Investigating Semantic Functionality of 3D Geometry for Land Administration

George Floros, Eva Tsiliakou, Dimitrios Kitsakis, Ioannis Pispidikis and Efi Dimopoulou

Abstract Significance of semantic data during the recent years is growing. This trend, combined with facilitation of new 3D object modeling has led to semantically enriched 3D models, serving various applications where relations between objects' components and their environment need to be stored and presented. In the field of Land Administration, semantics can greatly contribute to optimize land management and land policies. Integration of semantics to 3D building models is currently achieved through two differently structured models: semantic-oriented CityGML and structural-oriented BIM/IFC. Integration of the semantic information of each model is still an object of intense research worldwide. In this paper, a 3D building model designed in SketchUp Pro software was transformed using FME software to a CityGML file; land use features were assigned to the model and attribute queries were executed in order to check the exported models' functionality in terms of semantics.

Keywords 3D modeling · Land use · SketchUp Pro · CityGML · Attribute query

---

G. Floros (✉) · E. Tsiliakou · D. Kitsakis · I. Pispidikis · E. Dimopoulou
School of Rural and Surveying Engineering, National Technical University of Athens,
9 Iroon Polytechneiou Str, 15780 Zografou, Greece
e-mail: flwrosg@gmail.com

E. Tsiliakou
e-mail: eva.tsiliakos@gmail.com

D. Kitsakis
e-mail: dimskit@yahoo.gr

I. Pispidikis
e-mail: pispidikisj@yahoo.gr

E. Dimopoulou
e-mail: efi@survey.ntua.gr

A. Abdul-Rahman (ed.), *Advances in 3D Geoinformation*,
Lecture Notes in Geoinformation and Cartography,
DOI 10.1007/978-3-319-25691-7_14

1 Introduction

Semantics have gradually attracted international scientific interest due to their ability of storing data that describe relations between different object parts and their environment (Diakité et al. 2014). Therefore, semantic based modeling has grown very popular internationally, incorporating a variety of applications of different scientific fields including energy applications, urban planning, indoor navigation, noise propagation simulation and mapping, disaster management and homeland security, cultural heritage, water management, environmental and real time simulations (Groeger and Plumer 2012). Semantic modeling is also promising for depicting relations between legal and physical space which is required to 3D Cadastre applications, where formal definition of 3D space and its containing elements is still an abstract concept, while volumetric parcels are not conceivable in reality but are established via connections to physical objects (Aien et al. 2013). 3D models' semantic enrichment allows for direct correlation between legal and physical property, improving the accuracy that legal spaces' volumes or locations are defined (Dimopoulou et al. 2014a). In the field of Land Administration, different modeling approaches such as IFC, a Building Information Modeling (BIM) standard or BIM ready software along with CityGML are exploited to attribute semantic data to 3D constructions or 3D city models. CityGML allows by the Application Domain Extension (ADE) to create extensions to the schema, to deal with special applications in 3D city modeling. Çağdaş (2013) exploits these capabilities of semantically rich CityGML information model along with its versatility to extend data features, to develop an ADE for immovable property taxation, overcoming the fact that CityGML does not model legal and administrative objects. However, each modeling approach serves different purposes (Cheng et al. 2013) while semantic description of buildings and their parts does not equal to semantic relationship between the buildings and their interior real property objects (Hu 2008). Attribution of semantic data becomes more important to the exploitation of 3D objects' models given that existing 3D modeling techniques have facilitated generation of high accuracy geometrical 3D object models. Literature provides a variety of techniques that are developed towards this approach, which however serve different objectives and cannot fully accommodate emerging issues. According to literature research, impediments of 3D objects' semantic data enrichment may be summarized as follows:

- Existing 3D object geometries created using CAAD systems lack semantic information. (Nagel et al. 2009).
- 3D data acquired from TLS/airborne laser points and images only pertain objects' exterior (Diakité et al. 2014), while do not include high level semantics (Xiong and Huber 2013). Especially in case of already built constructions, 3D acquisition of non visible components such as slabs or pipes cannot be achieved (Nagel et al. 2009).

- Data inconsistency between BIM and CityGML data (Diakité et al. 2014), as BIM models represent the built environment as designed rather than observed (Kolbe and Plümer 2004).
- Preservation of consistency between geometry and topology of spatial data (Groeger and Plümer 2009).
- Automation of transformation procedure between different data types as presented by Nagel et al. (2009).
- Preservation of Level of Detail (LoD) during transformation process. To this, issues of generalization of objects' components also need to be considered (Geiger et al. 2014).

Topology issues also need to be considered since topology constitutes the basis for the sufficient support of correct semantics.Topology issues are analyzed in Kolbe (2009). The author notes that "solids of adjacent objects like BuildingParts must touch but their interiors are not allowed to permeate each other, because space can only be occupied by one physical object". Different frameworks for the representation of 3D topology have been presented, most of them proposing a geometric-topological structure where coordinates are stored only within the nodes or the points associated with the nodes. Higher dimensional primitives are then constructed by connecting primitives of lower dimensions. Kolbe (2009) counter poses reusing common wall surfaces by providing the definition of the surface geometry inline within the specification of the solid geometry (bounded by a composite surface) of either building parts or the building itself. In the representation of the other solid this surface is then included by reference (and not by value) which creates the connection between both solids. The LADM also provides a conceptual description for a land administration system, including a 3D topology spatial profile. In case of the 3D topology representation, a 3D boundary face has plus/minus information included in the association to a 3D spatial unit (Dimopoulou and Elia 2012). Ying et al. (2012) address topology by introducing the real 3D geometric primitive "3D BODY" and two feature classes (3D land/legal space and 3D construction/building space) that are inherited from class "3D Parcel". The topological elements are hierarchically interrelated, and (n-1)-dimensional geometric primitives are used as boundary of n-dimensional geometric primitives. Zhao et al. (2011) focus on the topology checking among polyhedra in 3DGIS systems stating this is a technology problem, which should be solved with help of computational geometry, topology rules, the Euler–Poincaré formula etc.

