Student thesis series INES nr 486

3D cadastral visualization and integration of CityGML3.0 with Land Administration Domain Model

Siying Mi

2019
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Siying Mi (2019).

3D cadastral visualization and integration of CityGML3.0 with Land Administration Domain Model

Master degree thesis, 30 credits in *Geomatics*
Department of Physical Geography and Ecosystem Science, Lund University

Level: Master of Science (MSc)

Course duration: *January* 2019 until *June* 2019

Disclaimer

This document describes work undertaken as part of a program of study at the University of Lund. All views and opinions expressed herein remain the sole responsibility of the author, and do not necessarily represent those of the institute.

3D cadastral visualization and integration of CityGML3.0 with Land Administration Domain Model

---

Siying Mi

Master thesis, 30 credits, in *Geomatics*

Supervisor:
Per-Ola Olsson
Department of Physical Geography and Ecosystem Science, Lund University

Exam committee:
Helena Borgqvist and Weiming Huang
Department of Physical Geography and Ecosystem Science, Lund University

Acknowledgements

First, I would like to thank my supervisor Per-Ola Olsson from the Department of Physical Geography and Ecosystem Science at Lund University. Throughout my master thesis project, he provided me with constructive suggestions, technical supports, and outstanding encouragement whenever I needed. Moreover, I would like to thank Lars Harrie for his critical feedback and guidance. He used his expertise in BIM and CityGML to help me figure problems out. Finally, I want to thank my family and friends for their care and support. Without their companionship and encouragement I would not have the courage and confidence to complete my master's degree abroad.

Abstract

During the last years, virtual 3D city models have been widely used in application fields such as urban planning, environment simulations, and disaster management. With the development of high-rise buildings and the increasing densely built-up areas, an increasing number of authorities and companies have shown interest in integrating 3D city models with the cadastre. This is because on one hand, the integration can improve the visualization of cadastres and promote the cadastral management. On the other hand, it can enrich the cadastral information in 3D city models and further facilitate spatial analysis. As one of the important standards used in 3D city models, part of CityGML3.0 has been published so far; hence this study is one of the first to integrate CityGML3.0 with the cadastral data model.

Considering the challenges of cadastral management, the purpose of this study is threefold: (1) representing physical building objects in CityGML3.0, (2) visualizing legal spaces in 3D models, and (3) validating if it is viable to integrate CityGML3.0 with Land Administration Domain Model (LADM) effectively. For this purpose, an integrated approach was developed, which can also be separated into three parts. Since the format of original data is Industry Foundation Classes (IFC), converting physical building objects from IFC to CityGML3.0 was taken as the first step in this method. And then, legal boundaries were extruded into legal spaces by using a python script and built-in functions in FME Workbench. Lastly, the integration of CityGML3.0 and LADM was implemented. In this approach, a prerequisite was that legal boundaries in the Building Information Model (BIM) should have been connected with physical objects accurately.

Based on the proposed method, three results can be derived: (1) transformed building models in CityGML3.0, (2) extruded legal spaces, as well as (3) an attribute table integrated CityGML3.0 with LADM. Among them, the first result suggests that the differences of a building in LoD2 between CityGML2.0 and CityGML3.0 are the definition of feature types and the hierarchy of semantic structures other than the geometrical shapes. And the second result illustrates that it is possible to visualize legal spaces in 3D city models, as long as the legal boundaries can be combined with physical objects in the BIM model. As for the third result, it indicates that CityGML3.0 can be related to LADM without using any extension model. However some details still need to be validated in future as the final specification of CityGML3.0 has not been released.

Keywords: CityGML3.0, Cadastral information, Visualization, LADM, IFC

Table of Contents

List of Abbreviations

2D: 2 Dimensional

3D: 3 Dimensional

ADE: Application Domain Extension

AEC: Architecture, Engineering and Construction industry

BIM: Building Information Model

B-Rep: Boundary Representation

CityGML: City Geography Markup Language

GIS: Geographic Information Systems

GML: Geography Markup Language

IFC: Industry Foundation Classes

LADM: Land Administration Domain Model

LoD: Level of Detail

OGC: Open Geospatial Consortium

UML: Unified Modeling Language

XML: Extensible Markup Language

XSD: XML Schema Definition

1. Introduction

1.1 Background

In Sweden, all land is subdivided into real property units and recorded on the real property register (Lantmäteriet, 2011). Swedish real property register includes two parts that are cadastral index map in 2D and the land register (El-Mekawy et al. 2015). With the development of high-rise buildings and the increasing densely built-up areas, the complexity of ownership spaces with multi-storey buildings pose a challenge to 2D index map (Larsson et al. 2018). In addition, even if the registration of 3D properties has been conducted in Sweden for several years, the 3D cadastral information such as the vertical extension is still registered in documentation with a brief description of height, e.g. between level “CA” +31.2 meters and level “CA” +55 meters on the construction drawing (El-Mekawy et al. 2015). Thus the efficiency for searching and managing cadastres has not been improved so far. In order to improve the visualization of cadastres and facilitate the 3D cadastral management, an increasing number of authorities and companies have shown interest in using building information models (BIM) and 3D city models to manage cadastral data. BIM is an intelligent 3D-model based process that has a great impact on architecture, engineering and construction (AEC) industry (Figure 1). Its highly detailed information of building objects can model physical space for 3D cadastres. In comparison to BIM, 3D city models pay more attention to represent landscapes and urban areas (Figure 2). This enables 3D city models to provide rich environmental information for the 3D cadastre for macro analysis.

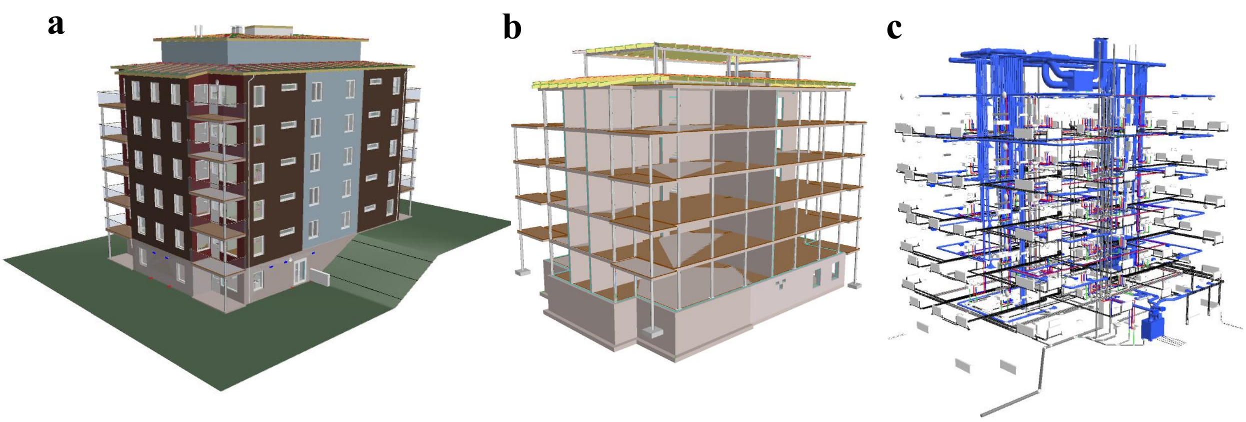


Figure 1. An example of a BIM model (a) that consists of basic building structures (b) and installations (c).

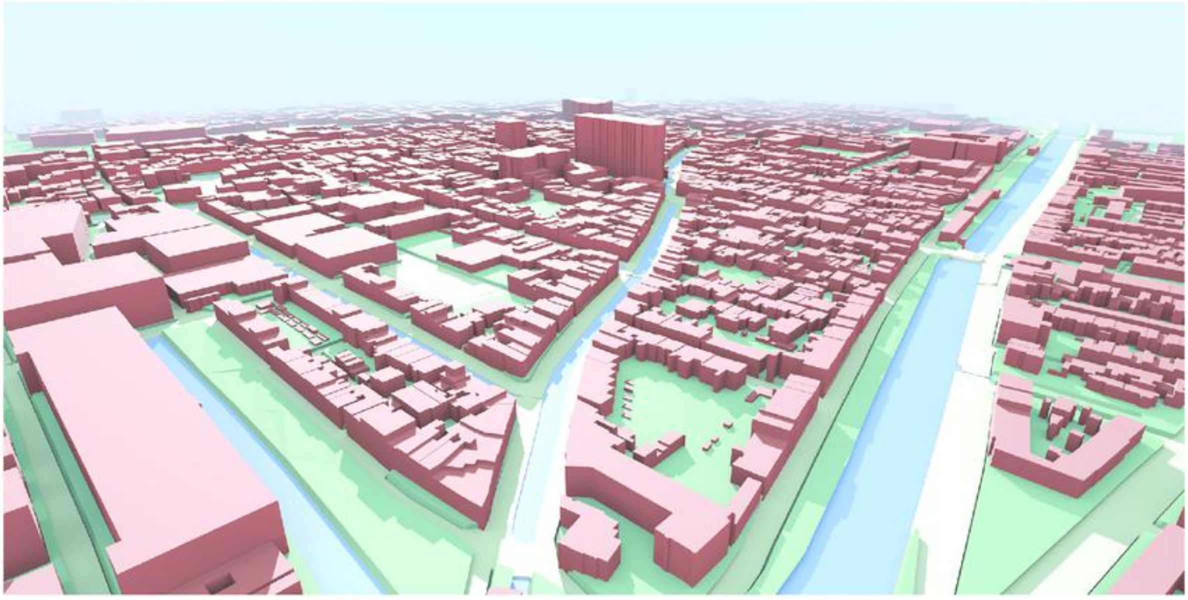


Figure 2. An example of 3D city models (Biljecki et al. 2016), licensed under Creative Common 4.0

However, combining BIM or 3D city models with 3D cadastre is challenging. The first reason is that different definitions of buildings and building parts among various standards hinder the data integration. In a broad sense, a building is an enclosed construction used for the shelter of humans, animals or things. As a subdivision of buildings into building parts, it can be homogeneous related to its physical, functional or temporal aspects (INSPIRE 2014). Industry Foundation Classes (IFC) is one of the standards following this definition. IFC is a prominent standard used in BIM that describes a building with respect to its geometric and semantic properties by using physical spaces such as rooms, corridors, as well as walls. Another representative for using physical spaces is City Geography Markup Language (CityGML). CityGML is an important specification used in 3D city models that defines classes and relations for the most relevant topographic objects in urban area (Löwner et al. 2016). Differing from IFC and CityGML, an international cadastral specification, Land Administration Domain Model (LADM) is more focused on legal spaces. LADM is one of the conceptual models used for recording and managing land administration data. It describes both semantic and spatial information associated with rights, responsibilities, and restrictions (RRRs) affecting the land, buildings, and airspaces (ISO19152, 2012).

Apart from the different definitions, the gap between theoretical researches and practical implements should be noticed. Even though, a large literature has focused on the 3D cadastral registration and standards' integration like introducing approaches for upgrading original cadastral information into 3D cadastral database (Sucaya 2009; Rajabifard et al. 2018) or combining legal spaces with physical objects (Aien et al. 2015; Atazadeh et al. 2016; El-Mekawy et al. 2015), how to implement the theoretical knowledge in existing or experimental 3D cadastral systems has not been studied much so far. Consequently, not only the land administration, but other application fields such as urban planning and real estate industry will benefit from it if these problems mentioned above can be addressed.

1.2 Research questions and approach

According to the format of source data and the status of cadastral management, three specific research questions are formulated:

- Can physical building objects be represented in CityGML3.0?

- Can legal spaces be visualized in 3D models?

- Is it viable to integrate CityGML3.0 with LADM without using any application domain extension (ADE)?

For these questions, an integrated approach was developed that can also be separated into three parts: 1) converting physical objects from IFC to CityGML3.0, 2) extruding legal boundaries into legal spaces, as well as 3) complementing the legal information in CityGML3.0 with LADM. Since the two vital elements for representing 3D urban environment are building information and its integration with geospatial data (Isikdag and Zlatanova 2009), the specific concern in this study is given to buildings and building objects. Thus some other environmental objects like roads, tunnels and bridges will not be involved.

The current employed version of CityGML is still CityGML2.0 that was published in late 2011. Even if the CityGML3.0 has not been completely released so far, the new conceptual model and the XML schema derived from the Unified Modeling Language (UML) model can be used. Based on the new schema and the published UML diagrams, this project attempted to transform IFC to CityGML3.0 and integrate CityGML3.0 with LADM.

2. Literature Review

This chapter starts by introducing the definition of buildings and building objects among diverse specifications. Then the approaches towards integration of IFC and CityGML2.0, and combing CityGML2.0 with LADM are presented.

2.1 Definition of buildings and building parts among different standards

IFC, CityGML and LADM are three data specifications applied to BIM, 3D city models, and legal information field. Even though both IFC and CityGML define the building and building objects from a physical aspect, it is still difficult to convert them from each other completely as the definition of building objects between them are different. Moreover, since LADM models cadastral information from legal spaces, identifying the various definitions of building objects and finding the common relationship among space concepts are imperative.

