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# BIM to GIS-based building model conversion in support of urban energy simulation

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FACULTY OF GEO-INFORMATION SCIENCE AND EARTH OBSERVATION

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by

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Thesis submitted to the department of Physical Geography and Ecosystem Science, Lund University, in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation for Environmental Modelling and Management

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

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## Abstract

In the context of growing population and increasing greenhouse gas emissions, urban energy planning is becoming a topic of high concern. With the rapid pace of urban construction, it is claimed that 40% of America's total energy consumption is accounted by the building sector.

Energy modelling and simulation are believed to be effective in supporting urban energy planning. Today, the growing availability of 3D city models has facilitated energy simulations at various scales. While Building Information Model (BIM) provides users with the possibility to explore the energy consumption alternatives of a single building, GIS-based city-wide building models offer the chance to simulate urban energy demand at the city scale.

Considering that most of the existing GIS-based building energy simulations are using models with a lower Level of Detail (LoD), the aim of this study is to extract geometrically detailed and semantically correct information from BIM models to construct GIS models with a higher LoD in order to support more accurate Building energy simulations. Semantics of BIM models from different sources are matched with that of GIS-based building models, and geometry of BIM models are converted to conform to GIS-based building model standards. Specific concern is given to the extraction of openings that are absent from lower LoD CityGML.

After conversion, the result is used to perform a simple energy assessment to see how much influence a higher LoD CityGML model has on the energy simulation of a building.

Keywords: BIM, GIS, CityGML, Energy Assessment, Building Energy Modelling

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# 1. Introduction

## 1.1 BIM and GIS

In the world's most rapidly urbanizing regions, a booming population results in vast and urgent housing needs and accelerates the pace of civil construction. Therefore, housing in urban areas increases in density, height and architectural complexity, which adds pressure to urban planning management. Moreover, increasing attention is paid on the energy consumption of buildings, which accounts for a substantial portion of the overall annual energy consumption. Thanks to the development of 3D geographic information and 3D buildings as well as the extensive use of 3D city models, new approaches have been developed to evaluate the energy performance of individual buildings as well as for entire cities.

Today, two of the most received instances concerning 3D city models in the market are Building Information Model (BIM) and Geographical Information System (GIS). The two types of models developed in different domains for different purposes have contrasting advantages and limitations. The detailed and semantically rich 3D building models provided by BIM expose the information that is hidden by the physical exteriors and communication barriers, yet it lacks information of the surrounding environment which is accessible through GIS. On the contrary, GIS enables spatial analysis on a larger scale, which is essential for general planning and suitability estimation, but it is short in details of items such as indoor settings in a building. In an integration setting, developers aim to create a system to effectively manage information from heterogeneous sources in order to support decision making.

The aim of integrating BIM and GIS lies not only in enhancing the utilization of existing 3D models, but also in facilitating interoperability of 3D city models in domains like urban planning, architecture designing and environmental engineering. Today, 3D models are commonly seen as presentation tool and visual expression of city objects, yet they are still far from reaching their full potential. By integrating the use of BIM and GIS, selected details of BIM can be utilised as further inputs for large scale spatial analysis, which may contribute to the accuracy of urban analysis and in turn influence urban planning and decision making.

In this study, specific concern is given to the energy performance of the buildings in urban environments. 3D building models are studied, compared and converted from BIM to GIS-based models in order to achieve information integration and more detailed energy analysis.

## 1.2 Research objectives

The main objective of this study is to contribute to filling the gap between BIM-based energy analyses and GIS-based energy calculations by including BIM extracted geometric and semantic detail into a GIS-based city model to facilitate large scale building energy analysis with richer information source and higher accuracy.

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The specific research questions are:

1. Extract detail information about building opening (windows and doors) from BIM models.
2. Convert BIM-extracted information into a CityGML framework.
3. Test energy calculation algorithms with opening details included,
4. And compare the energy calculations in different scenarios (with openings, without openings and with a predefined opening ratio).

