Technical Report: Literature Review concerning IFC, gbXML and CityGML data models for Energy Performance Simulation

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I. INTRODUCTION

Multiple data models based on their applications are used to define, store, manage, manipulate and utilize building and spatial data digitally. Building scale and geographical scale information definitions to specific building attributes, extensive utilization of the data models is carried out for multiple researches, analysis and implementations. Simulation scientists, researchers, urban planners and engineers use different formats, different applications and different tools for energy performance simulation. Within the scope of this report, a literature review of IFC, gbXML and CityGML data models is made focusing on their formats, version releases, example files, usage platforms and energy simulation tools and software using these data models.

II. DATA FORMATS

A brief introduction to IFC, gbXML and CityGML, their release histories, example files and software using these data models are defined in the sections below.

A. Industry Foundation Classes

Industry Foundation Classes (IFC), an open file format is primarily intended to represent building constructional and architectural data. It is a data schema for representing buildings and associated activities for designing, constructing, and maintaining them can be used for multiple applications such as energy performance simulations. [1]
At the abstract level, IFC divides all entities into rooted and non-rooted entities. The rooted entities which derive from the IfcRoot have an identity, name, description, and revision control. Non-rooted entities do not have identity and instances but it only exists if referenced from a rooted instance directly or indirectly. IfcRoot is subdivided into three abstract concepts, namely, object definitions, relationships, and property sets: [1] [2]

- IfcObjectDefinition captures tangible object occurrences and types
- IfcRelationship captures relationships among objects
- IfcPropertyDefinition captures dynamically extensible properties about objects

A.1 IFC Definition Formats

IFC can be defined using multiple file formats [1]:

- .ifcXML: a *XML* based file format defined according to the norm ISO 10303-28 [3]
- .ifc : a text based file format defined as a *STEP* file according to norm ISO 10303-21 [4]
- IFC-ZIP: It is a ZIP compressed format of a *".ifcXML"* or *".ifc-STEP"* file format

A.2 IFC Versions and Releases

IFC models have undergone a number of modifications and alterations. A brief overview of the different versions and release years can be found in Table 1.

IFC Version	Year
IFC 1.0	1996
IFC 1.5	1997
IFC 1.5.1	1998
IFC 2.0	1999
IFC 2x	2000
ifcXML 1 for IFC2x	2001
IFC 2x Addendum 1	2001
IFC 2x2	2003
ifcXML2 for IFC2x2 (RC1)	2003
IFC2x2 Addendum 1	2004
ifcXML2 for IFC2x2 Addendum 1	2004
IFC2x3	2005
ifcXML2x3	2007
IFC4	2013
IFC4 Addendum 1	2015
IFC4 Addendum 2	2016
IFC4 Addendum 2 TC1	2017
IFC 4.1	2018
IFC 4.2	2019

Table1: An overview of IFC model version specification along with the year of releases. (Information retrieved from [5]*)*

A.3 An example building definition in IFC-STEP format

A sample file of an example building “FZK - Haus” created by [6]. Information retrieved from [7].

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ISO-10303-21;
HEADER;FILE_DESCRIPTION(('ViewDefinition [, QuantityTakeOffAddOnView, SpaceBoundary2ndLevelAddOnView]','Option [Drawing Scale: 100.000000]','Option [Global Unique Identifiers (GUID): Keep existing]','Option [Elements to export: Entire project]','Option [Partial Structure Display: Entire Model]','Option [IFC Domain: All]','Option [Structural Function: All Elements]','Option [Convert Grid elements: On]','Option [Convert IFC Annotations and ARCHICAD 2D elements: On]','Option [Convert 2D symbols of Doors and Windows: Off]','Option [Explode Composite and Complex Profile elements into parts: Off]','Option [Export geometries that Participates in Collision Detection only: On]','Option [Multi-skin complex geometries: Building element parts]','Option [Elements in Solid Element Operations: Extruded/revolved]','Option [Elements with junctions: Extruded/revolved without junctions]','Option [Slabs with slanted edge(s): Extruded]','Option [Use legacy geometric methods as in Coordination View 1.0: Off]','Option [IFC Site Geometry: As boundary representation (BRep)]','Option [IFC Site Location: At Project Origin]','Option [Properties To Export: All properties]','Option [Space containment: Off]','Option [Bounding Box: On]','Option [Geometry to type objects: On]','Option [Element Properties: On]','Option [Properties To Export: All]','Option [IFC Base Quantities: On]','Option [Window Door Lining and Panel Parameters: On]','Option [IFC Space boundaries: On]','Option [ARCHICAD Zone Categories as IFC Space classification data: On]'),'2;1');
FILE_NAME('S:\\[IFC]\\[COMPLETE-BUILDINGS]\\FZK-MODELS\\FZK-Haus\\ArchiCAD-20\\AC20-FZK-Haus.ifc','2016-12-21T17:54:06',('Architect'),('Building Designer Office'),'The EXPRESS Data Manager Version

5.02.0100.09 : 26 Sep 2013','IFC file generated by GRAPHISOFT ARCHICAD-64 20.0.0 GER FULL Windows version (IFC2x3 add-on version: 4009 GER FULL).','The authorising person');
FILE_SCHEMA(('IFC4'));
ENDSEC;

