPARQL version 1.1 consists of a Core module, a Topology Vocabulary extension, a Geometry extension, a Geometry Topology extension, an RDFS Entailment extension, and a Query Rewrite extension. Each of these modules will be briefly explained below.

#### 11.1.1.3. Core Module

GeoSPARQL version 1.1 includes a CORE module. This defines the basic classes, relationships, and literals. These classes are suitable for both 2D and 3D.

##### 11.1.1.3.1. Topology Vocabulary Extension

This extension provides standard definitions for spatial relationships that can exist between one spatial object and another.

Relations between geometries have been defined using three different sets of rules:

- Simple Features Relations
- Egenhofer Relations
- Region Connection Calculus RCC8

These topological definitions specify topological relations in a 2D-context.

#### 11.1.1.3.2. Geometry Extension

GeoSPARQL 1.1 geometry module defines a class *Geometry* as a subclass of *SpatialObject*.

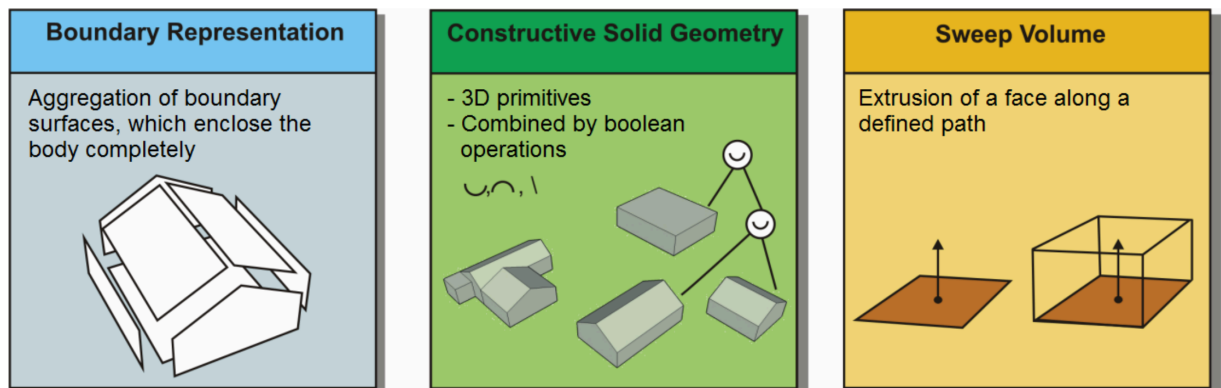
An instance of *Geometry* is not restricted to two dimensions.

A fine-grained classification of *Geometry* can use the Simple Feature Vocabulary which extends the class *Geometry* with further types, such as *Point*, *Polygon* etc.

The Simple Features vocabulary allows for the definition of 3D variants of:

- (Multi)Points
- (Multi)LineStrings
- (Multi)Polygons
- Polyhedralsurface

It does not include commons 3D primitives, such as *Cube* or *Mesh* surfaces which are integral parts of 3D representations. Nor does it include extruded geometry.



**Figure 1** – Possible approaches for representing 3D objects in IFC

Concerning metadata of 3D models, GeoSPARQL 1.1 provides properties which can be reused in 3D contexts. In particular, the properties are:

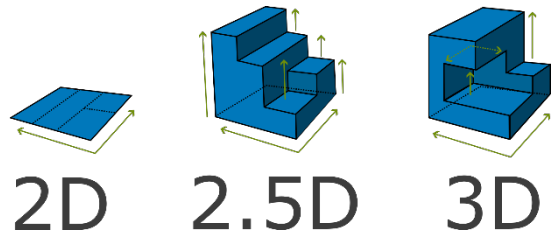
- `geo:hasVolume`
- `geo:hasMetricVolume`

Further 3D-related metadata properties such as projection matrices are not part of the current GeoSPARQL 1.1 standard.

A first requirement for 3D support is the ability to save 3D data in a knowledge graph.

The Geometry extension enables geometries to be defined within the GeoSPARQL framework. Supported geometry formats include RDF literals in WKT, GML, GeoJSON, and KML.

These literals are investigated for the storage of 3D data.



**Figure 2** – Difference between 2D, 2.5D and 3D geometry

Table 2

Literal Type	Z-Coordinate Supported	2.5D	3D
WKT Literal	Yes	Yes	Yes
GML Literal	Yes	Yes	Only with extension Schema
KML Literal	Yes	Yes	As import from COLLADA
GeoJSON Literal	Yes	Yes	Yes
DGGS Literal			

GeoSPARQL 1.1 also does not restrict the usage of coordinate reference systems with 3D support. There are currently almost 300 coordinate reference systems in the database [epsg.io](http://epsg.io) which can be used to describe 3D data encoded in the GeoSPARQL graph literals listed above.

GeoSPARQL already supports linking multiple geometries (e.g., 2D and 2.5D) to a single feature. We aim to extend this with 3D geometries.

For example, a tree in the real world may be represented in databases with both a 2D and a 3D geometry.

This should not require duplication of the tree entity – there can be one tree instance with both geometries linked, avoiding redundancy in the data model.

#### 11.1.1.4. Query functions with 3D support

GeoSPARQL 1.1 functions currently do not offer fully-featured 3D support. However, there are functions which may take into account the Z coordinate, if they are available.



Table 3

GeoSPARQL function	Z-Coordinate Supported	2.5D	3D
geof:is3D	Yes	Yes	Yes
geof:minZ	Yes	Yes	Yes
geof:maxZ	Yes	Yes	Yes

These functions check for the presence of Z coordinates or filter out maximum and minimum Z coordinates of the given geometry.

