Modeling Standards and File Formats for Indoor Mapping

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Abstract: Indoor maps provide abstractions of the physical spaces where we spend most of our lives. General purpose indoor maps have historically taken the form of two-dimensional floor plans, commonly found in public venues such as shopping malls and cruise ships. Until recently, innovation and development of indoor maps have remained confined to urban planning and the building industry. Recent interest in indoor mapping for other applications has extended indoor mapping to 3D and to other domains, with a growing emphasis on commerce and general wayfinding. This paper reviews prevailing modeling standards and file formats relevant to the modeling and visualization of indoor spaces with the goal of assisting researchers and developers with finding appropriate formats for indoor modeling and visualization.

1 INTRODUCTION

The absence of positioning and reality capture systems for indoor spaces has historically limited indoor mapping to the two domains of urban planning and the building construction industry. However, recent advancements in indoor positioning systems and reality capture technologies and a maturing market for outdoor mapping and navigation aids have catalyzed the mapping of indoor features (Zlatanova et al., 2013). Sample applications include the eeGeo 3D indoor mapping platform, MediNav by Connexient for hospital wayfinding, and Indoor Atlas and Google Maps for commerce and general wayfinding. Growing interest in gamification for virtual training also points to other areas of future growth for research and development in indoor maps (Muller et al., 2004; Popescu and Mudure, 2008; Spicer et al., 2016).

We use the term indoor mapping for both the geometric and semantic abstractions of physical indoor spaces, defined as inhabitable spaces with overhead obstructions, e.g., building interiors, ship interiors, and caves. Reality capture technologies produce meshes or point clouds—valuable data for maps but not necessarily maps themselves. A map is a model that further abstracts the raw reality-capture data into geometric shapes (i.e., symbols) with both topology and semantic meaning.

This review examines the three big players in indoor mapping (CityGML, IFC, and IndoorGML) that provide data models, semantic frameworks, and file formats for working with buildings and indoor data. We also examine other file formats from computer graphics that have potential relevance to indoor mapping.

2 CRITERIA FOR REVIEW

We used four criteria for our review: geometric abstraction, semantic support, spatial referencing method, and level-of-detail (LOD) support. Geometric abstraction is the type of geometry used to represent building features, while semantic support describes the ability of a model or format to support higher-level abstractions of the entities being modeled (Hammer & McLeod, 1981; Mayer et al., 2013; Stephens, 2008). Spatial referencing is the method used for describing model measurements and LOD is a standard or file format's way of managing geometric complexity.

Most modeling standards and file formats follow a handful of approaches for representing geometry (Mayer et al., 2013; Molenaar, 1989;). 2D representation uses points, lines, and areas to symbolize entities. 2.5D representation uses height or depth values added to each 2D horizontal coordinate pair to produce a surface. 2.5D surfaces with equally-spaced points are called *grids* or

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rasters, while surfaces with irregularly spaced and connected points are called triangulated irregular networks (TIN).

Mayer et al. (2013) listed six different 3D geometric representations. **Voxels** are extensions of rasters in 3D. In **cell decomposition**, geometric objects are formed by a Boolean union of geometric primitives. For **constructive solid geometry (CSG)** objects are formed by merging or subtracting primitive objects using Boolean operations. **Boundary representation (BRep)** uses objects defined by connected faces, edges, and vertices at the boundary of the solid object. In a **parametric** description, objects are defined by numerical parameters in the form of constraints and dimensions. Lastly, a **tessellation** is an extension of TINs in 3D.

Semantics help associate geometries with entities in the physical world, such as building parts or furniture (Billen et al., 2014). Under the semantic object modeling framework, semantic objects represent real entities using levels of attributes: simple, group, and object (Stephens, 2008).

Spatial referencing uses descriptors to define the locations of objects in physical space. The International Standards Organization (ISO) and Open Geospatial Consortium (OGC) identify two approaches to spatial referencing: by identifier and by coordinates (ISO, 2002, 2003; OGC, 2010). Referencing by coordinates uses measurements to define location, while referencing by identifier uses geocodes as surrogates for coordinates. Street addresses, building numbers, and room numbers are examples of identifiers.