DATA;
#1= IFCPERSON($,'Nicht definiert',$,$,$,$,$);
#3= IFCORGANIZATION($,'Nicht definiert',$,$,$);
#7= IFCPERSONANDORGANIZATION(#1,#3,$);
#10= IFCORGANIZATION('GS','GRAPHISOFT','GRAPHISOFT',$,$);
#11= IFCAPPLICATION(#10,'20.0.0','ARCHICAD-64','IFC2x3 add-on version: 4009 GER FULL');
#12= IFCOWNERHISTORY(#7,#11,$,.ADDED.,$,$,$,1482339244);
#13= IFCSIUNIT(,.LENGTHUNIT.,$,.METRE.);*
#14= IFCSIUNIT(,.AREAUNIT.,$,.SQUARE_METRE.);*
#15= IFCSIUNIT(,.VOLUMEUNIT.,$,.CUBIC_METRE.);*
#16= IFCSIUNIT(,.PLANEANGLEUNIT.,$,.RADIAN.);*
#17= IFCMEASUREWITHUNIT(IFCPLANEANGLEMEASURE(0.0174532925199),#16);
#18= IFCDIMENSIONALEXPONENTS(0,0,0,0,0,0,0);
#19= IFCCONVERSIONBASEDUNIT(#18,.PLANEANGLEUNIT.,'DEGREE',#17);
#21= IFCSIUNIT(,.SOLIDANGLEUNIT.,$,.STERADIAN.);*
#22= IFCMONETARYUNIT('EUR');
#23= IFCSIUNIT(,.TIMEUNIT.,$,.SECOND.);*
#24= IFCSIUNIT(,.MASSUNIT.,$,.GRAM.);*
.
.
.
.
.
.
.
.
#79072= IFCCOMPOSITECURVE((#79071),.F.);
#79075= IFCCURVEBOUNDEDPLANE(#79056,#79072,());
#79077= IFCCONNECTIONSURFACEGEOMETRY(#79075,$);
#79078=
IFCRELSPACEBOUNDARY('0dxBkPkUSBXBx7uHwKy0y2',#12,'2ndLevel','2a',#76214,#60012,#79077,.PHYSICAL.,.EXTERNAL.);
#79080= IFCDIRECTION((1.,0.,0.));
#79082= IFCDIRECTION((0.,1.,0.));
#79084= IFCCARTESIANPOINT((0.,0.,0.673205080757));
#79086= IFCAXIS2PLACEMENT3D(#79084,#79082,#79080);
#79087= IFCPLANE(#79086);
#79088= IFCCARTESIANPOINT((0.,0.673205080757,0.));
#79090= IFCCARTESIANPOINT((11.4,0.673205080757,0.));
#79092= IFCCARTESIANPOINT((11.4,0.,0.));
#79094= IFCCARTESIANPOINT((0.,0.,0.));
#79096= IFCCARTESIANPOINT((0.,0.673205080757,0.));
#79098= IFCPOLYLINE((#79088,#79090,#79092,#79094,#79096));
#79100= IFCCOMPOSITECURVESEGMENT(.CONTINUOUS.,.F.,#79098);
#79101= IFCCOMPOSITECURVE((#79100),.F.);
#79104= IFCCURVEBOUNDEDPLANE(#79087,#79101,());
#79106= IFCCONNECTIONSURFACEGEOMETRY(#79104,$);
#79107=
IFCRELSPACEBOUNDARY('13UjdmCIGNmNY28Gtm7OlY',#12,'2ndLevel','2a',#76214,#67536,#79106,.PHYSICAL.,.EXTERNAL.);
ENDSEC;

END-ISO-10303-21;

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A.4 Portals, Platforms and Software using IFC models

An overview of the list of freeware IFC portals, platforms and software that can be used for visualization, geometrical checks and validation in Table 2.

S.No.	Name of the Portal, Platform or Software	Description
1	Areddo [8]	BIM viewer for IFC and pointclouds.
2	BIMData [9]	The BIM collaborative platform.
3	Bimserver.org [10]	Open Source BIM Server, an open source BIM Server based on IFC.
4	BIM surfer WebGL Viewer [11]	BIM Surfer, an open source WebGL viewer for IFC in a web browser.
5	IFC2SKP [12]	IFC Import Plugin for Google SketchUp 8 and 2013 version 0.86 Beta.
6	Constructivity Model Viewer [13]	A viewer for IFC Data that allows browsing 100% of IFC objects including building models, product types, structural models, building systems, schedules, estimates, work orders, libraries, documents, classifications, approvals, constraints, materials, and more.
7	eveBIM [14]	Multi-scale viewer for IFC, BCF, CityGML and GIS files. Multiples plugins for viewpoints, clipping, colorization, properties edition.
8	datacomp [15]	BIM Vision, first Polish browser for IFC format.
9	DDS-CAD Viewer [16]; DDS-IFC Reader [16]	A viewer for IFC Data *.ifc, *.ifcZIP, *ifcxml, *gbxml. Drag & drop IFC files and examine.
10	IFC Quick Browser [17]	Text-browser for large IFC files. The IFC file is displayed in a tree structure.
11	IfcOpenShell [18]	A free open source IFC geometry engine. Besides the library itself, it features an importer for Autodesk 3ds Max, an importer for Blender and a stand-alone application to convert into the Wavefront .OBJ file format.
12	IfcWebServer [19]	IfcWebServer.org is a free to use data model server and online viewer for Building Information Models (BIM) based on IFC standards. BIM managers and designers can query, filter and make reports about any information inside IFC models easily. The IFCWebServer can be used in universities for BIM courses. Students can register and upload IFC models, explore the structure, apply filters, create sub-models and generate reports.
13	FZKViewer 5.1 [20]	A viewer for IFC and CityGML data. It is used for the visualization of semantic data models in the areas of BIM (Building Information Modeling) and GIS (Geographic Information Systems).
14	Nemetschek IFC Viewer [21]	Free 3D IFC Viewer, supports IFC format and XML IFC Format.
15	IFC File Analyzer v.2.63; [22] SteelVis v.8.90	Generate an Excel spreadsheet or CSV files from an IFC file. CIS/2 to IFC Translator, CIS/2 is the product model for structural steel. [23]
16	Open Source BIM collective [24]	Open source BIM collectiveThe open source BIM Collective is created to support and build the highest-quality open source Building Information Modeling software for open standards like IFC. Projects like IfcWebServer, BIM tools for sketchup, UBERviewer (CityGML and IFC), BIMserver.org, IfcOpenShell and BIMsurfer team up to create a stable suite of free and open source tools for everybody to use.
17	Open IFC Tools [25]	Open IFC tools, a set of tools for open source IFC development. including open Java toolbox, IFC loader for Java-3d, Boolean modeler, and Schedule assistant.