## 2. Literature Review

### 2.1 Building energy efficiency

Building energy efficiency is a topic of major concern when it comes to modern building construction. According to the annual energy review conducted by the US department of energy (DOE) in 2008, the building sector alone had been responsible for 40% of the world' energy consumption. Building energy modelling is believed to be effective in energy reduction. In Sweden the construction and renovation of a building always need to comply with the regulations by National Board of Housing, Building and Planning (Swedish: *Boverket*), *Boverket's* Building Regulation (*Boverkets byggregler*, BBR). This is ensured by the supervision of municipalities which approve building permits according to BBR. It is mandatory for buildings under construction to pass the test for energy efficiency. Figure 1 shows the online self-checking portal "Energy Balance calculation BBR" provided by the Swedish building regulation authorities that take user input information and calculate the maximum power demand and annual energy demand according to the specific version of BBR the building should apply.

The screenshot shows the 'Energy Balance Calculation BBR' portal. The main content area is titled 'Bereken warmtekracht en energiebehoefte voor een gebouw, in elk land.' and includes a search bar and a navigation menu on the left. The main content area is divided into several sections:

- BBR building code version, climate, temperature:** A table with columns for BBR version, County, Climatic zone due to BBR, and temperature values.
- Losses: Transmission, ventilation, infiltration:** A table with columns for Predefined buildings, Envelope area [m2], Insulation: About [W / m2 ° C], Infiltration at 50 Pa [l / s m2], Total ventilation flow [l / s], Extra ventilation through open windows [kWh / m2 year], Domestic hot water [W / flat], Electric Appliances Energy [kWh / year], and AC cooling [kWh / year].

BBR building code version, climate, temperature			
BBR version	County	Climatic zone due to BBR	
2009	Norrbottn County	IN	
Electric heating	Temperature per city	Dim Winter outdoor temperature DVUT [° C]	-30.3
	Kiruna Airport	Indoor temperature [° C]	20
		Summer day [° C]	12
		Winter My average day [° C]	-13.9

Losses: Transmission, ventilation, infiltration			
		Watt / ° C	Watt
Predefined buildings	Envelope area [m2]	250.2	
Choose building	Insulation: About [W / m2 ° C]	0.344	
	Infiltration at 50 Pa [l / s m2]	0.6	
	Total ventilation flow [l / s]	42	
	Extra ventilation through open windows [kWh / m2 year]	4	
	Domestic hot water [W / flat]		500
	Electric Appliances Energy [kWh / year]	800	100
	AC cooling [kWh / year]		

Figure 1 Energy calculation program in Sweden (Boverket, 2015)

A number of parameters are required for a thorough calculation of the energy consumption of a building. Traditionally, all the information required in building energy calculation were entered by the modeler. Simplification of building geometry was often applied due to the amount and complexity of the input. DOE2 and EnergyPlus are examples of expert building energy simulation tools that require re-entering of all relevant information such as building geometry, enclosure and HVAC (heating, ventilation, and air conditioning) system. The entire process is labour-intensive and often requires on-spot

inspections (Cho et al., 2015).

## 2.2 BIM and GIS

As one of the most promising developments in architecture, engineering, and construction industries, BIM had been used in the field of construction industry many years before it was brought into the sight of GIS users. It was designed to enhance interoperability between different stakeholders during the building process. Virtual models with clear physical structure and precise geometry are constructed digitally to facilitate analysis and control. BIM has already been adopted in the use of land administration under the concept of 3D cadastre in a few cities over the world (Ho & Rajabifard, 2016). With this background, the common standard Industrial Foundation Classes (IFC) was developed as a reference model for BIM models in the building industry. IFC was initiated with the idea of archiving the details of a building project throughout its life cycle. More fundamentally, it is a shared data model. Besides representing building components, IFC also supports advanced processes and analyses based on the spatial relationships between these components. An IFC building model has the basic structure as displayed in Figure 2 according to the specifications made by International Alliance of Operability (IAI) and International Standards Organization (ISO) in the IFC standard documentation.