Although various tools of conversion between BIM/IFC to CityGML and vice versa have been developed, e.g. BIMserver, KIT IFCExplorer and Safe Software FME, none of the converters is currently capable of automatically creating valid geometries nor fully correct semantics, especially when high levels of detail are involved (Donkers 2013). Several approaches towards this direction have been implemented by a number of researchers internationally. Isikdag and Zlatanova (2009) define a framework automating generation of buildings from BIM to CityGML, claiming that it is possible to define rules for geometrical transformation and facilitation of semantic matching from IFC to CityGML models, De Laat and van Berlo (2011) describe the development of GeoBIM extension on CityGML for IFC data, while El-Mekawy et al. (2011) proposed a unified building model (UBM) for integration of IFC and CityGML, allowing bilateral transformation between the two models. Dimopoulou et al. (2014b) investigate integration and interoperability between procedural modeling techniques and BIM-ready software within the CityGML framework from a semantic viewpoint using ESRI CityEngine environment and Trimble SketchUp Pro software to create 3D building models and evaluate modeling techniques. This paper aims to investigate semantic relations for Land Administration purposes through attribute querying of a building's indoor space. The paper is structured as follows: In Sect. 2 the role of semantics in Land Administration is presented, through exploitation of CityGML and BIM models. Sect. 3 describes exploitation of 3D geodatabases for 3D modeling applications specifying to integration of BIM with CityGML models and IFC with CityGML models focusing on urban applications. In Sect. 4, a case study is examined involving a 3D building model modeled in Trimble SketchUp and transformed into CityGML via FME software, in which land use features were assigned and attribute queries were executed. The paper ends with discussion and concluding remarks on Sect. 6.

2 Semantics in Land Administration

Semantic enrichment and spatio-semantic coherence could assist the integration of physical objects with their relevant cadastral attributes within robust cadastral models, although it has not been yet applied broadly for cadastral applications or the land administration domain. Evidently interoperability amongst data has triggered the need for "semantically enriched information in 3D cadastral data models meaning enriching the content and context of the available data by categorizing or classifying data in relationship to other data" as explained in Aien et al. (2013). Guo et al. (2012) argue that "semantic data in the field of land administration are used to regulate and coordinate relationships among people and property under a given legal system". Undoubtedly, inconsistencies between the spatial extension of physical structures such as building parts and the imperceptible extension of legal rights imposed on buildings or parcels are tackled via data semantic enrichment. Guo et al. (2012) explain that current 3D GIS models capture 3D objects and their spatial and physical features, but not their semantics. One might claim though that this practice is ambiguous when referring to cadastral data models; that is registered 3D objects are defined by physical structures such as walls, floors and are described by spatial and topological relations. Actual physical boundaries distinguish the extent of RRRs within a single building or even a room, or according to (Isikdag et al. 2013) the boundary of a parcel coincides with a physical real world object. El-Mekawy et al. (2014) also claim that a 3D legal boundary surface follows the outer surface of a building in which the legal basic property unit is located.

2.1 Semantics—CityGML

Semantic modeling approaches along with the appliance of 3D geometry and topology of real-world objects is realized via CityGML, which constitutes the first 3D semantic standard not "only representing the shape and graphical appearance of city models but specifically addressing object semantics" (Kolbe 2009). CityGML involves a very interesting concept employed mainly for visualization efficiency, the LoD, which differs from the LoDs used in Computer Graphics. The latter facilitates the LoD concept for speeding up the rendering process of holistic 3D city models in terms of visualization, while CityGML comprises five discrete Levels of Details starting from LoD0 to LoD4 (indoor), not purely geometrical but extended to semantics as well; with increasing LoD, the semantic richness increases accordingly (Kolbe 2009). The most significant component of this model is the Building module, facilitating the depiction of buildings and their components in terms of geometry, topology and semantics.

2.2 Semantics—BIM

Besides CityGML, Building Information Models (BIM) as a digital version of all the substantial and functional features of a building through its entire life cycle (Isikdag et al. 2013), refer to sophisticated geometric and semantic representations of the building parts. According to Isikdag et al. (2013) each BIM building element contains comprehensive property sets on the elements' functions or properties, while the "large set of utility elements embedded or located inside the building in 3D comprise detailed semantics". An important difference between IFC and CityGML is related with the use of different concepts for the same semantic objects. For example, IFC addresses the buildings' construction or design of buildings and defines construction elements such as wall, etc., while CityGML describes "how buildings are observed or used" (Nagel et al. 2009), thus providing definitions of rooms and walls (Gröger and Plümer 2012). The creation of a synergy between the strong (technology) parts of both worlds" by integrating CityGML and IFC (De Laat and van Berlo 2011) is highly recommended. Utilizing CityGML or IFC for cadastral applications, differences between geometric locations are identified; that is because BIM or CityGML are characterized by thickness information that may "be depicted by physical walls", while cadastral representations are limited to "linear legal boundaries" (Ying et al. 2012).