2.1.1 Industry Foundation Classes (IFC)

As a building model developed within AEC industry, BIM contains rich details of building structures, elements, spaces, schedules, and other aspects of a construction project. One of the most important specifications used in BIM is IFC that defines the data required for buildings over their life circle. As an open standard, IFC enables multiple data to be exchanged and shared among AEC software applications (ISO 16739, 2013). According to the specification developed by buildingSMART, the hierarchy of IFC entities is shown below (Figure 3).

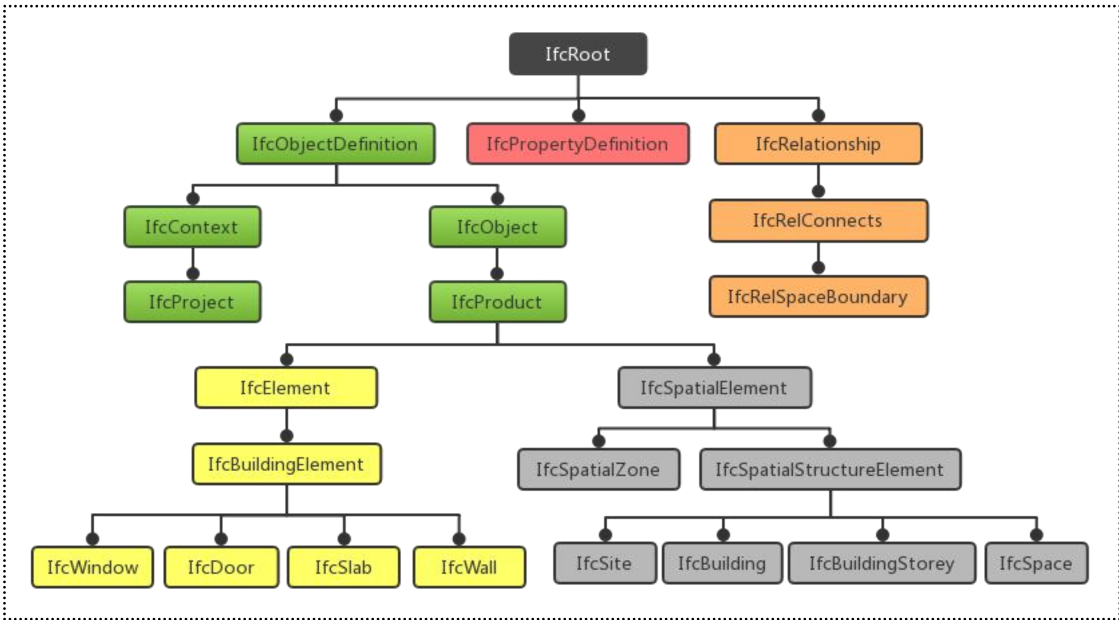


Figure 3. Hierarchy of IFC entities
(Source: http://www.buildingsmart-tech.org/ifc/IFC4x1/final/html/)

As shown in Figure 3, *IfcRoot* is the most abstract class for all entity definitions in IFC. Its three components *IfcObjectDefinition*, *IfcPropertyDefinition*, and *IfcRelationship* generalize the physically tangible items, characteristics of objects, and relationships among objects, respectively. As one of the subtypes of *IfcObjectDefinition*, *IfcProduct* not only defines the physical elements from geometric and spatial aspects but also describes non-physical items. Its components *IfcElement* and *IfcSpatialElement* are mainly used to represent objects from the geometric aspect and the spatial context, respectively.

From the geometric aspect, *IfcElement* defines all existing objects of a building. Its subtype *IfcBuildingElement* represents all elements that participate in a building system such as windows, doors, slabs, and walls. These elements in IFC are all represented by solid geometries. From the spatial aspect, *IfcSpatialElement* represents spatial structures or spatial zones in a building project. Its subtype *IfcSpatialStructureElement* is the generalization of all spatial elements that might be used to define a spatial structure. Furthermore, *IfcSpatialStructureElement* can be decomposed into four components: *IfcBuilding*, *IfcBuildingStorey*, *IfcSite*, and *IfcSpace.* Among them, *IfcBuilding* is defined as a structure that provides shelter for its occupants in IFC (ISO 16739, 2013). *IfcBuildingStorey* represents a horizontal aggregation of spaces that are vertically bound. According to the semantic definition of *IfcBuildingStorey*, a storey can not only span over several connected storeys, but can also be decomposed in several horizontal parts. As for the *IfcSpace*, it is a suitable entity for modelling the spatial extent of legal spaces inside buildings (Atazadeh et al. 2017). In addition to *IfcObjectDefinition* and *IfcPropertyDefinition*, *IfcRelationship* plays an important role in connecting BIM with 3D cadastres. Since its subclass *IfcRelSpaceBoundary* provides the semantic linkage between the physical elements and spaces, the boundaries defined in LADM can be connected with physical elements by this way.

2.1.2 City Geography Markup Language (CityGML)

Geographic Information System (GIS) is a tool for visualizing information from a macro perspective as it stores, manipulates, and analyzes all types of geospatial data rather than a single building in a detail view. During recent years, 3D GIS has been widely used in application fields with the development of visualization techniques and software improved. As an open standard used in 3D GIS, CityGML defines the classes and relations for the relevant topographic objects in cities with regard to their geometrical, topological, semantic, and appearance properties (Gröger, 2012). Differing from IFC, objects defined in CityGML are represented by using boundary representation (B-Rep) that describes an object with the predefined primitives such as points, edges, faces, and volume (Abdul-Rahman and Pilouk, 2007).

A new version of CityGML is CityGML3.0 that has not been released completely. According to the description of new conceptual model, CityGML3.0 brings a number of improvements, extensions, and new functionalities. Among them, the alterations of levels-of-detail (LoD) and the changes of the core module are two important improvements related to this project (Kolbe and Kutzner, 2018). These two alterations are explained in detail below.

In CityGML3.0, all objects can be represented in up to four various, well-defined LoDs, which are different from the LoDs in CityGML2.0. In current version, there are 5 LoDs from LoD0 to LoD4, in which only LoD4 contains the interior design of the building. However, the LoD4 will be replaced by LoD0 to LoD3 for exterior and indoor objects in CityGML3.0 and all feature types can be represented in each LoD. In principle, the definitions for LoD0 to LoD3 are identical to the definitions in CityGML2.0 (Löwner et al. 2016). A major difference is that the interior of objects can also be expressed in different LoDs 0-3. And it is even possible to model the outside shell of a building in LoD2 while representing the interior structure in LoD2 or 3. Another improvement related to this project is the core model. CityGML consists of two components that are the core model and thematic extension modules, in which core model defines the basic concepts and components of the CityGML data model and thematic extension modules define the specific thematic field of 3D city models based on the core module. Figure 4 shows UML diagram of the Space concepts that is one of the parts of the new core module, where all spatial representations are rephrased based on the *AbstractSpace* and the *AbstractSpaceBoundary* in CityGML3.0 rather than associated with geometry classes directly. This to some extent simplifies the geometry handling of CityGML for software developers.

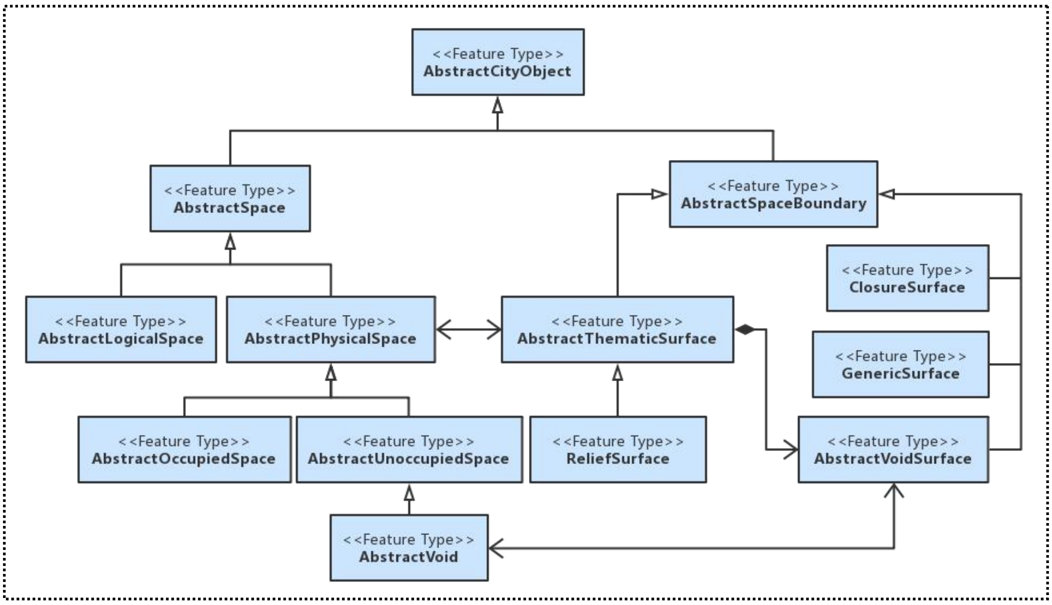


Figure 4. UML diagram of the Space concept in CityGML3.0

AbstractSpace in CityGML3.0 can be divided into two subclasses, *AbstractPhysicalSpace* and *AbstractLogicalSpace*. Figure 5 shows one of the thematic modules named building module in CityGML3.0 that allows the representation of thematic and spatial aspects of buildings, building parts, building installations, and interior building structures in 4 levels of detail. According to the classification of *AbstractSpace*, classes in the building model are discussed from the physical aspect and the logical aspect.

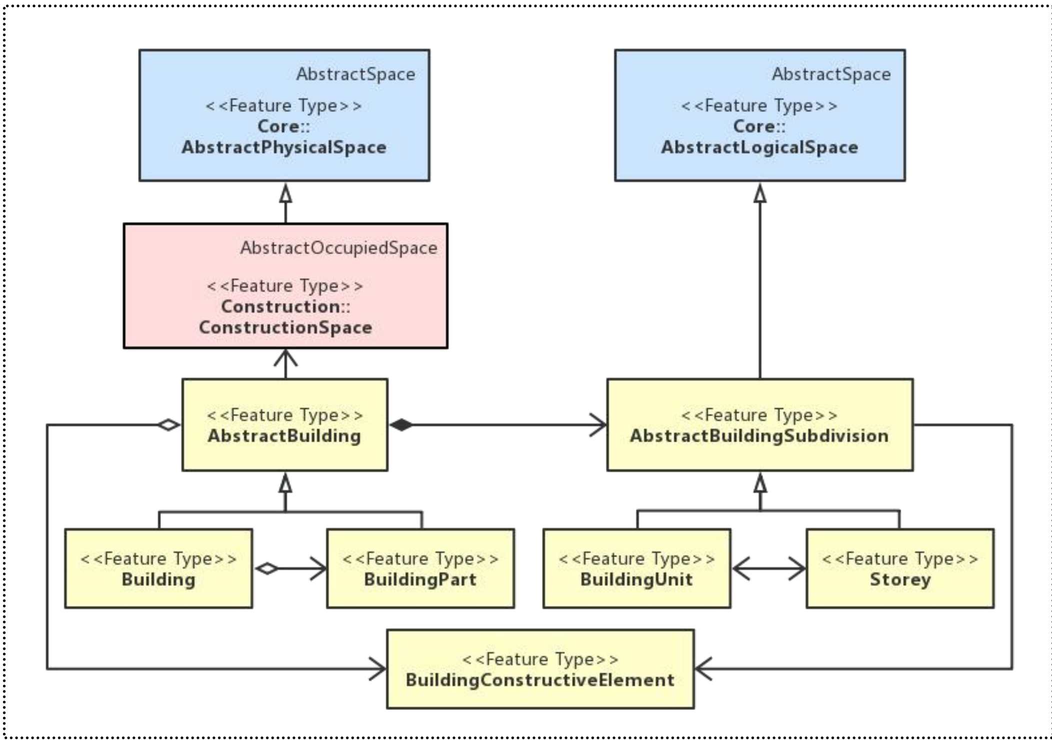


Figure 5. UML diagram of the Building module in CityGML3.0

From physical aspect, one of the essential subclasses of *AbstractPhysicalSpace* is *ConstructionSpace* from which *Building* and *BuildingPart* can be derived (Figure 5). The building in CityGML refers to a homogeneous part. If it composes of structural segments differing in the number of storeys or the roof type, the building should be separated into one or more additional building parts. From logical aspect, *AbstractLogicalSpace* is a new notion in CityGML3.0, which is used to model spaces that are not bounded by physical objects but defined according to legal considerations instead. *BuildingUnit* as one of the subclasses of *BuildingSubdivision*, it represents such as apartments and public spaces in buildings. Meanwhile, the *BuildingStoreys* is taken as a logical instead of physical subdivision because the boundaries of slabs are vaguely. With the *LogicalSpace* proposed in CityGML3.0, combining 3D city models with cadastral models based on the LADM will be efficient to a large extent.Another new class related to this project in the building module is *BuildingConstructiveElement*. It supports to map constructive elements from BIM datasets (e.g. *IfcWall*, *IfcRoof*, and *IfcSlab* etc.) to objects in 3D city models. These changes mentioned above satisfied the increasing need for better interoperability with other relevant specifications.