## 11.1.2. Adoption of GeoSPARQL 1.1

### 11.1.2.1. GeoSPARQL Alignments

**Table 4** — Alignment: GeoSPARQL and Open Source Relational Databases with Geospatial Support

GeoSPARQL	PostGIS	H2GIS	Spatialite
geof:area	st_area	st_area	area
geof:asGeoJSON	st_asgeojson		asgeojson
geof:asGML	st_asgml	st_asgml	asgml
geof:asKML	st_askml		askml
geof:asWKT		st_aswkt	aswkt
geof:asEWKB	st_asewkb		asewkb
geof:boundary	st_boundary	st_boundary	boundary
geof:bounding Circle		st_boundingcircle	
geof:buffer	st_buffer	st_buffer	buffer
geof:centroid	st_centroid	st_centroid	centroid

geof:concaveHull			concavehull
geof:sfContains	st_contains	st_contains	contains
geof:convexHull	st_convexhull	st_convexhull	convexhull
geof:ehCoveredBy	st_coveredby		coveredby
geof:ehCovers	st_covers	st_covers	covers
geof:sfCrosses	st_crosses	st_crosses	crosses
geof:difference	st_difference	st_difference	difference
geof:sfDisjoint	st_disjoint	st_disjoint	mbrdisjoint
geof:distance	st_distance	st_distance	distance
geof:envelope	st_envelope	st_envelope	envelope
geof:sfEquals	st_equals	st_equals	equals
geof:geometryN	st_geometryn	st_geometryn	geometryn
geof:getSRID	st_srid	st_srid	srid
geof:intersection	st_intersection	st_intersection	intersection
geof:sfIntersects	st_intersects	st_intersects	intersects
geof:isEmpty	st_isempty	st_isempty	isempty
geof:isSimple	st_issimple	st_issimple	issimple
geof:length	st_length	st_length	length
geof:numGeometries	st_numgeometries	st_numgeometries	numgeometries
geof:numPoints	st_numpoints	st_numpoints	numpoints
geof:sfOverlaps	st_overlaps	st_overlaps	overlaps
geof:perimeter	st_perimeter	st_perimeter	perimeter

geof:relate	st_relate	st_relate	relate
geof:sym Difference	st_symdifference	st_symdifference	symdifference
geof:sfTouches	st_touches	st_touches	touches
geof:transform	st_transform	st_transform	transform
geof:union	st_union	st_union	gunion
geof:sfWithin	st_within	st_within	within
geof:endPoint	st_endpoint	st_endpoint	endpoint
geof:exteriorRing	st_exteriorring	st_exteriorring	exteriorring
geof:interiorRingN	st_interiorringn	st_interiorringn	interiorringn
geof:isRing	st_ising	st_ising	ising
geof:pointN	st_pointn	st_pointn	pointn
geof:startPoint	st_startpoint	st_startpoint	startpoint
geof:x	st_x	st_x	x
geof:maxX	st_xmax	st_xmax	
geof:minX	st_xmin	st_xmin	
geof:y	st_y	st_y	y
geof:maxY	st_ymax	st_ymax	
geof:minY	st_ymin	st_ymin	
geof:z	st_z	st_z	z
geof:maxZ	st_zmax	st_zmax	maxz
geof:minZ	st_zmin	st_zmin	minz
geof:m	st_m		

geof:asDGGs
geof:ehContains
geof:ehDisjoint
geof:ehEquals
geof:ehInside
geof:ehMeet
geof:ehOverlap
geof:metricArea
geof:metricBuffer
geof:metricLength
geof:metric Perimeter
geof:rcc8dc
geof:rcc8ec
geof:rcc8eq
geof:rcc8ntpp
geof:rcc8ntppi
geof:rcc8po
geof:rcc8tpp
geof:rcc8tpi
geof:easting
geof:northing
geof:metric Distance

geof:transform CRS84		
geof:asGeocode		
geof:numInterior Ring		
geof:numPatches		
geof:patchN		
geof:isClosed		
		3ddistance
st_length3d	st_3dlength	3dlength
		3dmaxdistance
		abs
		acos
		addedgemodface
		addedgenewfaces
		addfdogeometrycolumn
		addgeometrycolumn
		addisoedge
		addisonetnode
		addisonode
		addlink
st_addmeasure		addmeasure
st_addpoint	st_addpoint	addpoint
		addtemporarygeometrycolumn

st_asbinary	st_asbinary	asbinary
		asencodedpolyline
st_asewkt		asewkt
		asfgf
		asgpb
		asin
st_assvg		assvg
st_astext	st_astext	astext
		astwkb
		asx3d
		atan
		atan2
		atm_astext
		atm_create
		atm_createrotate
		atm_createscale
		atm_createtranslate
		atm_createxroll
		atm_determinant
		atm_invert
		atm_isinvertible
		atm_isvalid

		atm_multiply
		atm_rotate
		atm_scale
		atm_transform
		atm_translate
		atm_xroll
		atm_yroll
		autofdostart
		autofdostop
		autogpkgstart
		autogpkgstop
st_azimuth	st_azimuth	azimuth
st_bdmpolyfromtext		bdmpolyfromtext
		bdmpolyfromwkb
st_bdpolyfromtext		bdpolyfromtext
		bdpolyfromwkb
		blobfromfile
		blobtofile
		bufferoptions_getendcapstyle
		bufferoptions_getjoinstyle
		bufferoptions_getmitrelimit
		bufferoptions_getquadrantsegments

	bufferoptions_reset
	bufferoptions_setendcapstyle
	bufferoptions_setjoinstyle
	bufferoptions_setmitrelimit
	bufferoptions_setquadrantsegments
st_buildarea	buildarea
	buildcirclebr
	buildmbr
	buildmbrfilter
	castautomagic
	casttoblob
	casttodouble
	casttogeometrycollection
	casttointeger
	casttolinestring
	casttomulti
st_tomultiline	casttomultilinestring
	casttomultipoint
	casttomultipolygon
	casttopoint
	casttopolygon
	casttosingle



		casttotext
		casttoxy
		casttoxym
		casttoxyz
		casttoxyzm
		ceil
		ceiling
		centimeter
		changeedgegeom
		changelinkgeom
		check_strict_sql_quoting
		checkduplicaterows
		checkgeopackagemetadata
		checkshadowedrowid
		checkspatialindex
		checkspatialmetadata
		checkwithoutrowid
		circularity
		clonetable
st_closestpoint	st_closestpoint	closestpoint
st_collect	st_collect	collect
st_collectionextract	st_collectionextract	collectionextract

	compressgeometry
st_constraineddelaunay	constraineddelaunaytriangulation
	coorddimension
	cos
	cot
	countunsafetriggers
	createclonedtable
	createisometadatatables
	creatembrcache
	createmetacatalogtables
	createmissingrasterlite2columns
	createmissingsystemtables
	createnetwork
	createrastercoveragestable
	createrouting
	createrouting_getlasterror
	createroutingnodes
	createspatialindex
	cretestylingtables
	createtemporaryspatialindex
	createtopogeo
	createtopology

