SEMANTIC MAPPING: AN ONTOLOGY ENGINEERING METHOD FOR INTEGRATING BUILDING MODELS IN IFC AND CITYGML

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Abstract. *One of the main problems facing 3D city modelling applications is lack of interoperability among various Building Information Models (BIM) and Geographic Information Systems (GIS) models. CityGML (representing a wide range of 3D urban objects) and IFC (representing a very detailed semantic model for buildings) are considered the most prominent semantic models in GIS and BIM, respectively, today. When integrating the two models, substantial difficulties may arise in transforming information from one to the other. Professionals from both domains have made significant efforts to integrate CityGML and IFC models for seeking useful common applications. However, most of these efforts use a unidirectional method (mostly from IFC to CityGML) for a conversion process. As a formal mapping between both domains is required, researchers have suggested that harmonising semantics is the best approach for such integration. In this paper, we focus on semantic integration of IFC and CityGML building models for bidirectional conversion. Both IFC and CityGML use different terminologies to describe the same domain. Additionally, there is a great heterogeneity in their semantics. This paper, therefore, propose more expressive reference ontology between IFC and CityGML semantic models and an intermediate Unified Building Modelled (UBM) is built. The result of the paper contributes, through the reference ontology, towards a formal mapping between IFC and CityGML ontologies that allows bidirectional conversion between them. It also contributes towards a design of meta-standard for 3D city modelling that can support applications on both domains.*

Keywords. IFC, CityGML, Interoperability, Reference Ontology, Unified Building Model (UBM)

1 INTRODUCTION

3D city models are digital representation of the Earth's surface and its related spatial objects. In a defined urban area, these models enable a wide variety of applications that in turn create a demand for detailed models of a specific area or even a focused building model. In such focused models, representation and relationships among spatial objects should be also understood and modelled [1]. Models in this area are divided in two types, design and real world models. On one hand, the design models usually exist before the final product or design of a specific building/s. As their purpose is to fulfil needs for the AEC industry, these models are designed for representing the maximum level of detail in geometric models. On the other hand, real world models are geospatial information systems that represent existing spatial objects around us [2].

Recently, several design's Building Information Models (BIM) for storing semantic information about building and 3D geospatial information models for representing real world objects have been reported. The aim of these models is to offer means for defining spatial objects with both geometry and semantics. Industry Foundation Classes (IFC) and City Geography Markup Language (CityGML) today are considered as two most prominent semantic models in the design and real world objects, respectively [3].

Interoperability between Building Information Models (BIM) and Geographic Information Systems (GIS) is one of the major problems that face building information systems and practitioners today. The aim of this integration is to meet the increased demand for construction analysis, urban planning applications, disaster management, cadastre and homeland security and other applications [3, 4]. These applications do not only require 3D geometry and appearance information. Instead, they require complex semantic information. Conceptual models have been developed in the two worlds, BIM and GIS, in forms of geometric and semantic models. For only visualization purposes, geometric along with appearance and texture information are sufficient to represent 3D spatial objects. However, semantic models are needed for different engineering and planning applications that require complex queries and analyses [1, 5].

All languages in different domains are characterised by its syntax and semantics. The syntax part, on one hand, describes how symbols and words are recognised in the language. It also contains rules of how to shape well formulated sentences using the recognised symbols. Not only symbols should be agreed on when communicating. However, the syntax rules have to be well defined and understood [6]. In the case of spatial information, the agreement between IFC and CityGML means that each of them uses grammatically correct natural language in verbal spatial directions and mapping that conform to geometric accepted procedures in the other. The semantic part, on the other hand, concerns about meaning of language expressions which reflects the interpretation of objects and parts in spatial languages.

Integration of IFC and CityGML is seen today as a needed step for getting a more complete picture of 3D modelling at different levels of detail i.e., sharing and exchanging information between building industry objects (represented in IFC) and geospatial object (represented in CityGML). Several efforts have been made to integrate CityGML and IFC. These efforts are mainly in form of; developing frameworks, extended discussion for addressing requirements, or developing conversion tools. For frameworks, IFC for GIS (IFG) Project was initiated by The Norwegian Strate Planning Authority (Statens Bygningstekniske Etat) and completed in 2007. This framework aimed to exchange building information between CAD systems and GIS using IFC. The project succeeded to create a mapping specification from XML version of IFG geometry to GML and vice versa [7]. Looking specifically on technical aspects, another framework was proposed by Nagel (2007) and aimed for algorithms that automatically transform IFC building models into CityGML models [8]. In 2009, Isikdag & Zlatanova (2009) have complemented Nagel's framework by proposing a framework for automatic generation of buildings in CityGML using BIM based on definition of building semantics and components [3]. Following the holistic view of 3D city modelling aspects, an extended discussion on conceptual requirements for converting CityGML to IFC models was proposed in 2009 by a team led by Thomas Kolbe at the Technical University of Berlin [9]. They proposed a framework that integrates 3D graphics/data of buildings and urban areas (X3D, DXF, KML, COLLADA, etc.) with semantic data in a CityGML target schema. Additional to that, a few conversion environments can be seen in this area. Van Berlo (2009) demonstrated his team's latest Application Domain Extensions (ADE) that integrates Building Information Model (BIM) data based on the open standard Industry Foundation Classes (IFC) into CityGML [10]. Not only research efforts, but commercial software products for conversion from IFC to CityGML (e.g., IfcExplorer [11] and Safe Software [12]) also contribute to the development of 3D city modelling integration. However, these attempts have either; a) an approach for a unidirectional conversion with a focus on converting geometries (mostly from IFC to CityGML), b) a discussion about what should be done in terms of integration i.e., an operational solution has not been implemented yet, c) focused on down-grading IFC to lower LoDs in CityGML or d) a discussion on the interest of rich semantics of IFC.