18	IFC Viewer [26] IFC Viewers Source Code [26] IFC Examples [26]	IFC Viewer, an IFC Viewer for Windows (DirectX 9), Unicode, IFC 2x3 (TC1) as well as IFC 4 and both 32/64 bit versions. IFC Viewers Source Code, the same viewer with C++ source code for 32/64 bit Unicode, including non-Unicode versions and a C# 32 bit version. IFC Examples Source Code, C++ and C# examples of IFC applications reading/writing and IFC Viewers.
19	Solibri IFC Optimizer Solibri Model Viewer and Checker v9.10.1 [27]	A tool for optimizing/compressing IFC files. A viewer for IFC. Solibri software run on Windows and Mac OS X.
20	Tekla BIMsight [28]	Can combine models and run clash detection for free. *.ifc, *.ifcZIP, *ifcxml,.dgn, .dwg, .xml files.

Table 2: An overview of different platforms, portals and software using IFC data. Information retrieved from [7]

B. Green Building XML schema (gbXML)

The Green Building XML schema (gbXML), was developed to facilitate the usage of building information stored in CAD-based building information models, enabling interoperability between disparate building design and engineering analysis software tools [29]. gbXML allows different users in multiple domains to use and transfer the properties of 3D building models to analysis and simulation software. Based on a XML Schema Definition (XSD), gbXML has over 500 elements and attributes that can be used to define all the aspects of a building.

B.1 Timeline and History of gbXML

Year	Milestone
1999	Development of Green Building XML started by Green Building Studio, Inc. Development was funded by the California Energy Commission PIER Program, Pacific Gas and Electric, and Green Building Studio.
2000	The first version of the gbXML schema was published in June of 2000.
2002	The gbXML.org website was launched to better promote the schema.
2008	Autodesk acquires Green Building Studio, the company that created and maintained gbXML.
2009	New gbXML advisory board formed consisting of consortium of software development firms. gbXML is incorporated as a California public non-profit with the official name: Open Green Building XML Schema, Inc.
2012	gbXML elects new Board of Directors including Amir Roth from DOE, Nathan Kegel from IES, and Todd Gottshall from Taylor Engineering. Releases version 5.01 of gbXML.
2013	Receives funding from U.S. DOE. Releases version 5.11 of gbXML. Releases a new schema validator. Releases version 5.10 of gbXML.

2014	Releases version 5.12 of gbXML. Releases a new schema validator (Version 2). Receives funding from U.S. DOE and PNNL for Phase II.
2015	Receives funding from U.S. DOE and NREL for Phase III of ongoing contract. Releases version 6.01 of gbXML. Receives funding from Autodesk for schema updates.
2016	NREL's Open Studio software tool is the 1st tool to become gbXML compliant. gbXML presents its validation findings at the ASHRAE/IBPSA SimBuild Conference in August. gbXML hosts software vendor webinar to receive feedback on new validation process. New gbXML website launched.
2017	Autodesk funds gbXML to perform Level 3 validation. gbXML is a Silver Sponsor at the IBPSA Building Simulation Conference in San Francisco in August 2017.
2018	Over 45 software tools now support integration with gbXML. gbXML hires Georgia Tech University to work on Level 3 validation research. A free and new web-based gbXML viewer is now available.
2019	gbXML is officially 20 years old. A new ASHRAE-funded test case and validation research project begins courtesy of BuildSimHub. Over 50 software tools now support integration with gbXML. Georgia Tech University begins Phase II of the Level 3 validation work.

Table 3: An overview of the history and timeline of gbXML. Information retrieved from [30].

B.2 *An example building definition in gbXML*

An example "Office" building defined in the gbXML schema. Information retrieved from [31]

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```
<?xml version="1.0"?>
<gbXML temperatureUnit="F" lengthUnit="Feet" areaUnit="SquareFeet" volumeUnit="CubicFeet"
useSIUnitsForResults="false" xmlns="http://www.gbxml.org/schema">
        <Campus id="cmps-1">
        <Location>
                <Name>Boston, MA </Name>
                <ZipcodeOrPostalCode>4205</ZipcodeOrPostalCode>
                <Latitude>42.213000</Latitude>
                <Longitude>-71.033000</Longitude>
        </Location>
                <Building id="bldg-1" buildingType="Office">
                <Area>15811.390974</Area>

                .
                .
                .
                .
```

.