2.3 Semantics-Coherence

Current trends focus on the semantic enrichment of distinctive city objects or 3D geometries which can be decomposed into their structural elements including attributes and their correlations, also addressing spatio-semantics coherence issues even for complex building models. Stadler and Kolbe (2007) discuss the spatio-semantic coherence of 3D city models with special focus on virtual 3D city models and the semantic data model CityGML. Coherence refers to solid and consistent relations between spatial and semantic features, established solely in case of structural similarity, meaning that if semantic and geometric aggregations reveal the same structure, they are considered coherent (Stadler and Kolbe 2007). The coherent thematic and spatial configuration of objects, secures that each complex (or not) geometric entity is assigned a specific semantic component, since semantics diminish ambiguities for geometric amalgamation. CityGML supports spatio-semantic coherence, since geometry entities are assigned thematic attributes while simultaneously semantic entities are accompanied by spatial information (e.g. location etc.). Spatio-semantic coherence could assist the integration of legal and physical objects within robust cadastral models (Dimopoulou et al. 2015). Table 1 summarises the key features of currently used 3D standards along with their level of compatibility to each feature according to Zlatanova et al. (2012).

3 3D Geodatabase for 3D Modeling

"3D reality needs 3D design, engineering and analyses" while modeling cities, requires a "more holistic approach to creating, building and managing infrastructure" (de Vries and Zlatanova 2011). This approach is feasible through 3D

Table 1 Comparison of 3D standards. *Source* Zlatanova et al. (2012)

Standard/criterion	X3D	KML	COLLADA	CityGML	DXF	SHP
Geometry	++	+	++	+	++	+
Topology	0	–	+	+	–	–
Texture	++	0	++	+	–	–
LOD	+	–	–	+	–	–
Objects	+	–	–	+	0	+
Semantic	0	0	0	++	+	+
Attributes	0	0	–	+	–	+
XML based	+	–	–	+	–	–
Web	++	++	+	+	–	–
Georeterencing	+	+	–	+	+	+
Acceptance	0	++	+	+	++	++

(– not supported; 0 basic; + supported; ++ extended support) modeling and visualization, while support systems such as “geo-databases may serve as platforms to integrate 2D maps, 3D geo-scientific models, and other geo-referenced data” (Breunig and Zlatanova 2011). For example, the efficient storage of CityGML data requires both carefully optimized database schemas and data access tools (Stadler et al. 2009). El-Mekawy (2010) defines two types of 3D city models design which are usually “used for maximum level of detail in the architecture, engineering and construction (AEC)” and real world models which “are geospatial information systems representing spatial objects in GIS applications”. A 3D cadastral object is a synthesis of geometry, attributes and social and legal semantics, which is built processing 3D object construction, topological reconstruction and semantic information joining and spatial query and analysis (Ying et al. 2011) comprising both the legal space and the physical component, and may be physically represented by the Building Module of CityGML. However, according to Löwner et al. (2013) the current Level of Detail concept seems to be insufficient, since “the interior structure of a building can only be modeled when, simultaneously, there is a geometrically exact model for the exterior shell of the building, thus limiting the application of indoor models”.

3.1 Integration of CityGML and BIM Models

Based on the above, it is evident that both CityGML and IFC are flexible data models that aim at spatio-semantic coherence while enabling the visualization of 3D city models at different levels of geometric and semantic complexity (Stadler and Kolbe 2007). Isikdag et al. (2013) argue that the most evident obstacle preventing the employment of these models in real life applications have been deficiencies in “appropriate and applicable” representations of building geometry and thorough semantics for indoors, since the models developed are either too composite to query, characterized by complex geometric representations or not defined with sufficient semantics for sustaining indoor navigation. In their study, defined a new BIM based model (BO-IDM) for facilitating indoor navigation by introducing a new BIM Oriented Modeling methodology. Brown et al. (2013) discuss the concept of Topographic Space, defining it as a basic element of indoor navigation, entailing the buildings’ interior structure as well as the semantic decomposition into building elements (e.g. rooms and storeys). De Laat and van Berlo (2011) introduce Geo-BIM, which is a CityGML extension employed to obtain IFC semantic information data into a GIS framework, via a conversion process of IFC to CityGML implemented in the open source Building Information Modelserver. Zhu et al. (2011) conclude that the development of 3D city models accompanied by semantics has become a consensus and present their CityGML based semantic model, which supports the concept of Spaces (Stair, Corridor) for indoor navigation purposes.

4 Case Study

4.1 Workflow

The 3D building model was designed in Trimble SketchUp 2015. The boundaries of the entire modeling area were digitized based on the corresponding true orthophoto using AutoCAD 2015. Digitized boundaries (in .dwg format) were imported into SketchUp. Interior and exterior parts of the building were designed based on the architectural plans forming the entire 3D building model. The final model as seen in Fig. 2, was saved as a distinct .skp file, and imported in FME Workbench producing a single GML file by using key transformers. The final GML file is viewed with FME Data Inspector module (Fig. 3). In order to check the 3D model's functionality in terms of semantics and to execute queries based on the building's CityGML properties a database (utilising postgreSQL) was created and linked to the CityGML database through importer/exporter software, produced by 3DCityDB. The CityGML file was connected to this database, where various queries related to Land Use or building semantics are executed.

4.2 Trimble SketchUp

Trimble SketchUp is a user-friendly software for the design of 3D models; it provides full ability for the user, to design buildings, including their outer and inner parts. Within Sketchup, several design methods can be used, either through solids or surfaces and floors, depending mostly on user's requirements (Dimopoulou et al. 2014) (Fig. 1).

4.2.1 SketchUp as BIM Ready Software

SketchUp software allows for 3D building modeling comprising features that are able to classify objects and export files according to common Building Information Modeling (BIM) standards, constituting a BIM ready tool as presented below:

1. Sketchup provides the component feature along with geometry grouping when designing the model to form a component e.g., stairs or furniture. Different floors can also be manipulated as components, since each one can be geometrically grouped, thus generating distinctive geometries for each floor (as applied in this paper). These components can be moved and copied within the model, without affecting the rest of the model's geometry.
2. Sketchup provides the shadowing tool, which is a very useful BIM-like tool. The ability to analyze daylight on a project is a functional characteristic and very applicable for urban planning.