Several studies [3, 4, 9] have emphasized that a formal framework for strict semantic and geometry conversion is required for a complete integration of CityGML and IFC. As a consequence, the purpose of this paper is to propose and describe a unified model oriented approach that can be used for bidirectional conversion between IFC and CityGML. The proposed approach thereby contributes towards increasing integration of CityGML and IFC for extending 3D city models' applications.

Geometry is highlighted as one of the main problematic concerns for integrating IFC and CityGML [9, 13]. However, most of the recent efforts have focused on the conceptual integration or conversion processes. Considering the vast amount of efforts for defining geometric differences and developing conversion algorithms [14], this type of problem is not in our objectives. In this study we focus our discussion on the conceptual integration and mapping of different objects in both IFC and CityGML standards.

The rest of the paper is organized as follows: Section 2 represents our research method and a conceptual framework for the proposed reference ontology. A motivation of the proposed ontology is also provided. In section 3, we present our results in an IFC building model, CityGML building model and the proposed Unified Building Model (UBM). A formal mapping, through the proposed reference ontology, between IFC and CityGML extended with discussion and conclusions is represented finally in Section 4.

2 RESEARCH METHOD

Ontologies are very important tools in the interoperability domain. They are used for defining well defined and unambiguous semantics of terminology systems [15, 16]. Ontologies are mainly used for communication languages either between humans or computers. They have also recently been used for spatial information by specifying the semantics of the spatial objects and their interrelationships. Three main uses of ontologies may be observed; i) for assisting communication between human beings, ii) for achieving interoperability between software systems, and iii) for improving design and quality of software systems. For the purpose of this paper, we focus only on issues related to achieving interoperability between IFC and CityGML.

On one hand, logical-based ontologies are based on the logical theory proposed by Copi (1979). This kind of ontology, from its name, is specified by logical axioms and definitions that are defined for expressing the relationships between entities and classes. Through its logical definitions, direct interoperations between the two logical-based ontologies can be admitted or rejected [17]. On the other hand, non-logical ontologies do not have consistent rules for constraining or permitting interpretations based on semantics of terminology systems. This type of ontology is often used for developing standards that specify meaning of a terminology by fixing a domain for interpretation. Van Oosterom et Al. (2006) and Zlatanova et al. (2006) argue that the best approach for interoperability between BIM (i.e., IFC) and GIS (i.e., CityGML) models is integrated geometric models and harmonised semantics [18, 19]. Bittner et al. (2005) state that when semantics have big differences, interoperability will be difficult through direct matching of different objects from the two integrated domains [20]. Big errors may then take place. Interoperability or integration between such two heterogeneous domains (e.g., IFC and CityGML) may be achieved by a third more expressive terminology that intermediates their interoperability and transfer of information. This type of ontology is known as reference ontology [21, 22].

Our research approach for IFC and CityGML integration is based on developing a more expressive intermediate model that facilitates the transformation of spatial information from IFC to CityGML and vice versa. We focus our model only on buildings, therefore, we call it Unified Building Model (UBM). As our proposed UBM should be more expressive than both IFC and CityGML building models, it holds all concepts and relationships that exist in both building models. The conversion between IFC and CityGML is a two-steps process in which a model is firstly converted to the UBM and secondly to the target model. For our proposed reference ontology, and based on study of Bittner et al. (2005), we use logical-base ontology to specify clear rules that defines relationships between objects and classes in the UBM and transformation rules as well. The proposed UBM may be then extended to formulate a communication standard between IFC and CityGML that is often called meta-standard [23, 24].

