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Multi-disciplinary Use of Three-Dimensional Geospatial Information

Thomas Krijnen, Francesca Noardo, Ken Arroyo Ohori, and Jantien Stoter

Abstract In this chapter, we start from the typical concepts from Geographic Information System (GIS): data representation, acquisition, querying and analysis. We follow with the transition from 2 to 3D GIS and describe open standards such as CityGML and CityJSON and recent advances on 3D geospatial simulations, computing and real-time GIS and Internet of Things (IoT). Then we discuss the discrepancies in information management and modelling with respect to Building Information Modelling (BIM) and the related open standard, Industry Foundation Classes (IFC). We highlight the difference between Cartesian engineering coordinate systems and geospatial coordinate reference systems, contrast the procedural geometry definitions of IFC with the explicit geometries of GIS and look at implementation mechanisms such as boundary representations and polyhedral surface models and describe the semantic Level of Detail used in CityGML. The section that follows describes relevant processes supporting integration such as georeferencing, conversion of formats using semantic and geometric approaches and linking of heterogeneous information. We also highlight interoperability challenges that stem from consistency and validity of data, by interpreting the results of a recent benchmark on interoperability of the most common involved data formats (CityGML and IFC). We close with a conclusion and perspectives on the future with case studies on geo-enabled building permit checking and geospatial artificial intelligence and machine learning.

Keywords GIS · Interoperability · Geometry · BIM · IFC · CityGML

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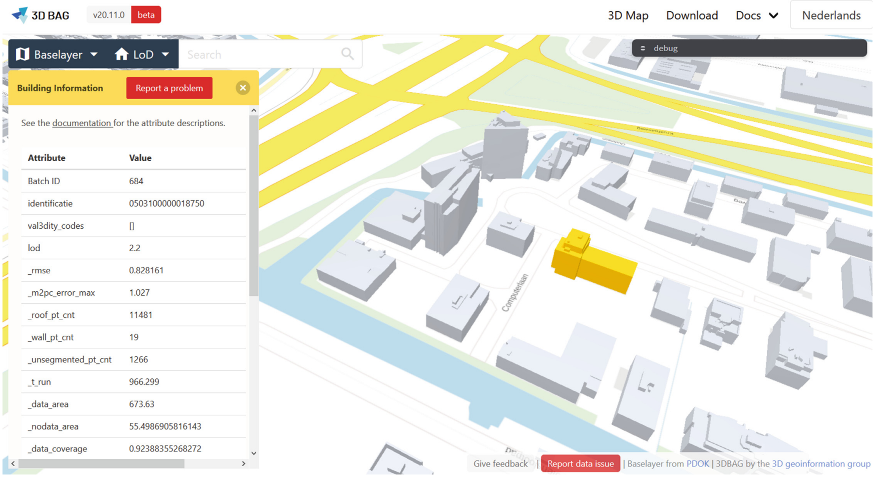
1 Introduction

The field of Geographic Information System (GIS) deals with the acquisition, representation, visualization and analysis of geospatial and geographic data. Traditionally, a primary means of communication has been maps, but more and more this shifts towards fully three-dimensional (3D) scenes to accommodate for the spatial complexity of dense urban environments, to cater to the complexity of geospatial simulations, such as heat and noise analyses, and to provide an accurate 3D backdrop for new construction works.

With 3D geospatial information, the parallels with disciplines such as Building Information Modelling (BIM, see Chapter "Building Information Modelling and Information Management") and Asset Management become immediately apparent. Both BIM and GIS have experienced a similar paradigm shift in industry from 2 to 3D. In the case of BIM this was a shift from 2D Computer Aided Design (CAD) to semantic data models with 3D representations.

Whereas traditionally the open standards in construction and GIS were fairly disjoint, we now see considerable overlap in audience and objectives (fig. an illustration) (Fig. 1). The mainstream standards IFC (Industry Foundation Classes, the main prevalent open standard to exchange building information models) and CityGML overlap; but even more so their extensions and novel standardization efforts such as IndoorGML and the infrastructure extensions to IFC: IfcAlignment, IfcRoad, IfcBridge and existing initiatives for tunnels and landworks.

At the same time, and perhaps less immediately apparent, there are also deeply rooted discrepancies in the worldviews of these disciplines. On the one hand, we see rigid breakdown structures in BIM akin to the systems engineering methodology to decompose a system into elements and couple those elements with requirements. On the other hand, in GIS, we see a more geometry-first focus on simply unordered sets of features with geometry and location or raster fields. These geometries are often acquired from visible surfaces using remote sensing techniques, and semantics are more or less secondary attributes in lookup tables. Spatial relationships are determined using spatial computation during analysis. The construction of a BIM model is instead semantics-first, where a modeller will select a "Wall tool," for example, which will determine the kind of parametric geometry and constraints that are available (although when exported to IFC a more generic set of geometry resources is used). These differences can be traced back to, on the one hand, a focus on engineering, planning, producing construction documentation and verifying requirements in the BIM domain and on the other hand in GIS starting from the acquisition of geospatial measurements. This difference in focus has a profound impact on their worldview, the lifetime of data and therefore focuses on open standards, validity of data and an explicit representation of the temporal dimension in GIS data.



See the documentation for the attribute descriptions.

Attribute	Value
Batch ID	684
identificatie	0503100000018750
val3dity_codes	[]
lod	2.2
_rmse	0.828161
_m2pc_error_max	1.027
_roof_pt_cnt	11481
_wall_pt_cnt	19
_unsegmented_pt_cnt	1266
_t_run	966.299
_data_area	673.63
_nodata_area	55.4986905816143
_data_coverage	0.92388355268272

Fig. 1 Example of an online GIS viewer: a raster base layer of the land cover and 3D building models gathered from open data. Attributes are shown on the left for the selected building in yellow. https://tudelft3d.github.io/3dbag-viewer

In this chapter, we start from the typical GIS concepts: data representation, acquisition, querying and analysis. We follow with the transition from 2 to 3D GIS and describe open standards for 3D GIS such as CityGML and CityJSON and recent advances on 3D geospatial simulations, computing and real-time GIS and Internet of Things (IoT). Then we discuss the discrepancies in information management and modelling with respect to BIM and the related open standard, IFC. We highlight the difference between Cartesian engineering coordinate systems and geospatial coordinate reference systems, contrast the procedural geometry definitions of IFC with the explicit geometries of GIS and look at implementation mechanisms such as boundary representations and polyhedral surface models and describe the semantic Level of Detail used in CityGML. The section that follows describes relevant processes supporting integration such as georeferencing, conversion of formats using semantic and geometric approaches and linking of heterogeneous information. We also highlight interoperability challenges that stem from consistency and validity of data, by interpreting the results of a recent benchmark on interoperability of the most common involved data formats (CityGML and IFC). We close with a conclusion and perspectives on the future with case studies on geo-enabled building permit checking and geospatial artificial intelligence and machine learning.