Referencing by coordinates requires both a measurement system and a measurement starting point (Bernhardsen, 2002; ISO, 2002; OGC, 2010; Van Sickle, 2010). A *coordinate system* defines properties of the measurement system while a *datum* defines the measurement starting point. The combination of a coordinate system and a datum forms a unique *coordinate reference system* (CRS), which often assumes the classification of the datum. Earth-based datums can be *engineering*, *geodetic*, or *vertical*. An engineering datum has local geographic scope and uses local physical markers as the starting point. A geodetic datum uses Earth itself as the starting point, usually Earth's center or the surface of an ellipsoidal. A vertical datum uses a gravity-based geoid to approximate mean sea level for vertical measurements. Engineering CRSs are nearly always planar and use linear units of measurement, which does not pose a problem for most buildings and indoor spaces. In contrast, geodetic CRSs can use the angular units of an ellipsoid or the linear units of a planar projection. Various CRS transformations exist to convert one CRS to another.

Level of detail (LOD) describes the different ways a geometric object can be represented at different levels of generalization (Pham et al., 2015; Tolmer et al., 2013). The computer graphics community uses varying polygon counts to describe LOD, while architects use the term level of development—LODt here for clarity—to show representations of architectural objects at various stages of design and construction. In cartography and GIS, LOD can imply both differences in geometric abstractions and in object semantics.

3 MODELING STANDARDS

IFC (Industry Foundation Classes), CityGML (City Geography Markup Language), and IndoorGML (Indoor Geography Markup Language) are three major international standards with relevant guidance for the 3D modeling of indoor spaces. Each standard meets the unique needs of a specific application—IFC for building construction and management, CityGML for urban modeling, and IndoorGML for indoor navigation—but they can interoperate. While the theory behind building modeling has existed since the 1960s and parallels GIS development, standardization of building models and modeling processes is recent—IFC in 2000, CityGML in 2008, and IndoorGML in 2014.

IFC represents both a standard data exchange schema for building information modeling (BIM) data and a file format used by the architecture, engineering, and construction (AEC) and facilities management (FM) industries. BIM software such as Autodesk Revit and Graphisoft ARCHICAD use their own proprietary formats based on IFC but can export to IFC format. IFC formats are the ISO STEP file structure (.ifc), a text file formatted using extensible markup language, XML (.ifcXML), or a compressed file (.ifcZIP) containing a .ifc or .ifcXML file.

As a modeling standard, IFC serves as the centerpiece of three standards that make up openBIM, the *de facto* international BIM framework; the other two are the buildingSmart Data Dictionary (bSDD) and information delivery manuals (IDMs).

IFC mainly supports CSG and sweep geometries, but it can also support BRep and tessellation. While IFC supports parametric models, incomplete implementation by BIM software may make it necessary to convert proprietary parametric BIM models into CSG, sweep, or BRep for IFC (Ji et al., 2011). IFC provides strong support for semantics by offering true object-based modeling with class definitions and inheritance. The bSDD serves as the multi-lingual data dictionary to provide ontologies and attributes of IFC objects, such as doors, walls, and structural elements (Petrie, 2016). For spatial referencing, IFC uses an engineering CRS with an option to place a building site on a geodetic CRS using geographic coordinates, an elevation, and, optionally, the direction of true north using OGC CRS guidelines (buildingSMART, 2013).

IFC uses the American Institute of Architects (AIA) version of level of detail called *level of development* (LODt) (Reinhardt & Bedrick, 2016). LODt is the refinement level of building elements at various stages of design and construction. IFC uses the five LODts in AIA protocol G202-2013 (LODt 100, 200, 300, 400, and 500) and a sixth for openBIM (LODt 350), with 100 as the least refined and 500 as actual construction. Refinement level may not correspond to geometric detail; detailed models of building elements can be used in LODt 200 even if they are only placeholders.