In addition to represent abstract spaces with new definitions, geometric boundaries in CityGML3.0 have also been restructured. As shown in Figure 6, the *RoofSurface*, *GroundSurface*, *FloorSurface*, and other objects' surfaces are all derived from *ConstructionSurface.* It is different from CityGML2.0 that groups these boundaries into *BoundarySurface*.

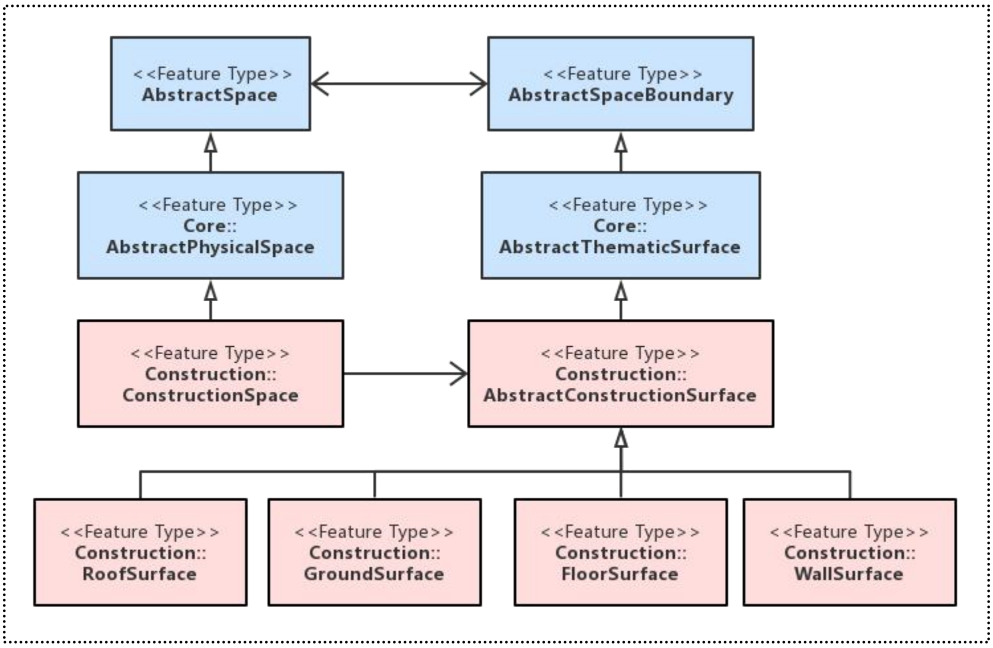


Figure 6. UML diagram of Surface boundaries in CityGML3.0

2.1.3 Land Administration Domain Model (LADM)

LADM is one of the conceptual models used for recording and managing land administration data. It describes both semantic and spatial information associated with RRRs affecting the land, buildings, and airspaces (ISO19152, 2012). With the increasing number of 3D cadastral information, LADM has been used widely around the world as it supports the increasing use of 3D representations of spatial units without adding any additional burden on the existing 2D representations. In comparison to other cadastral data models like ICSM Harmonized Data Model (Aien et al. 2013), LADM is an international standard developed and endorsed by the International Organization for Standardization (ISO). It provides a reference model for exchanging and sharing cadastral information between multiple systems in different organizations. Furthermore, advantages of LADM such as higher cost efficiency, and higher data qualities are all the reason why it can be adopted as the 3D cadastral model in this project.

LADM is organized into four packages: Party Package, Administrative Package, Spatial Unit Package, and Surveying and Representation Subpackage (ISO19152, 2012) (Figure 7). These four packages are related to parties, RRRs, spatial units, and geometries respectively.

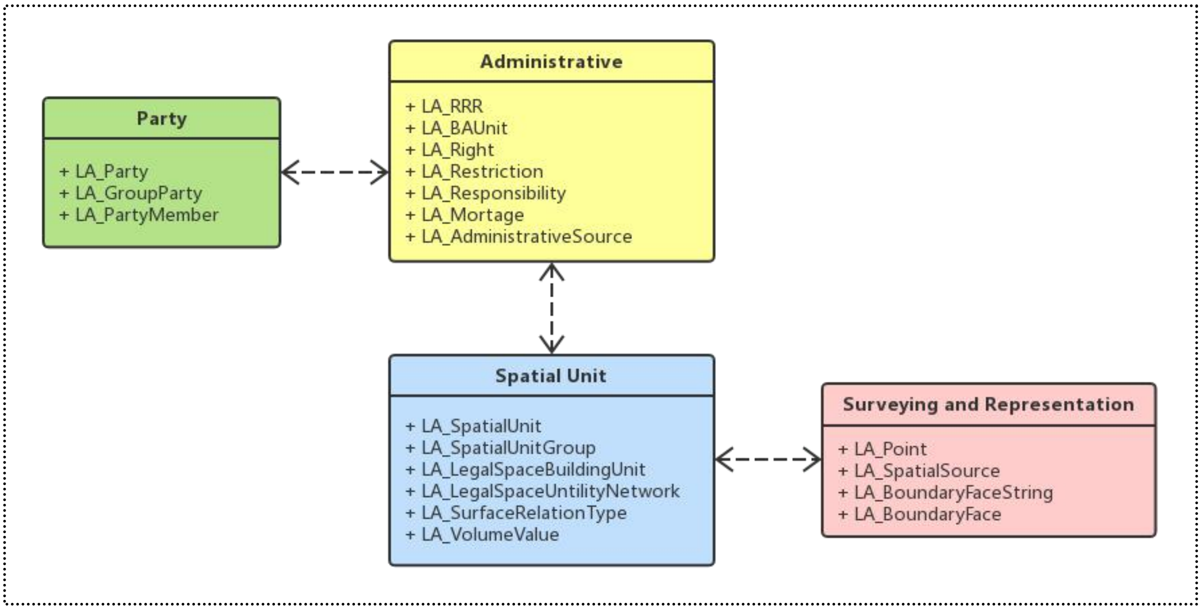


Figure 7. Four packages of Land Administration Domain Model (LADM)

LA_Party is the main class of the Party Package, which defines the actors such as people or organizations in the land administration. *LA_Party* can be associated to zero or more *LA_RRR* and *LA_BAUnit* that are two distinct classes belonging to Administrative Package. *LA_RRR* is used for modeling various types of RRRs in which the right may entitle an owner of a property, for certain purposes, to use a range of other owners' property or facility such as way, bridge, and lines. *LA_BAUnit* are basic administrative units that can be subdivided into several spatial units belonging to a party with the same *LA_RRRs* (Rajabifard et al. 2018). The definition of *LA_BAUnit* is similar to the *Building* class in CityGML. Figure 8 illustrates the relationship among *LA_Party*, *LA_Right*, *LA_BAUnit* and *LA_SpatialUnit* where the *LA_BAUnit* '10013' contains four spatial units and all of them belong to the party of 'FarmerPekka' with the same right.

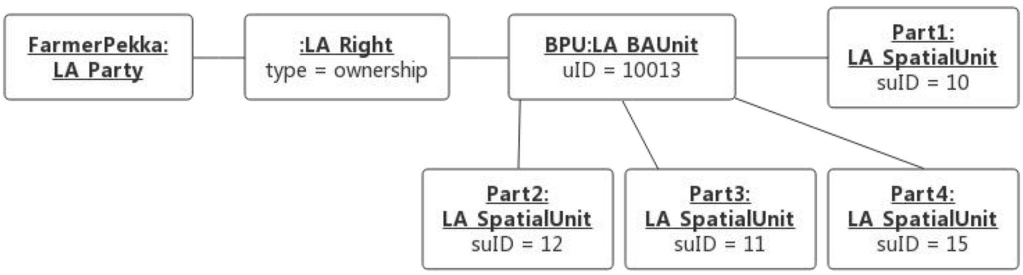


Figure 8. An example for showing relationships among basic property units.
(Modified from ISO 19152, 2012, annex C)

As for the Spatial Unit package, it includes two main classes related to this project, namely *LA_SpatialUnit* and *LA_LegalSpaceBuildingUnit*. *LA_SpatialUnit* contains various spatial representations of ownership interests and it can be grouped into *LA_SpatialUnitGroup* or split into sub spatial units. According to the function of spatial unit, *LA_SpatialUnit* can also be refined into two specializations that are *LA_LegalSpaceBuildingUnit* and *LA_LegalSpaceUtilityNetwork* (ISO19152, 2012). As a bridge to connect LADM with CityGML3.0, *LA_LegalSpaceBuildingUnit* defines the building unit with legal spaces that may be used for different purpose (e.g. living or commercial) where a building or a part of it is not equivalent to the physical separation (Rajabifard et al. 2018). Its attribute "BuildingUnitID" or "suID" inherited from *LA_SpatialUnit* can be used to link the legal space to physical elements.

The last package is Surveying and Representation Subpackage that are mainly used for surveying spatial sources and representing geometries and topology (Lemmen et al. 2015). The three key elements *LA_Point*, *LA_BoundaryFaceString*, and *LA_BoundaryFace* can be used for modeling boundaries of spatial units based on the different demanding. For example, 2D spatial units like land parcels and 3D spatial units like 3D properties can be represented by *LA_BoundaryFaceString* and *LA_BoundaryFace*, respectively (ISO19152, 2012). Figure 9 shows the relationship between this package and the Spatial Unit.

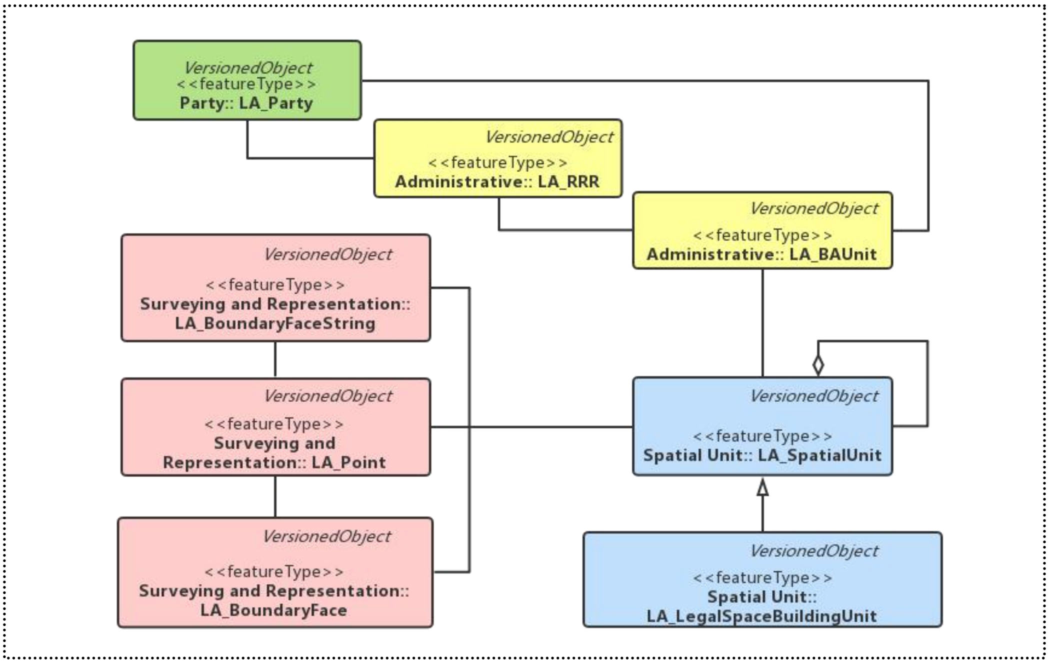


Figure 9. Relationships between different packages with their basic classes

2.2 Integration among different standards

2.2.1 Integration of IFC and CityGML2.0

Several studies have demonstrated that the BIM domain and the GIS domain have mutual needs of information from each other. On one hand, BIM data can be used as a source for updating building objects in 3D city models due to its rich geometric and semantic information of building (Isikdag and Zlatanova 2009; El-Mekawy 2010; Donkers et al. 2016).

On the other hand, geospatial information can broaden the application fields of BIM and facilitate urban management tasks (Isikdag and Zlatanova 2009).

However, there are some differences in the geometric and semantic representations between IFC and CityGML and these differences should be noticed during the integration. For the geometric representation, IFC represents the structural components of buildings with solid geometries rather than the B-Rep used in CityGML. For the semantic representation, IFC and CityGML using different expressions interpret objects and building parts. For example, the area within a building is defined as *IfcSpace* in IFC, while it is defined as *room* in CityGML. In addition, as IFC classifies elements in more detail than CityGML, some of them have to be composed into one feature class for integration, e.g. windows and doors in IFC are substituted by a feature class named openings in CityGML. Table 1 (Tang et al. 2014; Bengtsson and Grönkvist 2017) demonstrates more differences between IFC and CityGML.