2 Geospatial Concepts

2.1 Coordinate Systems

GIS disciplines deal with the entire framework of acquiring, managing, analysing and presenting spatial and geographic data. The kind of information managed by GIS is strongly connected with the representation of its position on the Earth. Given Earth's complex and irregular shape, its surface has to be approximated for practical purposes. Depending on the needed accuracy, one can abstract the Earth shape as an ellipsoid (or oblate spheroid, where two radii are equal and the third smaller) or a geoid: an approximation of the equipotential gravitational surface of Earth. Smaller regions are instead approximated through a projection to cylinders, cones or planes that are suitable for the region. Alternatively, small pieces of land can be represented in a local Cartesian system, although this is generally only used for local computations.

A geographic coordinate system [1] is composed of a reference ellipsoid that approximates the geoid, either locally (local datum) or as a geocentric datum, where centre of geoid and ellipsoid are coincident, to represent global datasets (nowadays, most used geocentric datum is probably the WGS84,[1] the basis for GPS navigation among others). Geographic coordinate systems are generally measured in angular units relative to the equator and the prime meridian. A 3D location is therefore composed of latitude, longitude and elevation. Elevation is not angular but linear and typically refers to a vertical system based on the geoid height values or national references. Geographic spherical coordinates have some undesirable characteristics, such as non-Euclidean properties and are therefore computationally expensive and unintuitive. A location on Earth has infinitely many equivalent representations in spherical coordinates due to periodic nature of the latitude and longitude, and at the poles, the latitude component is insignificant. Different units of measure for components (latitude and longitude are angular, elevation linear) can potentially cause issues in applications. For this reason, projected coordinate reference systems are mainly used in practice, to alleviate these issues by projecting the spherical coordinates onto a Cartesian plane. However, the process of representing an irregular (and curved) surface on a plane comes at the expense of distortions in the shape, areas, distance or direction of the data.[2] Therefore, it is of critical importance to choose a suitable projection system for the region in which the represented data is located, often prescribed by standardization documents or national laws and to document it properly within the dataset's metadata.

The correct management of coordinate reference systems is necessary to visualize and use data consistently, especially when integrating several datasets. Although many variations and national coordinate reference systems are used in

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[1] https://epsg.io/4326. Accessed 30th November 2020.

[2] https://www.earthdatascience.org/courses/earth-analytics/spatial-data-r/intro-to-coordinate-reference-systems/. Accessed 30th November 2020.

practice, most of the systems commonly in use are documented within the EPSG database,[3] which stores the related parameters allowing a correct representation and conversions. Many GIS software and geo-datasets refer to the EPSG code to document and retrieve them.

Among the sets of projections that can be used for the entire world, the Universal Transverse Mercator (UTM) is commonly used, as a good attempt to reduce the distortions due to map projections. It cuts longitudinally the Earth surface in 60 zones, each a long North-to-South strip 6-degrees of longitude in width.[4] Generally, these zones exclude the areas near the poles, and each zone is then cut into latitude bands. A combination of a zone and a band is then used by being projected to a specific section of an oblate spheroid.

2.2 Objects and Fields

Most typically in GIS, there are two ways of representing data: vector objects and raster fields.[5] In a vector representation, isolated discrete objects are identified using a geometric form. In a raster representation, there is a continuous field discretized over cells (or voxels in 3D). The identification of the demarcation of an object and its permanent identity is a topic that traces back to ancient Greek philosophy from Euclid, Aristotle and Heraclitus "A boundary is that which is an extremity of anything". [Euclid, Elements I] and "[A boundary] is the first point beyond which it is not possible to find any part [of it]" and [Aristotle, Metaphysics V] and Heraclitus paraphrased by Plato: "one cannot step into the same river twice as different water will flow onto you". In practice, it is not possible to demarcate unambiguously where a mountain begins and a valley ends. It is easier to reach agreement on that as a height map as a product of satellite imagery sensing or of airborne laser scanning. Vector objects are only models containing a selection of the real world; they represent but makes deriving and managing spatial information simpler, see [2] for discussion and a graphic representation of the differences in Fig. 2.

With the increase in computation and storage facilities, it has become possible to manage information as 3D point clouds, representing large sets of precise Euclidean measurements from acquisition devices. Their density makes them comparable to continuous fields, traditionally obtained from interpolation of fewer local measurements. Point clouds recently became widely used in geospatial data acquisition, visualization and analysis.

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[3] https://epsg.org/home.html. Accessed 30 November 2020.

[4] https://pubs.usgs.gov/fs/2001/0077/report.pdf. Accessed 30 November 2020.

[5] Vector representations of fields and raster representations of objects are also possible, but these are less common.

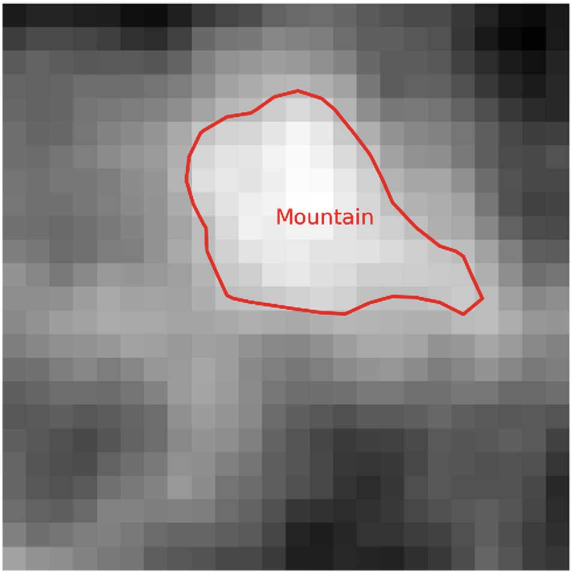

Fig. 2 Colour-coded height map representing a height field and vector representation of a mountain embedded in it

2.3 Formats, Standards and Tools

Coordinate components derive their spatial meaning from a coordinate reference system. A wide set of formats and encodings exists that provide the set of geometric primitives and govern their storage on disk or memory.

The Shapefile format is a vector data format developed and regulated by Esri. It can contain point, line and polygon vector features described as a set of files (with extensions.shp,.shx,.dbf and others). Attributes are stored in tables. Roughly the same structure of data can be folded into a geodatabase so that the information is stored and queryable in a relational database management system (RDBMS), when SQLite is chosen as the database engine. The result is still a portable file.