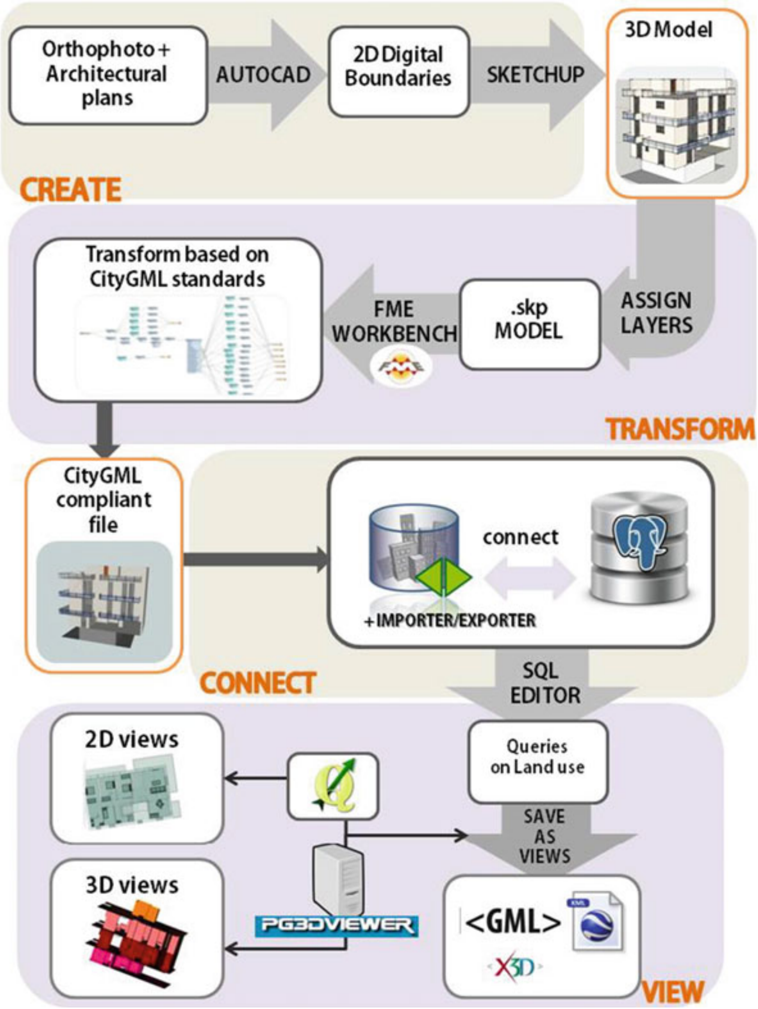


Fig. 1 Workflow

3. SketchUp can also be used to create large pieces of equipment for strictly visual purposes in various BIM software; for example SketchUp is compatible with programs such as Revit. Furthermore, connecting to the 3D SketchUp Warehouse and exploiting component libraries (such as furniture) offers a more realistic and professional model visualisation (Figs. 2 and 3).

Fig. 2 Building model designed using SketchUp Pro

4.3 Transformation via FME

FME (Feature Manipulation Engine) is a transformation engine produced by Safe Software Inc. and helps users convert data (both geometry and attributes) into several formats. FME is compatible to CityGML up to version 2.0 and includes key transformers for CityGML such as Attribute Creator and Geometry Property Setter as shown in Fig. 4. The SketchUp model can be processed within FME. The main steps for compiling CityGML from the .skp file were the addition of CityGML specific attributes (for instance, gml_id,) and geometry properties. CityGML entities need to be interrelated based on the standard's specifications and the appropriate geometry must be applied to all entities (e.g. Wallsurface, Door, etc.). For example, the corresponding CityGML role for all kinds of surfaces is defined as "boundedby". The "Opening" role applies for doors and windows while "intbuildinginstallation" applies for stairs and finally "building furniture" applies for furniture. Surfaces were assigned to lod4multisurface, doors and windows were assigned to lod3 and stairs and furniture were assigned to lod4geometry. After compilation of the preferable format using FME Workbench, it is possible to optimize and represent the output in the FME Data Inspector.

4.3.1 Modeling Using Safe Software FME

Five feature types:Room were defined, each one corresponding to each building's floor. Land use was assigned to each feature type: Room (defined by 4digit codes)