Table 1. Different representations between CityGML and IFC

	CityGML	**IFC**
Geometry	Boundary representations.	Solid geometry, boundary, and Boolean operations.
Semantics	According to the LoDs. The higher the level, the more details are revealed.	Numerous architectural details.
Modeling appearance	Rich texture features.	Representation of texture is less in comparison with the material representation.
Representation scales	A broader presentation as it includes more environmental information	Only focuses on the single or multiple building objects.
Reference system	Based on the geodetic reference system and projection system.	Cartesian coordinate system.
Applications	Urban management and urban planning but also fields such as logistics and marketing.	Planning, construction and management of buildings or infrastructure.

The approaches for integration of IFC with CityGML can be classified into two categories. The first approach is suitable for converting IFC to lower LoDs, as it is focused on transforming outer building shells. Nagel and Kolbe (2007) proposed an algorithm for transforming IFC to LoD2 with CityGML. This algorithm is mainly based on the building footprint and the elevation of the BIM, in which building footprint was a simplified contour polygon derived from the element-based contour polygons for each building storey. And the composition of the resulting surface model was acquired from implementing the linear extrusion of storey footprints. Similarly, Olsson (2018) presented another method for converting BIM into LoD1-LoD2 with CityGML. This method aims at identifying all outer wall surfaces from the IFC model with a ray-casting method and then the new wall surfaces are extended in vertical direction to touch the upper roof surfaces.

In comparison to the first approach emphasized the geometry, the second one is more focused on the transformation of semantic information, where the integration of IFC with CityGML is implemented by creating extensions. El-Mekawy and Östman (2010) provided an intermediate model named Unified building model (UBM) that holds all concepts and relations existed in both IFC and CityGML. The advantage of this method is that the bi-direction conversion of data between two standards can minimize the data loss during the conversion for the exchange. As for the unidirectional method, Berlo and Laat (2011) developed a new CityGML extension named GeoBIM for integrating IFC semantics and properties, which was classified into two parts. The first part was extending the known CityGML object such as Rooms, Windows, and Doors with extra attributes from IFC. And the second part took the extra property such as the *AbstractBuilding* into account, where the new objects in CityGML were created. Tang et al. (2014) and Wang et al. (2018) also provided methods for mapping semantic information that from IFC to CityGML, in which the existed objects were mapping directly and the nonexistent objects in CityGML were created.

2.2.2 Integrating CityGML2.0 with LADM

The reason for integrating 3D city models with cadastral information can be summarized into two aspects. On one hand, the 2D index map is no longer effective for storing current cadastral information (Larsson et al. 2018) especially with the increasing complexity of buildings and infrastructures. On the other hand, 3D city models contain wealthy environmental information and thus combing LADM with CityGML could facilitate land administration or other industries to manage and analyze the cadastral information from a macro aspect.

Similar to the integration of BIM and CityGML, most of researchers focus on the extension of CityGML and LADM. Aien et al. (2013) provided a model named 3D cadastral data model (3DCDM) for integrating legal and physical objects. In this model, *LegalPropertyObject* and *PhysicalPropertyObject* are two important components for supporting semantics that define every aspect of legal and physical objects. The legal object could be linked to the corresponding physical counterparts according to the identifier if the physical model has been created before. Otherwise, the physical objects have to be created at first. GÓŹDŹ et al. (2014) proposed a method named CityGML-LADM ADE that was focused on creating new classes and thus linked the legal space and physical space together. In this method, *PL_LegalSpaceBuilding* and *PL_Building* are two of new classes used for representing legal part of a building and physical part of a building, which were also defined as subclasses of LA_LegalSpaceBuildingUnit (from LADM) and AbstractBuilding (from CityGML).

Therefore, the relationship between legal spaces and physical spaces are linked as the new classes inherent the common attributes from each other. El-Mekawy et al (2015) generalized these methods into two classifications. The first one is using generic city objects and attributes on the original schema. The new attributes and names can be linked to the corresponding physical counterparts in the city model during the application runtime, while the second one is focusing on using application domain extension (ADEs). In this method, the new properties will be created and then these properties can be added in a new XML schema file.

2.3 Visualization of legal spaces

With the emerging technology of virtual simulations and the development of 3D cadastre, various approaches for visualizing legal spaces have been developed across the world. According to the storing format of cadastral boundaries and the objective of researches, proposed approaches can generally be separated into three categories. The first is extruding legal spaces based on the digital 2D plans. Since cadastral boundaries in some countries are stored in digital 2D survey plans, legal spaces can be extruded based on the processed boundary polylines directly. Ying et al. (2011) proposed a method for constructing 3D models with SketchUp software, in which 3D cadastral units can be constructed from 2D survey plans automatically. Furthermore, Gulliver et al. (2017) proposed a similar method based on the existing robust 2D digital cadastre, where the legal spaces were captured by digitizing the extruded 3D models with other cadastral information. Even though these methods are simple and effective, higher requirements for the source data were also put forward. The second is visualizing property units based on the 3D cadastral data. A prerequisite of these methods is that cadastral information should be stored in a 3D cadastral model. Višnjevac et al. (2019) developed a method that was retrieving cadastral data such as Multi-surface coordinates from the 3D cadastral database. And then, legal spaces can be visualized after converting the coordinates to an array by using the JavaScript and Cesium Primitive API. Stoter et al. (2017) also explored a method for representing legal spaces based on the 3D data. The main step in the implementation is translating the 3D representations of rights into 3D PDF software, and then legal volumes can be visualized. Lastly, using BIM or 3D city models to represent legal spaces has been a focus area for several recent studies (El-Mekawy et al. 2015; Larsson et al. 2018; Andrée et al. 2018a; Shojaei et al. 2018). However, due to the multiple problems such as legal, technical, registration and organizational aspects (Paulsson and Paasch 2013; El-Mekawy et al. 2015), most of researches were only focused on the theoretical part.

3. Methodology

Considering the objective of this study is to represent building objects in CityGML3.0, visualizing legal spaces in 3D models, and validating the new concepts of CityGML3.0 an integrated approach was developed. Specifically, it can be separated into three steps: 1) converting physical objects from IFC standard to CityGML3.0, 2) visualizing legal spaces and cadastral information in 3D city models, 3) integrating CityGML3.0 with LADM. An illustration of the method is given in Figure 10.

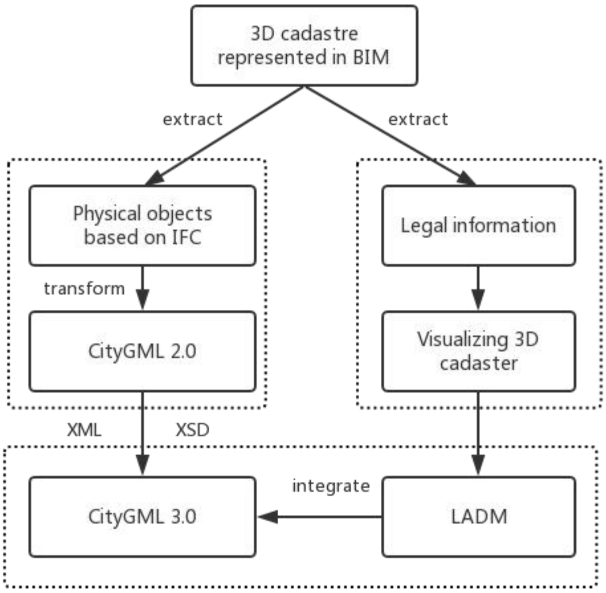


Figure 10. Flow chart for implementing the method.

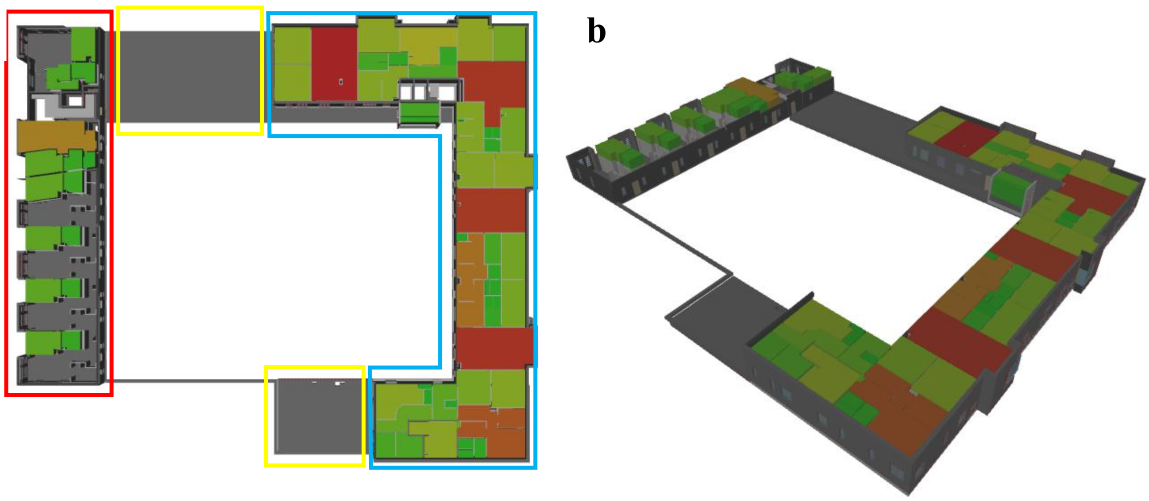
3.1 Data employed and Study area

In this project, the dataset consists of three parts:

1) BIM model. The main dataset employed in this project is a BIM model that contains a certain storey of a building with legal boundaries. Figure 11 demonstrates that the physical components of this model are slabs, walls, spaces, doors, and windows where only the first two elements were used in this project. As for the cadastral information, this floor involved multiple property unites whose legal boundaries have been dealt with already. In Figure 11a, the red boundary, yellow boundary, and blue boundary represent the residence, courtyards, and the preschool, respectively. This dataset is provided by the department of Physical Geography and Ecosystem Science, Lund University, while its raw data was from NCC (https://www.ncc.group/).

a

b



'**Figure 11.** The original BIM model was shown from the top view (a) and oblique view (b).

2) The Extensible Markup Language (XML) schema and a CityGML3.0 instance document. The XML schema language is also referred to XML Schema Definition (XSD), which is used to describe the structure of an XML document. The CityGML3.0 instance document is an XML file that describes a building and building objects based on the definition of CityGML3.0. Since FME Workbench 2018 cannot convert IFC to CityGML3.0 directly, XML schemas of building module and construction module, as well as the instance document were used. Both the XML schema and the CiytGML3.0 instance document can be retrieved from GitHub (https://github.com/opengeospatial/CityGML-3.0).

3) A digital cadastral database. Employed data such as the property owners, relevant rights, and the number of land parcels were created arbitrarily, except for some cadastral information stored in the BIM already. The structure of this system was built according to the requirement of LADM.

FME Workbench 2018 (Safe Software, Vancouver, Canada), Notepad++ (Don Ho, Taiwan), and ArcMap 10.5.1 (Esri, Redlands, United States) are the main software used in this project. Among them, FME Workbench was mainly used for converting standards from IFC to CityGML2.0 and visualizing legal spaces in 3D city models where the programming language Python was used to calculate the height of walls and create wall surfaces. As an auxiliary tool, Notepad++ was manipulated to transform CityGML from 2.0 to 3.0. And the digital cadastral database was created by using ArcMap 10.5.1.

The study area of this project is Multihuset Bryggan located in Limhamn, southern district of Malmö Municipality, Sweden. Multihuset Bryggan is a multifunctional building that includes parking garage, pharmacy, grocery, residences and more. In this study, only the top floor of Multihuset Bryggan (Figure 12) was involved that includes the residence (red part), courtyards (yellow part), as well as a preschool (blue part).

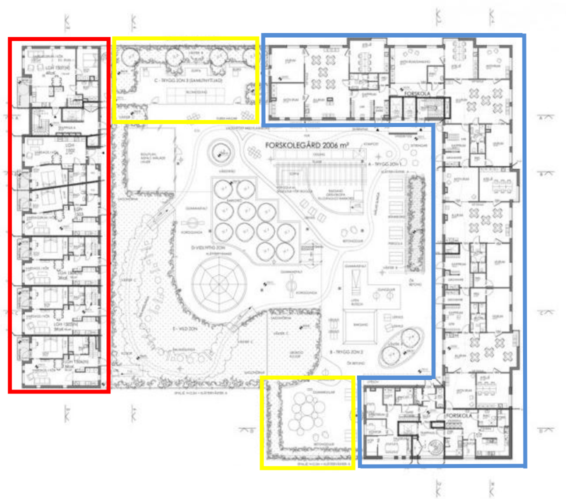


Figure 12. The 2D floor plan of the top storey in the Multihuset
(Source: https://www.kamikaze.nu/projekt/kv-bryggan-i-limhamn/)

3.2 Integration of IFC and CityGML3.0, and legal spaces visualization

Since BIM contains so much details with regard to the construction information that are not efficient for doing spatial analysis, 3D city models are used to represent legal spaces in this project. In this section, the main work is converting physical objects from IFC to LoD2 in CityGML3.0 and then visualizing legal spaces in 3D city models. The flow chart of this section was shown in Figure 13.