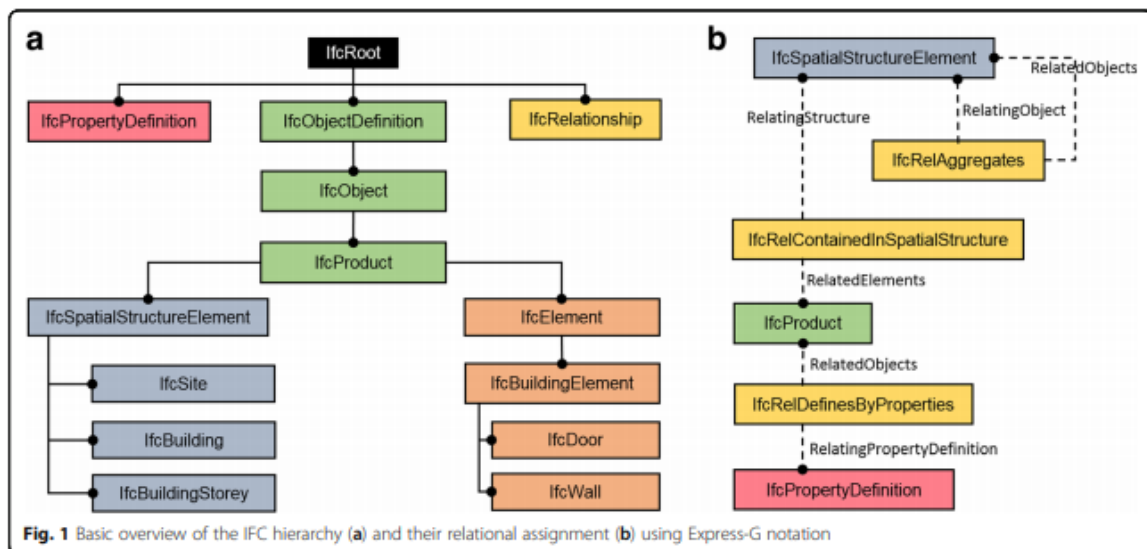


Fig. 1 Basic overview of the IFC hierarchy (a) and their relational assignment (b) using Express-G notation

Figure 2 Basic Hierarchy of IFC (Vonthron et al., 2018), licensed under Creative Common 4.0

In IFC hierarchy three major classes *IfcPropertyDefinition*, *IfcObjectDefinition* and *IfcRelationship* are defined under the superclass *IfcRoot*. Among the three classes, *IfcRelationship* realises abstraction of all objectified relationships (preferred relationship semantics among objects) in IFC, *IfcPropertyDefinition* defines all characteristics that can be assigned to objects and *IfcObjectDefinition* encapsulates the generalization of all semantically-treated objects and processes. *IfcObjectDefinition* is involved in primarily four relationships-- assignment of other objects, association with external source, aggregation of other objects and nesting of other objects. *IfcProduct*, as the abstract class that represent all objects with a geometric or spatial content, contains the subtype *IfcElement* that covers physical items and *IfcSpatialElement* that covers spatial items. Building elements like doors (*IfcDoor*) and Walls (*IfcWall*) are instances of *IfcBuildingElement* which

is in turn the subclass of *IfcElement* while building structural information such as *IfcBuildingStorey* is an instance of *IfcSpatialStructureElement* which is in turn the subclass of *IfcSpatialElement*. A simplified structure of IFC hierarchy is shown in Figure 3.