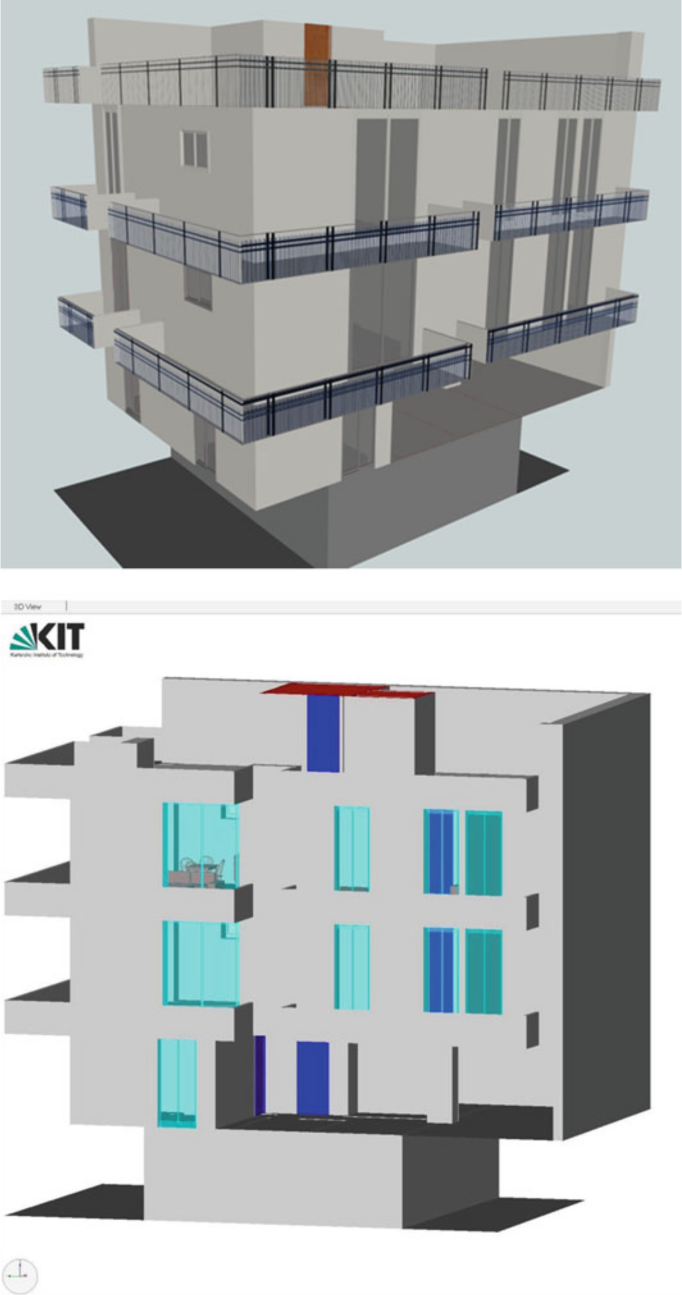


Fig. 3 *Up* 3D building model in FME Inspector *Down* 3D building model in FZK Viewer

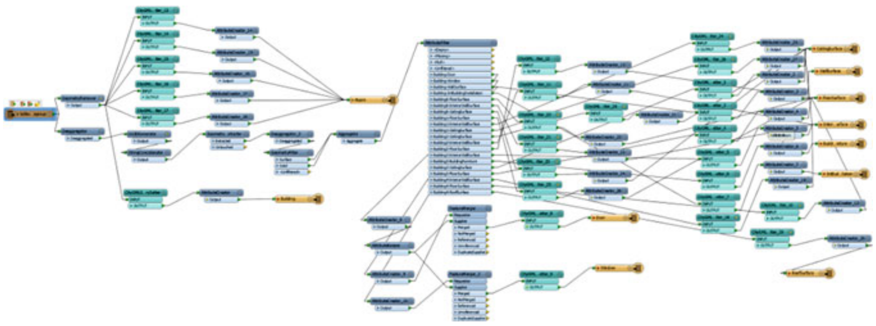


Fig. 4 Transformation via Workbench

based on the CityGML standard. Room geometries were defined by the surfaces: ceilingsurface, floorsurface, interiorwallsurface. Features' restructuring in FME was achieved through various transformers. Within the case study examined in this paper the following transformers were exploited:

1. De-Aggregator: De-aggregator transformer allows classification of each layer to its relative feature type (e.g. wallsurface) through separation of the 3D plan to its constituent parts. Nevertheless, openings (doors and windows) were not decomposed in parts, since this action would considerably increase the data size.
2. Attribute filter: Using attribute filter transformer allows for manual SketchUp Pro layers' insertion. Layer names in SketchUp pro, are required to match those of the attribute filter layer.
3. Attribute creator: Attribute creator is a table generating attribute features. Entities definitions to CityGML database require creation of a new attribute gml_name, aiming to generate a detailed object's description. Association between the building and its constituent building parts, within the case study examined, was achieved by creating a gml_parent_id for each room.
4. Citygml_geometrysetter: Using this transformer allows assigning each feature's Level of Detail (LoD), from LoD2 to LoD4, along with its geometry type, (e.g. multisurface, solid, etc.) and feature role (such as opening, boundedby, building installation, etc.).

In the final CityGML file, each object was classified accordingly as wallsurface, buildinginstallation, etc., with their corresponding geometries as defined in CityGML. These components were finally integrated within feature module: building.

4.4 Database Creation

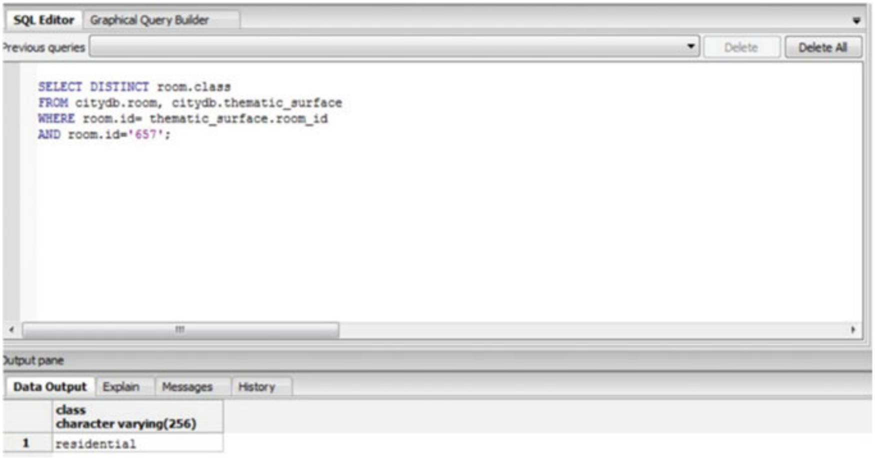
The database (postgreSQL) was structured according to the 3DcityDB. Furthermore, the spatial extension of postGIS was inserted in postgreSQL. The database was processed via the importer/exporter software which enables the CityGML file import in the database. The comprehension of the CityGML conceptual model is crucial; that is the accurate data analysis (meaning that the relations among the different entities need to be identified) enables execution of correct SQL queries on the database.