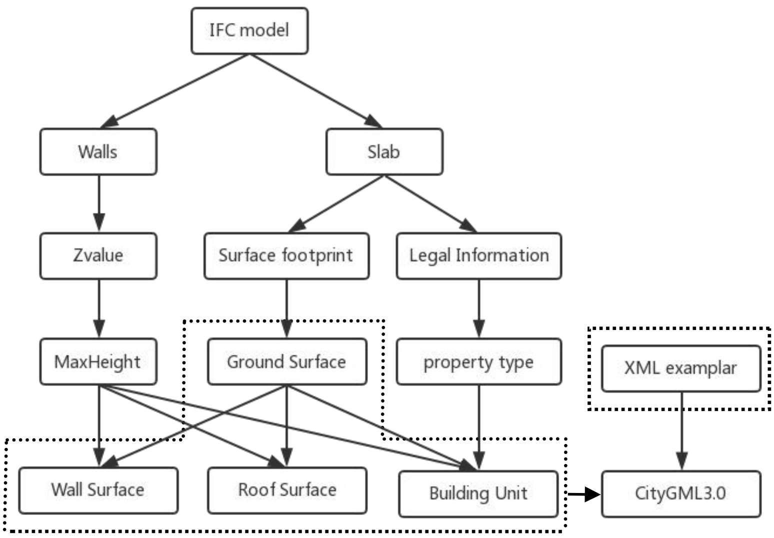


Figure 13. The flow chart for integration of IFC and CityGML3.0

3.2.1 Converting IFC to CityGML2.0

As mentioned in the literature review, LoD2 represents outer shells of a buildings with horizontal and vertical outer surfaces, as well as simplified roof shapes, hence extruding wall surfaces based on the footprint is one of the efficient approaches. During the process, two essential parameters: footprints and the height of the storey are needed.

Surface footprint is a planar representation that replaces the geometry of a feature with its shadow. The interior boundaries attached on the slabs such as legal boundaries can also be projected into the surface footprint. Considering that the dense projected points on the outer boundaries could increase the data redundancy (Figure 14), some vertices were removed. In addition, some parts whose area smaller than ten square meters were also filtered out in this study.

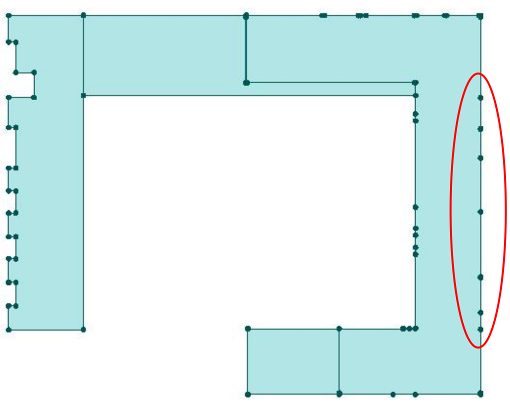


Figure 14. The dense projected points attached on the footprint

The height of each storey is another important parameter for extruding footprints. It normally depends on the ceiling height of rooms plus the thickness of floors between each plane. Since the provided model only contained one slab for testing, the height of storey was substituted by the height of walls in this project. The methods for finding the heightest and lowest points among all walls, and creating wall surfaces based on the footprint were adopted from Olsson (2018).

Since wall surfaces of this model in FME consist of multiple triangles (Figure 15b), the first step for getting relative height of a wall was finding the highest and lowest point among these triangles. The highest and lowest points can be screened out according to the value of 'Z'. And then a 'for loop' written in python language was implemented. The 'for loop' compared the highest and the lowest points of each wall among all walls where the maximum and minimum value among all walls were recorded. Thus, the relative height of a building storey can be calculated by subtracting the minimum value from the maximum value. Figure 16 illustrates the process for finding the maximum Z value among all walls where 'i' represents each wall in this model and Z(i) represents the Z value of the hightest point in the wall 'i'. As for the wall surfaces, they can be extruded by using another python script that creates each wall surface based on the outer lines of the footprint and the calculated height of the storey. In addition, as there was no roof in the provided building model, ground surfaces were taken as the roof surfaces in this project.

a

b

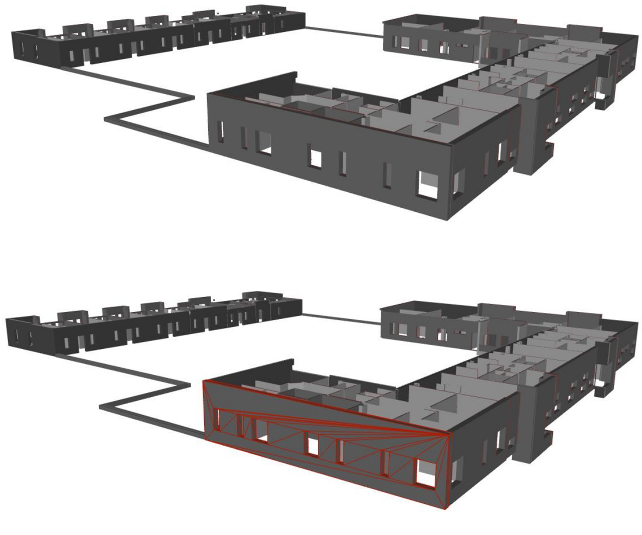


Figure 15. Wall surfaces of IFC in the Multihuset Bryggan model were presented in (a) where each wall surface consists of multiple triangles (b).

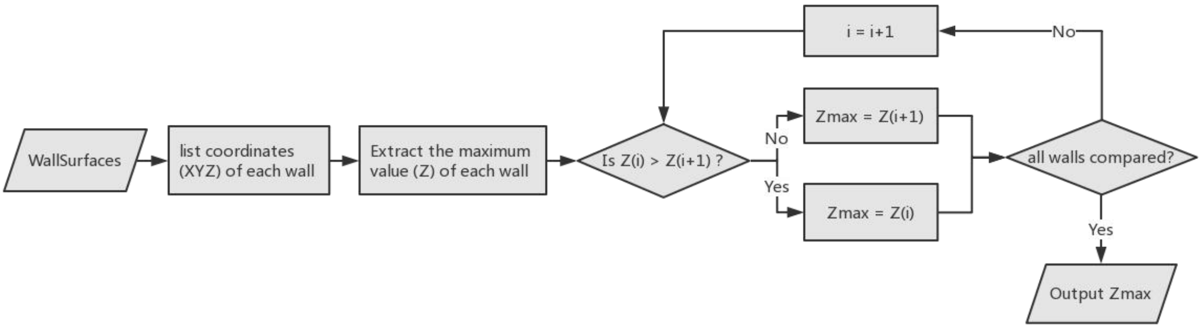


Figure 16. The process for finding the maximum Z value among all walls

Except for transforming geometries from IFC to CityGML2.0, semantic information such as the gml_id and the gml_parent_id have also to be defined and converted in this part. This step was implemented by using the built-in functions, namely *'CityGMLGeometrySetter'* and *'AttributerCreator'* in FME Workbench 2018.

3.2.2 3D Visualization for the cadastre

In keeping with physical boundaries, imagined legal boundaries were also simplified and generalized in this project. Thus, legal spaces can then be directly extruded from the footprint according to the calculated height of the storey. Differing from the model created in the last part, this extrusion consists of multiple solid geometries other than the various surfaces. Since legal boundaries have been processed and projected on the original BIM model already, the building parts extruded from the footprint are the legal spaces. Apart from legal boundaries, the property type is another cadastral information stored in the BIM model. Appearance of building parts were colored according to the property type. At last, superfluous attributes were removed in order to reduce the data redundancy.

3.2.3 Syntactical transformation for CityGML3.0

A new spatial concept, namely *'LogicalSpace'* is proposed in CityGML3.0, which aims at improving the interoperability between CityGML3.0 and other cadastral models. In order to validate if it is possible to integrate CityGM3.0 with LADM effectively, the building model in CityGML2.0 has to be transformed into CityGML3.0 at first. Since the FME Workbench 2018 cannot transform building objects from IFC to CityGML3.0 directly, manually upgrading CityGML2.0 to CityGML3.0 was implemented. The process in this part consists of two executables, one for referring the CityGML3.0 instance document and the other for updating the relevant contents.

Considering that CityGML3.0 and CityGML2.0 define building objects with different XML schema, XML documents (Kutzner 2018) defined a building model with CityGML3.0 were referenced. The excerpts in Figure 17 and Figure 18 exemplify how the roof surfaces are defined in different version of CityGML. In comparison to create a new CityGML document based on the schema of CityGML3.0, this approach improved the working efficiency to a large extent. In this case, the geometric and semantic information of building surfaces and building units were retrieved from the original CityGML2.0 document. Even if the building unit is not defined in CityGML2.0, the extruded building parts can be taken as the building unit because both of them represent the legal spaces based on the CityGML standard.

```
<core:cityObjectMember>
    <bldg:WallSurface gml:id="gml_da1e132c-9a31-4488-94e7-89776176d0b6">
        <gen:stringAttribute name="feature_type">
            <gen:value>Wall</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="gml_parent_property">
            <gen:value>boundary</gen:value>
        </gen:stringAttribute>
        <bldg:lod2MultiSurface>
            <gml:MultiSurface srsDimension="3">
                <gml:surfaceMember>
                    <gml:Polygon>
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 0 29.9100162454826
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
            </gml:MultiSurface>
        </bldg:lod2MultiSurface>
    </bldg:WallSurface>
</core:cityObjectMember>
```

Figure 17. Part of a referenced XML document defined wall surfaces in CityGML2.0

```
<bldg:buildingSpace>
    <con:ConstructionSpace gml:id="cs1">
        <boundary>
            <con:RoofSurface gml:id="DEBY_LOD2_5744682_5e13d1c8-7fb5-479f-9794-7b9e1f89ca1e">
                <lod2MultiSurface>
                    <gml:MultiSurface gml:id="ms1">
                        <gml:surfaceMember>
                            <gml:Polygon gml:id="DEBY_LOD2_5744682_5e13d1c8-7fb5-479f-9794-7b9e1f89ca1e_poly">
                                <gml:exterior>
                                    <gml:LinearRing>
                                        <gml:posList>4490663.450 5322007.590 555.191 4490663.250 5322006.210 554.643
                                    </gml:LinearRing>
                                </gml:exterior>
                            </gml:Polygon>
                        </gml:surfaceMember>
                    </gml:MultiSurface>
                </lod2MultiSurface>
            </con:RoofSurface>
        </boundary>
```

Figure 18. Part of a referenced XML document defined wall surfaces in CityGML3.0 instance document

3.3 Integration of CityGML3.0 with LADM

A preprocessing of this part is to create a relational database prototype in ArcMap 10.5.1. This prototype includes five classes that are LA_Party, LA_RRR, LA_BAUnit, LA_SpatialUnit, and LA_LegalSpaceBuildingUnit. According to the requirement of LADM and the Swedish real property register system, attributes of each class were created and stored in multiple tables. As for the value of the attributes, they were created arbitrarily except that has been provided before. Following is the attributes of each class (Table 2 to Table 6).

Table 2. The attributes of LA_Party class

Attributes	Definition	Value type
name	The name of party	CharacterString
pID	The identifier of the party (Primary key)	Oid
party_type	The type of the party	LA_PartyType

Table 3. The attributes of LA_RRR class

Attributes	Definition	Value type
right_type	The type of right	LA_RightType
pID	Foreign key	Oid

Table 4. The attributes of LA_BAUnit class

Attributes	Definition	Value type
BA_name	The name of the basic administrative unit	CharacterString
uID	The identifier of the basic administrative unit (Primary key)	LA_PartyType
pID	Foreign key	Oid

Table 5. The attributes of LA_SpatialUnit class

Attributes	Definition	Value type
suID	The spatial unit identifier (Primary key)	Oid
uID	Foreign key	Oid

Table 6. The attributes of LA_LegalSpaceBuildingUnit class

Attributes	Definition	Value type
type	The type of the building unit	LA_BuildingUnitType
suID	Foreign key	Oid
buildingUnitID	The identifier of the building unit (Primary key)	Oid

Among these attributes, the primary key and the foreign key were defined according to the requirement of LADM. After connecting primary keys with foreign keys, cadastral information was integrated into one table, namely *LA_LegalSpaceBuildingUnit*. In principle, CityGML3.0 and LADM can be integrated from two aspects that are geometric aspect and attribute aspect. Considering that there is no geographic information with regard to the coordinates systems in this study, the approach for combing these two standards was totally relied on the attributes' value. Similar to the gml_id of *Buildingunit* in CityGML3.0, buildingUnitID in LADM is a reference to the identifier of the spatial building unit. Thus, the gml_id of *Buildingunit* and the buildingUnitID of *LA_LegalSpaceBuildingUnit* were regarded as a bridge to connect CityGML3.0 with LADM.