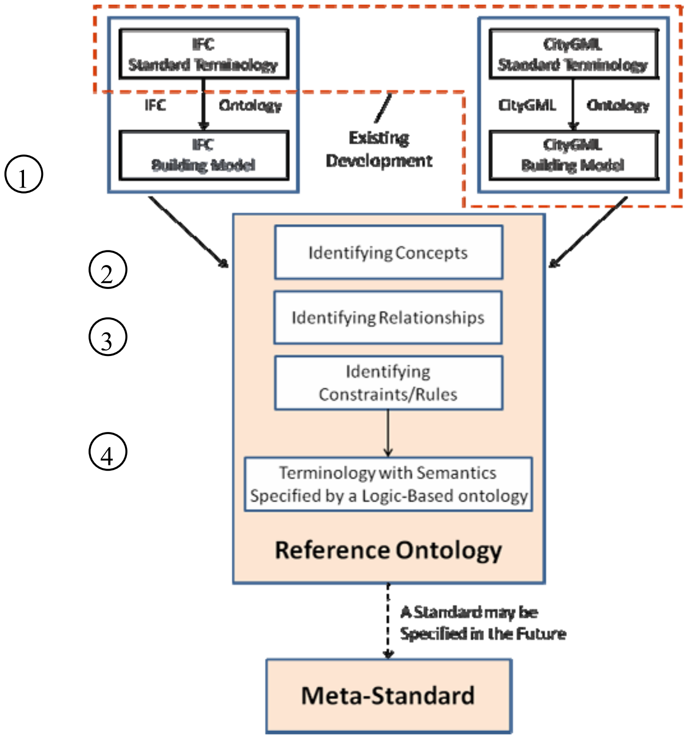

***Figure 1**. Research Methodological Framework*

The proposed reference ontology in this study highlights an extended ontology that contains all features and object from both IFC and CityGML domains. As it is mentioned above, the focus in this study is on models of buildings. Therefore, our ontology represents the transformation of only building models information between IFC and CityGML and vice versa as well storing of their information. Due to its wide acceptance, Unified Modelling Language (UML) has been selected for building the structure of our proposed ontology i.e., the proposed Unified Building Model (UBM). Developing the reference ontology consists of different steps as shown in (Figure 1):

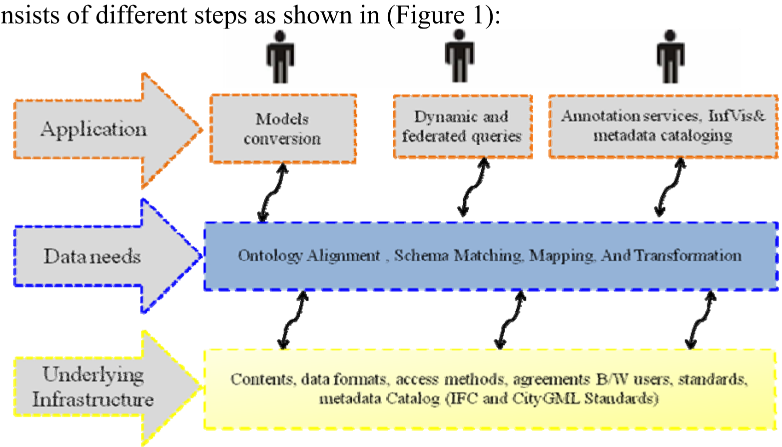

***Figure 2**. Conceptual Framework of the Proposed Reference Ontology*

1) As there is no universally accepted building model for IFC; different researchers like Benner et al. (2005) and Nagel (2007) have provided informal UML models for IFC according to their understanding of the IFC standard. In a similar manner, we firstly develop a UML model for IFC building model.
2) Identification of identical concepts in both IFC and CityGML ontologies. This process is used to specify direct and indirect mapped object.
3) Identification of relationships among objects and combined concepts. For example how different building elements are related to each other in IFC and how their faces are combined in CityGML in the *_BoundarySurface* class.
4) Identification of constraints in forms of rules for information transformation between IFC and CityGML through the reference ontology.

A conceptual model helps research to understand the problem and formulate research questions and hypothesis is represented in (Figure 2). At an early stage of this research we propose a high-level conceptual framework that shows three layers. Users interact with the model using different application interfaces; we mentioned some of them as examples. In reality, an application can be any number of services that facilitate engineering work based on both IFC and CityGML standard.

2.1 Why Reference Ontology?

Reference Ontology was introduced the first time as a definition during the 26th German Conference on Artificial Intelligence [25]. Many reference ontology definitions, since then, have been proposed by different researches and to highlight different fields such as: describing specific domain, being specific about real application, being independent from specific objects and increasing validation with usage of a reference domain from two specific domains [26]. In spatial information domain, the first initiatives have been done a few years earlier linking between Geographic Information Systems and CAD terminologies and applications [22].

By applying reference technology over IFC and CityGML conversion, we can establish semantic relationships between their specific terminologies and the broader terminology in our proposed UBM. This relationship is established by firstly transform from IFC or CityMGL to the broader terminology in the UBM and secondly from the UBM to the other specific terminology.