4.5 Querying

Queries utilize geometry data types such as points, lines and polygons and consider their spatial relationships. There are numerous examples for using queries in 3D modeling applications such as queries required for 3D display applied e.g. to computer games or queries providing options for spatial analysis in BIM data.

4.5.1 Visualization

Queries related to land use or the building's parts were executed within SQL editor. The result of the query that is posed as "find the land use corresponding to the third floor" in natural language, can be seen below (Fig. 5). The rooms' geometries



```sql
SELECT DISTINCT room.class
FROM citydb.room, citydb.thematic_surface
WHERE room.id= thematic_surface.room_id
AND room.id='657';
```

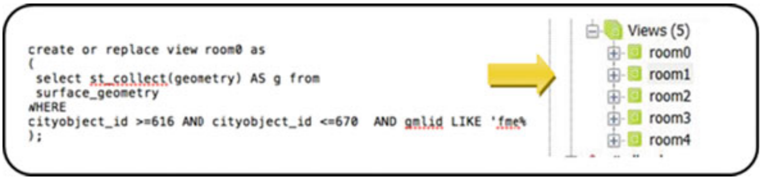
```
  class
  character varying(256)
1 residential
```

Fig. 5 Attribute query

weren't generated via FME (skp file's transformation to CityGML) but the views comprising each room's geometry were generated through postGIS.

The next SQL paradigm (Fig. 6) exports views of the executed query, meaning it exports each building floor's view (tagged as room) distinctively. The geometries can be exported in various formats such as GML, KML, X3D.

It is possible to visualize the queries' views both in 2D and 3D. Concerning the 2D approach the database was connected to QGIS, which is also open source. The pictures below (Fig. 7) present the third floor's 2D views applying different



```
create or replace view room0 as
(
 select st_collect(geometry) AS g from
 surface_geometry
WHERE
cityobject_id >=616 AND cityobject_id <=670  AND gmlid LIKE 'fme%
);
```

Fig. 6 Exported view of the semantic query

Fig. 7 2nd floor 2D views in different transparency levels

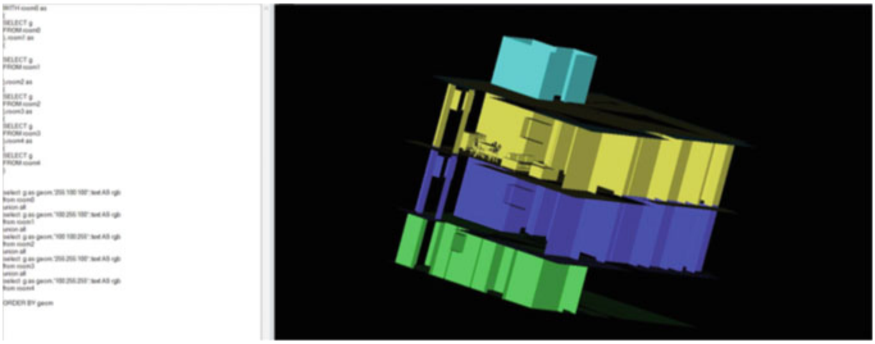


Fig. 8 3D building visualization using pg3dviewer

transparency values. All entities of the third floor (e.g. furniture) are visible because their corresponding geometry was selected from the table surface_geometry.

Concerning the 3D approach, the building was visualised through pg3DViewer (compliant with database), applying color grading per room (Fig. 8).

5 Discussion and Conclusions

The variety of solutions and different methodologies employed for the integration of semantics into 3D city models or the semantic enrichment of distinct building models, reveals the present need to define in detail and in a higher dimensionality all thematic areas or concepts within an urban environment. The various proposals examined in this paper offer pragmatic solutions for modeling urban areas within a semantic context. Current trends based on 3D models' semantics refer to the wider thematic areas of urban development, energy management, property taxation, indoor navigation, natural disasters simulation, cultural heritage registration and military operations. More specifically for this research project:

- Sketchup is a solid tool for architectural or land uses, but not that effective in environmental uses. FME is a flexible program, supporting CityGML adequately, providing transformation to CityGML format rapidly. The entities' information, such as their geometry and interrelations are maintained in high level of semantics during the translation.
- The described procedure can be characterized as cost-efficient. The postgreSQL database, the postGIS extension and the pg3DViewer, are all open-source software, while FME offers an educational license. In terms of pre- based knowledge, the user should comprehend the CityGML structure before performing analysis. Also, a basic knowledge of databases is necessary to define the tables' connections, while basic knowledge of SQL is needed for the syntax of the queries.
- An issue still under investigation, is the limitations in adding solid geometry in the feature type:Room through the FME translation. The issue is solved manually, through the database, by creating 5 views with their including geometry that matches the 5 feature types: Room.
- According to CityGML standard, land use features are applied to volumetric spaces such as buildings or rooms instead of surface objects (e.g. groundsurface, wallsurface etc.). Feature type: Room was selected in this case study, alternatively to feature type:Building in order to assign different land use attributes to each floor, instead of the whole building. Separation of the building to its constituent floors through generation of different buildings including each of the floors assigned with different land uses was also not qualified in order to ensure indivisibility of the building object.

A further extension of this project might include the building block. The surrounding buildings could be designed as well and could be assigned with further information, such as value and view. Through a few modifications, it is feasible to perform analysis related to land use to the whole building block.

The next step would be the import, for example into Google Earth, for the whole block. The user will have the ability to right-click on every building and read the information included.

The compatibility between SketchUp and BIM programs will be investigated. Adding a building with precise architectural information into the IFC for example to further add mechanical parts, makes it a solid file for both cadastral and environmental purposes.