ISO 19,125, called simple feature access, standardizes a set of geometric primitives for use in spatial computing. The standard comes in two parts. 19,125–1, the Common Architecture (SFA-CA), defines the data model and their representation in Well-Known Text (WKT), see example in Fig. 3. Part two defines an implementation and a set of geometric predicates as functions in SQL. GeoSPARQL is an OGC standard for representing spatial data and querying based on RDF and SPARQL, and WKT can be embedded in the RDF graphs as text literals, and SPARQL functions can operate on these (and include DE-9IM and RCC8 as well). There is a well-known binary (WKB) equivalent that uses a binary encoding of the same data model.

While the WKT text strings are human readable, their grammar is not widely implemented in general-purpose software tooling as it is a format specific to geospatial use cases. GeoJSON tackles this issue by using the commonly used

```
POLYGON ((-5.0 -0.15, 5.0 -0.15, 5.0 0.15, -5.0 0.15, -5.0 -0.15))

GEOMETRYCOLLECTION Z(POLYHEDRALSURFACE Z(
  ((-5.0 -0.15 0.0, -5.0 -0.15 3.0, -5.0  0.15 3.0, -5.0  0.15 0.0)),
  (( 5.0 -0.15 3.0,  5.0 -0.15 0.0,  5.0  0.15 0.0,  5.0  0.15 3.0)),
  ((-5.0 -0.15 0.0,  5.0 -0.15 0.0,  5.0 -0.15 3.0, -5.0 -0.15 3.0)),
  (( 5.0  0.15 0.0, -5.0  0.15 0.0, -5.0  0.15 3.0,  5.0  0.15 3.0)),
  ((-5.0 -0.15 0.0, -5.0  0.15 0.0,  5.0  0.15 0.0,  5.0 -0.15 0.0)),
  ((-5.0  0.15 3.0, -5.0 -0.15 3.0,  5.0 -0.15 3.0,  5.0  0.15 3.0))
))
```

Fig. 3 Well-known text representation of a wall footprint and wall body (shown in 3D in Fig. 6) as two examples. The polygon is two-dimensional, and the polyhedral surface is three-dimensional. The geometry definition in IFC is an extrusion, but it is converted into an explicit polyhedral surface. A geometry collection is instantiated to mimic the concept of multiple shape representations in IFC. This is according to the WKT example in [3]

JavaScript Object Notation (JSON). TopoJSON is an extension to GeoJSON with a focus more on topology, where geometry defines the position of elements in space, and topology is about the connections between these constructs. By specifying "arcs" in a separate section and referencing them from the topological definition of objects, the connectivity between objects becomes more immediately apparent. This ensures an explicit planar partition, a useful representation for land cover models where the set of parcel geometries is supposed to provide a connected land cover. See for example this work [4] for validation and repair of such partitionings.

XML is a markup language that predates JSON. Keyhole Markup Language (KML) is an XML notation for geographic annotation and visualizations for virtual globes. It was developed for use with Google Earth, but it is now also an OGC standard. KML uses a fixed coordinate reference system: WGS84 and the EGM96 Geoid vertical datum.

Whereas KML focuses on isolated annotations or landmarks to be placed on an otherwise populated virtual globe, 3D Tiles is also intended for virtual globes, but focuses on sharing, visualizing, fusing and interacting with more extensive and heterogeneous 3D geospatial content. It consists of a JSON encoding of hierarchical bounding volumes with glTF (GL Transmission Format, an open standard for 3D models geared towards efficient visualization on the web) files storing the actual geometric content. Tiles are annotated with a geometric error (the deviation resulting from reduction of complexity) and can be specified to be additive or replacing, as such the hierarchical structure in itself enables interactive level of detail and interactive loading on extensive datasets.

A similar approach is taken with i3s, an Open Geospatial Consortium (OGC) community standard, originating from Esri. It also enables the juxtaposition of various layer types ranging from integrated mesh (a representation of the earth geography) to point layers for locations and raw 3D point clouds to the building scene layer where building components and sublayers are included for managing the various aspects of a construction project.

Another XML-based standard is CityGML. It is an open standard that originates mostly from academia [5]. The focus is on digital 3D models of cities and landscapes and contains feature classes such as buildings, roads, rivers, bridges, vegetation and city furniture. The relationships between such elements are included, which sets it a bit apart from some of the other geospatial standards that tend not to include hierarchical structures. CityGML also defines a set of semantics and levels of detail for the 3D objects, mostly buildings, which not only determines geometric detail, but targets various purposes, such as exterior thematic visualization, assessment of solar potential and simulations, facility management. CityGML's geometric primitives are derived from a subset of GML, which provides quite a few permutations of polyhedral geometry definitions. A recent attempt at simplifying the modelling permutations is provided in [6], where the XML syntax is exchanged for JSON, and the modelling choices are greatly constrained, therefore simplifying implementation in software and improving interoperability.

The formats discussed above were vector formats. Raster data can be stored in raw binary or ASCII encoded files, but in such cases metadata such as CRS, bit depth and semantics are absent. An initiative called GeoTIFF [7] aims to embed such metadata in the existing versatile TIFF raster image format. For point cloud data, the LAS format is considered an industry standard, especially in geospatial context, for example, the point definitions in the file have a designated field for storing classification data (vegetation, terrain, building, for example). The e57 file format [8] is more aimed at terrestrial scanners and supports, for example, spherical coordinates and additional per-point attributes such as surface normals. There are also extensions to the building SMART Industry Foundation Classes (IFC)[6] file format to store point cloud scans along with human modelled contents in IFC building models to facilitate hybrid modelling, progress measurements and model inspection [9].

Some of these formats originated as the native formats of specific software packages and were later turned into open interoperable solutions. Other initiatives started out as independent efforts to provide interoperability from the beginning. For example, the 3D tiles specification is tied to the Cesium virtual globe software. A widely used geospatial database is PostGIS. RasDaMan (raster data manager) [10] is a database for array data such as geospatial and voxel grids. Shapely is a lightweight Python library manipulation and analysis of planar geometric objects often in a geospatial context. QGIS is an open-source toolkit for geospatial information that supports viewing, editing and analysis.

To conclude, most of these formats and tools are complementary in their approaches, aims and methods. By catering to use cases, some formats favour rapid partial reading with specialist software (Geodatabase, i3s) over interoperability (CityGML; by relying on XML). Sometimes specification and data format are

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[6] https://technical.buildingsmart.org/standards/ifc/. Accessed 30 November 2020.

intertwined. In other cases, they are fairly independent, such as SFA being a database schema and a textual and binary serialization. Some formats retain the traditional separation in GIS between geometry and attribute tables (Shapefile); others have developed a unified semantic data model (CityGML). Some formats store only raster (GeoTIFF), only vector (shapefile, SFA), only triangles (3D tiles) or topology (TopoJSON) and other systems integrate the various representation mechanisms as different layers in their tools.