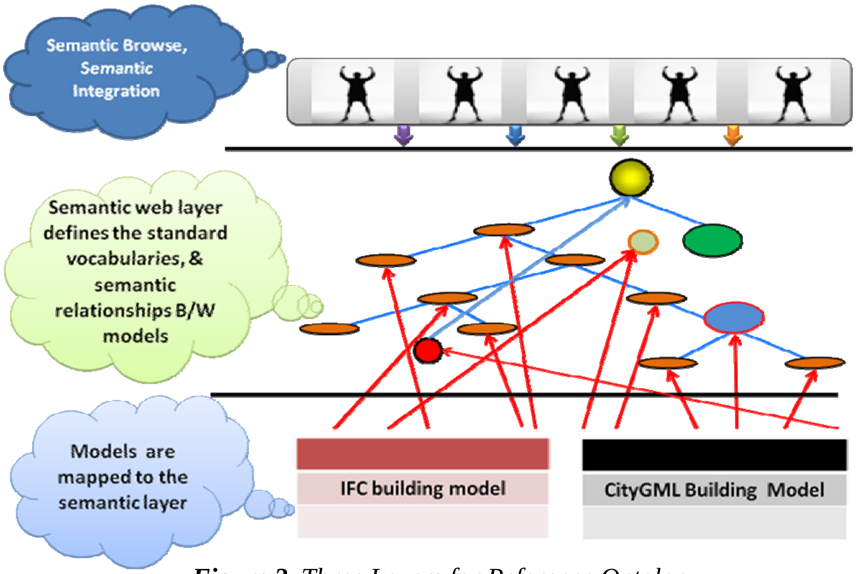

***Figure 3**. Three Layers for Reference Ontology*

Despite of the similarity between IFC and CityGML with respect to the representation of geometric and toplogical information, there is complex semantic heterogeneity between them. By developing reference ontology, a number of advantages can be achieved. With reference ontology, there is no need to establish direct links between their various terminologies that are represented in object and classes. Instead, we only need to transfer between terminologies in each standard, IFC and CityGML, and the reference ontology i.e., the UBM. Additional to that, the UBM terminologies allow us to use an expressive modelling language (e.g., UML) that has capabilities for representing various terminologies of the two domains. Additional to that, reference ontology is useful in the case of IFC and CityGML as both standards have a very rich semantic models which increases the complexity of relationships at different LoDs). Moreover, further development for meta-standard may be seen as a natural extension of reference ontology. Meta-standard in this area may be very useful for being a common platform with relational database management system (RDBMS) that represents data directly from both domains and contributes to the 3D city modelling domain. Semantic layer that represents the reference ontology is meant to handle the semantic heterogeneity between the building models in both standards. A common and independent vocabulary in term of class hierarchy can be created using either frame ontology tools or language like OWL (Ontology Web Language). Figure 3 demonstrates the approach with the following main features that make it feasible:

1. Models integration is one of the key problems that semantic web aims to address.
2. To go beyond data model, semantic web relies on using standard ontology to integrate different models like IFC and CityGML.
3. Several standards based on XML are used to encode ontologies e.g., Resource Description Framework (RDF/RDFS), Sesame, DataLink, Web Ontology Language (OWL), etc.
4. Available tools and methods supporting this approach are on-hand, both open source and commercial on shelf products.

There are several semantic languages that can be used for semantic integration of different models. Examples of these languages that we may use for the implementation of our proposed reference ontology are: i) **RDF & RDFS**; these frameworks offer semantic model based on the directed acyclic graph structure. Additional to that, they can be used for defining resources (Databases) and relationships among them, ii) **OWL**, which provides a more sophisticated XML-based knowledge representation language based on a description logic (DL), and iii) **D2RQ**, which is a declarative language and a platform that describes mappings between relational database schemata and ontologies of OWL/RDFS. The mapping can be further used to enable application for accessing RDF views on a non-RDF database.

3 RESULTS

In order to interoperate CityGML and IFC it is essential to develop building models for both. This section discusses the development of building models for IFC and CityGML.

3.1 IFC Building Model

Industry Foundation Classes (IFC) is designed as an object oriented format that provides a universal base for information sharing in building lifecycle (Eastman, 1999). It has been developed by the International Alliance for Interoperability (IAI) based on the EXPRESS language as a part of the STEP standard (ISO 103030) for the product data exchange [27]. The schema of IFC is quite complex. In order to only represent an IFC model, we had to extract only the needed objects that formulate a building according to our proposed ontology. As there is no universally accepted building model for IFC [28], we therefore present our IFC building model based on the work done by IAI and ISO in the form of IFC standard documentation [27] and ISO 16739 standard [29]. UML standard notations are used for developing the IFC building model and shown in (Figure 4).

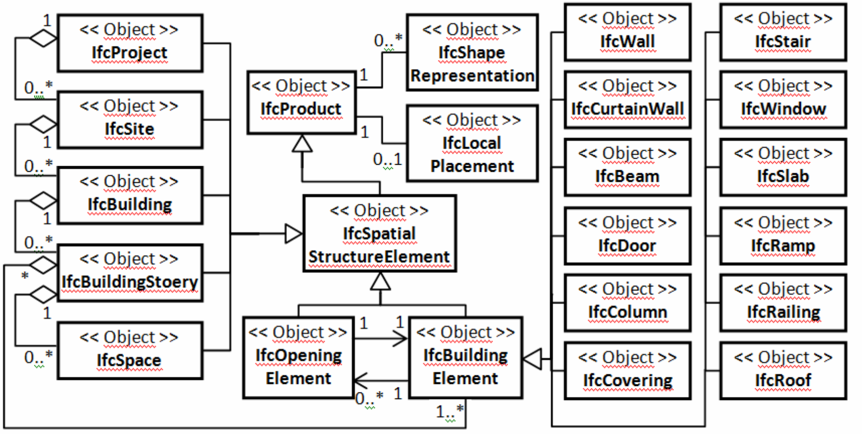

***Figure 4**. IFC Building Model*

The IFC building model is represented with a hierarchical spatial structure starting from *IfcProject* and *IfcSite* that are not out of our scope for this paper. A building (*IfcBuilding*) in IFC may have at least one storey (*IfcStorey*) or multiple stories. Each building storey may have zero or multiple stories. Each building storey may have zero or more spaces (*IfcSpace*) related to it i.e., a building structure which has only one wall is a building with zero spaces. Rooms in IFC are represented by *IfcSpaces* class. Building elements and opening elements are represented as subtypes of spatial structure elements (*IfcSptailaStructureElement*). Each building element (*IfcBuildingElement*) has zero or more opening elements (*IfcOpeningElement*) i.e., a wall without any door or window has zero openings, whereas each opening element (like door, window) is attached to only one building element. Figure 4 shows that *IfcSpatialStructureElement* links between building elements and upper structure of building (project, site, building, storey and space) as it defines spatial structure of a building and its parts. It is derived from *IfcProduct* that refers to geographic locations (*IfcLocalPlacement*) of building elements and their geometries (*IfcShapeRepresentation*). Geometric representation in IFC is based on geometric model schema part 042 of STEP standard format. Although, that there are different geometric models defined and implemented in the standard (e.g., Constructive Solid Geometry (CSG), Boundary Representation (BRep) or Sweeping), but most of the practiced IFC models are built on solid geometries.