References

Aien, A., Kalantari, M., Rajabifard, A., Williamson, I., & Wallace, J. (2013). Towards integration of 3D legal and physical objects in cadastral data models. *Land Use Policy, 35*, 140–154.

Balogun, A. L., Matori, A. N., & Lawal, D. U. (2011). Geovisualization of sub-surface pipelines: A 3D approach. *Modern Applied Science, 5*(4), p158.

Biljecki, F., Zhaoa, J., Stoter, J., & Ledouxa, H. (2013, September). Revisiting the concept of level of detail in 3D city modelling. In *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Proceedings of the ISPRS 8th 3D GeoInfo Conference & WG II/2 Workshop* (pp. 63–74).

Billen, R., Zaki, C. E., Servières, M., Moreau, G., & Hallot, P. (2012). *Developing an ontology of space: application to 3D city modeling*. Usage, usability, and utility of 3D city models.

Breunig, M., & Zlatanova, S. (2011). 3D geo-database research: Retrospective and future directions. *Computers & Geosciences, 37*(7), 791–803.

Brown, G., Nagel, C., Zlatanova, S., & Kolbe, T. H. (2013). Modelling 3D topographic space against indoor navigation requirements. In *Progress and New Trends in 3D Geoinformation Sciences* [pp. 1- 22]. Springer Berlin Heidelberg.

Çağdaş, V. (2013). An application domain extension to citygml for immovable property taxation: A Turkish case study. *International Journal of Applied Earth Observation and Geoinformation, 21*, 545–555.

Cheng, J., Deng, Y., & Du, Q. (2013). Mapping between BIM models And 3D GIS city models of different levels of detail. In N. Dawood & M. Kassem (Eds.), *Proceedings of the 13th International Conference on Construction Applications of Virtual Reality*, 30–31 October 2013, London, UK.

de Laat, R., & van Berlo, L. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In *Advances in 3D Geo-information sciences* (pp. 211–225). Berlin: Springer.

de Vries, T., & Zlatanova, S. (2011). 3D intelligent cities. *GEO Informatics, 14*(3), 6–8.

Diakité, A. A., Damiand, G., & Gesquière, G. (2014). Automatic semantic labelling of 3D buildings based on geometric and topological information. In *Proceedings of 9th International 3D GeoInfo Conference (3D GeoInfo)*, Nov. 2014, Dubai. United Arab Emirates. Karlsruhe Institute of Technology, 3DGeoInfo conference proceedings series. <http://nbnresolving.org/urn:nbn:de:swb:90-438043>. <hal-01122533>.

Dimopoulou, E., & Elia, E. (2012). Legal aspects of 3D property rights, restrictions and responsibilities in Greece and Cyprus. In *Proceedings of the 3rd International Workshop on 3D Cadastres, Developments and Practices* (pp. 25–26).

Dimopoulou, E., Kitsakis, D., & Tsiliakou, E. (2014). Investigating correlation between legal and physical property: possibilities and constraints. In *Proceedings of SPIE 9535, Third International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2015)*, 95350A 19 June 2015. doi:10.1117/12.2192572.

Dimopoulou, E., Tsiliakou, E., Kosti, V., Floros, G., & Labropoulos, T. (2014). Investigating integration possibilities between 3D modeling techniques. In *Proceedings of 9th International 3D GeoInfo Conference (3D GeoInfo), Nov. 2014*, Dubai. United Arab Emirates.

Donkers, S. (2013). Automatic generation of CityGML LoD3 building models from IFC models. MSc thesis, Delft University of Technology, Department of GIS Technology, OTB Research Institute for the Built Environment.

El-Mekawy, M. (2010). *Integrating BIM and GIS for 3D city modelling: The case of IFC and CityGML.*

El-Mekawy, M., Östman, A., & Shahzad, K. (2011). Towards interoperating cityGML and IFC building models: A unified model based approach. In *Advances in 3D Geo-information sciences* (pp. 73–93). Berlin: Springer.

Frédéricque, B., Raymond, K., & Van Prooijen, K. (2011, May). 3D GIS as applied to cadastre–A benchmark of today's capabilities. In *FIG Working Week.*

Geiger, A., Benner, J., & Haefele, K. H. (2014). Generalization of 3D IFC building models. In M. Breunig, M. Al-Doori, E. Butwilowski, P. V. Kuper, J. Benner, & Haefele, K. H (Eds.), *3D Geoinformation sciences, The Selected papers of the 3D GeoInfo 2014* (pp. 19-35). Berlin: Springer.

Góźdź, K., Pachelski, W., & Poland, P. V. (2014). The possibilities of using CityGML for 3D representation of buildings in the cadastre. In *Proceedings 4th International Workshop on 3D Cadastres*, 9–11 Nov 2014, Dubai, United Arab Emirates. International Federation of Surveyors (FIG).

Gröger, G., & Plümer, L. (2009). Updating 3D City models—How to preserve geometric-topological consistency. In W. G. Aref, D. Agrawal, M. F. Mokbel, C.T. Lu, C. Shahabi, P. Scheuermann, et al. [Eds.], Proceedings of the 17th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (ACM SIGSPATIAL GIS 2009) Seattle, Washington, 4–6 Nov 2009, ACM Press, New York, pp. 536–539.

Gröger, G., & Plümer, L. (2012). CityGML–Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing, 71*, 12–33.

Guo, R., Li, L., Ying, S., Luo, P., He, B., & Jiang, R. (2013). Developing a 3D cadastre for the administration of urban land use: A case study of Shenzhen, China. *Computers, Environment and Urban Systems, 40*, 46–55.