2.4 Acquisition and Classification

There are various ways to acquire and classify GIS data, both manually and (semi) automatically. These data can be at different levels of detail (i.e. scale) and comprising raster as well as vector data. A common mechanism to collect GIS data is to use satellite or aerial photography with photogrammetry and structure from motion-based processing to obtain orthophotos, which are a human-intuitive, measurable representation of the Earth. A benefit of this approach is that it does not require high proficiency levels to consume this data in standard tools. By using standard perceptual compression methods such as JPEG, the data can be stored efficiently. And by using downsampling, the data can be disseminated effectively in virtual globes or a web map service. It is possible to derive vector objects by using shape analysis and classification mechanisms such as [11], but especially urban structures object detection in 3D can be enhanced by relying on the elevation data.

Therefore, LIDAR instruments fitted to aircraft and satellites can be used to capture additional accurate three-dimensional datasets. Dukai et al. [12] demonstrate the generation of a country-wide 3D semantic data model acquired from the combination of aerial height maps and two-dimensional polygon footprints of building models, both supplied as open data in the Netherlands.

Terrestrial laser scanning is applied to also measure building interiors and complex three-dimensional urban scenes. Naturally not all information can be observed from an aerial device alone, like buildings under vegetation. At the same time, geospatial data is acquired either to support or to complete the more automatically generated data, by means of manual methods such as geodetic measurements, manual modelling or reconstruction and digitalization of analogue media. Further data collection is often carried out to add more semantics to objects, like materials of facades, construction date and number of inhabitants to buildings, either manually or by superimposing other datasets such as governmental open data.

2.5 Spatial Analysis and Urban Applications

The previous sections have outlined geospatial concepts, formats and acquisition mechanisms. This section briefly outlines how geospatial data is used in practice. Geospatial data is often an input for policy and decision making. Communication is therefore an important part of geospatial analysis and as such generating charts and maps, geospatial statistics, and querying is a common task of a geospatial engineer. Contrary to explicitly modelled (BIM) models, where sequential changes on the model can be recorded, in GIS, typically, data acquisition for different years yields completely independent datasets. By overlaying such datasets geometrically, changes on the level of individual features can be detected and interpreted automatically, which can further aid decision making [13]. With the abundance of open data and technological advancements, machine learning becomes a more common tool in this field, to be discussed later in this chapter. Environmental factors such as noise [14], computational fluid dynamics (CFD) for wind comfort and pollution [15] and solar potential [16] are all urban applications that are actively researched. It should be noted that geometry validity is an important prerequisite in geospatial analysis and applications beyond visualisation.

3 Contrasting BIM and GIS

3.1 Coordinate Reference Systems

The coordinate systems in use in BIM are exclusively Cartesian. In a Cartesian coordinate system, the components are the signed distances along all axes to the origin point, the point where all orthogonal axes meet. Contrary to geographic coordinate systems, all components use the same unit. The Euclidean properties imply that given two points, there is exactly one line segment between them and an infinite line that runs through them; for a line L and a point P, there is exactly one line parallel to L through P, and by extension, the sum of the corners of a triangle is exactly 180 degrees. In spherical geometry, the sum of triangle angles is increasing with the area of the sphere being covered. Therefore, on small fragments of the sphere, Euclidean geometry is a good approximation, and Cartesian coordinates are viable on the scale of building models.

Typically, in BIM, the definition of an object can be considered as an addition of its semantics (properties, classifications, material characteristics), its geometrical representation and its placement, which is its location and orientation in space. IFC defines three types of placements: local, which is a transformation relative to the parent node in the hierarchy, grid, based on the intersection of grid axes, and linear, a one-dimensional offset parameter along an alignment curve for long linear infrastructure. Conversely, in GIS, within a CRS, the points of the geometry are fully explicit. Note that there is always a geographic coordinate system associated with a geospatial point, and for a relationship between a point in a different CRS, a transformation is necessary that maps from the one CRS to the other. Depending on the projection method, such a mapping may not always be possible. In Sect. 4.1, the use of georeferencing is explained which is the concept of providing geospatial metadata to a BIM model so that it can be embedded in a geospatial coordinate system.

3.2 Procedural and Curved Geometry Definitions in BIM

There are various types of geometric representation forms in a BIM model. There are explicit boundary representations or tessellations, sweeps such as extrusions, revolutions and profiles swept along a path and Boolean operations (sometimes called computational solid geometry). Therefore, most geometry definitions in BIM are rather implicit and procedural, which in this case means that limited parametric behaviour and design intent is encoded in the geometry definitions. Even in basic exchanges, such as the IFC2X3 coordination view, which is intended for visualization and coordination not for exchanging the parametric design information, one typically encounters Boolean subtractions for window and door openings and clippings with “half space solids” for walls running up to a slanted roof, and a hierarchical placement structure where a window is placed relatively to its opening, wall, storey, building and site. And procedural geometry definitions such as extrusions where a two-dimensional base face is extruded along a direction vector over a certain length to form a three-dimensional solid body. Conversely in GIS, while Boolean operations are used in analysis, they are typically not part of the data model, and coordinates (while potentially stored in different CRS) are all explicit.

In addition, BIM models support arbitrarily curved surfaces. In parametric BIM applications, the semantics of the element, construction and geometric form are tightly coupled. But in IFC exchanges, the geometry is modelled using a generic set of geometries. Curved surfaces can originate from various constructions, such as curved primitives (a sphere, although rare in IFC and outside of Coordination View), an extrusion of a curved 2D basis (typically composite curve with trimmed curve segments), a revolution, or a sweep along a curved directrix (common for reinforcing bar elements) or advanced boundary representations (new in IFC4).

GIS geometry is almost exclusively modelled as polyhedral surfaces. Simple feature access version 1.2.1 defines some reserved class definitions such as CircularString and CurvePolygon. These are further elaborated in SQL for multimedia part 3 ISO/IEC 13,249–3:2006 and implemented in software and allow for circular arc segments.

3.3 Implementation Mechanisms for Spatial Data

As we have argued, geometry can be seen as the key concept to integrate various spatial data sources. But the geometric encodings, mechanisms, modelling and acquisition workflows are widely different between domains. This section highlights four computational (Fig. 4) geometry models and discusses their role in spatial integration. As mentioned above, given the differences between geometric forms, the implementation mechanisms in GIS and BIM are also typically different. The BIM implementations typically follow the boundary representation (Fig. 4d) mechanism, although some viewers are mesh-based (Fig. 4b). GIS software is typically implemented using mesh or polyhedral models.