3.2 CityGML Building Model

CityGML is defined as a common semantic information model and an open standard that has been implemented as an application schema for Geographic Markup Language 3 (GML3). It is used for representing 3D urban objects that can be shared over different applications [30, 31]. Developed by the Open Geospatial Consortium (OGC) [32] and the ISO TC211 [33], GML3 is the extendible international standards for spatial stat exchange. CityGML has been also developed as an open data model expressed by an XML schema. Likewise in IFC, this schema however, allows CityGML to store and exchange 3D objects and city models of different applications. In Figure 5, we present CityGML building model that has been developed based on ISO 19107 [34] and ISO 19109 [35]. The figure represents an excerpted version from the CityGML standard in which only the building elements that are used for our conversion to IFC.

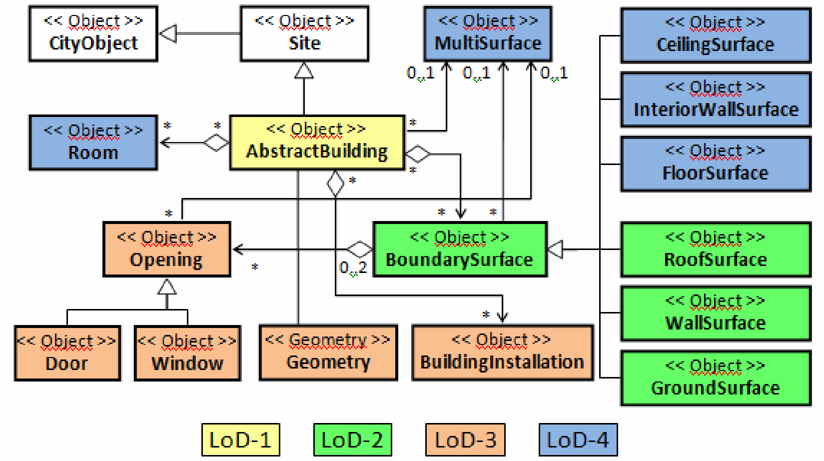

Figure 5. *CityGML Building Model*

CityGML is developed in five levels of detail (LoDs) ranging from the less detailed (LoD0) for two and a half dimensional Digital Terrain Model (DTM) to the more detailed (LoD4) for interior details in buildings. These five levels give CityGML the capability to range in 3D modelling from large areas to very specific areas or even single buildings simultaneously under the same application. A brief explanation for LoDs is provided as follows:

- ***LoD0,*** represents 2,5 dimensional Digital Terrain Model (DTM) for at a regional scale with built areas as blocks.
- ***LoD1,*** is the first representation of single buildings. They appear only as block with flat roofs for all types of buildings as an abstract level.
- ***LoD2,*** represents single buildings with their roofs and exterior surfaces differentiated. From this LoD, *_BoundarySurface* becomes a core for defining the outer building as well as space facades by classes of *WallSurface*, *RoofSurface*, *GroundSurface* and *ClosureSurface*. External details attached to building facades also appear at LoD2. This is done by the help of *BuildingInstallation* class for defining the appearance of building elements like ramps, chimneys, balconies, beams and columns.
- ***in LoD3,*** a building is represented in an architectural model with details of roofs, walls and exterior as well as interior structural elements. The opening also starts appearing at this LoD in different boundary surfaces of building elements as Doors or Windows.
- ***LoD4,*** gives a complete model of a building by adding interior structures of building elements. Rooms are the basic units at this LoD to define building interior structure by boundary surfaces such as *CeilingSurface InteriorWallSurfaces* and *FloorSurface*. At LoD4, all desired details can be presented in BuildingInstallation class, interior installations in *IntBuildingInstallation* class or even movable furniture elements in BuildingFurniture. In this paper, we focus only on building structural elements. Therefore, furniture objects are not considered in our model or ontology.

In CityGML, the most common two types of geometric models are Sweeping and Boundary Representation (BRep). However, primitive solid objects can be constructed from boundaries of building elements that are defined by *_BoundarySurface* class. This information is very important when converting from IFC to CityGMl model or vice versa as conversions among geometric models have to be considered as well.

3.3 The Unified Building Model (UBM)

IFC model does not have level of details. The model represents a building with all exterior and interior details. Level of details depends on the amount of features in the model itself. By omitting features or removing layers of specific details (e.g., layer of doors, windows, furniture, etc.) a model can be less detailed. In this section, we present our UBM model that is based on the proposed reference ontology for integrating IFC and CityGML building models. Being reference ontology, the UBM has been developed in a way to represent all objects in both IFC and CityGML building models. It uses therefore more expressive terminology than IFC or CityGML building models separately. For building our reference ontology, all classes and their concepts have been collected from both IFC and CityGML building models with omitting their relationships. In case of overlapping objects, concepts were merged; otherwise new concepts have been created to capture all indoor and outdoor objects. Finally, relationships among all objects have been built with consideration of semantic and geometric properties.