		createtopotables
		createuuid
		createvectorcoverageables
		curvosityindex
		dd to dms
		decimeter
		decodeurl
		degrees
		delaunaytriangulation
st_dimension	st_dimension	dimension
		dirnamefrompath
		disablegpkgamphibiousmode
		disablegpkgmode
		disablepause
		disablespatialindex
		disabletinypoint
		discardfdogeometrycolumn
		discardgeometrycolumn
		dissolvepoints
		dissolvesegments
		distancewithin
		dms to dd

		downhillheight
		drapeline
		drapelineexceptions
		dropnetwork
		droptable
		droptopology
		dropvirtualgeometry
		elementarygeometries
		enablegpkgamphibiousmode
		enablegpkgmode
		enablepause
		enabletinypoint
		encodeurl
		ensureclosedrings
	st_envelopesintersect	envelopesintersects
		eval
		exp
st_expand	st_expand	expand
		exportdbf
		exportdxf
		exportgeojson2
		exportkml

		exportshp
st_extent	st_extent	extent
		extractmultilinestring
		extractmultipoint
		extractmultipoint
		extractmultipolygon
		fileextfrompath
		filenamefrompath
		filtermbrcontains
		filtermbrintersects
		filtermbrwithin
		floor
		forceasnull
st_forcerhr		forcelhr
		forcepolygonccw
		forcepolygoncw
		frechetdistance
		freexl_version
		fullfilenamefrompath
		garsmbr
		gcp_astext
		gcp_compute

		gcp_isvalid
		gcp_transform
		gcp2atm
		geodesic length
		geodesicarcarea
		geodesicarcheight
		geodesicarclength
		geodesiccentralangle
		geodesicchordlength
st_geohash		geohash
		geomcollfromtext
		geomcollfromwkb
		geometrycollectionfromtext
		geometrycollectionfromwkb
		geometrypointencode
geometrytype		geometrytype
st_geomfromewkb		geomfromewkb
st_geomfromewkt		geomfromewkt
		geomfromexifgpsblob
		geomfromfgf
		geomfromgeojson
st_geomfromgml	st_geomfromgml	geomfromgml

		geomfromgpb
st_geomfromkml		geomfromkml
st_geomfromtext	st_geomfromtext	geomfromtext
st_geomfromwkb	st_geomfromwkb	geomfromwkb
		geos_version
		geosconcavehull
		geosdensify
		geoslargestemptycircle
		geosmakevalid
		geosmaximuminscribedcircle
		geosminimumboundingcenter
		geosminimumboundingcircle
		geosminimumboundingradius
		geosminimumclearance
		geosminimumclearanceline
		geosminimumrotatedrectangle
		geosminimumwidth
		getcuttermessage
		getdbobjectslope
		getdecimalprecision
		getfacebypoint
		getfaceedges

getfacegeometry
getgpkgamphibiousmode
getgpkgmode
getisometadataid
getlastnetworkexception
getlasttopologyexception
getlayerextent
getlinkbypoint
getmimetype
getnetnodebypoint
getnodebypoint
getpointindex
getvirtualtableextent
gpkg_isassignable
gpkgaddgeometrycolumn
gpkgaddgeometrytriggers
gpkgaddspatialindex
gpkgaddtiletriggers
gpkgcreatebasetables
gpkgcreatetilestable
gpkgcreatetileszoomlevel
gpkggetimagetype



gpkggetnormalrow
gpkggetnormalzoom
gpkginsertepsgsrid
gpkgmakepoint
gpkgmakepointm
gpkgmakepointz
gpkgmakepointzm
great circle length
gunion
hasepsg
hasfreexl
hasgcp
hasgeocallbacks
hasgeopackage
hasgeos
hasgeos3100
hasgeos3110
hasgeosadvanced
hasgeosonlyreentrant
hasgeosreentrant
hasgeostrunk
hasiconv

	hasknn
	haslibxml2
	hasmathsql
	hasminizip
	hasproj
	hasproj6
	hasrouting
	hasrttopo
	hastopology
st_hausdorffdistance	hausdorffdistance
	hexagonalgrid
	hilbertcode
	importdbf
	importdxf
	importdxffromdir
	importgeojson
	importshp
	importwfs
	importxls
	importzipdbf
	importzipshp
	indian chain

		indian foot
		indian yard
		initfdospatialmetadata
		initspatialmetadata
		initspatialmetadatafull
		inittopogeo
		inittoponet
		insertepsgsrid
		international chain
		international fathom
		international foot
		international inch
		international link
		international nautical mile
		international statute mile
		international yard
		interpolatepoint
		invalidatelayerstatistics
	st_is3d	is3d
st_isclosed	st_isclosed	isclosed
		iscompressedgeometryblob
		isdecimalnumber

		isexifblob
		isexifgpsblob
		isgeometryblob
		isgifblob
		isinteger
		isjp2blob
		isjpegblob
		islowascii
		ismeasured
		isnumber
		ispauseenabled
		ispdfblob
		ispngblob
		ispolygonccw
		ispolygoncw
		istiffblob
		istinypointblob
		istinypointenabled
st_isvalid	st_isvalid	isvalid
	st_isvaliddetail	isvaliddetail
		isvalidgpb
st_isvalidreason	st_isvalidreason	isvalidreason

		isvalidtrajectory
		iswebpblob
		iszipblob
		kilometer
		libxml2_version
		line_interpolate_equidistant_points
st_line_interpolate_point		line_interpolate_point
st_line_locate_point		line_locate_point
st_line_substring		line_substring
		linefromencodedpolyline
st_linefromtext	st_linefromtext	"linefromtext linestringfromtext"
		"linefromwkb linestringfromwkb"
st_linemerge	st_linemerge	linemerge
		linescutatnodes
		linesfromrings
		linestringavgsegmentlength
		linestringfromtext
		linestringfromwkb
		linestringminsegmentlength
		ln
st_locate_along_measure		locatealongmeasure
st_locate_between_measures		locatebetweenmeasures

		log
		log10
		log2
		loginetfromtgeo
		m
		makearc
		makecircle
		makecircularsector
		makecircularstripe
	st_makeellipse	makeellipse
		makeellipticarc
		makeellipticsector
st_makeline	st_makeline	makeline
st_makepoint	st_makepoint	makepoint
st_makepointm		makepointm
		makepointz
		makepointzm
st_makepolygon	st_makepolygon	makepolygon
		makestringlist
	st_makevalid	makevalid
		makevaliddiscarded
st_maxdistance	st_maxdistance	maxdistance