```
                <Coordinate>35.585852</Coordinate>
                <Coordinate>25.000000</Coordinate>
        </CartesianPoint>
        </PolyLoop>
        </PlanarGeometry>
                <CADObjectId>44536</CADObjectId>
        </Surface>
        </Campus>
        <Zone id="zone-Default">
                <Name>Default</Name>
                <DesignHeatT unit="F">70.000000</DesignHeatT>
                <DesignCoolTunit="F">74.000000</DesignCoolT>
                <CADObjectId>149032</CADObjectId>
        </Zone>
</gbXML>
```

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B.3 Software complaint with gbXML

An overview of different software, their vendors/developers along with the applications is given in Table 4.

S.No.	Vendor	Tool	Application	gbXML Verified
1	Arup	EnergySave	Analysis	Not Yet
[32]	An easy to use intelligent interface to Arup's Energy2 building energy analysis program.			
2	ASHRAE	Building EQ	Energy Rating	Not Yet
[33] [34]	ASHRAE's Building EQ Portal provides a quick energy analysis that benchmarks a building's energy performance. Building EQ assists in the preparation of an ASHRAE Level 1 Energy Audit to identify means to improve a building's energy performance including low-cost, no-cost energy efficiency measures and an Indoor Environmental Quality survey with recorded measurements to provide additional information to assess a building's performance. Two different evaluations can be used independently to compare a candidate building to other similar buildings in the same climate zone or together for an assessment of a building's design potential compared to actual operation: 1. In Operation compares actual building energy use based on metered energy information. 2. As Designed compares potential energy use based on the building's physical characteristics and systems with standardized energy use simulation. The ASHRAE Building EQ portal is able to import a gbXML file to populate basic building information.			
3	Autodesk	Green Building Studio (GBS)	Analysis	Not Yet
[35] [36]	A building energy analysis web service designed for easy integration with existing 3D-CAD/BIM software tools. Below are files that are produced by the GBS: 1. DOE-2.2 One of the most advanced and widely used building energy analysis engines.			

[37] [38] [39]	2. EnergyPlus The successor to DOE-2 that has advanced building analysis capabilities. 3. eQuest The most widely used graphical building energy analysis tool in the world. 4. VRML & X3D Virtual Reality Modeling Language and its XML version used for describing 3D environments.			
4	Autodesk	Insight	Analysis	Not Yet
[40]	Autodesk Insight is a cloud-based software tool that empowers architects and engineers to design more energy-efficient buildings with advanced simulation engines and building performance analysis data integrated inside Revit. Insight exports energy analysis results to gbXML after analysis has been performed.			
5	Bentley	Bentley-AECOsim	Analysis	Not Yet
[41]	AECOsim Energy Simulator is a rigorous yet intuitive application for the design, simulation, and analysis of building mechanical systems, environmental conditions, and energy performance. Used in both design and retrofit work, the software contributes to better-performing, more sustainable buildings that consume less energy; provide greater occupant productivity, comfort, and safety; and control lifecycle operational energy costs for their owners. AECOsim fully supports gbXML.			
6	Bentley	Bentley-Hevacomp	Analysis	Not Yet
[41]	Bentley Hevacomp offers software for building performance design, simulation, and energy certification based on the EnergyPlus analysis engine. Hevacomp is used worldwide to predict a building's real-world performance and provide compliance checking and documentation for international standards.			
7	Bionova Ltd.	One Click LCA	Analysis	Not Yet
[42]	One Click LCA has ready-to-use tools for dealing with many of the most demanding green building analyses — choose the ones you need and manage everything efficiently through one platform. 1. Life-cycle costing 2. Materials sourcing credits 3. Climate resiliency 4. Site impacts monitoring 5. Operational performance monitoring 6. More than 80 other tools and templates in One Click LC			
8	blueCape	BlueCFD-AIR	Analysis	Not Yet
[43]	BlueCFD-AIR is a brand new Graphical User Interface that allows a more efficient application of CFD to problems in buildings and structures. AEC professionals thus gain access to an easy to use and highly precise tool, to aid in the analysis of one or several design alternatives. It can import gbXML (Green Building XML) files generated by CAD and BIM applications, as well as other LEED applications that use gbXML for building and energy information exchange. The CFD capabilities used by blueCFD-AIR are provided by blueCFD-Core, which is a high quality cross-compiled build version of OpenFOAM for Windows; the possibility to couple to other software like STAR-CCM+ is planned for future versions of blueCFD-AIR.			
9	CADLine	Cymap	Analysis	Not Yet
[44]	An integrated building services design suite, covering both mechanical and electrical. Imports gbXML building data for use in services design, energy analysis and demonstrating compliance with Building Regulations.			

10	Carrier	HAP (Hourly Analysis Program)	Analysis	Not Yet
[45]	HAP is a dual function program - full-featured load estimating and system sizing for commercial buildings plus versatile hour-by-hour energy and operating cost analysis.			
11	CYPE	CYPETHERM Loads, HVAC, EPlus, and CYPELUX	Analysis	Not Yet
[46]	CYPE is a firm that develops and distributes technical software for Architecture, Engineering and Construction professionals. CYPETHERM Suite is a group of CYPE programs for thermal and energy analysis of buildings in accordance with current national and international standards. The applications that work with the 3D model of the building are integrated into the Open BIM workflow via the gbXML and IFC standards: • CYPETHERM Loads. Thermal load calculation of buildings according to the Radiant Time Series Method (RTSM), proposed by ASHRAE. • CYPETHERM HVAC. Design of HVAC installations (heating, ventilation and air conditioning). • CYPETHERM EPlus. Modelling and energy simulation of buildings with EnergyPlus™. • CYPELUX. Design of normal and emergency lighting installations, as well as their evaluation.			
12	DesignBuilder	DesignBuilder v6	Analysis	Not Yet
[47]	DesignBuilder is a state-of-the-art software tool for checking building energy, CO2, lighting and comfort performance. Developed to simplify the process of building simulation, DesignBuilder allows users to rapidly compare the function and performance of building designs and deliver results on time and on budget.			
13	DIAL	DIALux evo 8.2	Analysis	Not Yet
[48]	The free and complete software developed for professional light planning is open to luminaires of all manufacturers. A software by planners for planners. Used by many hundreds of thousands of light planners and designers worldwide. And their number is growing from day to day. Create your virtual worlds simply and intuitively with DIALux. Document your results in breath-taking, photorealistic visualizations. Delight your customers with daylight and artificial light scenarios through which they can glide with wild camera runs. Rely on the CAD data of other architecture programmes and re-export your files easily. Receiving data from an architect is the normal start for the lighting designer. Supported formats are DXF, DWG and STF. The latest innovation is the gbXML interface to DIALux. All mayor CAD manufacturers support this interface. The Green Building XML (gbXML) open schema helps to facilitate the transfer of building geometry and properties stored in a 3D BIM database (e.g. Revit, ArchiCAD) to analysis tools like DIALux.			