4. Results

The final results are split into three parts. The first part shows the physical objects transformed from IFC to CityGML2.0 and CityGML3.0. The second part visualizes the 3D legal information in 3D city models. The last part demonstrates the results after combining CityGML3.0 with LADM.

4.1 Integration of IFC and CityGML3.0

In this section, the results include projected and filtered footprints, transformed wall surfaces, CityGML2.0 (3.0) building models, as well as the updated XML document. Figure 19 showed three footprints of the top floor of the Multihuset Bryggan where the solid lines represent the physical and legal boundaries in this project, and the points represent the vertices of triangles. In comparison to the left footprint, smaller areas and densely vertices were removed in the latter two footprints.

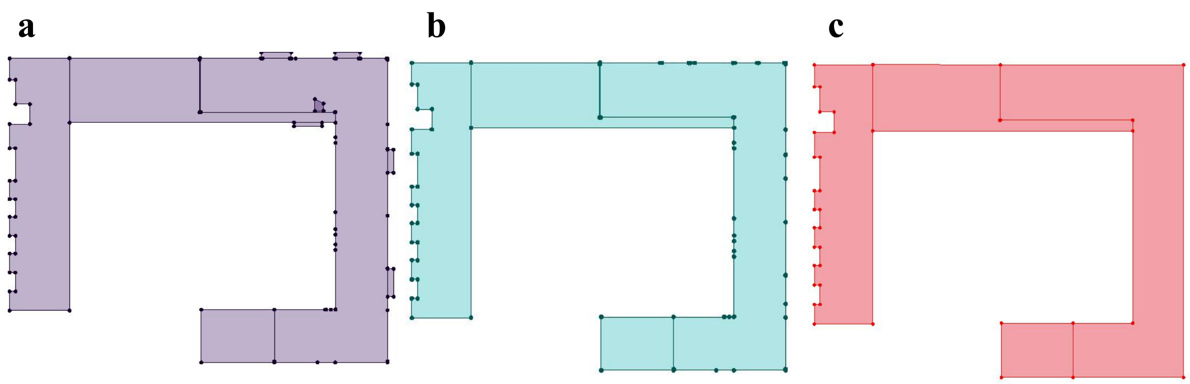


Figure 19. Footprints of Multihuset Bryggan model: (a) the original footprint; (b) the footprint after filtering; and (c) the footprint after generalizing.

Based on the generalized external contours of the footprint (Figure 19c) and the height of the storey, outer walls were created. In comparison to the walls in BIM model, the wall surfaces of LoD2 in CityGML2.0 only consist of one side (Figure 20).

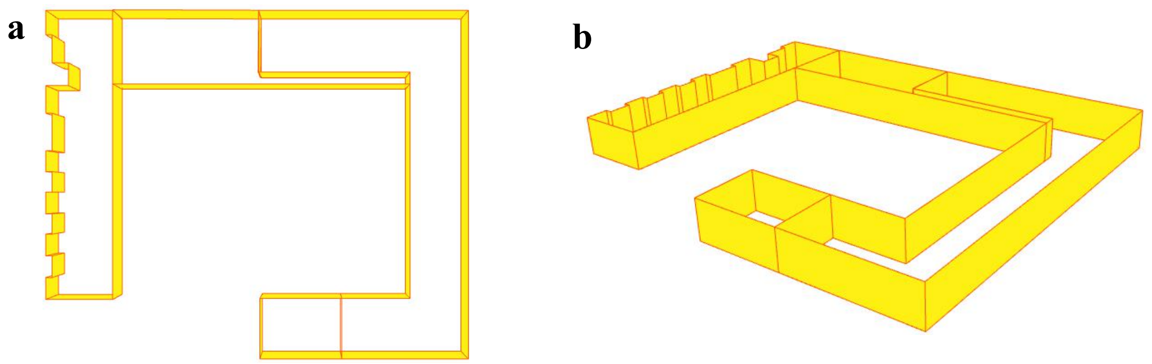


Figure 20. Wall surfaces of CityGML2.0 in the Multihuset Bryggan model. (a) top view; and (b) oblique view.

Figure 21 shows a complete transformed building model that consists of roof surfaces, wall surfaces, as well as ground surfaces. According to the feature types in the building model, these surfaces were colored in pink (the roof), yellow (the wall) and brown (the ground), respectively. Since the transformed appearances of the building model are same in CityGML2.0 and CityGML3.0, only one set of figures were demonstrated below.

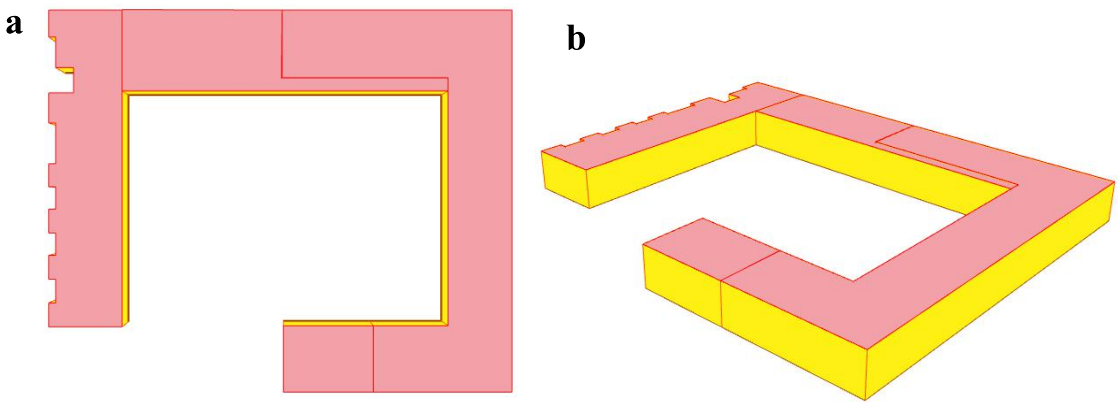


Figure 21. Visualization of the CityGML2.0 and 3.0 in the Multihuset Bryggan model. (a) Top view; and (b) oblique view.

The following clips (Figure 22) indicate that the feature types of CityGML2.0 in this building model are city model, generic city object, ground surfaces, roof surfaces, as well as wall surfaces. Among them, all of the feature types have their corresponding geometries except the city model. Differing from the CityGML2.0, *Building*, *BuildingUnit* and *ConstructionSpace* are new feature types added in CityGML3.0 where the information of *BuildingUnit* were retrieved from the extruded legal spaces, namely GenericCityObject in CityGML2.0. Nevertheless, all of these new classes can only be demonstrated in a table view even if the geographic information has been defined in the XML document (Figure 24). Table 7 shows the attribute information of *BuildingUnit* in CityGML3.0 where the gml_parent_id and the gml_parent_property describe the information of its superclass *BuildingSubivision*.

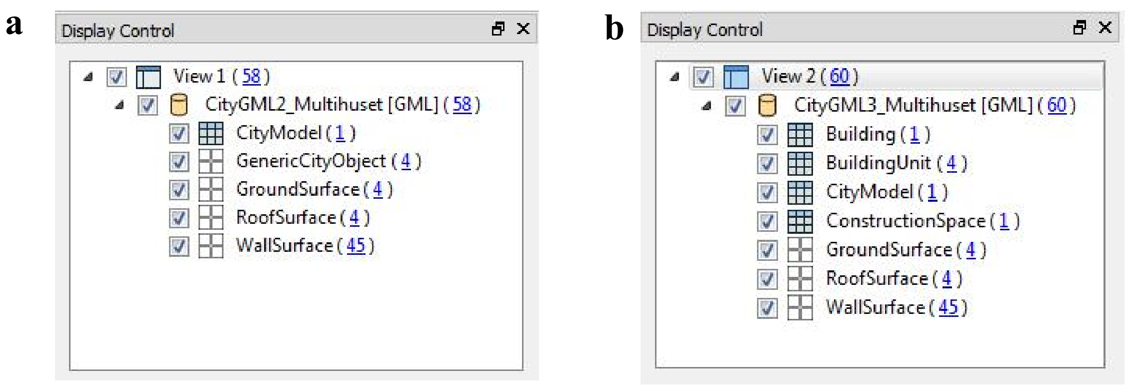


Figure 22. Feature types of the CityGML2.0 (a) and 3.0 (b) in the Multihuset Bryggan model

Table 7. Attributes value of *BuildingUnit* in CityGML3.0

gml_id	gml_parent_id	gml_parent_property	Property_type
300101	Multihuset_LOD2	buildingSubdivision	residence
301101	Multihuset_LOD2	buildingSubdivision	courtyard
301201	Multihuset_LOD2	buildingSubdivision	preschool
301301	Multihuset_LOD2	buildingSubdivision	courtyard

The following excerpts show the physical information and semantic definition of legal spaces in CityGML2.0 and CityGML3.0. Differing from CityGML2.0, legal spaces in CityGML3.0 can be refined into *BuildingUnit* and *Room* where both of them are the subclass of *BuildingSubdivision.* In addition, *GroundSurface*, *RoofSurface*, and *WallSurface*are are classified into *ConstructionSurface* in CityGM3.0 rather than the *BounndarySurface*. Their semantic definitions were shown in the appendix (Figure A1 – Figure A6).

```
<core:cityObjectMember>
    <gen:GenericCityObject gml:id="gml_f84db629-056c-4b4e-b66a-a3cbb2879f27">
        <gen:stringAttribute name="gml_parent_property">
            <gen:value>buildingSubdivision</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="feature_type">
            <gen:value>BuildingPart</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_parent_id">
            <gen:value>1HeRFbeBDBIuMgfcmp$5r$</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_id">
            <gen:value>0jiVcSpLH1cAVDnEPxO_PG</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="PropertyType">
            <gen:value>Bostad</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="_area">
            <gen:value>459.67447435071881</gen:value>
        </gen:stringAttribute>
        <gen:lod4Geometry>
            <gml:Solid srsDimension="3">
                <gml:exterior>
                    <gml:CompositeSurface>
                        <gml:surfaceMember>
                            <gml:Polygon>
                                <gml:exterior>
                                    <gml:LinearRing>
                                        <gml:posList>19.198 29.698 0 19.198 33.192 0
                                    </gml:LinearRing>
                                </gml:exterior>
                            </gml:Polygon>
                        </gml:surfaceMember>
```

Figure 23. Extruded legal spaces are defined in CityGML2.0 schema.

```xml
<bldg:BuildingUnit gml:id="300201">
    <bldg:function>courtyard</bldg:function>
    <boundary>
        <con:InteriorWallSurface>
            <lod2MultiSurface>
                <gml:MultiSurface gml:id="_ms_bu2">
                    <gml:surfaceMember>
                        <gml:Polygon gml:id="Multihuset_lod2_bu2">
                            <gml:exterior>
                                <gml:LinearRing >
                                    <gml:posList>53.2595234704439 75.8020028346211 0 53.2595234704439
                                    <gml:posList>53.2595234704439 75.8020028346211 0 29.9100519090199
                                    <gml:posList>29.9100519090199 75.868061936021 0 29.9100519090199
                                    <gml:posList>29.9100519090199 64.0499868791674 0 77.4722420796869
                                    <gml:posList>77.4722420796869 64.0499868791674 0 77.472242079687
                                    <gml:posList>77.472242079687 65.9719868791673 0 53.2595234704439
                                    <gml:posList>53.2595234704439 65.9719868791673 0 53.2595234704439
                                    <gml:posList>53.2595234704439 75.8020028346211 5.89172090466918 2
                                </gml:LinearRing>
                            </gml:exterior>
                        </gml:Polygon>
                    </gml:surfaceMember>
                </gml:MultiSurface>
            </lod2MultiSurface>
        </con:InteriorWallSurface>
    </boundary>
</bldg:BuildingUnit>
```

Figure 24. *BuildingUnit* is defined in CityGML3.0 schema.

4.2 Visualization of 3D cadastres

A preliminary 3D visualization of cadastral information was shown on Figure 25. Although the extruded building model included certain cadastral information, unprocessed attributes cannot be visualized practically.