	maxm
	mbrcontains
	mbrdisjoint
	mbrequal
	mbrintersects
	mbrmaxx
	mbrmaxy
	mbrminx
	mbrminy
	mbroverlaps
	mbrtouches
	mbrwithin
	md5checksum
	md5totalchecksum
	millimeter
	minm
	mlinefromtext
	mlinefromwkb
	modedgeheal
	modedgesplit
	modgeolinksplit
	modlinkheal

		modloglinksplit
		moveisonetnode
		moveisonode
		mpointfromtext
st_mpointfromtext	st_mpointfromtext	"mpointfromtext multipointfromtext"
		"mpointfromwkb multipointfromwkb"
		mpolyfromtext
		mpolyfromwkb
		multilinestringfromtext
		multilinestringfromwkb
		multipolygonfromtext
		multipolygonfromwkb
st_ndims		ndims
		newedgeheal
		newedgessplit
		newgeolinksplit
		newlinkheal
		newloglinksplit
		normalizelonlat
st_npoints	st_npoints	npoints
st_nrings		nrings
st_numinteriorring	st_numinteriorring	numinteriorring



st_numinteriorrings	st_numinteriorrings	numinteriorrings
		offsetcurve
		orientedenvelope
		pause
		pi
st_pointfromtext	st_pointfromtext	pointfromtext
st_pointfromwkb	st_pointfromwkb	pointfromwkb
st_pointonsurface	st_pointonsurface	pointonsurface
		polyfromtext
		polyfromwkb
		polygonfromtext
		polygonfromwkb
st_polygonize	st_polygonize	polygonize
		postgresql_getlasterror
		postgresql_resetlasterror
		postgresql_setlasterror
		pow
		power
		proj_asprojstring
		proj_aswkt
		proj_getdatabasepath
		proj_guesssridfromshp

proj_guesssridfromwkt
proj_guesssridfromzipshp
proj_setdatabasepath
proj_version
project
ptdistwithin
radians
rebuildgeometrytriggers
recoverfdogeometrycolumn
recovergeometrycolumn
recoverspatialindex
recreateisometareftriggers
recreaterrastercoveragetriggers
recreatestylingtriggers
recreatetopotriggers
recreatevectorcoveragetriggers
reduceprecision
reflectcoordinates
reflectcoords
registerdatalicense
registerisometadata
registervirtualgeometry

		relatemark
		remedgeupdateface
		remedgeupdateface
		remisoedge
		remisonetnode
		remisonode
		removeduplicaterows
		removeextraspaces
		removelink
st_removepoint		removepoint
		renamecolumn
		renamedatalicense
		renametable
st_reverse	st_reverse	reverse
		ringscutatnodes
		rl2_mapconfigurationabstractn
		rl2_mapconfigurationnamen
		rl2_mapconfigurationtitlen
		rl2_nummapconfigurations
		rl2_registermapconfiguration
		rl2_reloadmapconfiguration
		rl2_unregistermapconfiguration

	rotatecoordinates
	rotatecoords
	rttopo_version
	sanitizegeometry
	scalecoordinates
	scalecoords
	se_autoregisterstandardbrushes
	se_registerexternalgraphic
	se_registerrastercoveragekeyword
	se_registerrastercoveragesrid
	se_registerrasterstyle
	se_registerrasterstyledlayer
	se_registerspatialviewcoverage
	se_registertopogeocoverage
	se_registertoponetcoverage
	se_registervectorcoverage
	se_registervectorcoveragekeyword
	se_registervectorcoveragesrid
	se_registervectorstyle
	se_registervectorstyledlayer
	se_registervirtualtablecoverage
	se_reloadvectorstyle

	se_setvectorcoveragecopyright
	se_setvectorcoverageinfos
	se_setvectorcoveragevisibilityrange
	se_unregisterexternalgraphic
	se_unregisterastercoveragekeyword
	se_unregisterastercoveragesrid
	se_unregisterasterstyle
	se_unregisterasterstyledlayer
	se_unregistervectorcoverage
	se_unregistervectorcoveragekeyword
	se_unregistervectorcoveragesrid
	se_unregistervectorstyle
	se_unregistervectorstyledlayer
	se_updatevectorcoverageextent
st_segmentize	segmentize
	selfintersections
	sequence_currval
	sequence_lastval
	sequence_nextval
	sequence_setval
	setdatalicenseurl
	setdecimalprecision

		setendpoint
		setmultiplepoints
st_setpoint		setpoint
st_setsrid	st_setsrid	setsrid
		setstartpoint
		sharedpaths
		shiftcoordinates
		shiftcoords
st_shortestline	st_shortestline	shortestline
		sign
st_simplify	st_simplify	simplify
st_simplifypreservetopology	st_simplifypreservetopology	simplifypreservetopology
		sin
		singlesidedbuffer
	st_snap	snap
		snapandsplit
st_snaptogrid		snaptogrid
		spatialite_target_cpu
		spatialite_version
		spatnetfromgeom
		spatnetfromtgeo
	st_split	split

	splitleft
	splitright
	sqlproc_allvariables
	sqlproc_cookedsql
	sqlproc_execute
	sqlproc_executeloop
	sqlproc_fromfile
	sqlproc_fromtext
	sqlproc_getlasterror
	sqlproc_getlogfile
	sqlproc_isvalid
	sqlproc_numvariables
	sqlproc_rawsql
	sqlproc_return
	sqlproc_setlogfile
	sqlproc_variablen
	sqlproc_varvalue
	sqrt
	squaregrid
	sridfromauthcrs
	st_cutter
st_node	st_node

st_point	st_point	st_point
st_shift_longitude		st_shift_longitude
		st_subdivide
st_translate	st_translate	st_translate
st_wkbtoql		st_wkbtoql
st_wkttosql		st_wkttosql
		stddev_pop
		stddev_samp
		storedproc_createtables
		storedproc_delete
		storedproc_execute
		storedproc_executeloop
		storedproc_get
		storedproc_register
		storedproc_updatesqlbody
		storedproc_updatetitle
		storedvar_delete
		storedvar_get
		storedvar_getvalue
		storedvar_register
		storedvar_updatetitle
		storedvar_updatevalue



	swapcoordinates
	swapcoords
	tan
	tinypointencode
	togars
	topogeo_addlinestring
	topogeo_addlinestringnoface
	topogeo_addpoint
	topogeo_clone
	topogeo_createtopolayer
	topogeo_ disambiguatesegmentededges
	topogeo_exporttopolayer
	topogeo_fromgeotable
	topogeo_fromgeotableext
	topogeo_fromgeotablenoface
	topogeo_fromgeotablenofaceext
	topogeo_getedgeseed
	topogeo_getfaceseed
	topogeo_inittopolayer
	topogeo_ insertfeaturefromtopolayer
	topogeo_lineedgeslist
	topogeo_modedgeheal