CityGML serves as the official standard for urban modeling within the Open Geospatial Consortium (OGC) framework, which addresses the modeling of all things geospatial. Specifically, it exists as a specialized *application schema* of the base-level OGC Geography Markup Language (GML). Similar to IFC, CityGML represents both a modeling standard and a file format. As a file format, CityGML uses an XML schema as defined in the standard. As a standard, CityGML provides the foundational framework for urban modeling upon which more specialized applications—called *application domain extensions* or ADEs—can be built. Examples of CityGML ADEs include applications for noise, hydrology, solar irradiance, energy, utilities, and other areas, as well as integration with IFC. CityGML exclusively uses BRep geometries, provides the framework for rich object-based semantics (especially with the use of ADEs), can accommodate a wide variety of engineering and geodetic CRSs, and has five levels of detail (Buyukaslih et al. 2013; Kolbe et al., 2005; OGC, 2012). For an engineering CRS, the CityGML 2.0 specifications recommend identifying an anchor point based on a geodetic CRS (OGC, 2012).

LODs for CityGML closely follow the cartographic concept of LOD, in which an object's geometry and semantics (features) are kept separate. CityGML has five LODs from LOD0 (most generalized) to LOD4 (most detailed). Since features and geometry are separated, a single feature can have different shapes at different LODs and even have different appearances based on theme. LOD4 has particular relevance to indoor cartography since it provides the only LOD that reveals indoor features; building interiors remain void and empty from LOD0 to LOD3.

IndoorGML was developed solely to support navigation within indoor environments (Kim, Yoo, & Li, 2014; Nagel et al., 2010). As a topological modeling standard, IndoorGML places a strong emphasis on semantic objects and their topological relationships and it uses non-overlapping *cells* in lieu of geometric representations to model indoor spaces. These object-based cells need neither dimension nor spatial location, although the standard supports adding either or both as an option. As such, IndoorGML supports both engineering and geodetic CRSs. Cells can have topological relationships and can relate to geometry by linking to CityGML or IFC. The standard does not require geometry-based LODs, but uses multi-layering to represent different uses of the same space. One layer may represent pedestrian travel while another may represent wireless internet coverage.

Shapefiles require files stored in the same directory: feature geometries or shapes (.shp), shape index (.shx), and attribute tables (.dbf). They can include optional files, such as the projection file (.prj) for storing for CRS. Shapefiles represent real-world entities using simple 2D and 3D vector geometries based on points, lines, areas, and tessellation (LOC, 2011a). Shapefile features have no topological capabilities, have basic semantic capabilities through the use of attributes, can use engineering or geodetic CRSs through the .prj file, but have no built-in capabilities for defining LOD. For 3D representation, shapefiles use multipatch geometry, a type of BRep (Esri, 2008).

Geodatabases represent real world entities using semantic objects called features, which allow for object-based development using feature classes. In terms of geometry, the geodatabase format uses the same vector format as shapefiles—i.e., points, lines, areas, and 3D multipatches—with additional support for rasters in 2D (LOC, 2011b). The format currently does not support voxels (Shephard, 2015). For spatial referencing, the geodatabase supports both engineering and local CRSs as well as referencing by identifiers. Geodatabases support different user-defined LODs due to the separation of features and geometry. There are three implementations of the geodatabase—personal, file, and enterprise—with increasing features and capabilities (Esri, 2016). Personal geodatabases use Microsoft Access data files to store data, file geodatabases use a directory-base file structure, and enterprise geodatabases use servers.

The open source Facilities Information Spatial Data Model (FISDM) emerged in 2014 from the Building Interior Space Data Model (BISDM) started by Esri and other organizations in 2007 (Rich & Smith, 2014). FISDM is not a standard but a best practices framework for CAD-GIS integration built on the geodatabase format for fusing GIS data with CityGML, IFC, and other formats. While BISDM focused exclusively on interior spaces, FISDM extends those capabilities to include exterior spaces and the outside built environment. FISDM has the same 2D and 3D capabilities of its underlying geodatabase file format.