14	Digital Alchemy	Simergy	Analysis	Not Yet
[49]	Simergy was developed by Digital Alchemy in conjunction with the Lawrence Berkeley National Laboratory (LBNL) and a number of other software partners. It is a comprehensive graphical user interface (GUI) for EnergyPlus that includes a complete workflow solution that takes the user all the way through the building design and analysis process starting from the early stages to detailed design. The workflows facilitate the cycles of analysis that enable exploration of system types and enable innovative HVAC system design.			
15	E4 Tech	Lesosai	Analysis	Not Yet
[50]	Lesosai from E4 Tech is a software for the certification, thermal balance calculation of buildings containing one or more heated or cooled zones. Lesosai allow a building life cycle calculation. It is designed primarily for building engineers, HVAC engineers and architects. It's certified for Switzerland, Luxembourg and France.			

16	Elite Software	Chvac - Commercial HVAC Load Calculations	Analysis	Not Yet
[51]	Chvac quickly and accurately calculates the maximum heating and cooling loads for commercial buildings. The cooling loads can be calculated with either the CLTD method or the new RTS (Radiant Time Series) method. The program allows an unlimited number of zones which can be grouped into as many as 100 air handling systems. CHVAC now imports/exports gbXML files and a video demonstration of that feature can be seen here.			
17	EnergySoft, LLC	EnergyPro	Analysis	Not Yet
[52]	EnergyPro is currently certified for use with the California Title 24 Standards. It is the only Windows based program certified for use with BOTH Residential and Nonresidential Buildings. EnergyPro imports gbXML schemas for true interop with BIM authoring software.			
18	Environmental Design Solutions Limited	Tas Engineering	Analysis	Not Yet
[53]	Tas Building Designer simulation software from EDSL (www.edsl.net) is a new generation product, no old legacy code to slow you down. Try it for room load and plant component sizing, energy use and running costs, CO2 emissions, natural ventilation and passive design with solar shading.			
19	eTool	eToolLCD	Analysis	Not Yet
[54]	eToolLCD is an intuitive, open-use, web-based, whole building life cycle assessment (LCA) and design software developed by two engineers with a passion for sustainable buildings. Design focused and performance based, genuinely sustainable outcomes are made easy. eToolLCD produces comprehensive reports complete with comparable sustainable building data with outputs compliant with international standards ISO 14044 and EN 15978. Used in hundreds of projects across all industry sectors, our web-based platform enables us to make seamless updates without interrupting use of the software by our 3,000 and growing users around the globe.			
20	greenspace Live	greenspace Live Energy Design and Analysis Tools	Analysis	Not Yet
[55]	Online products work together to provide you with an easy-to-use rapid workflow. Design activities start in gWorkspace, where facility owners, architects and energy assessors can share key information including building documents, site photos and plans. gModeller is a greenspaceLive plug-in for Google SketchUp, one of the most popular 3D modelling tools in the world. It turns SketchUp models into Green Building XML (gbXML) models which can then be analyzed for energy purposes using downstream tools. gEnergyEPC generates government accredited Energy Performance Certificates (EPC's) in line with the EU Energy Performance of Buildings Directive and building energy analysis reports. gDashboard presents rich information and reports about the full building portfolio managed by greenspaceLive.			
21	HVAC Solution	HVAC Solution	Analysis	Not Yet
[56]	HVAC Solution software is a 2D schematic software tool that helps users design air handing, airflow, hydronic and steam systems. It can import HVAC-related information from software tools such as Trane, Trace and Elite CHVAC using gbXML.			
22	IES Limited	Virtual Environment (VE)	Analysis	Not Yet
[57]	The Virtual Environment (VE) from IES is a unique, integrated system for building performance assessment that brings productivity and excellence to every aspect of building design.			
23	IZUBA énergies	Pleiades	Analysis	Not Yet
[58]	IZUBA Energies is a cooperative French company dedicated to the energy transition in the building sector. IZUBA Energies develops and distributes Pleiades, a building eco-design software combining:			

	- Dynamic energy simulation of buildings (STD COMFIE) - French building regulation calculation (Pleiades RT 2012 and RT existant) - Thermal loads (Radiant Time Series) and heat loss calculations (NF EN 12831) - Life cycle analysis (Pleiades ACV) With Pleiades, energy and environmental optimization of the building is part of an openBIM process. Pleiades imports IFC4 or gbXML models.			
24	Ladybug Tools	Ladybug Tools gbXML Viewer	Viewer	Not Yet
[59]	This open-source web-based gbXML viewer allows you to upload any gbXML file and view, pan, zoom, and rotate the geometry within your favorite browser.			
25	mh-software GmbH	RaumGEO	Analysis	Not Yet
[60]	RaumGEO is a German CAE application that has a gbXML-import-module for building data to calculate heating and cooling loads and energy requirements for buildings with mh-software. A 3D viewer lets you visually check and define the gbXML data before it is imported. Within RaumGEO the building data may be edited or completed before HVAC calculations are started. Calculated HVAC networks may be returned to any CAD system.			
26	National Renewable Energy Laboratory	Open Studio v 2.8.0	Analysis	Level 2 Certification
[61]	OpenStudio is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modeling using EnergyPlus and advanced daylight analysis using Radiance. OpenStudio is an open source (LGPL) project to facilitate community development, extension, and private sector adoption. OpenStudio includes graphical interfaces along with a Software Development Kit (SDK). The graphical applications include the OpenStudio SketchUp Plug-in, OpenStudio Application, ResultsViewer and the Parametric Analysis Tool. The OpenStudio SketchUp Plug-in is an extension to Trimble's popular SketchUp 3D modeling tool that allows users to quickly create geometry needed for EnergyPlus. Additionally, OpenStudio supports import of gbXML and IFC for geometry creation. The OpenStudio Application is a fully featured graphical interface to OpenStudio models including envelope, loads, schedules, and HVAC. ResultsViewer enables browsing, plotting, and comparing simulation output data, especially time series. The Parametric Analysis Tool enables studying the impact of applying multiple combinations of OpenStudio Measures to a base model as well as export of the analysis results for EDAPT submission. In addition to the graphical interface, OpenStudio allows building researchers and software developers to quickly get started through its multiple entry levels, including access through C++, Ruby, and C#. Users can leverage the Ruby interface to create OpenStudio Measures that can be easily shared and applied to OpenStudio Models.			
27	National University of Ireland, Cork	Cylon Controls Ltd. & Ace Controls ltd.	Analysis	Not Yet
[62]	Development of a generic web based software tool that integrates standard building management systems and third party auditing applications.			
28	Relux Informatik AG	ReluxSuite	Analysis	Not Yet
[63]	Relux Informatik AG, located in Switzerland, is involved in the development, production and distribution of ReluxSuite, the free lighting planning software tool for lighting and sensor planners. This suite provides users with all the software and data necessary for professional lighting planning. The ReluxSuite includes the following software tools: ReluxPro ReluxSensor ReluxOffer ReluxEnergy ReluxSuite imports geometric data from gbXML files produced by BIM authoring tools such as Autodesk Revit.			