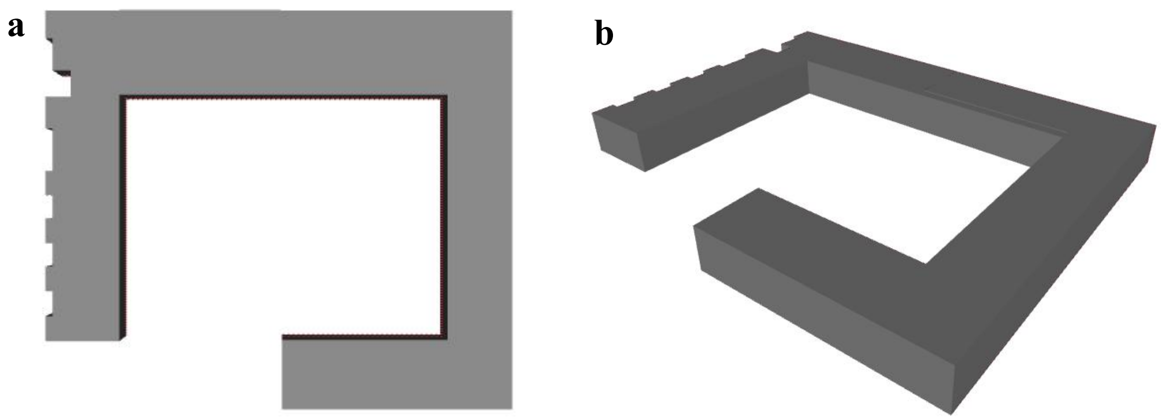


Figure 25. The 3D model extruded from footprints is shown as the top view (a) and the oblique view (b).

After processing the cadastral information, legal spaces were visualized in Figure 26 where the various color of building parts represented different property units. Based on the cadastral information, the red part, yellow part, and blue part represent the residential area, courtyards, and kindergarten, respectively. In Figure 27, a combination of legal spaces with physical wall surfaces was demonstrated where the yellow polygons and red boundaries are the components of wall surfaces.

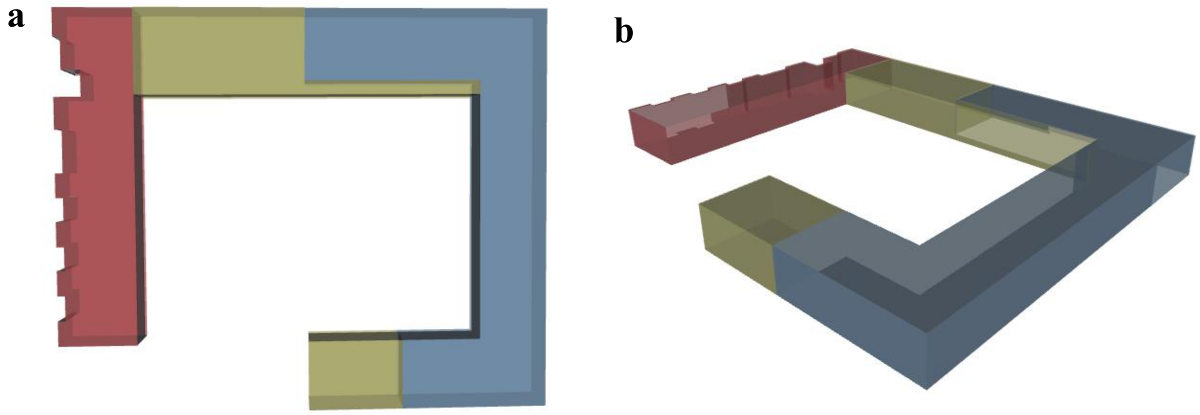


Figure 26. The visualization of legal spaces in 3D models. (a) The top view and (b) the oblique view

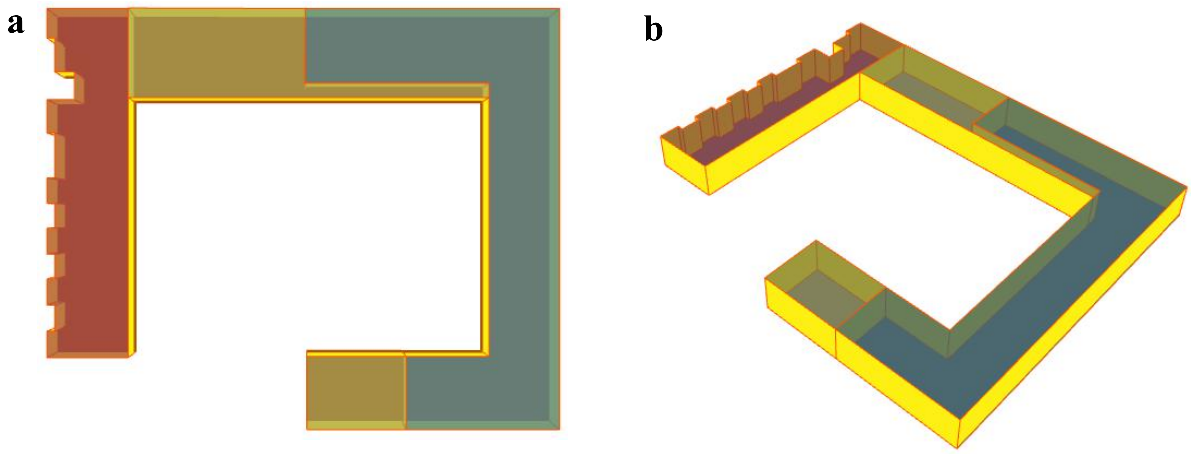


Figure 27. The visualization of legal spaces with physical objects. (a) The top view and (b) the oblique view.

As for the attribute information of the legal space model, only 9 properties were kept (Table 8). Among them, ‘area’ represented the area of different building parts and the unit was square meters. ‘diffZBuilding’, ‘maxZBuilding’, and ‘minZBuilding’ described the height of walls from different aspects, which were created during the last process. As for the ‘PropertyType’, it is one of the legal information extracted from the original model. However, its contents were adjusted to a certain degree. The rest of attributes were created automatically, which recorded the basic information of the transformed model such as the pathways and the geometric type.

Table 8. Attribute information with regard to the different property units

Attributes	Value			
	residence	**courtyard_1**	**courtyard_2**	**kindergarten**
area	459.67	322.48	126.63	863.75
diffZBuilding	5.89	5.89	5.89	5.89
fme_dataset (string)	C:\Users	C:\Users	C:\Users	C:\Users
fme_featuretype (string)	Slab	Slab	Slab	Slab
fme_geometry (string)	Aggregate	Aggregate	Aggregate	Aggregate
fme_type (string)	Solid	Solid	Solid	Solid
maxZBuilding	30.10	30.10	30.10	30.10
minZBuilding	24.21	24.21	24.21	24.21
PropertyType	Bostad	Gård	Gård	Förskola

4.3 Integration of CityGML3.0 with LADM

Based on the definitions of packages in LADM, all classes were created and separated into different tables. Table 9 demonstrates a comprehensive result that integrated all tables together. For this research, all values in the table were created arbitrarily except the field of type. After connecting the database with CityGML3.0, cadastral information was associated with geographic information (Table 10).

Table 9. Cadastral information stored in a database based on LADM

ObjectID	name	pID	party_type	right_type	BA_name	uID	suID	type	buildingUnitID
1	Frank	1001	naturePerson	ownership	Multihuset Residence	300	3001	residence	300101
2	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3011	courtyard	301101
3	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3012	preschool	301201
4	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3013	courtyard	301301

Table 10. Cadastral information after integrating CityGML3.0 with LADM

gml_parent_id	gml_parent_property	gml_id	name	pID	party_type	right_type	BA_name	uID	suID	type	buildingUnitID
Multihuset_LOD2	buildingSubdivision	300101	Frank	1001	naturePerson	ownership	Multihuse Residence	300	3001	residence	300101
Multihuset_LOD2	buildingSubdivision	301101	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3011	courtyard	301101
Multihuset_LOD2	buildingSubdivision	301201	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3012	preschool	301201
Multihuset_LOD2	buildingSubdivision	301301	Lucy	1002	naturePerson	ownership	Multihuset Preschool	301	3013	courtyard	301301

5. Discussion

5.1 Integration of IFC and CityGML3.0

In this project, the approach for integrating IFC to LoD2 in CityGML3.0 was separated into two steps. The first step was converting IFC to CityGML2.0 and the second step was transforming CityGML2.0 to CityGML3.0. The results indicate that this method is feasible and reliable even though the working efficiency is lower than other methods. In the first step, the transformation was focused on removing the interior objects of BIM and simplifying the outer building shells. Since dense vertices will result in the data redundancy, some extra points were removed. The transformed wall surfaces and ground surfaces illustrate that projecting ground surfaces on the footprint and extruding wall surfaces according to the storey height is an efficient way to transform IFC to lower LoD in CityGML2.0. The result theoretically can be considered as satisfied the requirement, even though there was only one storey converted. In the second step, retrieving geographic information from the GML document and updating the value of XML document were implemented. The final 3D model and the XML file indicate that the differences between CityGML2.0 and CityGML3.0 in LoD2 are the definition of feature types and the hierarchy of semantic structures other than the geometrical shapes. Since the CityGML3.0 standard has not been completely released so far, fewer methods were proposed. In early 2019, a java tool was developed by Nguyen that supports various city models to be transformed from CityGML2.0 to CityGML3.0, and the feature types in building models can be changed according to the need. In comparison to the java tool, the advantage of this approach is that it is easier to be executed and the final results are more accurate. This is because the attributes of each feature type are created not only based on the building schema but based on the construction schema. However, the drawback is that it is difficult to create CityGML3.0 file on a large scale with this method as the semantic information has to be updated manually.

5.2 Visualization of 3D cadastres

The precondition of this part is that legal boundaries should have been defined with physical objects in the BIM model. As one of the most important cadastral information in the cadastre, legal boundaries visualize the RRRs in geospatial environment and split the building into building parts from a legal perspective. However, there is no specific legal rule for how to draw cadastral boundaries with the building construction in Sweden (Larsson et al. 2018), as defining legal boundaries with physical objects in BIM and 3D city models is complicated. In addition, the visualization for combining legal boundaries with their interior and exterior boundaries (or central boundaries) are different, as physical objects in the BIM model have thickness. In consideration of the non-determinacy and the complexity, combining legal boundaries with physical walls and slabs was not involved in this project.

The result of this part indicates that it is available to visualize legal spaces in 3D models. Since legal boundaries and physical boundaries in this study are the same, there are no difference between legal spaces in the cadastral model and physical spaces in the 3D city model (Figure 27). In comparison to represent the cadastre in a BIM model, the extruded 3D cadastral model simplifies the building structures to a large extent but retains the essential building features. In addition, this extruded model strengthens the cadastral information by coloring different property types, which improves the visualization to some degree. However, the drawback of this model is that users cannot update the geometric and cadastral information of cadastral models directly because both of them are derived from the BIM model. In this case, the next work could focus on connecting the extruded cadastral model with LADM. And thus the cadastral information can be updated efficiently.

5.3 Integration of CityGML3.0 with LADM

The combined result of CityGML3.0 and LADM illustrates that these two standards can be integrated, especially with the new classes proposed in CityGML3.0. The attribute table of LADM suggests that a *BAUnit* in LADM can contain several spatial units as long as they have the same party and rights. In this study, since both courtyards and the preschool belong to a *BAUnit* named Multihuset Preschool, the uID of them are the same. As an identifier of *LegalSpaceBuildingUnit*, *BuildingUnitID* is taken as the primary key to connect legal spaces in LADM with the building units in CityGML3.0. In comparison to use ADE to integrate LADM with CityGML, the new class *LogicalSpace* reduces the complexity of integrating procedures and increases the interoperability of CityGML with LADM.

In terms of visualization, the integrated result indicates that legal spaces cannot be visualized in CityGML3.0 no matter what kind of data is stored in the XML document. According to the exemplar of XML with CityGML3.0 and the result produced by using the java tool, new feature types such as *BuildingUnit* and *Room* can only be shown in the table view, even though the geometric information has been defined in the XML or GML document. One assumption for this result is that the current software cannot parse the new schema in CityGML3.0 and thus the geometric information cannot be used for visualization. In addition, since the building units in CityGML3.0 were extruded based on the simplified legal boundaries, legal spaces in CityGML3.0 will be a little different from those in LADM. The problem of this method is that it is only suitable for a small scale transformation as the value of *BuildingUnitID* has to be assigned manually. In principle, this problem can be solved if the coordinates of building units are contained in the LADM and the CityGML dataset. With this in mind, the future work can focus on trying to visualize the building units in CityGML3.0 and integrating LADM with CityGML3.0 by using coordinates.

6. Conclusion

This project aims at representing physical building objects in CityGML3.0, visualizing legal spaces in 3D models, and validating if it is possible to integrate CityGML3.0 with LADM efficiently. In general, this aim should be considered as fulfilled.

The first result presented in this study indicates that projecting ground surfaces on the footprint and extruding walls based on the storey height is an efficient way to transform IFC to lower LoD in CityGML. In addition, the transformed building surfaces and the attribute tables suggest that the differences between CityGML2.0 and CityGML3.0 are the definition of feature types, as well as the hierarchy of semantic structures instead of the geometry. The second result shows that cadastral information can be visualized in 3D city models. Since legal boundaries and physical boundaries in this study are the same, the extruded legal spaces completely overlaid with physical spaces in the 3D city model. In comparison to represent legal spaces in BIM, the biggest advantage of using 3D city models is that it can simplify the building structures and further strengthen the cadastral information. As for the third result, it illustrates that it is viable to integrate CityGML3.0 with LADM without using any ADE, even though only the attribute integration of both standards was verified. However, the problem is that these new classes can only be visualized in a table view, even if the geometric information has been defined and stored in the XML document.