Figure 6 shows the UBM in which different colours are used to represent different LoDs. As the study is limited to building structure, the building object is the starting point of our discussion of the UBM. In the proposed ontology, room concept (from CityGML) and storey concept (from IFC) have been merged together by dividing a building into storeys (*UBMStorey*), at least one storey in each building. A building storey is defined by different opened (*UBMOpenedSpace*) and closed spaces (*UBMClosedSpace*) as subtypes of *UBMSpace*. The *UBMClosedSpace* represents a room that is surrounded by six boundaries (e.g., 4 walls, floor and ceiling), while *UBMOpenedSpace* represents other spaces like atriums and corridors. Boundary surfaces' concept (from CityGML) is merged with the concept of solid building elements (from IFC) in our ontology. Boundary surface is useful when a box model or surrounding of the whole building, part of a building or a specific storey is required. However, building elements (UBMBuildingElements) are useful for more detailed information about structural elements of building that is usually exist in an IFC model. In this case, opening (UBMOpening) information about doors (UBMDoor) and windows (UBMWindow) is linked to both boundary surfaces and building elements.

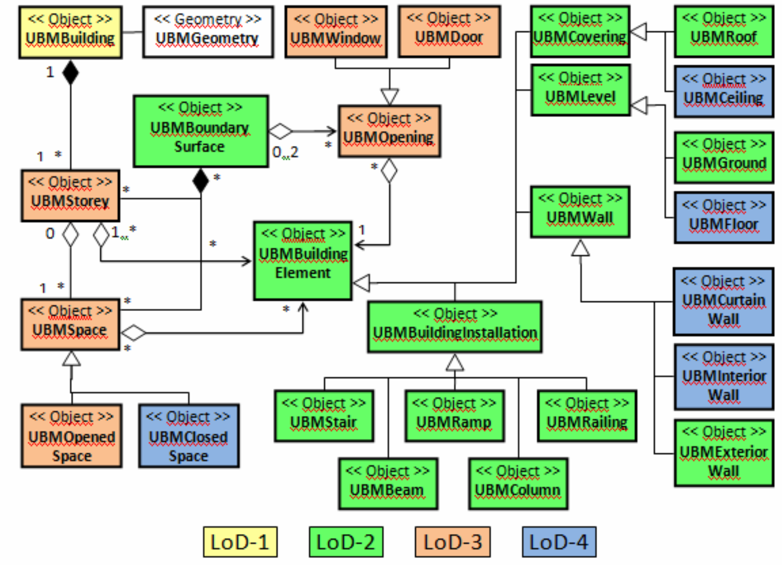

Figure 6. *The Unified Building Model*

For building elements, new concepts have been proposed to give more expressive terminology for including IFC and CityGML representation methods. Combining definitions of building elements, following concepts have been defined:

- *Covering*, a closing level that covers a space from upside. It has two types; *Roof* for the top covering of a building or the top storey, and *Ceiling* for the covering of a space in any intermediate storey.
- *Level*, a walkable (not only horizontal) level that represents bottom level of a space. It has two types; *Ground* for the bottom level of ground floor which has a connection to the outer ground, and *Floor* for the bottom level of a space in any intermediate storey.
- *Wall*, vertical/semi-vertical element that surrounds a storey or space. It has three subtypes; i) *CurtainWall*, an outer wall that covers a complete building facade or a part of it. It is usually unlimited or attached to only one storey, ii) *Interior*, an internal wall between rooms or spaces (does not have any connection with outer environment), and iii) *Exterior,* an external wall that has connection with outer environment and represents parts of external facades.

Objects like (ramps, chimneys, balconies, beams, column, etc.) are defined as building elements in IFC with solid geometry. However, they are defined as building installations in CityGML with multi surface definition (*CityGMLMultiSurface*). To combine these two concepts, we have adopted the building installation concept from CityGML (*UBMBuildingInstallation*) and connected the *UBMBuildingInstallation* class as a subtype of *UBMBuildingElement* class.

3.4 Conversion between IFC and CityGML

Conversion between IFC and CityGML as described above is done in two steps. Firstly, a model (IFC or CityGML) is converted through logical-based ontologies to the proposed UBM reference ontology. Secondly, another set of logical-based ontologies are used to convert from the UBM to the target model. In this paper we present the conversion methodology on a hospital building in Sweden as case a study. The building is owned by a company called Locum AB, one of the biggest owners for hospital buildings in Sweden [36]. In the company, they have decided to adopt the IFC standard in all of their upcoming buildings [36]. Figure 8 (a) shows an IFC model for the Norrtälje City Hospital in the north of Stockholm, Sweden which is used as a case study for our paper. In this paper, for the space limit we present our method for the intended conversion at only the LoD4 and the result is shown in Figure 8 (a-c).