29	Sankom Sp. z o.o.	Auditor OZC 6.9 Pro	Analysis	Not Yet
[64]	Sankom Sp. z o.o is a company out of Warsaw, Poland. It develops and publishes software supporting the process of sanitary systems design. Auditor OZC 6.9 Pro is a desktop software tool and Autodesk Revit plug-in. The Revit plug-in extends the capabilities of a standard Revit building block export to gbXML. For example, Revit does not always export building materials that correctly define heat parameters. In this case, the layers that are exported to gbXML are not defined in the material layer. The gbXML Auditor plug-in eliminates this problem.			
30	Software für Haustechniker	Win_Ht	Analysis	Not Yet
[65]	Win_Ht is a calculation program focused on calculations for Swiss standards - e.g. SIA Norms. Win_Ht Version 3.11 will import versions 5.0 to 6.01 of gbXML. Imported data can be used to calculate heating loads, underfloor heating, radiators, system redundancy, thermal energy, heat transmission and more.			
31	Solar-Computer	Green-Building-Information-System (GBIS)	Analysis	Not Yet
[66]	GBIS is a CAD application that provides a bidirectional gbXML-based connection to the SOLAR-COMPUTER suite of calculation programs for buildings (energy analysis, heat load, and cooling load) and systems (radiators, heat piping, ventilation, and drinking water). GBIS enhances the gbXML file with internal CAD data. This allows for a very detailed building model and error checking. SOLAR-COMPUTER building programs can also import gbXML files directly.			
32	Trane	Trace 700 v 6.3.4	Analysis	Not Yet
[67]	A comprehensive and widely used energy and economic analysis tool for mechanical engineers.			

Table 4: An overview of different software, their vendors and applications using gbXML. Information retrieved from [29]

C. City Geographical Markup Language (CityGML)

The City Geographical Markup Language (CityGML) is an XML based open data model representing cities, districts and individual buildings. Defining the geometrical and semantic information, CityGML data models also defines the topological and appearance properties of the topographic city objects [68]. It complies to the application schema for the Geography Markup Language version 3.1.1 (GML3), which is the extendible international standard for spatial data exchange issued by the Open Geospatial Consortium (OGC) and the ISO TC211 [69]. Based on the ISO 191xx family, the Open Geospatial Consortium, the W3C Consortium, the Web 3D Consortium and OASIS standards, CityGML has 13 thematic extension modules namely, [69]

- *Appearance*
- *Bridge*
- *Building*
- *CityFurniture*
- *CityObjectGroup*
- *Generics*
- *LandUse*
- *Relief*
- *Transportation*
- *Tunnel*
- *Vegetation*
- *Waterbody*
- *TexturedSurface*

According to [69], the aim of the development of CityGML is to reach a common definition of the basic entities, attributes, and relations of a 3D city model. This is especially important with respect to the cost-effective sustainable maintenance of 3D city models, allowing the reuse of the same data in different application fields. The availability of external re-definable dictionaries, code lists, provides the allowed values for enumerative attributes such as building class, function and usage for energy performance simulations [68]. As shown in Table 5, depending on the amount of information in the *core* CityGML data models, five *Levels of Detail (LoD0-4)* can be defined for CityGML.

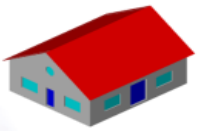
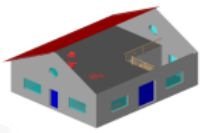
Overview of LoD concept in CityGML (LoD0 – LoD4)	
	**LOD0** (2.5D model definition) • Regional and landscape scale representation • Lowest accuracy • No information over building installations • Information about roof representations available • No information about city furniture
	**LOD1** • City and region scale representation • 5/5m 3D point accuracy (Low) • Object blocks as generalised features (>6*6m/3m) • Flat roof structures • No information over building installations and city furniture
	**LOD2** • City, districts and project scale representation • 2/2m 3D point accuracy (Middle) • Objects as generalised features (>4*4m/2m) • Differentiated roof representations • Information over building installations available • City furniture as prototypes, generalized objects
	**LoD3** • City districts, exterior architectural models, landmark scale representation • 0.5/0.5m 3D point accuracy (High) • Object as real features (>2*2m/1m) • Building installations as exterior features • Real object form for roof structures and city furniture
	**LOD4** • Interior architectural models, landmark representation • 0.2/0.2m 3D point accuracy (Very High) • Constructive elements and openings are represented • Real object forms for building Installations, roof structures and city furniture

Table 5: Level of Detail concept in CityGML (LoD0-4). [69] [70]

C.1. Timeline and version releases

A brief history of the different version of CityGML is given in Table 6.

CityGML version	Year
1.0	2007
2.0	2012
3.0	2019 (proposed)

Table 6: Overview of CityGML versions and their releases [69]

C.2. CityGML Application Domain Extensions (ADE)

With the aim to use CityGML data models in multiple domains and implementations, extensions depending upon the applications are currently available and are also being developed. The following Table 7, gives an overview of the available extensions.

S. No.	Application Domain Extension (ADE)	Purpose	XSD	UML	Origin
1	Energy ADE	Application	•	•	Europe
2	Energy Efficiency ADE	Application	•	•	Italy
3	Energy Efficiency ADE (ii)	Application		•	Spain
4	Noise ADE	Application	•	•	Germany
5	Extended Noise ADE	Application		•	Netherlands
6	Road Traffic Noise ADE	Application	•	•	India
7	Robotics ADE	Application	•	•	Japan
8	Utility Network ADE	Application	•	•	Germany
9	CAFM ADE	Application	•	•	Germany
10	Immovable Property Taxation ADE	Application	•	•	Turkey
11	Cadastre ADE	Application	•		Netherlands
12	CityGML–LADM ADE	Application		•	Mixed
13	Cultural Heritage ADE	Application		•	Spain
14	Cultural Heritage ADE (ii)	Application	•	•	Italy
15	Cultural Heritage ADE (iii)	Application	•	•	Italy
16	Heritage house ADE	Application			Malaysia
17	Intervention ADE	Application		•	Spain
18	BCH Management ADE	Application			Belgium
19	Indoor N&P ADE	Application		•	India
20	Indoor ADE	Application	•	•	Korea
21	i-SCOPE	Application			Europe
22	Hydro ADE	Application			Germany
23	AR ADE	Application		•	Canada
24	Collada FX ADE	Application			Germany
25	ENC ADE	Application			Germany
26	Air Quality ADE	Application			Italy
27	IMGeo ADE	Generic	•	•	Netherlands
28	CityGML-TRKBIS	Generic		•	Turkey
29	INSPIRE ADE	Generic	•	•	Germany
30	ACRoofADE	Generic	•	•	China
31	CityGML iTINs ADE	Generic	•	•	Netherlands
32	Vegetation Objects ADE	Generic			Mexico
33	Dynamizers	Generic		•	Germany
34	Dynamic ADE	Generic		•	Spain
35	Geodata Join ADE	Generic			Germany
36	Topo ADE	Generic			China
37	Transport ADE	Generic			Netherlands
38	Traffic Sign ADE	Generic			Spain
39	3D-GEM	Generic		•	Netherlands
40	New LOD ADE	Generic		•	Netherlands
41	Semantic City Model	Generic		•	China
42	GeoBIM	Generic	•	•	Netherlands
43	PANTURA ADE	Generic			Netherlands
44	3D Metadata ADE	Generic	•	•	Netherlands

Table 7: Information about different ADEs and table retrieved from [71] [69] [72]

C.3. An example city district definition in CityGML

An example city district from Hamburg modelled with CityGML version 1.0 standards. The available data file is in LoD2 with a coordinate system EPSG 25832: ETRS89 / UTM Zone 32N. Information retrieved from [73].

****