	topogeo_newedgeheal
	topogeo_newedgessplit
	topogeo_polyfaceslist
	topogeo_polygonize
	topogeo_removedanglingedges
	topogeo_removedanglingnodes
	topogeo_removesmallfaces
	topogeo_remove_topolayer
	topogeo_snaplinetoseed
	topogeo_snappedgeotable
	topogeo_snappointtoseed
	topogeo_subdividelines
	topogeo_togeotable
	topogeo_togeotablegeneralize
	topogeo_toposnap
	topogeo_updateseeds
	toponet_clone
	toponet_disambiguatesegmentlinks
	toponet_fromgeotable
	toponet_getlinkseed
	toponet_linelinkslist
	toponet_togeotable

toponet_togeotablegeneralize
toponet_updateseeds
trajectoryinterpolatepoint
transformxy
transformxyz
triangulargrid
u.s. chain
u.s. foot
u.s. inch
u.s. statute mile
u.s. yard
unaryunion
uncompressgeometry
unregisterdatalicense
updatelayerstatistics
updatemetacatalogstatistics
updownheight
upgradegeometrytriggers
uphillheight
validatetopogeo
validlogicalnet
validspatialnet

	var_pop
	var_samp
	voronojdiagram
	wms_createtables
	wms_defaultrefsys
	wms_defaultsetting
	wms_getfeatureinforequesturl
	wms_getmaprequesturl
	wms_registergetcapabilities
	wms_registergetmap
	wms_registerrefsys
	wms_registersetting
	wms_registerstyle
	wms_setgetcapabilitiesinfos
	wms_setgetmapcopyright
	wms_setgetmapinfos
	wms_setgetmapoptions
	wms_unregistergetcapabilities
	wms_unregistergetmap
	wms_unregisterrefsys
	wms_unregistersetting
	xb_addfileid

xb_addparentid
xb_cacheflush
xb_compress
xb_create
xb_getabstract
xb_getdocument
xb_getdocumentsize
xb_getencoding
xb_getfileid
xb_getgeometry
xb_getinternalschemauri
xb_getlastparseerror
xb_getlastvalidateerror
xb_getlastxpatherror
xb_getparentid
xb_getpayload
xb_getschemauri
xb_gettitle
xb_iscompressed
xb_isgpx
xb_isisometadata
xb_ismapconfig

	xb_isschemavalidated
	xb_issldsevectorstyle
	xb_issldstyle
	xb_issvg
	xb_isvalid
	xb_isvalidxpathexpression
	xb_loadxml
	xb_mlinefromgpx
	xb_schemavalidate
	xb_setfileid
	xb_setparentid
	xb_storexml
	xb_uncompress
	zipfile_dbfn
	zipfile_numdbf
	zipfile_numshp
	zipfile_shpn
	st_3darea
st_perimeter3d	st_3dperimeter
	st_accum
	st_addz
	st_closestcoordinate

	st_compactnessratio
	st_coorddim
	st_delaunay
	st_densify
	st_drape
st_dwithin	st_dwithin
	st_explode
	st_extrude
	st_flipcoordinates
	st_force2d
	st_force3d
	st_furthestcoordinate
	st_geometryshadow
st_geometrytype	st_geometrytype
	st_geometrytypecode
	st_googlemaplink
	st_holes
	st_interpolate3dline
	st_isovist
	st_isrectangle
	st_linefromwkb
	st_lineintersector

st_locatealong	
st_longestline	
st_makeenvelope	
st_makegrid	
st_makegridpoints	
st_minimumrectangle	
st_mlinefromtext	st_mlinefromtext
st_mpolyfromtext	st_mpolyfromtext
st_multiplyz	
st_normalize	
st_octogonalenvelope	
st_orderingequals	
st_osmmaplink	
st_polygonfromtext	st_polyfromtext
st_polyfromwkb	
st_precisionreducer	
st_projectpoint	
st_removeduplicatedcoordinates	
st_removeholes	
st_removepoints	
st_removeRepeatedpoints	
st_reverse3dline	



	st_ringbuffer
	st_ringsidebuffer
st_rotate	st_rotate
	st_scale
	st_sidebuffer
	st_split
	st_sunposition
	st_svf
	st_tessellate
	st_tomultipoint
	st_tomultisegments
	st_triangleaspect
	st_trianglecontouring
	st_triangledirection
	st_triangleslope
	st_updatez
	st_voronoi
	st_zupdatelineextremities
@	
&&	
&<	
&<	

&>
<<
<<
=
>>
&>
>>
~
~=
box3d
find_srid
st_accum
st_affine
st_ashexewkb
st_containsproperly
st_coorddim
st_curvetoline
st_dfullywithin
st_distance_sphere
st_distance_spheroid
st_dump
st_dumprings

st_estimated_extent
st_extent3d
st_force_2d
st_force_3d
st_force_3dm
st_force_3dz
st_force_4d
st_force_collection
st_geogfromtext
st_geogfromwkb
st_geographyfromtext
st_geometryfromtext
st_gmltosql
st_hasarc
st_length_spheroid
st_length2d
st_length2d_spheroid
st_length3d_spheroid
st_linecrossingdirection
st_linefrommultipoint
st_linefromwkb
st_linestringfromwkb

st_linetocurve
st_locatebetweenelevations
st_longestline
st_makebox2d
st_makebox3d
st_makeenvelope
st_mem_size
st_memunion
st_minimumboundingcircle
st_multi
st_orderingequals
st_perimeter2d
st_point_inside_circle
st_polygon
st_rotatex
st_rotatey
st_rotatez
st_scale
st_summary
st_transscale
st_zmflag

#### **11.1.2.2. Geometry Topology Extension**

Another extension is the Geometry Topology extension. This provides query functions that return relationships between different geometries based on the topology vocabulary extension.

#### **11.1.2.3. RDFS Entailment Extension**

The RDFS Entailment extension provides rules for reasoning over geometries. Based on specific statements, additional information can be inferred. This kind of logical inference can also be applied to geometry. GeoSPARQL includes logic for reasoning over simple features geometries.

#### **11.1.2.4. Query Rewrite Extension**

GeoSPARQL allows queries such as whether “Feature A” is located within “Feature B” using its vocabulary. The Query Rewrite extension specifies a RIF rule that enables query rewriting. However, this extension does not support the rewriting of 3D queries.