4 OTHER GRAPHIC FORMATS

Many graphic formats exist for the production, transmission, or presentation of 2D and 3D building geometry. McHenry and Bajcsy (2008) identified 140 formats for 3D graphics alone. Data conversion software Safe FME lists over 250 formats: 197 2D vector-based formats, some of which also support 3D, with 39 for 3D graphics; 68 2D raster formats; and 13 point cloud or voxel formats (Safe Software, 2017). Software that can handle IFC, CityGML, or GIS data can also export graphics into one or more these formats; conversion software such as Safe FME can also perform conversions. Here we examine some key formats relevant to building modeling and indoor modeling, with an emphasis on data sources, data exchange, and visualization.

Drawings produced using CAD software document the design, construction, and modification of buildings and are excellent sources of data for indoor mapping. Although BIM has significant advantages over CAD, industry-wide adoption of BIM only began less than a decade ago and is not yet universal (McGraw-Hill Construction, 2012). 2D and 3D CAD remain widely used in AEC and most legacy drawings prior to the advent of BIM only exist in CAD format or hard copy (Business Advantage, 2016; Coumans, 2017) Prevailing CAD formats include DXF, DWG, and DGN.

Despite having been around since 1982, the Autodesk DXF exchange format remains popular and widely used due to its semi-public nature, simple structure, and high level of software compatibility (LOC, 2016b). The open portion of DXF supports points, lines (including curves), and areas in 2D/3D, as well as tessellation in 3D; but the "3D Solid" capability is proprietary to Autodesk and cannot be edited. DXF uses an engineering CRS and has support for neither semantics nor LOD, although Zlatanova et al. (2012) noted that layers can simulate semantic objects. Note that the terms *objects* and *entities* in the DXF specifications refer to graphical features (e.g., points and lines) rather than physical entities (e.g., walls and doors) (Autodesk, 2011). DWG is Autodesk's native CAD format for its AutoCAD software and shares the same properties as DXF with explicit support for tessellation (meshes) and BRep with sweeping and extrusion capabilities (LOC, 2016a).

The DGN format is Bentley's native CAD format for its Microstation software and supports both engineering and geodetic CRSs, with no LOD capabilities and no semantics, but supports points, lines (including curves), and areas in 2D/3D and 3D solids through extrusion in BRep (Bentley Systems, 2016). Unlike DWG/DXF, DGN does not support tessellation/TINs.

COLLADA is an XML-based ISO-adopted standard for the exchange of 3D digital assets among different interactive 3D software applications (Barnes & Finch, 2008; Khronos Group, 2017). It uses an object-based approach, has BRep geometry with limited support for tessellation, supports custom object-based semantics insofar as they relate to geometry, and supports multiple LODs. COLLADA supports use of a local engineering CRS and one geodetic plus vertical CRS (WGS84 and WGS84-EGM96).

Web browsers provide universally accessible platforms for viewing and interacting with building models and indoor maps. X3D and SVG represent open XML-based standards for the delivery of 3D and 2D vector content through HTML5 compliant web browsers. X3D is a family of open ISO standards for representing and exchanging 3D scenes and objects managed by the Web3D Consortium (Web3D Consortium, 2017). X3D emerged from an earlier standard called the Virtual Reality Modeling Language (VRML), which had a geographic version (GeoVRML). While X3D has no native capability for custom attributes, it does allow the linking of attributes in other XML files for that capability (Geroimenko & Geroimenko, 2006). A quasi-object-based semantic capability called grouping allows for the definition and re-use of constructed geometries, called groups. Other properties of X3D include multiple LODs, as well as support for both local engineering and a few geodetic CRSs (Web3D Consortium, 2008). X3D data can be presented in XML, Javascript, and Java. X3D has many other graphical capabilities. Special capabilities include the ability to handle voxel data and the ability to support CAD models, including the use of BRep geometries (Brutzman, 2012).