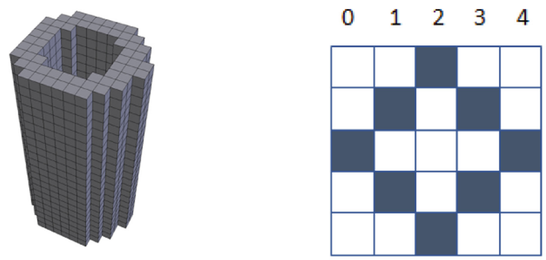
Voxel grids (Fig. 4a) are three-dimensional grids that associate a value with an index. This value can be a bit (i.e. on or off), but also real numbers for example for signed distance fields or simulations or a set of building elements that contributed to that voxel. The benefit of this approach is that implementation is rather trivial. Boolean operations are simple to implement as it boils down to simply overlaying the grids of several operands and performing Boolean calculus on the cells. This is rather different from Boolean operations on higher-order geometric primitives where the operands need to be intersected first to find cells and tolerances need to be considered. Voxel grids can only contain orthogonal surfaces and as such slanted surfaces need to be approximated as staircase geometries.

Especially, a computational model that requires relatively few data points per wavelength so that it does not require dense grids such as PSTD as implemented in OpenPSTD [17] is a potentially interesting solution to create interoperable acoustic simulation models that bridge the urban and building scale. Voxelization, especially when adaptive, while not the same as the kind of grids that OpenPSTD requires is a first step towards such a discretization for acoustics.

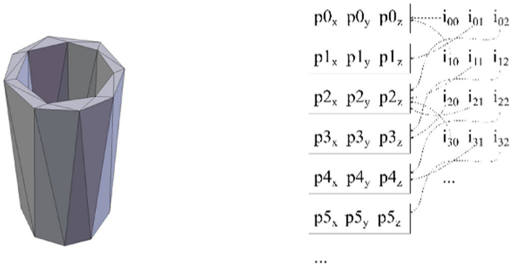
Triangle meshes (Fig. 4b) are an extensively used format for visualization and analysis. It is the canonical data format for visualization. A triangle is always planar, and there is one and only one plane between three points when they are not all on the same line, and a triangle is convex. Every triangle mesh is a polyhedron, but not the other way around.

Polyhedra (Fig. 4c) can contain faces with more than three vertices and edges interpolating those as straight line segments. Additional measures have to be taken into account to maintain planar faces, and polyhedral faces can be concave. A widely used open-source implementation of Polyhedra and Nef Polyhedra (a polyhedron modelled as set operations on two- and three-dimensional halfspaces) can be found in CGAL [18]. Polyhedra are commonly implemented in geospatial computing frameworks such as the SFCGAL extension in PostGIS.

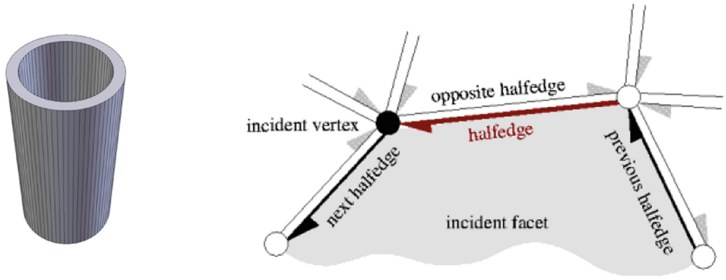
Boundary representations (Fig. 4d) provide a clear separation between topological and geometric entities. Geometrically there is the 0-dimensional point, 1-dimensional curve and 2-dimensional surface, with curves and surfaces not necessarily linear and planar. A point is associated with the topological entity vertex, and a curve is associated with an edge and a surface with a face. Using the



(a) voxel

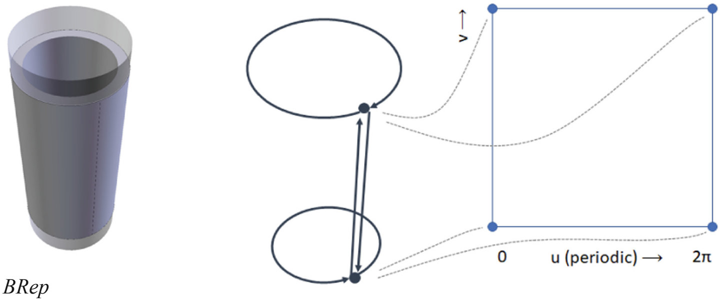


(b) triangle mesh



(c) polyhedron

https://doc.cgal.org/latest/HalfedgeDS/index.html



(d) BRep

Fig. 4 Graphic representation of various geometry implementation mechanisms for a cylinder hollow cylinder on the left and accompanying data model on the right topological hierarchy of solid, shell, face, loop, edge and vertex, a definition of the boundary is completed. Every construct further stores a tolerance, orientation and location. The tolerance is necessary to assure that various curved entities form a closed topological whole as due to rounding errors and approximate solutions to intersections of higher-order NURBS surfaces. It cannot be guaranteed that connected entities actually meet at exactly the same point. The extensive set of geometric subtypes, for example, a curve typically has line, circle, ellipse, hyperbola, parabola, NURBS, Bézier curve, make it in particular suitable for CAD as the geometric entities carry desirable semantics such as radii. A widely used open-source implementation is provided in open CASCADE. Boundary representations are a common implementation mechanism in BIM modelling tools (some viewers use triangle meshes for robustness and efficiency).

3.4 Levels of Detail and Information

Roughly speaking, there are three partly overlapping views on Level of Detail (LoD) in the wider domain of computational geometry. Due to the different ways of working and information acquisition, these levels are conceived with different purposes and measure distinct concepts; as such in practice, we see that recent specifications move away from the generic concept of detail and rephrase this to more specific definitions.

In film and games, Level of Detail primarily has to do with efficiency. Objects further away from the virtual camera can be rendered with less detail to decrease rendering time and memory consumption.

In GIS, Level of Detail is yet considered from another view, with its origin in the 3D standard CityGML. In this view, the concept of Level of Detail is tied to different use cases, where depending on the use case 3D data is modelled according to a specific Level of Detail. This LoD concept defines both geometry and semantics. The most known realization of this concept is the LoD of a building model (currently being reconsidered for the next version of CityGML): a building can be represented by a surface representing the footprint or roof-edge (LoD0), by a block model at LoD1 usually obtained by extruding an LoD0 model, by a model at LoD2 with roof shapes and possibly semantics assigned to parts of the building (e.g. roof, wall; CityGML LOD is rather specific to buildings), at LoD3 by a model with windows and doors and at LoD4, also including indoor feature. Biljecki et al. [19] refined this model to provide a stricter specification of these Levels of Detail and to allow less modelling freedom to improve implementation, see Fig. 5.

In the context of BIM, underpinned by a collaborative and iterative development process, focus of LOD is more on information levels at various phases of the design and handover, see Chapter "Building Information Modelling and Information Management".