12

# REQUIREMENTS FOR GEOSPARQL 3D

---

## 12.1. 5.1 Existing implementation of 3D geometry in GeoSPARQL

---

This section provides an overview of feedback received on the current version of the GeoSPARQL standard (version 1.1) regarding 3D usage. It helps to identify some of the barriers to use, and to outline requirements that have not been addressed that may encourage greater uptake.

### 12.1.1. Proposed extensions for GeoSPARQL 3D

#### 12.1.1.1. Extension 1: 3D representations

##### 12.1.1.1.1. GitHub Issue URI

<https://github.com/opengeospatial/ogc-geosparql/issues/583>

##### 12.1.1.1.2. Category

Semantic improvement

##### 12.1.1.1.3. Description

GeoSPARQL should include ways to represent 3D data in a knowledge graph.

3D data should be included in common 3D formats and 3D data should be includable as a text literal and a file representation.

Some common formats which could be considered for inclusion are:

- [Polygon File Format \(PLY\)](#)
- [Wavefront OBJ Format \(OBJ\)](#)
- [GLTF Format \(GLTF\)](#)
- [X3D Format](#)

### **12.1.1.2. Extension 2: Relations of 3D geometries**

#### **12.1.1.2.1. GitHub Issue URI**

<https://github.com/opengeospatial/ogc-geosparql/issues/416>

#### **12.1.1.2.2. Category**

Semantic improvement

#### **12.1.1.2.3. Description**

GeoSPARQL should include ways to represent relations between 3D geometries and relations between 3D geometries and geometries of lower dimensions. The relations should be expressable in property relations and should be queryable using SPARQL extension functions.

### **12.1.1.3. Extension 3: Appearance of 3D geometries**

#### **12.1.1.3.1. GitHub Issue URI**

- <https://github.com/opengeospatial/ogc-geosparql/issues/584>
- <https://github.com/opengeospatial/ogc-geosparql/issues/592>

#### **12.1.1.3.2. Category**

Semantic improvement

#### **12.1.1.3.3. Description**

GeoSPARQL should include ways to represent materials and textures of 3D geometries, so that geometries can be styled accordingly.

Materials include:

- Colors of surfaces with light diffusion parameters
- Images as textures, which are associated with surfaces of the 3D object



#### **12.1.1.4. Extension 4: Multi-component 3D geometries**

##### **12.1.1.4.1. GitHub Issue URI**

<https://github.com/opengeospatial/ogc-geosparql/issues/591>

##### **12.1.1.4.2. Category**

Semantic improvement

##### **12.1.1.4.3. Description**

GeoSPARQL should include ways to define multi-component 3D geometries, whereas each component expresses its own semantics. For example, parts of a building could have different semantics according to the function of the building components and would be classified as such in an RDF graph.

#### **12.1.1.5. Extension 5: Positioning of 3D geometries**

##### **12.1.1.5.1. GitHub Issue URI**

- <https://github.com/opengeospatial/ogc-geosparql/issues/587>
- <https://github.com/opengeospatial/ogc-geosparql/issues/588>
- <https://github.com/opengeospatial/ogc-geosparql/issues/589>
- <https://github.com/opengeospatial/ogc-geosparql/issues/591>

##### **12.1.1.5.2. Category**

Semantic improvement

##### **12.1.1.5.3. Description**

GeoSPARQL should include ways to position 3D geometries in a 3D space. Commonly 3D geometries are rotated, translated and scaled using commonly defined operators in computer graphics. Similar operations are needed for the relative positioning of 3D objects in GeoSPARQL, as properties and potentially as functions.

### 12.1.1.6. Extension 6: Alignments of GeoSPARQL 3D

#### 12.1.1.6.1. GitHub Issue URI

- <https://github.com/opengeospatial/ogc-geosparql/issues/590>
- <https://github.com/opengeospatial/ogc-geosparql/issues/574>
- <https://github.com/opengeospatial/ogc-geosparql/issues/571>

#### 12.1.1.6.2. Category

Semantic improvement

#### 12.1.1.6.3. Description

GeoSPARQL 3D should be aligned to other vocabularies and standard which currently provide 3D support in different knowledge domains. Especially alignments to ifcOWL and the X3D vocabulary would position the GeoSPARQL vocabulary as a link between these different standards.

### 12.1.1.7. Extension 7: Alignments of Engineering CRS to Geospatial CRS

#### 12.1.1.7.1. GitHub Issue URI

<https://github.com/opengeospatial/ogc-geosparql/issues/586>

#### 12.1.1.7.2. Category

Semantic improvement

#### 12.1.1.7.3. Description

GeoSPARQL 3D should provide the opportunity to align a local coordinate system in which most 3D geometries are defined with a coordinate reference. While this work might only be partially done within the scope of GeoSPARQL itself, GeoSPARQL should be aligned with the emerging Ontology CRS developments of OGC and provide necessary functions or properties to create the link.

## **12.1.1.8. Extension 8: Geometry Extrusion**

### **12.1.1.8.1. GitHub Issue URI**

- <https://github.com/opengeospatial/ogc-geosparql/issues/556>
- <https://github.com/opengeospatial/ogc-geosparql/issues/547>

### **12.1.1.8.2. Category**

Semantic improvement

### **12.1.1.8.3. Description**

GeoSPARQL 3D should provide the opportunity to extrude 2D geometries to 3D geometries and vice versa.

## **12.1.1.9. Extension 9: Geometry Attributes**

### **12.1.1.9.1. GitHub Issue URI**

- <https://github.com/opengeospatial/ogc-geosparql/issues/568>
- <https://github.com/opengeospatial/ogc-geosparql/issues/550>
- <https://github.com/opengeospatial/ogc-geosparql/issues/549>
- <https://github.com/opengeospatial/ogc-geosparql/issues/548>
- <https://github.com/opengeospatial/ogc-geosparql/issues/558>

### **12.1.1.9.2. Category**

Semantic improvement

#### 12.1.1.9.3. Description

GeoSPARQL 3D should provide functions and properties that describe essential properties of a 3D Geometry such as its minimum and maximum height, width and depth and its CompactnessRatio.