SVG provides XML-based 2D graphics that are viewable with web browsers. The latest version, 1.1, includes support for lines and areas (i.e., rectangle, circle, ellipse, and polygon) as well as rasters; however, SVG currently does not support point geometry. A draft recommendation for version 2 adds a mesh geometry that allows for shape distortions, but it still omits point geometry. As with X3D, SVG allows the definition of re-usable groups and allows linking to other XML files for custom attributes, although not a native capability (Adams, 2005; Geroimenko & Geroimenko, 2006). It natively supports engineering CRSs and has a flexible system for specifying geodetic CRSs using one of three methods: a web-based uniform resource identifier (URI), a well-known CRS identifier, or directly defining the CRS within the xml document. As with X3D, SVG also supports multiple-representation LODs (Chang et al., 2004).

KML is an XML-based OGC international standard for providing 2D and 3D geographic visualizations in online mapping and virtual globe browsers. KML supports point, line, and polygon geometry and 3D geometry using BRep (Isikdag & Zlatanova, 2010). The KML standard provides a limited ability to add user-defined attributes to features (Google, 2013). KML exclusively uses the World Geodetic System of 1984 (WGS84) for horizontal coordinates and Earth Gravitational Model 1996 based on the WGS84 ellipsoid for elevations (WGS84 EGM96 Geoid). It also supports user-defined levels of detail through the use of regions (Burggraf, 2015).

PDF with 3D content provides a convenient format for delivering 3D models using widely available PDF readers. 3D models reside in external files (in one of only two formats, U3D or PRC) embedded into the PDF document. U3D supports the visualization of geometric models with attached attributes, but lacks object-based capabilities such as inheritance. U3D only supports the use of tessellation for 3D geometry, uses a local engineering CRS, and its implementation of LOD uses reduced polygon counts instead of multiple representations (Klawonn, 2012). The ISO-adopted PRC format supports geometry with attached attributes but falls short of being truly object-based. In addition to tessellation, PRC also supports BRep and other geometric representations (PDF3D, 2015). PRC natively uses a local engineering CRS but some PDF implementations can provide software-based transformations to a geodetic CRS.

Table 1 provides a summary of the modeling standards and file formats covered in this review. SVG is the only item on this list that cannot support 3D geometry. Items that have points/lines/areas in addition to 3D geometry denote a format that can support 2D as well as 3D geometry.

5 DISCUSSION

We divide our discussion into three areas: data sourcing, software accessibility, and modeling capabilities. Data sourcing examines data import, software compatibility examines practical issues of working with and sharing indoor maps, and modeling capabilities assesses capabilities and potential limitations.

Existing building designs serve as excellent sources of data for creating indoor maps. Among the reviewed models and formats, BIM models based on IFC have the greatest potential use for 2D and 3D indoor mapping due to their very high level of detail, native 3D geometry, and rich semantics. However, BIM models only exist for newer structures natively designed in BIM or for the few older structures documented in BIM after the fact. For older structures, CAD drawings provide the next best data source. If CAD drawings do not exist, then available hard copy drawings can be used, either through a scan-to-CAD or scan-to-BIM process or through manual transcription. Most CAD and hard copy drawings only exist as 2D line drawings, which require manual interpretation to convert to 3D.

While CityGML has LOD4 for indoor modeling, few CityGML models exist at that level of detail. Of the 15 public urban models listed on the official CityGML website, none uses LOD4 and only one uses LOD3. This may be due to a current lack of use cases for indoor maps—the subject of our research. Meanwhile, BIM will continue to serve as the most reliable source of detailed indoor data due to a commercial need in the AEC/FM industry.

Reality capture takes 3D measurements of indoor spaces using laser scanning and photogrammetry and delivers point clouds—massive collections of points with optional attributes such as color or intensity. Most BIM and CAD software support importing point clouds for transforming into their respective formats.

Table 1: Summary of standards and file formats.