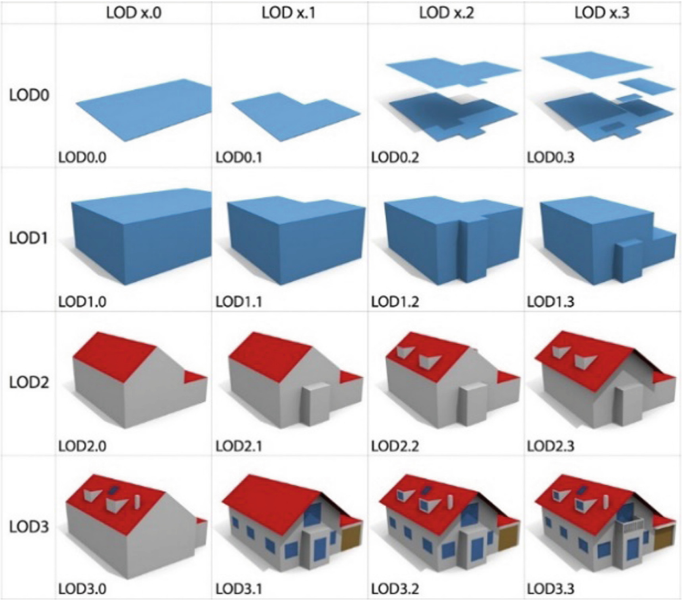


Fig. 5 Two-dimensional extension of the typical CityGML LOD mechanism with a clearer separation between geometry and semantics from [19]

4 Integrating BIM and GIS

4.1 Georeferencing

Although not always common practice in the field of BIM, the initial attempts to the integration of BIM with geoinformation and, later, the addition of long linear infrastructure definitions to the IFC schemas has provided additional incentive to formally study georeferencing in the field of BIM. Jaud et al. [20] provide a thorough investigation of this subject. Clemen and Hendrik [21] discuss various options for storing georeferencing information in IFC, which they called "Levels of georeferencing" (LoGeoRef) without the focus on infrastructure. Georeferencing describes the mapping from the Cartesian coordinates of the model to a georeferenced coordinate reference system. The current options in the IFC4 schema are depicted in Table 1.

While Level 50 uses semantic constructs that have been introduced in IFC4, it has been backported to IFC2X3 by using property sets. Property sets are a generic extensible mechanism in IFC by which key-value pairs can be associated to definitions in IFC. In the view of the authors, Level 50 is the recommended way forward to embed BIM models in a geospatial context. A priority to advance successful georeferencing in IFC is increasing awareness and knowledge of georeferencing theory and practice by modellers and designers, such that they can

Table 1 Georeferencing levels from [21]

LoGeoRef 10	Postal address as textual metadata
LoGeoRef 20	WSG84 coordinates and on the IfcSite attributes
LoGeoRef 30	Location and True North rotation within the placement of the root level spatial structure
LoGeoRef 40	Level 30 but with the TrueNorth attribute in the IfcGeometricRepresentationContext
LoGeoRef 50	CRS metadata in IfcMapConversion
LoGeoRef 60	And a last undefined option to specify a set of points with a Cartesian representation and geospatial coordinates

control the calculation of such information and store it suitably, according to the user needs (which could be effectively part of the level of information need definition, as reference system and required precision are project-specific and will evolve as the project matures). On the other hand, tools dedicated to BIM and IFC modelling and georeferencing should better support such a control on the georeferencing options, which is at present lacking [22].

An example instance diagram is provided in Fig. 6, which starts in the top left with the IfcProject and follows the decomposition relationships downwards to IfcSite and IfcWall. The wall is defined as the extrusion of a rectangle. The various IfcAxis2Placement*n*D govern the location of the rectangle, extrusion, wall and site, respectively, in model coordinates. Important to note is the IfcMapConversion associated to the geometric representation context, which has a reference to a GIS coordinate reference system and includes Eastings and Northings as offsets into this CRS.

4.2 Conversion of Formats Using Semantic and Geometric Approaches

The advantages of actual conversion of building data to GIS datasets and vice versa are obvious and bidirectional. On the one hand, it allows reuse of the urban situation as a blueprint for further developments. Vice versa, the direct use of BIM models as input for city models simplifies the procedure to update city models. Prime examples of this are initiatives for 3D cadastral registration and building model imports [23, 24]. In these latter cases, it is important for the building models to conform to requirements of an idiomatic city model or cadastral representation, which typically means an appropriate level of geometric detail and sometimes topological requirements on a valid and complete separation between interior and exterior for spatial analysis and legal definition. This last part is especially challenging as BIM models are a set of building elements where the elements themselves are typically solid volumes, and there is only a rough definition of an interior volume and no definition of an exterior facade.

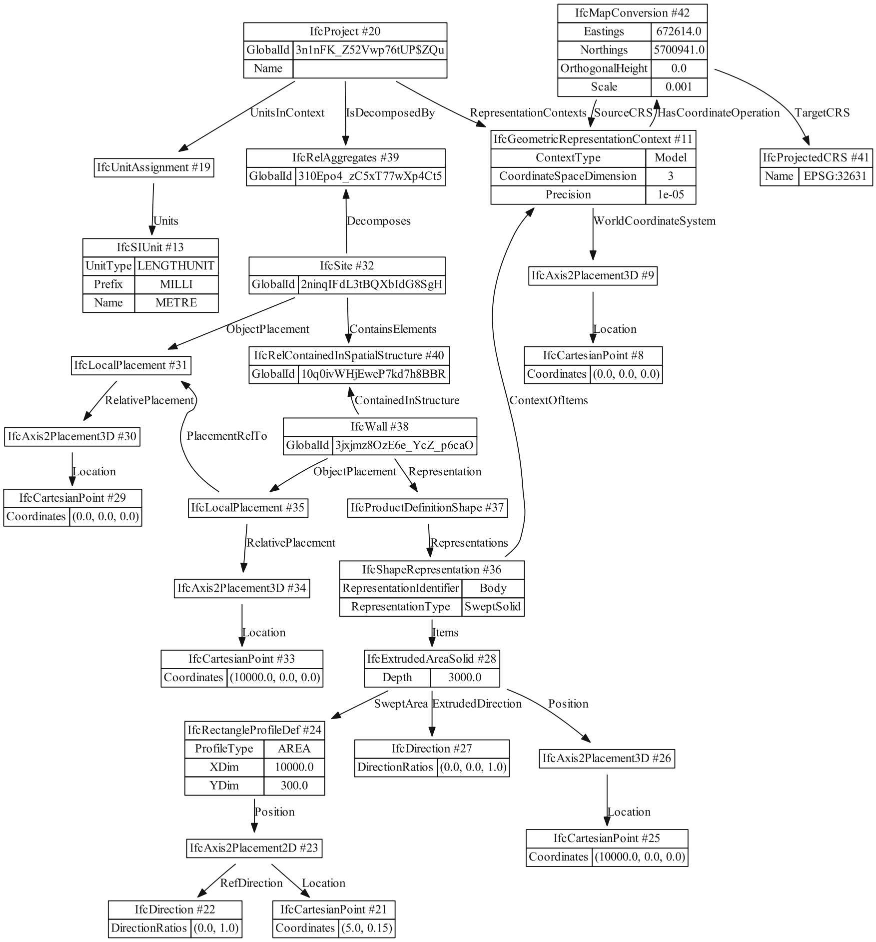


Fig. 6 Instance diagram of georeferencing applied to a trivial building model with IfcSite and IfcWall