Though *IfcDoor* and *IfcWall* are both subclasses of *IfcBuildingElement* (which means there is no hierarchical difference between them), *IfcRelationshipDefinition* allows them to be interconnected using two different relationships. Openings are cut from the walls using Boolean difference, the relationship is referred as *IfcWall*→*IfcRelVoidsElement*→*IfcOpeningElement*. *IfcRelxxx* are relationships defined in IFC standard, arrow here indicates how relationships are connecting objects. In turn doors and windows are placed in the openings to fill the gap with another relationship *IfcOpeningElement*→*IfcRelFillsElement*→*IfcWindow/IfcDoor* (Isikdag & Zlatanova, 2009). One *IfcOpeningElement* can be filled with none to many elements. This kind of relationship is referred to as implicit geometry in IFC where the geometry is implied in the parameters of an IFC file or hidden in the object model specifications (Donkers, 2013).

The structure of IFC supports dynamic models. There are core elements and containers for building elements which store information about elements in general. Other elements can be added using the core elements. This feature provides users with more flexibility in the way to connect different object types. For example, *IfcWindow* is linked to a building element such as *IfcWall*, many walls together enclose a space (*IfcSpace*) and the space is connected to a building storey (*IfcBuildingStorey*). In this case the schema of how *IfcWindow* is connected to *IfcSpace* (*IfcWindow* – *IfcSpace* – *IfcBuildingStorey*) is user-defined and stored in a separate data file. If, in specific models, a space is expanded for multiple storeys, the route can be altered as *IfcWindow* – *IfcBuildingStorey* – *IfcSpace* (El-Mekawy et al., 2012b).

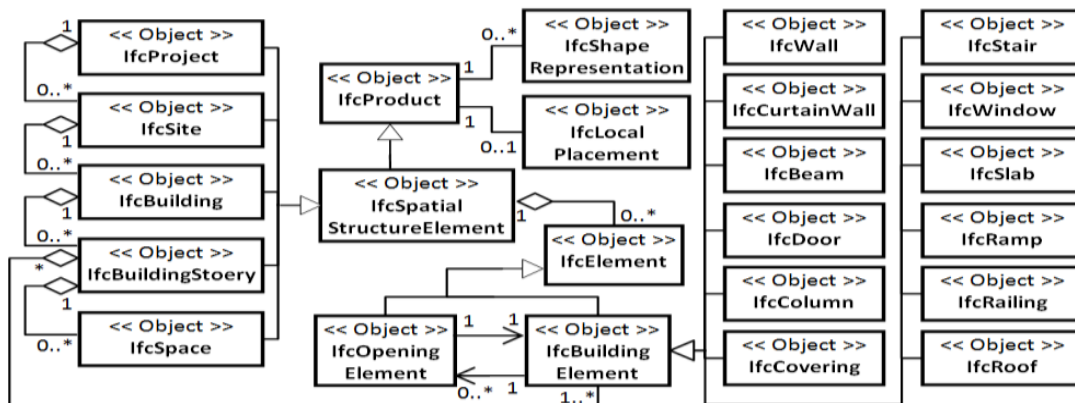


Figure 3 UML model of IFC building model (El-Mekawy et al., 2012b), licensed under Creative Common 4.0