	Supported Geometry	Semantic Support	Spatial Referencing	Level of Detail …	Indoor / Total
IFC	V D C B P T	X S G O	I E G	Arch	6/6
CityGML	V D C B P T	X S G O	I E G	GIS	1/5
IndoorGML	N/A	X S G O	I E G	None	N/A
Shapefile	(Point) (Line) (Area) V D C B P T	X S G O	I E G	None	N/A
Geodatabase	(Point) (Line) (Area) V D C B P T	X S G O	I E G	GIS	User
FISDM	See geodatabase				
DXF/DWG	(Point) (Line) (Area) V D C B P T	X S G O	I E G	None	N/A
DGN	(Point) (Line) (Area) V D C B P T	X S G O	I E G	None	N/A
COLLADA	V D C B P T	X S G O	I E G	User	User
X3D	V D C B P T	X S G O	I E G	User	User
SVG	(Point) (Line) (Area)	X S G O	I E G	User	User
KML	(Point) (Line) (Area) V D C B P T	X S G O	I E G	GIS	User
PDF (U3D)	V D C B P T	X S G O	I E G	CG	User
PDF (PRC)	V D C B P T	X S G O	I E G	CG	User

Level of Support	# Full	# Partial or With Workaround	# None
Geometry	Voxels, BRep, (Point)	Decomposition, Parametric, (Line)	CSG, Tessellation, (Area)
Semantics	Simple, X (None)	Group	Object
Spatial Referencing	Identifier	Engineering	Geodetic
LOD Type	Arch Architectural, CG Computer Graphics	GIS Cartographic/GIS, User User Defined	

All file formats covered in this review, except DWG and DGN, are *open specification* formats and have high levels of compatibility and accessibility using various software. An open specification format allows software makers to incorporate it into their products for cross-platform exchanges. Closed formats such as DWG, DGN, and RVT only work with proprietary programs—in this case, AutoCAD, Microstation, and Revit.

IFC, DXF, and COLLADA are open exchange formats designed to maximize compatibility and minimize conflicts when transferring between different software programs. While software makers often accommodate these exchange formats, data loss can still occur. For example, incomplete integration of parametric geometries between Revit and IFC can sometimes cause Revit to convert parametric geometries into BRep or tesselation, resulting in a loss of geometric parameters.

Of the remaining formats, CityGML, X3D, and SVG hold significant value for indoor mapping. CityGML provides the greatest level of support for the diverse requirements of indoor mapping. It supports rich semantics, can accommodate both engineering and geodetic CRSs, and supports the conventional concept of LOD as used in the mapping sciences. Additionally, application domain extensions allow CityGML to be extended for indoor mapping. While IFC provides greater flexibility with geometry and offers even richer semantics support, its lack of robust CRS support and use of LODt make it too restrictive for indoor mapping.

A shortcoming of CityGML is its lack of multiple LODs for indoor spaces. Use of the single LOD4 provides an all-or-nothing approach in which LOD4 shows everything indoors while LOD3 shows the hollow shell of a building. Providing multiple LODs for indoor spaces can allow various levels of generalization to occur, e.g., generalizations of rooms or entire floors.

While CityGML provides a viable framework for generating and storing indoor maps, it is not optimized for visualization. For that capability, CityGML can export to X3D and SVG formats, which work with most modern web browsers, or to prevailing 2D GIS web mapping formats. X3D holds significant promise for the display of 3D indoor maps. X3D supports rich semantics, engineering and geodetic CRSs (though limited), and cartographic LODs. It can also display voxels, which may provide an alternative form of visualization, as popularized by the video game Minecraft. While SVG holds some promise for 2D visualization, mature GIS products that use shapefiles or geodatabases may provide a more practical solution. Using a GIS system for 2D indoor maps can allow the indoor maps to seamlessly integrate with outdoor maps, benefit from GIS functionality, and take advantage of the existing infrastructure already in place for web-based mapping. FISDM was developed for this purpose.

6 CONCLUSIONS

Indoor mapping can provide significant economic value due to the amount of time people spend indoors. While a multitude of formats exist for modeling and visualizing indoor spaces, certain formats can make indoor map development and presentation more effective based on the specific needs of a process. Potential areas of continued development to support indoor mapping include better integration of indoor and outdoor CRSs, a more refined concept of LOD for indoors, and the use of voxels as alternative representations for viewing by the general public.

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