Space boundaries are an additional geometric relational view that can be embedded in a BIM in addition to the main "Body" representation of the elements. In theory, they can form a manifold boundary representation of the entire building. Assuming the boundaries are correctly identified, the work in [25] provides a semantic approach to use the space boundaries for a conversion from IFC to CityGML. In particular, research like [26] shows the state of the validity of geometric relationships such as space boundaries, wall connectivity and spatial containment and shows how problematic they are. Luttun and Krijnen [27] show the same for the IsExternal property metadata that signifies on a per-element basis whether an element is part of the external facade of the building. More fundamentally though, space boundary geometries depend on a complete building model being represented in a single native BIM authoring tool and therefore disregard the multi-disciplinary practice of BIM authoring using aspect or discipline models. This is a practice in which all disciplines use their own choice of authoring tools, and IFC is used as a coordination mechanism, a practice common in Europe [28]. In addition, for complex building shapes with curved curtain walls, for example, the case tends to be that there is no definition of an IfcSpace that follows the bounded internal volume, and therefore, space boundaries are absent in such cases. Zhu et al. [29] describe a conversion of IFC to Shapefile that does not rely on space boundary geometries, but it does rely on the “Body” representations, and it poses strict requirements on building topology and element classes to make the necessary reinterpretation.

Donkers et al. [30] describe a conversion mechanism that is solely based on the main “Body” geometries of IFC building elements and does not impose any further requirements on semantics. The conceptual procedure is simple, but computationally intensive. Slightly enlarge all geometries, perform a Boolean union and shrink the result back to be coplanar to the original input geometries. This is implemented on the polyhedral geometry model using the CGAL library on Nef Polyhedra with exact number types for robustness. The result is a set of the visible surfaces (the Boolean union removed surfaces that are not visible) and a topologically valid separation between interior and exterior (as holes have been closed by the enlarging). The result can be further segmented by associating the original semantics back to the new surfaces by means of their coplanarity. The challenge is in firstly the robustness of the Boolean operations and secondly the performance. But due to the conceptual simplicity and only relying on explicit data, that is directly visible when inspecting the building model, it can be expected to give better results initially when the validity of building models is problematic. A result of this method is presented in Fig. 7.

4.3 Linking Heterogeneous Information

Conversion is often a lossy approach. Information that cannot be perfectly mapped is lost in the process. In GIS, it is a common mechanism to overlay layers of various kinds. See, for example, the various heterogeneous layers in the i3s specification that can include an integrated mesh, representing topography, and conventional GIS feature layers and semantic storage of building objects. The same applies to visualizing heterogeneous spatial content such as BIM and GIS. These kinds of visualization frameworks are often for facility management [31], where the owner has a portfolio of many assets, and a geospatial overview provides the most context and assessment of sustainability [32], where the overall performance of a building is not only derived by the building elements and systems but especially also influenced by its surroundings, shading and solar potential.

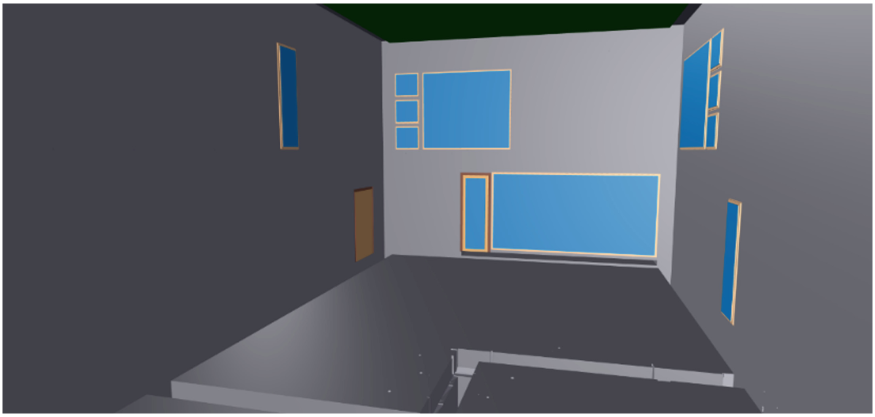


Fig. 7 Visualization of the method applied to the Duplex[7] apartment model with all interior surfaces removed suitable to apply topological geospatial queries

When more deep semantic connections are required as opposed to mere rendering in the same view, linked data is often mentioned as a viable approach to bring data of heterogeneous origin into a unified queryable environment. This is explained in Chapter "Knowledge Graphs and Linked Data for the Built Environment". One particularly interesting approach is GeoSPARQL and well-known text (WKT) serialization of geometries. The application of WKT in IFC models has been first proposed in [3] as an approach to deal with the storage requirements for lists in RDF (as ordered aggregates such as LIST in RDF need to be encoded into a binary tree structure of first-rest pairs) and further extended in [33]. In the latter, the GeoSPARQL predicates (being originally two-dimensional) are being applied to 3D bodies (similar to the topological queries in 3D as shown in [34]) and [35]. The interesting thing about spatial querying as a means of integration is that (assuming georeferencing is properly applied) "location" on the globe might be one of the most reliable keys to connect BIM, GIS and IoT data automatically.

5 Challenges

5.1 Interoperability

This chapter has provided an overview in the differences in worldview and implementation between BIM and GIS practitioners. As such, it is not surprising that there are interoperability issues when navigating between these two worlds, see [36] for a more detailed exploration. Open standards, such as CityGML, and tooling

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[7] https://github.com/buildingSMART/Sample-Test-Files/blob/master/IFC%202x3/Duplex%20Apartment/Duplex_A_20110907.ifc. Accessed 30 November 2020.

can be used to transliterate between these disciplines, but support for the various open standards in itself and the conversion between different open standards is not without issues. Noardo et al. [22, 37] review the state of the art of validity in building model and geospatial datasets, the ability of current tooling to perform tasks on these datasets and the possibilities to transliterate between disciplines. The conclusion from these benchmarks is that perfect validity is more of an exception than a rule and that this impacts the day-to-day work and expectations from engineers in these fields.