#### 12.1.1.10. Extension 10: Non-topological Query Functions – 3D Extension

##### 12.1.1.10.1. GitHub Issue URI

- <https://github.com/opengeospatial/ogc-geosparql/issues/556>

##### 12.1.1.10.2. Category

Semantic improvement

##### 12.1.1.10.3. Description

GeoSPARQL 3D should provide the opportunity to execute non-topological query functions on 2D and 3D geometries commonly used in geospatial databases. Proposed extensions include following functions:

- geometry extrusion to the specified line segment
- geometry extrusion to the specified height
- spatiotemporal geometry extrusion to the specified line segment with specific start and end time

## 12.2. 5.2 3D Geometry available in IFC

---

This section describes what kind of geometry is available in IFC, and how that relates to (1) different modelling kernels, and (2) geoSPARQL and geospatial geometry engines.

@Thomas Krijnen, Alex Donkers, Pieter Pauwels == to write here please

## 12.3. 5.3 Vanilla 3D geometry handling in the Semantic Web

---

This section describes in what other ways 3D geometry is currently handled in the Semantic Web, for example in BOT ontology, OMG and FOG ontologies, and few more.

## 12.4. 5.4 Concluding overview of requirements for 3D geometry in the semantic web

---

A concluding summary with a list of requirements to be taken into account for future development in different places and organisations.



13

# BENEFICIARIES AND BENEFITS

---

This section describes the beneficiaries and benefits of representing data, including geospatial data, using semantic and graph technologies. Furthermore, a collection of use cases demonstrate how semantic and graph technologies are used together with spatial data to tackle real world problems.

## 13.1. Semantic-functional value of 3D-GeoSPARQL

---

Value for data reasoning, formal description, and semantic interoperability

### 13.1.1. Meaningful creation and querying of 3D geometry

Whether manually or programmatically defining 3D geometries in BIM, GEO or CG environments, the GeoSPARQL standard could provide or connect to vocabulary to represent 3D structures. A 3D cube, for example, can be represented in multiple ways:

- As a set of bounding points, lines, and faces;
- As a base surface with an extrude function;
- As an 3D geometric primitive (e.g., the concept of a ‘cube’ as a spatial figure).

Once GeoSPARQL offers the means to define and link 3D geometries in these different ways, it will allow both humans and machines to interpret and interact with the data effectively.

### 13.1.2. Meaningful creation and querying of 3D topological relationships

Is “3D Geometry A” inside, touching, overlapping, intersecting or above “3D Geometry B”?

Being able to describe and use such topological relationships is crucial for conducting spatial analyses, formulating rules, and deriving knowledge from different heterogeneous datasets.

Beyond describing topological relationships, one should be able to query them:

What is the spatial relationship between 3D Geometry A and 3D Geometry B?

Such queries should return the appropriate topological result (e.g., “intersects”), which is essential for use cases like clash detection in design validation

### 13.1.3. Derivation of geometric and topological knowledge

From explicitly modeled geometric and topological data, one should be able to infer implicit knowledge.

For instance, if 3D Geometry A is 3D inside 3D Geometry B, then we can infer that:

A does not “touch” B, and A does not “overlap” with B,

even if these facts are not explicitly stated.

For entailment an application that is compliant with the geo-spatial 3D specification would be able to answer queries like: “Does this tree have a 3D geometry?”

If the tree is defined using a MultiSolid geometry, then the answer should be “yes,” even if this is not explicitly declared as such.

## 13.2. Value for user experience, visualization, and application use of 3D-GeoSPARQL

---

### 13.2.1. Visualization

There is a growing need to visualize how 3D data in BIM and GIS relate to one another. Stakeholders want to see BIM and/or 3D Geo data of a newly planned structure visualized within the 3D Geo and/or BIM context of the existing digital city. A shared vocabulary that can present both domains in an integrated way supports this goal.

### 13.2.2. Calculation and analysis

Semantic modelled 3D-model enables powerful computation and analysis. Analytical results can be displayed in dashboards operating within the GeoBIM domain. This creates a bridge between asset management (typically GIS-oriented) and project management (typically BIM-oriented), allowing for cross-domain collaboration and decision-making.

### 13.2.3. Spatial querying

Spatial querying is a key function within a federated GeoBIM Network. Questions such as “What material is located in this area?” or “Where is space available for new cables and pipelines?” are examples of 3D spatial queries that can be answered when GeoSPARQL 3D is functioning effectively across systems and semantics.



#### 13.2.4. Machine control

A shared semantic GeoBIM Network also supports machine control. The GIS domain typically describes the existing situation, while the BIM domain describes the intended or future situation. This combination can be used to automatically instruct and guide machines in the built environment.

#### 13.2.5. Modeling, simulation and planning

A network of datasets with 3D-data should support the modeling, simulation and planning of future changes to the built environment. Users — whether human or machine — can use the network and GeoSPARQL 3D to propose and model modifications in either BIM or GIS formats. A well-functioning 3D semantic GeoBIM Network enables this kind of forward-looking spatial planning and design.

### 13.3. Added value of the 3D-GeoSPARQL for Organisations

---

#### 13.3.1. Brings together different domains (GIS, BIM, CG)

GeoSPARQL 3D can help in bringing together different domains that work with 3D information.

#### 13.3.2. Enables extension to vocabularies from other domains

The vocabulary can have the possibility to extend to vocabulaires with 3D geometry or topology from other domains, for example the Building Ontology Topology (BOT) or RELOC Ontology. Multi-domain models with georeferenced 3D and 2D city models could be also linked by CityRDF ontology based on CityGML 3.0 standard. GeoSPARQL 3D would be important enabler for data retrieval, update and analysis for such models. In addition to ontologies, it can also establish relationships to 3D file formats from other domains, such as glTF.

#### 13.3.3. Facilitates better interoperability between knowledge domains with spatial components (geography, aerospace, architecture, product design, (bio)chemistry, IoT, ...)

A unified geometric language can help by migrating ideas and methods across fields, accelerating innovation. For example a parametric design algorithm, rule, or IIm making use of geometry and topology originated in aerospace, can be re-used in the architecture domain.