From IFC to the UBM (LoD4):

At LoD4 of the UBM, all objects of a building structure i.e., the interior walls, floors, ceilings, etc. are represented. In IFC, there is no concept of specific *Room* object as in CityGML. *IfcSpace* class defines all volumes and areas that are bounded actually or theoretically. This definition includes rooms that are bounded by different building elements. As all IFC objects, Sweeping/CSG geometry is used for spaces and their elements which requires conversions to BRep geometric models that we use in the UBM. For differentiating between exterior and interior elements, we however propose a generation of two projection footprints, vertical and horizontal. The vertical footprint is a result of projecting vertical structure elements e.g., *IfcWalls* and *IfcColumn*, whereas, the horizontal footprint is a result of projecting horizontal structure elements e.g., *IfcSlab* and *IfcBeam.* Using geometrical information, building elements are checked versus the two footprints. Only connected objects will be represented as exterior building elements and others are interior elements. To create spaces in the UBM, information from *IfcWall, IfcRoof* and *IfcSlab* that form the boundaries of rooms are used. Information about both *UBMCeiling* and *UBMFloor* can be acquired from *IfcSlab* where a slab may represent both a ceiling for a storey and a floor for another storey on the top of it (for example, a ceiling for the 2nd storey is a floor for the 3rd storey). Geometries of elements that form each *IfcSpace* are checked. If they close a shape (coordinates of starting point is the same as of ending point), the space is stored in *UBMSpace.Closed* class. Otherwise, it is stored in *UBMSpace.Opened* class. It is important here to mention that information of all building elements that form a space is stored in *UBMBuildingElement* class and all boundaries of the room are represented within the classes aggregated under the *UBMBoundarySurface* class. They are connected through the *UBMSpace* class.

In IFC, opening elements (*IfcOpeningElement*) are attached to building elements. Inside each opening element, there is usually one filling element (*IfcWindow* or *IfcDoor*). *IfcOpeningElement* is used itself as an element to describe the geometry and semantics of the opening. In this case, *IfcOpeningElement* may contain multiple *IfcDoor* and *IfcWindow* elements with referencing their geometry. Two classes in IFC define the representation of doors and windows. The first, *IfcRelVoidsElement*, is a one-to-one linking relationship between an element that contain an opening element (e.g., a wall) and one opening element that creates a void in the element. The second, *IfcRelFillsElement*, is another one-to-one relationship between an opening element and an element that fills that opening. Geometric information about doors and windows are defined as Sweeping and CSG models as other building elements (e.g., walls and slabs). In CityGML, Window and Door objects are defined as subclasses of the abstract class Opening. They are, however, represented by different surfaces and modelled by *gml::MultiSurface* geometry. In our proposed UBM, we apply the same concept for opening elements as in CityGML. Therefore, the Door and Window objects in the UBM can be generated by acquiring information from classes of *IfcDoor* and *IfcWindow*. However, conversions from Sweeping /CSG geometric models that are used in IFC to BRep models that are used in CityGML have to be performed.

*** For simplification, *BuildingFurniture* and *IntBuildingInstallation* are not included in our model.

Formally, examples of the transformation rules may be written as: $f_{\text{Combination}}: \Omega_{[\text{IfcSpace, IfcWall, IfcRoof, IfcSlab}]} \rightarrow \Omega_{\text{UBMSpace.Closed}}$, $f : \Omega_{\text{IfcWall}} \rightarrow \Omega_{\text{UBMWall.Interior}}$, $f : \Omega_{\text{IfcSlab}} \rightarrow \Omega_{\text{UBMCovering.Ceiling}}$, $f : \Omega_{\text{IfcSlab}} \rightarrow \Omega_{\text{UBMLevel.Floor}}$

Figure 7 shows a set of building elements conform to the proposed UBM for the Norrtälje Hospital Building at LoD4.

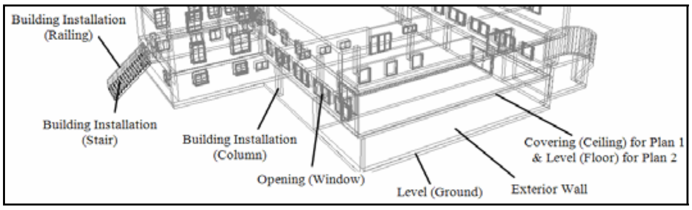

Figure 7. *A Part from Norrtälje Hospital Showing the UBM Objects*

From CityGML (LoD4) to the UBM (LoD4):

We have solved the problem of splitting an IFC element (for example a wall) in its exterior and interior faces by adding, in the UBM, exterior and interior classes as subtypes of wall. An opposite process should be carried out to aggregate different faces of a building element (for example wall) to form and IFC element. We, however, propose the generation of two projected footprints as it is introduced above to differentiate between exterior and interior elements. Information about building elements themselves is stored in different subclasses of the *UBMBuildingElements* class. In this case conversion from BRep to Sweeping/CSG geometric models are required. However, their surfaces information will be also referenced in the *UBMBoundarySurface*.