In the field of BIM and IFC in itself, interoperability is heavily discussed. Even in the building sector itself, there are various disciplines at work that have rather different views on a facility. The structural engineering and ventilation engineer both view the building as rather different systems, where the architect focuses more on the coherence of the entirety of building elements and the facility manager on rentable spaces. The IFC data model facilitates most of these disciplines, but the tooling that reads and writes IFC has more specific purposes. This is the core challenge of interoperability on IFC. Initially, the model view definition (MVD) was aimed as a way of specifying a subset of the IFC schema that a tool (or an information exchange) should support; but in the longer run, the fear is that this will greatly fragment the usage of IFC into incompatible subsets.

5.2 Building Permit Checking

Recently, there has been a fair share of renewed interest in the topic of automated building permit checking solutions. In earlier years, such a system had already been prototyped in Singapore as the e-CORENET system [38]. In many cases, the integration with geospatial information is important [39]. Even if a lot of the regulations in building codes appear to focus on the building as the main system in isolation, upon more thorough inspection, the geospatial context of the building plays a role in many cases. This is even more so in specific regulations that municipalities impose on building construction projects in their zoning plans, in addition to the national building codes.

Examples of such rules where the geospatial context is important are: requirements on accessibility for wheelchair users, i.e. from parking lot to the entrance of the building; the number of parking places that are realized in internal parking garages; external parking lots in addition to the parking spaces available in the near surroundings; the overall height of the building, measured according to the middle of the road profile; parametrization of rule values based on a spatial lookup of the corresponding zoning plan; minimum distances to neighbouring buildings; controlling the spread of fire between buildings; shadow and daylight requirements taking into account the surroundings. In addition to these, more complex environmental parameters can be checked by considering wider parts of the context and

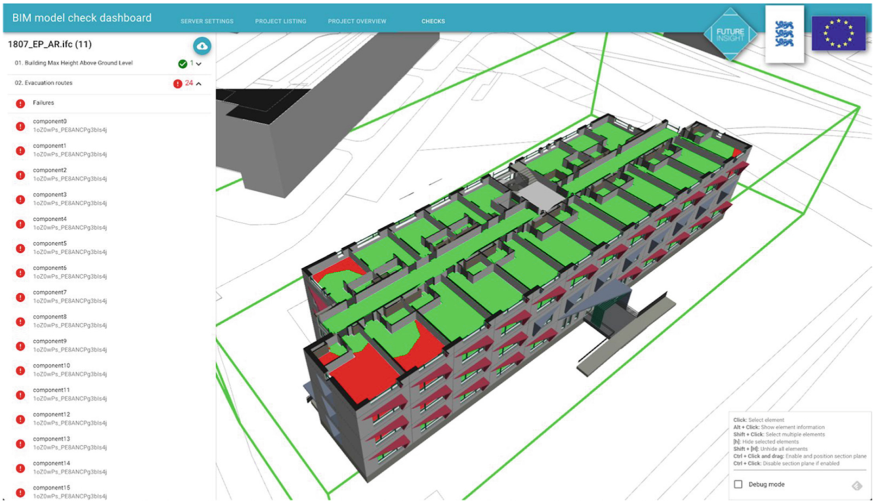

Fig. 8 Interactive visualization of the check on escape route lengths using voxelization. From: https://eehitus.ee/wp-content/uploads/2019/12/Final-report.pdf

having advantage of tools and algorithms allowing city analysis, such as noise modelling, microclimate simulations, flood simulations and so on.

A prototypical implementation of a set of municipal regulation checks is provided in [40] that focuses on building height, parking places and the formalization of rules on real-world regulations in collaboration with the municipality officers in Rotterdam, The Netherlands. A similar proof of concept has been presented in Estonia (Fig. 8) on a geo-enabled BIM-based permit checking solution that uses voxelization for detection of missing safety barriers and escape route lengths. Building permit checking is probably one of the use cases where the necessity of a bidirectional and seamless exchange between the two worlds of geospatial data and local building models is essential.

5.3 *Real-Time Data and Internet of Things*

Geospatial digital twins are being rolled out [41], but mostly as a single point of entry for data collection, not to the extent that the kind of intelligence is embedded for predictive maintenance as is the case, for example, in BIM [42]. Data strategies for smart cities, which uses digital data, actuation and communication for city administration and citizens, are being standardized [43]. Especially for disaster management and recovery, a robust decentralized approach such as peer-to-peer IoT is employed [44].

While general use of GIS in logistics for real-time routing and planning is not widespread [45], it has been demonstrated in tourist management [46] and fleet inventory [47]. In the field of construction, especially earthworks, excavation and mining operate on the intersection of BIM and GIS and benefits from resource optimization considering vehicle location and status in real-time [48].

5.4 AI and Machine Learning

The construction sector has often been considered to be slow in adopting digital innovation. It is questionable to what extent that is the case with active research in digital fabrication, robotics, design automation and the rapid adoption of BIM as can be read in this book.

The investigation area of GIS is by definition large, and therefore, search ranking and data discovery solutions [49] are active areas of research in the application of learning solutions. Contrary to construction, where data models are modelled into discrete objects, the data models under investigation in GIS are mostly acquired using remote sensing. As such, where BIM models have classification labels by definition (although learning can be applied to fix wrong classifications [43]), GIS data misses the semantic labels that are available in hand-modelled BIM models. Learning approaches can be found in, for example, assigning feature classes [50] to point clouds or even plant species [51] or land cover mapping [52]. These approaches are classification or segmentation tasks on the individual points of a point cloud or image regions (meshes) (see Chapter Reality Capture: Photography, Videos, Laser Scanning and Drones for more information on reality capture).

BIM is a fairly recent paradigm though. Therefore, reconstruction of BIM models from as-built situations is an active research area, for example, [53] which focuses on deriving IFC models from indoor terrestrial point cloud scans. Similar segmentation and reconstruction tasks are in place in geospatial data classification tasks, for example, the derivation of valid polyhedral surface models from urban-scale point clouds as presented in research such as [54].

Learning approaches in analysis and interpretation are presented, for example, in the assessment of flood risk [55], and machine learning in agriculture [56] is adopted to determine water needs and ideal harvest times.

6 Conclusion

In this chapter, we have provided an overview of computational geometry in solving some of the interoperability challenges of (geo) spatial computation. It is interesting to observe that epistemological discussions on old GIS topics on the identity of objects and fields are still relevant in state-of-the-art BIM-based building permit checking solutions where voxelization solutions are applied. Similarly, we see location and geometry as a driving contribution to the integration of heterogeneous data sources. Whether it is the elimination of invisible surfaces in the automatic conversion from IFC to CityGML presented in [30], the use of GeoSPARQL to query an interlinked dataset of BIM and GIS definitions per [3], the formalization of legal definitions using geometric concepts in [40], 3D geometry proves to be a key concept for interoperability.

GIS, and especially the correct use of 3D geometry, with location plus time being the one unique index for everything physical, can unlock the true potential of Industry 4.0 to integrate the various scales of real-time decision making from built element to structure, city, country, continent and planet.

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