```
<?xml version="1.0" encoding="UTF-8"?>
<core:CityModel xmlns:core="http://www.opengis.net/citygml/1.0"
        xmlns:bldg="http://www.opengis.net/citygml/building/1.0"
        xmlns:gen="http://www.opengis.net/citygml/generics/1.0"
        xmlns:gml="http://www.opengis.net/gml"
        xmlns:xAL="urn:oasis:names:tc:ciq:xsdschema:xAL:2.0"
        xmlns:xlink="http://www.w3.org/1999/xlink"
        xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
        xsi:schemaLocation="http://www.opengis.net/citygml/1.0
http://schemas.opengis.net/citygml/1.0/cityGMLBase.xsd http://www.opengis.net/citygml/building/1.0
http://schemas.opengis.net/citygml/building/1.0/building.xsd http://www.opengis.net/citygml/generics/1.0
http://schemas.opengis.net/citygml/generics/1.0/generics.xsd http://www.opengis.net/gml
http://schemas.opengis.net/gml/3.1.1/base/gml.xsd ">
        <gml:description>Created with Hexagon Software (URL:www.leica-
geosystems.com)</gml:description>
        <gml:name>LoD2_568_5934_1_HH</gml:name>
        <gml:boundedBy>
                <gml:Envelope srsName="urn:adv:crs:ETRS89_UTM32*DE_DHHN92_NH">
                        <gml:lowerCorner srsDimension="3">567981.636 5933956.176 -
0.027</gml:lowerCorner>
                        <gml:upperCorner srsDimension="3">569014.859 5935029.047
51.728</gml:upperCorner>
                </gml:Envelope>
        </gml:boundedBy>
        <core:cityObjectMember>
                <bldg:Building gml:id="DEHH_95c10b38-9c3a-474c-83dc-b30843a0e90e">
                        <core:creationDate>2019-02-14</core:creationDate>
                        <core:externalReference>
                                <core:informationSystem>http://repository.gdi-
de.org/schemas/adv/citygml/fdv/art.htm#_9100</core:informationSystem>
                                <core:externalObject>
                                        <core:name>DEHHALKA2ib000Jg</core:name>
                                </core:externalObject>
                        </core:externalReference>
                        <bldg:roofType>1000</bldg:roofType>
                        <bldg:measuredHeight uom="
.
.
.
.
.
                        <bldg:address>
                                <core:Address>
                                        <core:xalAddress>
                                                <xAL:AddressDetails>
                                                        <xAL:Country>