To conclude, though the preliminary results fulfilled the aim, much work is still needed to refine the method. Considering that the proposed approach is not efficient, the next work in this study will focus on transforming CityGML2.0 to CityGML3.0 automatically and visualizing the building units in CityGML3.0.

7. References

Abdul-Rahman, A., and M. Pilouk. 2007. 2D and 3D Spatial Data Representations. In *Spatial Data Modelling for 3D GIS*, 30 pp. Berlin: Springe.:

Aien, A., A. Rajabifard, M. Kalantari, and D. Shojaei. 2015. Integrating legal and physical dimensions of urban environments. ISPRS Int. J. Geo-Inf. 4, 1442–1479.

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

Andrée, M., J.M. Paasch, J. Paulsson, and S. Seipel. 2018a. BIM and 3D Property Visualisation. In *Proceedings of FIG Congress*.

Atazadeh, B., M. Kalantari and A. Rajabifard. 2016. Comparing Three Types of BIM-based Models for Managing 3D Ownership Interests in Multi-level Buildings. In *5th International FIG 3D cadastre Workshop*.

Atazadeh, B., R. Abbas, and K. Mohsen. 2017. Assessing performance of three BIM-based views of buildings for communication and management of vertically stratified legal interests. *ISPRS Int. J. Geo-Inf*, 198(6), 1-22.

Bengtsson, J., and M. Grönkvist 2017.Performing geographic information system analyses on building information management models. Master Thesis. Stockholm, Sweden: Royal Institute of Technology.

Berlo, L.V., and R.D. Laat. 2011. Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In *Advances in 3D Geo-Information Sciences,* ed. T.H. Kolbe, G. König, and C. Nagel, 17 pp. Berlin: Springer.

Biljecki, F., K.A. Ohori, H. Ledoux, R. Peters, and J. Stoter. 2016. A Multi-Scale Country-Wide Study in the Netherlands. *PLoS ONE 11*: 1 -22.

BuildingSMART (1996-2017) Industry Foundation Classes version 4.1, retrieved 19 January 2019, from http://www.buildingsmart-tech.org/ifc/IFC4x1/final/html/

Donkers, S., H. Ledoux, J. Zhao, and J. Stoter. 2016. Automatic conversion of IFC datasets togeometrically and semantically correct CityGML LOD3 buildings. *Transactions in GIS* 20(4): 547-569.

El-Mekawy, M., and A. Östman. 2010. Semantic mapping: an ontology engineering method for integrating building models in IFC and CityGML. In *Proceedings of the 3rd ISDE digital earth summit*.

El-Mekawy, M., J. M. Paasch, and J. Paulsson. 2015. Integration of legal aspects in 3D cadastral systems. *International Journal of E-Planning Research* 4(3): 47-71.

Góźdź, K., W. Pachelski, P.V. Oosterom, and V. Coors. 2014. The posibility of using CityGML for 3D representation of buildings in the cadastre. In *4th International Workshop on 3D cadastres*.

Gröger, G., T.H. Kolbe, C. Nagel, and K. H. Häfele. 2012. OGC City Geography Markup Language (CityGML) Encoding Standard v2.0., OGC Doc, 12-019, retrieved 19 January 2019, from http://www.opengeospatial.org/standards/citygml

Gulliver, T., A. Haanen, and M. Goodin. 2017. A 3D digital cadastre for New Zealand and the international opportunity. *ISPRS Int. J. Geo-Inf*, 375(6), 1-17.

ISO 16739. 2013. Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries, retrieved 08 February 2019, from http://www.buildingsmart-tech.org/specifications/ifc-releases/ifc4-release

ISO 19152. 2012. Geographic information--Land Administration Domain Model (LADM), retrieved 10 February 2019, from https://www.iso.org/standard/51206.html

Isikdag, U., and S. Zlatanova. 2009. A SWOT analysis on the implementation of building information models within the geospatial environment. In *Urban and Regional data management, UDMS Annuals 2009*, ed A. Krek, M. Rumor, S. Zlatanova, E. M. Fendel, 15 pp. Boca Raton: CRC Press.

Kolbe, T.H., and T. Kutzner. 2018. Notes on the CityGML3.0 Conceptual Model. Technique University Munich, Germany.

Kutzner, T. 2018. Test data for Building_CityGML_3.0. Retrieved April 27, 2019, from https://github.com/opengeospatial/CityGML-3.0/tree/master/Test%20data

Lantmäteriet. 2011. Cadastral procedures in Sweden. 2011. Retrieved April 23, 2019, from https://www.lantmateriet.se/globalassets/fastigheter/broschyrer/lant64_forattningsfolder_eng_0301_sfs.pdf

Larsson, K., J. Paasch and J. Paulsson. 2018. Conversion of 2D analogue cadastral boundary plans into 3D digital information - problems and challenges illustrated by a Swedish case. In 6th *International FIG 3D cadastre Workshop*.

Lemmen, C., P.V. Oosterom, and R. Bennett. 2015. The land administration domain model. *Land Use Policy* 49: 535-545.

Löwner, M.O., G. Gröger, J. Benner, F. Biljecki, and C. Nagel. 2016. Proposal for a new LOD and multi-representation concept for CityGML. In *11th 3D Geoinfo conference.*

Nguyen S.H., 2019. A small Java program used to transform CityGML v2.0 to CityGML v3.0 files. Retrieved April 25, 2019, from https://github.com/tum-gis/citygml2-to-citygml3

Nagel C., and T.H. Kolbe. 2007. Conversion of IFC to CityGML. Meeting of the OGC 3DIM Working Group at OGC TC/PC, Paris.

Olsson, P. O. 2018. Conversion of an IFC-model to a LoD2-3 3D-GIS building model. In *Proceedings of the AGILE Conference.* Lund, Sweden: 12-15.

Paulsson, J., and J. Paasch. 2013. 3D property research from a legal perspective. *Computers, Environment and Urban Systems.* 40: 7-13.

Rajabifard, A., M. Agunbiade, M. Kalantari, K. M. Yip, B. Atazadeh, F. Badiee, D. M. N. B. Isa, M. K. B. Adimin, et al. 2018. An LADM-based Approach for Developing and Implementing a National 3D cadastre - A Case Study of Malaysia. In *7th International FIG Workshop on the Land Administration Domain Model*.

Shojaei, D., H. Olfat, A. Rajabifard, and M. Briffa. 2018. Design and development of a 3D digital cadastre visualization prototype. *ISPRS Int. J. Geo-Inf*, 384(7), 1-13.

Stoter, J., H. Ploeger, R. Roes, E.V.D. Riet, F. Biljecki, H. Ledoux, D. Kok, and S. Kim. 2017. Registration of Multi-Level Property Rights in 3D in The Netherlands: Two Cases and Next Steps in Further Implementation. *ISPRS Int. J. Geo-Inf*, 158(6), 1-18.

Sucaya, I.K.G.A. 2009. Application and validation the Land administration domain model in a real life situation (A case study in Indonesia). Master Thesis. Enschede, The Netherlands: University of Twent.

Tang, S.J., Q. Zhu, and J.Q. Zhao. 2014. Towards interoperating of BIM and GIS model: geometric and semantic integration of CityGML and IFC building models. *Journal of Information Technology in Civil Engineering and Architecture* 6(4): 11-17 (in Chinese).

Wang, J.L., W.J. He, and J.P. Liu. 2018. The transformation of IFC and CityGML based on the architectural geometric and semantic information. *Scientific and technological innovation* 2: 150-151 (in Chinese).

Appendix A

The attachment demonstrates the transformed Multihuset Bryggan model in an XML format that defines the exterior building surfaces based on the CityGML2.0 and CityGML3.0.

```
<core:cityObjectMember>
    <bldg:GroundSurface gml:id="gml_11a10ff6-f889-4147-bf51-7fbdcdccc235">
        <gen:stringAttribute name="feature_type">
            <gen:value>Slab</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="gml_parent_property">
            <gen:value>boundary</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_parent_id">
            <gen:value>1HeRFbeBDBIuMgfcmp$5r$</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_id">
            <gen:value>0jiVcSpLH1cAVDnEPxO_PG</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="PropertyType">
            <gen:value>Bostad</gen:value>
        </gen:stringAttribute>
        <bldg:lod2MultiSurface>
            <gml:MultiSurface srsDimension="3">
                <gml:surfaceMember>
                    <gml:Polygon>
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 0 29.9100162454826
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
            </gml:MultiSurface>
        </bldg:lod2MultiSurface>
    </bldg:GroundSurface>
</core:cityObjectMember>
```

Figure A1. Ground surfaces are defined in CityGML2.0

```
<boundary>
    <con:GroundSurface gml:id="Multihuset_lod2_ground_1">
        <lod2MultiSurface>
            <gml:MultiSurface gml:id="ms50">
                <gml:surfaceMember>
                    <gml:Polygon gml:id="Multihuset_lod2_ground_1_poly">
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 0 29.910016245482552
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
            </gml:MultiSurface>
        </lod2MultiSurface>
    </con:GroundSurface>
</boundary>
```

Figure A2. Ground surfaces are defined in CityGML3.0

```xml
<core:cityObjectMember>
    <bldg:WallSurface gml:id="gml_da1e132c-9a31-4488-94e7-89776176d0b6">
        <gen:stringAttribute name="feature_type">
            <gen:value>Wall</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="gml_parent_property">
            <gen:value>boundary</gen:value>
        </gen:stringAttribute>
        <bldg:lod2MultiSurface>
            <gml:MultiSurface srsDimension="3">
                <gml:surfaceMember>
                    <gml:Polygon>
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 0 29.9100162454826
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
            </gml:MultiSurface>
        </bldg:lod2MultiSurface>
    </bldg:WallSurface>
</core:cityObjectMember>
```

Figure A3. Wall surfaces defined in CityGML2.0

```xml
<boundary>
    <con:WallSurface gml:id="Multihuset_lod2_wall_20">
        <lod2MultiSurface>
            <gml:MultiSurface gml:id="ms24">
                <gml:surfaceMember>
                    <gml:Polygon gml:id="Multihuset_lod2_wall_20_poly">
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 0 29.910016245482552
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
            </gml:MultiSurface>
        </lod2MultiSurface>
    </con:WallSurface>
</boundary>
```

Figure A4. Wall surfaces defined in CityGML3.0

```xml
<core:cityObjectMember>
    <bldg:RoofSurface gml:id="gml_9bb0058e-fc99-4763-9bfb-c5a4bfe9eda1">
        <gen:stringAttribute name="feature_type">
            <gen:value>Roof</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="gml_parent_property">
            <gen:value>boundary</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_parent_id">
            <gen:value>1HeRFbeBDBIuMgfcmp$5r$</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="element_id">
            <gen:value>0jiVcSpLH1cAVDnEPxO_PG</gen:value>
        </gen:stringAttribute>
        <gen:stringAttribute name="PropertyType">
            <gen:value>Bostad</gen:value>
        </gen:stringAttribute>
        <bldg:lod2MultiSurface>
            <gml:MultiSurface srsDimension="3">
                <gml:surfaceMember>
                    <gml:Polygon>
                        <gml:exterior>
                            <gml:LinearRing>
                                <gml:posList>19.198 29.698 5.89172090466918
                            </gml:LinearRing>
                        </gml:exterior>
                    </gml:Polygon>
                </gml:surfaceMember>
        </gml:MultiSurface>
        </bldg:lod2MultiSurface>
    </bldg:RoofSurface>
</core:cityObjectMember>
```


Figure A5. Roof surfaces are defined in CityGML2.0


```xml
<cityObjectMember>
    <bldg:Building gml:id="Multihuset_lod2">
        <gml:name>Multihuset_lod2</gml:name>
        <bldg:buildingSpace>
            <con:ConstructionSpace gml:id="cs1">
                <boundary>
                    <con:RoofSurface gml:id="Multihuset_lod2_roof_1">
                        <lod2MultiSurface>
                            <gml:MultiSurface gml:id="ms1">
                                <gml:surfaceMember>
                                    <gml:Polygon gml:id="Multihuset_lod2_roof_1_poly">
                                        <gml:exterior>
                                            <gml:LinearRing>
                                                <gml:posList>19.198 29.698 5.891720904669178
                                            </gml:LinearRing>
                                        </gml:exterior>
                                    </gml:Polygon>
                                </gml:surfaceMember>
                            </gml:MultiSurface>
                        </lod2MultiSurface>
                    </con:RoofSurface>
                </boundary>
```


Figure A6. Roof surfaces are defined in CityGML3.0