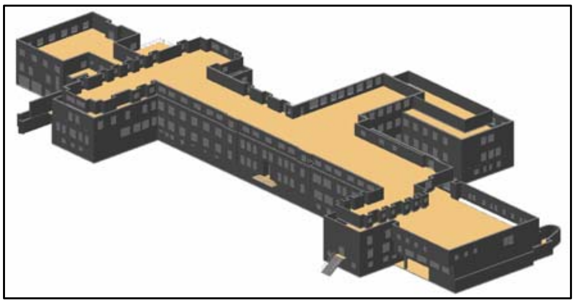

Figure 8 (a). IFC Model of Norrtälje Hospital

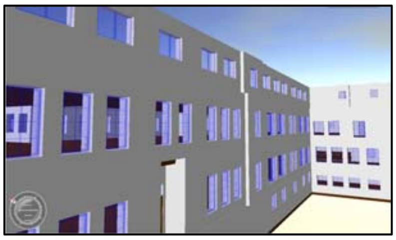

Figure 8 (b). *LoD4 for the Hospital Building - External View*

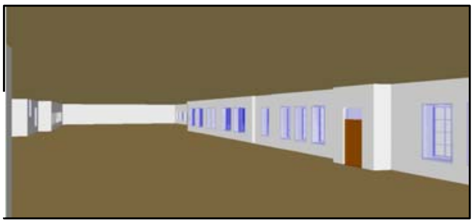

Figure 8 (c). *LoD4 for the Hospital Building - Internal View*

For the current step, to convert from CityGML to the UBM, we do not show transformation of all building elements, as objects in CityGML can be matched easily to their corresponding UBM objects, for example *CityGMLCeiling* is matched to *UBMCovering.Ceiling*. Opened spaces can be also formed at this level in a condition of a room in CityGML that does not have six bounding objects (4 walls or sides of walls, ceiling and a floor) or does not have a closing geometry of its bounding elements. Alternatively, classification of opened and closed spaces can be done manually or to be left for LoD4 as division of open spaces (e.g., dividing a long corridor in different open spaces). At this LoD, opening elements should also appear in the model. Our concept of opening elements is similar to that of CityGML as door and window are subclasses of the class opening. Therefore, one-to-one mapping can be done between *CityGMLOpening*, *CityGMLWindow* and *CityGMLDoor* into corresponding classes in the UBM. We have discussed differentiation between opened and closed (room) spaces at LoD3. Formally, examples of rules may be written as: $f : \Omega_{\text{CityGMLCeilingSurface}} \rightarrow \Omega_{\text{UBMCovering.Ceiling}}$, $f : \Omega_{\text{CityGMLInteriorWallSurface}} \rightarrow \Omega_{\text{UBMWall.Interior}}$, $f : \Omega_{\text{CityGMLFloorSurface}} \rightarrow \Omega_{\text{UBMLevel.Floor}}$, $f : \Omega_{\text{CityGMLRoom}} \rightarrow \Omega_{\text{UBMSpace.Closed}}$

4 Analysis and Discussion

IFC and CityGML represent indoor and outdoor spatial objects of a building. In order to fulfil the demands in urban planning applications and construction analysis, it is important to integrate IFC and CityGML. However, existing approaches do not provide complete integration because they mostly offer a unidirectional transformation i.e., from IFC to CityGML. Additional to that, the number of semantic models that support this integration is relatively small compared to geometric models.

In this paper, and by focusing on the semantic problem, we have presented an approach based on reference ontology for integrating IFC and CityGML. The aim is to create an ontology that supports a bidirectional conversion framework between both domains. We have then built, based on the reference ontology, a new Unified Building Model (UBM) that applies our rules and terminologies of the reference ontology. For converting from IFC to CityGML or vice versa, a two-steps approach can be used. Firstly, a building model can be converted from the source model to Unified Building Model (UBM), and secondly from the UBM to the target building model.

There is a significant overlapping for information content for mapping IFC and CityGML to the reference ontology UBM. However, there is no one-to-one mapping for all data. While there are concepts in the UBM are adopted as in IFC, there are others that are closer or adopted from CityGML definitions. The first step for this mapping is to extract the relevant semantic objects from IFC and CityGML that contain needed information and their geometries. That is followed by identifying the level of detail (LoD) which we target in the UBM. (Table 1) presents the corresponding elements for the mapping from IFC and CityGML into the UBM ontology.

Table 1. *IFC – UBM – CityGML Mapping*

IFC	UBM	CityGML
IfcBuilding	UBMBuilding	_AbstractBuilding
IfcBuildingStorey	UBMStorey	BoundarySurface - RoofSurface - WallSurface - GroundSurface - and other building elements
IfcSpace	UBMSpace - UBMOpenedSpace - UBMClosedSpace	Room
IfcSlab	UBMLevel	

- (Ground Slab) - (Floor Slab) - (Ceiling Slab)	- UBMGround - UBMFloor UBMCovering - UBMCeiling	GroundSurface FloorSurface CeilingSurface
IfcRoof	UBMCovering - UBMRoof	RoofSurface
IfcWall - (Exterior Wall) - (Interior Wall)	UBMWall - UBMExteriorWall - UBMInteriorWall	WallSurface InteriorWallSurface
IfcCurtainWall	UBMWall - UBMCurtainWall	WallSurface
IfcOpeningElement - IfcDoor - IfcWindow	UBMOpening - IfcDoor - IfcWindow	Opening - Door - Window
IfcBeam	UBMBuildingInstallation	BuildingInstallation
IfcColumn	UBMBuildingInstallation	BuildingInstallation
IfcCovering	UBMBuildingInstallation	BuildingInstallation
IfcStair	UBMBuildingInstallation	BuildingInstallation
IfcRailing	UBMBuildingInstallation	BuildingInstallation
IfcRamp	UBMBuildingInstallation	BuildingInstallation

From this study, we suggest that our proposed approach can be used for bidirectional conversion between CityGML and IFC. Additional to that, it may be developed towards a meta-standard application for developing a common platform for both domains in order to fully support their formats and 3D city models. Moreover, the approach provides a starting point towards complete integration of CityGML and IFC and the development of integration tools. We finally believe that our approach needs future research efforts on further extensions than only building models and for implementation process for testing and verification.

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