        <xAL:CountryName>Germany</xAL:CountryName>
                                                                        <xAL:Locality Type="Town">
```

```
        <xAL:LocalityName>Hamburg</xAL:LocalityName>
                                                        <xAL:Thoroughfare Type="Street">
        <xAL:ThoroughfareNumber>3</xAL:ThoroughfareNumber>
        <xAL:ThoroughfareName>XYZstraße</xAL:ThoroughfareName>
                                                        </xAL:Thoroughfare>
                                                            <xAL:PostalCode>
        <xAL:PostalCodeNumber>20537</xAL:PostalCodeNumber>
                                                                </xAL:PostalCode>
                                                        </xAL:Locality>
                                                    </xAL:Country>
                                                </xAL:AddressDetails>
                                            </core:xalAddress>
                                        </core:Address>
                                    </bldg:address>
                                </bldg:Building>
                            </core:cityObjectMember>
</core:CityModel>

**************************
```

C.4. Freeware and commercial software and tools complaint with CityGML

CityGML data models along with their extensions are currently been used for by researchers, urban planners, simulation scientists and geomatics specialists. Analysis and simulations of the 3D data models is carried out using multiple tools and environments. A list of such software using and complying to CityGML data models along with their descriptions are given in Table 8.

S.No.	Name of the Software and Vendor/Developers	Description
1	BIMserver [10], by BIMserver.org	Open source building information model server based on IFC. It has an export function from IFC to CityGML (including the GeoBIM ADE extension
2	libcitygml [74], by BRGM, Geoscience for a sustainable Earth	It is a small and easy to use open source C++ library for parsing CityGML files in such a way that data can be easily exploited by 3D rendering applications (geometry data are tessellated and optimized for rendering during parsing). For instance, it can be used to develop readers of CityGML files in many 3D based applications (OpenGL, OpenSceneGraph, ...) citygml2vrml is a command line utility based on libcitygml to convert CityGML files to a VRML97 representation.
3	CityGML2X [75]	CityGML2X is a free Java library for converting CityGML to X3D.
4	CityGML2XCLI [75]	CityGML2XCLI is a command line interface for the free CityGML2X converter library. It lets you convert your CityGML models to X3D.
5	Cesium Ion [76], by CESIUM	Cesium Ion enables a CityGML upload and a visualization in the Cesium Globe.

6	Code Synthesis [77]	CodeSynthesis XSD, an open source, cross-platform XML data binding compiler for C++. Supports generation of the object model as well as parsing and serialization code from CityGML schemas.
7	CityGML2OBJs [78], val3dity [79], Solar 3Dcity [80], Random 3Dcity [81], by Delft University of Technology, 3D Geoinformation research group	CityGML2OBJs, a semantic-aware utility to convert CityGML data to OBJ, featuring decoupling of objects and conversion of attributes to colors. val3dity, geometric validation of 3D primitives according to ISO 19107, with a web interface. Solar3Dcity, a simple utility to estimate the yearly solar irradiation of buildings stored in CityGML. Random3Dcity, a procedural modelling engine natively supporting CityGML, and capable of generating extensive multi-LOD representations.
8	GeoRES [82], by GEOPLEX	CityGML Plugins Sketchup™-Sketchsoftware, free and open-source plugins to export CityGML data from Sketchup™-Sketchsoftware.
9	3D City Database [83], by Technical University of Munich, Chair of Geoinformatics	3D City Database, a free 3D geo database for the storage and management of virtual 3D city models based on CityGML - to be used in conjunction with Oracle 11G Spatial/Locator (or higher) or PostGIS. 3DCityDB comes with tools for CityGML import/export, export of data into spreadsheets, visualization support for KML, COLLADA, and glTF. Since version 3.2, a 3D web client which is based on the Cesium Virtual Globe is part of the project.
10	ARISTOTELES VIEWER-GML 3D [84], by University of Bonn, Institute for Cartography and Geoinformation	Aristoteles, an Open Source viewer for CityGML Data.
11	citygml4j [85], by virtualcitySYSTEMS	citygml4j, an open-source Java class library and API for the processing of 3D city models encoded in CityGML.
12	TEASER [86] [87], RWTH Aachen University	An open python based tool for urban energy modelling of building stocks and heating demand simulations using Dymola.
13	FZK Viewer [20], IAI, KIT	The FZKViewer is a software tool for the visualization of semantic data models in the areas of BIM (Building Information Modeling) and GIS (Geographic Information Systems). The focus here is on open standardized data formats.
14	CityEditor [88] 3D-MAP [89], by 2DIS GmbH	Extension allowing the import, editing, export & presentation (3D-PDF & WebGL- based web presentation) of CityGML models and other 3D geo data using SketchUp Web-based platform for managing, editing, processing & visualizing of 3D city models.
15	Bentley Map [41]	Advanced 3D GIS tool for Microstation (or Standalone) fully compliant with OCG & CityGML. Reads/writes all CAD files, MapInfo, Shapefiles, Oracle Spatial, CSV and ODBC sources.
16	BS Contact Geo [90]	3D software from Bitmanagement for the visualization of GIS and geo-data with CityGML support.
17	CityGRID Manager [91], by UVM Systems	Software for management and editing 3D city models.

18	CityServer3D [92], by Fraunhofer Institute for Computer Graphics Research (IGD)	Software suite for data management of 3D city models. Implements different standardised interfaces like CityGML, X3D, KML, WFS, W3DS. Geospatial information is stored in a database which enables scenario-based querying and visualization.
19	FME Technology provides CityGML Reading and Writing [93], by Safe Software	FME Technology provides CityGML Reading and Writing – (con terra GmbH - FME European Service Center).
20	Galdos INscape CityGML Server [94] Galdos INdicio CityGML Registry [94] Galdos CityGML INspector [94], by Galdos Systems Inc.	Galdos INscape is a WFS-T which is fully compliant with the CityGML specification and which can support any ADE (user defined or otherwise) out of the box. Galdos INdicio for CityGML manages code lists, schema components (base CityGML schemas and ADE's). Galdos CityGML INspector is an advanced visual inspector and WFS client for the examination and quality assurance of CityGML data. Invoke special shaders for indoor, outdoor and underground structures. Adaptive camera view provides objects at the "right" size. Integral Python engine for advanced users.
21	GO Publisher WFS [95], by Snowflake Software	An OGC Compliant schema translating WFS capable of serving CityGML from any given relational model / bespoke 3D geometry model.
22	novaFACTORY [96], by M.O.S.S.	novaFACTORY is an advanced Spatial Data Management solution for efficient geodata cataloguing, exploitation and dissemination. Its enterprise class technology is robust, flexible, easy-to-use, and scalable and is designed for seamlessly integrating large geographical data from many different sources, e.g. topographic maps, digital surface models, aerial photographs or 3D building models.
23	PlexMap [97], by GEOPLEX.	PlexMap is a browser-based platform for storing, processing and visualizing CityGML data.
24	tridicon™ CityDiscoverer [98]	Software suite and authoring tool for visualization and analysing large scale 3D city and terrain models.

Table 8: Software and simulation tools using CityGML data models. Information retrieved from [99] [100]

III. CONCLUSION

Data models organize different elements of the data along with the standardization of the interaction between different elements and properties of the real world entities. Although it is always difficult to find detailed information about different data models together, this technical report gives a thorough overview of the IFC, gbXML and CityGML data models. From the brief description and history to the actual usage and implementation, the authors focus to achieve a better understanding of the models for energy performance simulations. This report will facilitate the decision-making processes of the research communities in order to adapt these models based on their interests and requirements. Furthermore, an extensive list of the available simulation tools, software, will help them to use these models for multiple applications.

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