Guo, R., Yu, C., He, B., Zhao, Z., Li, L., & Ying, S. (2012). Logical design and implementation of the data model for 3D cadastre in China. In *Proceedings 3rd International Workshop 3D Cadastres: Developments and Practices* (pp. 113–136).

Hu, M. (2008). Semantic based LoD models of 3D house property. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. XXXVII, Part B2), Beijing.

Isikdag, U., & Zlatanova. S. (2009). Towards defining a framework for automatic generation of buildings in CityGML using building information models. In J. Lee, & S. Zlatanova (Eds.), *3D geoinformation sciences* (pp. 79–96). Berlin: Springer.

Isikdag, U., Horhammer, M., Zlatanova, S., Kathmann, R., & van Oosterom, P. J. M. (2014). Semantically rich 3D building and cadastral models for valuation. In *Proceedings 4th International Workshop on 3D Cadastres*, 9–11 Nov 2014, Dubai, United Arab Emirates. International Federation of Surveyors [FIG].

Isikdag, U., Zlatanova, S., & Underwood, J. (2013). A BIM-oriented model for supporting indoor navigation requirements. *Computers, Environment and Urban Systems, 41*, 112–123. INSPIRE, D2.8.III.2 Data Specification on Buildings—Draft Technical Guidelines.

Jazayeri, I., Rajabifard, A., & Kalantari, M. (2014). A geometric and semantic evaluation of 3D data sourcing methods for land and property information. *Land Use Policy, 36*, 219–230.

Karki, S., McDougall, K., & Thompson, R. J. (2010). An overview of 3D Cadastre from a physical land parcel and a legal property object perspective. In *Proceedings of the XXIV FIG International Congress 2010: Facing the Challenges-Building the Capacity*, Sydney, 11–16 April 2010. FIG.

Kolbe, T. H. (2009). Representing and exchanging 3D city models with CityGML. In *3D geoinformation sciences* (pp. 15–31). Berlin: Springer.

Kolbe, T. H., & Plümer, L. (2004). Bridging the Gap between GIS and CAAD. *GIM International 2004, 18*(7).

Li, Y., & He, Z. (2008). 3D indoor navigation: A framework of combining BIM with 3D GIS. In *44th ISOCARP Congress*.

Löwner, M. O., Benner, J., Gröger, G., & Häfele, K. H. (2013). New concepts for structuring 3D city models–an extended level of detail concept for CityGML buildings. In *Computational Science and Its Applications–ICCSA 2013* (pp. 466–480). Berlin: Springer.

Nagel. C., Stadler, A., & Kolbe, T. (2009). Conceptual requirements for the automatic reconstruction of building information models from uninterpreted 3D models. In *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* (Vol. XXXIV, Part XXX).

Rönsdorff, C., Wilson, D., & Stoter, J. E. (2011). Integration of land administration domain model with CityGML for 3D Cadastre. In *Proceedings 4th International Workshop on 3D Cadastres, 9-11 November 2014*, Dubai, United Arab Emirates. International Federation of Surveyors [FIG].

Shojaei, D., Kalantari, M., Bishop, I. D., Rajabifard, A., & Aien, A. (2013). Visualization requirements for 3D cadastral systems. *Computers, Environment and Urban Systems, 41*, 39–54.

Shojaei, D., Rajabifard, A., Kalantari Soltanieh, S. A. E. I. D., Bishop, I., & Aien, A. (2012). *Development of a 3D ePlan/LandXML visualisation system in Australia*.

Shojaei, D., Rajabifard, A., Kalantari, M., Bishop, I. D., & Aien, A. (2014). Design and development of a web-based 3D cadastral visualisation prototype.*International Journal of Digital Earth*, [ahead-of-print], 1–20.

Stadler, A., & Kolbe, T. H. (2007). Spatio-semantic coherence in the integration of 3D city models. In *Proceedings of the 5th International Symposium on Spatial Data Quality, Enschede*.

Stadler, A., Nagel, C., König, G., & Kolbe, T. H. (2009). Making interoperability persistent: A 3D geo database based on CityGML. In *3D Geo-information sciences* (pp. 175–192). Berlin: Springer.

Van Berlo, L., & de Laat, R. (2009). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In: T. Kolbe, G. Konig, & C. Nagel (Eds.), *3D Geo-information sciences*. Lecture Notes in Geoinformation and Cartography (pp. 211–225). Berlin: Springer.

van Oosterom, P. (2013). Research and development in 3D cadastres. *Computers, Environment and Urban Systems, 40*, 1–6.

Xiong, X., & Huber, D. (2013). Using context to create semantic 3D models of indoor environments. In *Proceedings of the British Machine Vision Conference*, BMVA Press (2010), pp. 45.1–45.11. http://dx.doi.org/10.5244/C.24.45.

Ying, S., Guo, R., Li, L., & He, B. (2012). Application of 3D GIS to 3D cadastre in urban environment. In *3rd International Workshop on 3D Cadastres: Developments and Practices*, Shenzhen, China (pp. 25–26).

Ying, S., Li, L., & Guo, R. (2011). Building 3D cadastral system based on 2D survey plans with SketchUp. *Geo-spatial Information Science, 14*(2), 129–136.

Zhu, Q., Zhao, J., Du, Z., Zhang, Y., Xu, W., Ding, Y., et al. (2011). Towards semantic 3D city modeling and visual explorations. In T. Kolbe, G. Konig, & C. Nagel (Eds.), *3D Geo-information sciences* (pp. 275–294). Berlin: Springer.

Zlatanova, S., Stoter, J., & Isikdag, U. (2012, June). Standards for exchange and storage of 3D information: Challenges and opportunities for emergency response. In *Proceedings of the Fourth International Conference on Cartography and GIS, Albena, Bulgaria* (pp. 17–28).