14

# ANNEX N: N

---





15

# ANNEX O: HISTORY

---









# BIBLIOGRAPHY







## BIBLIOGRAPHY

---

- [1] Abhayaratna J, van den Brink L, Car N, Atkinson R, Homburg T, Knibbe F, McGlinn K, Wagner A, Bonduel M, Rasmussen MH, Thiery F: Abhayaratna2020wp, *OGC Benefits of Representing Spatial Data Using Semantic and Graph Technologies*. Open Geospatial Consortium (2020). <http://www.opengis.net/doc/wp/using-semantic-graph>.
- [2] Jabi W, Chatzivasileiadi A: Topologic: Exploring Spatial Reasoning Through Geometry, Topology, and Semantics. In: p. 277. Springer International Publishing, Cham. (2021).
- [3] Filip Biljecki HT: QUALITY OF BIM–GIS CONVERSION. (2019).
- [4] Anne Göbels JB: Relative Location Ontology: An ontological model for representing directional topological relationships between spatial entities in oriented space. (2024).
- [5] St\"otzner E, Homburg T, Mara H: CNN Based Cuneiform Sign Detection Learned from Annotated 3D Renderings and Mapped Photographs with Illumination Augmentation. In: pp. 1680–1688. (2023).
- [6] Behr J, Eschler P, Jung Y, Zöllner M: X3DOM: a DOM-based HTML5/X3D integration model. In: p. 127. (2009).
- [7] Bonduel M, Wagner A, Pauwels P, Vergauwen M, Klein R: Including widespread geometry formats in semantic graphs using RDF literals. In: vol. 1, p. 341. (2019).
- [8] Brutzman D, Daly L: *X3D: extensible 3D graphics for Web authors*. Elsevier, n.p. (2010).
- [9] Brutzman D, Flotyński J: X3D ontology for querying 3D models on the semantic web. In: p. 1. (2020).
- [10] D'Andrea A, Fernie K: CARARE 2.0: a metadata schema for 3D Cultural Objects. In: vol. 2, p. 137. (2013).
- [11] Donkers S, Ledoux H, Zhao J, Stoter J: Automatic conversion of IFC datasets to geometrically and semantically correct CityGML LOD3 buildings. *Transactions in GIS* vol. 20, p. 547 (2016).
- [12] Feichtenhofer C: X3d: Expanding architectures for efficient video recognition. In: p. 203. (2020).
- [13] Hansson F: Linked geodata: CityGML represented as a virtual knowledge graph. *Student thesis series INES* (2024).
- [14] Kolbe TH, Gröger G, Plümer L: CityGML: Interoperable access to 3D city models. In: p. 883. Springer. (2005).

- [15] Snyderman S, Sanderson R, Cramer T: The International Image Interoperability Framework (IIIF): A community & technology approach for web-based images. In: vol. 12, p. 16. (2015).
- [16] St{\'o}tzner E, Homburg T, Bullenkamp JP, Mara H: R-CNN based PolygonalWedge Detection Learned from Annotated 3D Renderings and Mapped Photographs of Open Data Cuneiform Tablets. (2023).
- [17] World Wide Web Consortium: *RDF 1.1 Concepts and Abstract Syntax*, W3C Recommendation, <https://www.w3.org/TR/rdf11-concepts/> (25 February 2014).
- [18] World Wide Web Consortium: *RDF 1.1 Turtle Terse RDF Triple Language*, W3C Recommendation, <https://www.w3.org/TR/turtle> (25 February 2014).
- [19] [NO INFORMATION AVAILABLE]
- [20] [NO INFORMATION AVAILABLE]
- [21] Chadzynski A, Krdzavac N, Farazi F, Lim MQ, Li S, Grišute A, Herthogs P, von Richthofen A, Cairns S, Kraft M: Semantic 3D City Database – An enabler for a dynamic geospatial knowledge graph. *Energy and AI* vol. 6, p. 100106 (2021).
- [22] Chadzynski A, Li S, Grišiūtė A, Chua J, Hofmeister M, Yan J, Tai HY, Lloyd E, Tsai YK, Agarwal M, Akroyd J, Herthogs P, Kraft M: Semantic 3D city interfaces—Intelligent interactions on dynamic geospatial knowledge graphs. *Data-Centric Engineering* vol. 4 (2023).
- [23] Perzylo A, Somani N, Rickert M, Knoll A: An ontology for CAD data and geometric constraints as a link between product models and semantic robot task descriptions. In: *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. pp. 4197–4203. IEEE. (2015).
- [24] Flotyński J, Walczak K: Ontology-Based Representation and Modelling of Synthetic 3D Content: A State-of-the-Art Review. *Computer Graphics Forum* vol. 36 no. 8, pp. 329–353 (2017).
- [25] Sikos LF: A novel ontology for 3D semantics: ontology-based 3D model indexing and content-based video retrieval applied to the medical domain. *International Journal of Metadata, Semantics and Ontologies* vol. 12 no. 1, p. 59 (2017).
- [26] Car NJ, Homburg T: GeoSPARQL 1.1: Motivations, Details and Applications of the Decadal Update to the Most Important Geospatial LOD Standard. *ISPRS International Journal of Geo-Information* vol. 11 no. 2, p. 117 (2022).
- [27] El Yamani S, Hajji R, Billen R: IFC-CityGML Data Integration for 3D Property Valuation. *ISPRS International Journal of Geo-Information* vol. 12 no. 9, p. 351 (2023).
- [28] Homburg T, Zwick R, Mara H, Bruhn K: Annotated 3D-Models of Cuneiform Tablets. *Journal of Open Archaeology Data* vol. 10 (2022).

- [29] Haynes R: Evolving Standards in Digital Cultural Heritage – Developing a IIIF 3D Technical Specification. In: *Lecture Notes in Computer Science*. pp. 50–64. Springer International Publishing, Cham. (2023).
- [30] Kutzner T, Chaturvedi K, Kolbe TH: CityGML 3.0: New Functions Open Up New Applications. *PFG – Journal of Photogrammetry, Remote Sensing and Geoinformation Science* vol. 88 no. 1, pp. 43–61 (2020).
- [31] Homburg T, Cramer A, Raddatz L, Mara H: Metadata schema and ontology for capturing and processing of 3D cultural heritage objects. *Heritage Science* vol. 9 no. 1 (2021).
- [32] Ropelewski AJ, Rizzo MA, Swedlow JR, Huisken J, Osten P, Khanjani N, Weiss K, Bakalov V, Engle M, Gridley L, Krzyzanowski M, Madden T, Maiese D, Mandal M, Waterfield J, Williams D, Hamilton CM, Huggins W: Standard metadata for 3D microscopy. *Scientific Data* vol. 9 no. 1 (2022).
- [33] Wang Y, Wang X, Liu A, Zhang J, Zhang J: Ontology of 3D virtual modeling in digital twin: a review, analysis and thinking. *Journal of Intelligent Manufacturing* vol. 36 no. 1, pp. 95–145 (2023).