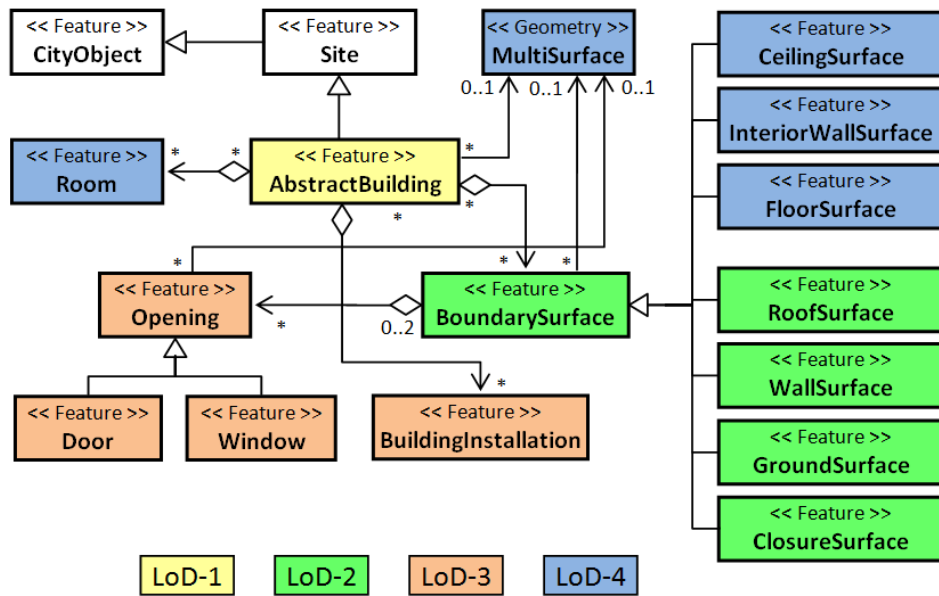


Figure 4 UML of CityGML building model (El-Mekawy *et al.*, 2012b), licensed under Creative Common 4.0

GIS, on the other hand, is a system to store, manage, analyse and present geographical data of all types. A comparison between BIM and GIS is shown in Table 1. 3D GIS emerged with the demand to acquire 3D attributes of objects in the real world (Deng *et al.*, 2016a). 3D GIS schemas such as GML are popular today in which 3D reference are given to semantic rich objects in the model. City Geography Mark-up Language (CityGML) is currently the most well-recognized instance of 3D models in GIS (Figure 4). Inheriting the structure of GML defined by Open Geospatial Consortium (OGC), CityGML is defined as an open and standardised data model as well as an exchange format to store digital 3D models of building blocks and landscapes in the city. It makes specifications of description for the most common 3D features in cities and relationships between them (OGC, 2018). The amount of detail captured in the 3D model is referred to as Level of Detail (LoD). The idea of classifying LoD is to indicate for city modelling how thoroughly 3D information should be inspected and how much detail a model should contain (Biljecki *et al.*, 2014). According to OGC standard, there are 5 LoDs for CityGML. As is shown in Figure 5, the first level of detail is denoted as LoD0, which records the footprint (either the ground occupancy or the roof coverage) of an object on a horizontal plane. LoD1 represents buildings by volumetric blocks with horizontal roof top; LoD2 attempts to add generalized shape of the roof; LoD3 includes more detail by adding openings such as windows and doors as well as other details that characterise the exterior shape of a building; and LoD4 contains also interior design of the building with the potential to include furniture (Donkers *et al.*, 2016).



Figure 5 Building represented in CityGML LoDs (Biljecki *et al.*, 2014), licensed under Creative Common 4.0

Table 1 BIM and GIS general comparison

	<b>BIM</b>	<b>GIS</b>
<b>Aim</b>	Enhance interoperability in building industry/ Describe a vision of a building even if it does not exist	Portray a part of the real world, storing, managing, analyse and present geographical data
<b>Level of detail</b>	Detailed in the physical structure	Not detailed in physical structure
<b>Spatial capability</b>	Cannot perform spatial analysis	Can perform spatial analysis
<b>Coordinate system</b>	Local coordinate system/ Flat surface	Use map projections
<b>File format</b>	IFC, dwg	GML, XML, shp
<b>Software</b>	IFCExplorer, Revit, FME	ArcGIS, QGIS

Today, most applicable CityGML models are still the coarse ones (up to LoD2) characterized by block-shaped buildings with simplified roofs. There is an increasing need for the construction of CityGML models with a higher level of detail. To include the openings (windows and doors) that are not portrayed in LOD2 models are believed to be beneficial in that it: 1) offers more realistic visualisation that are beneficial for urban planning; 2) facilitates more accurate energy cost estimates of buildings; and 3) serves as a contributing factor for the evaluation of housing prices since they are often related to the amount of inlet sunlight and the surrounding view (Donkers, 2013). In practice, efforts to fulfil a more-detailed structure often require additional data source and extra manual work. For example, Kada and McKinley (2009) managed to obtain a more detailed roof structure by fitting templates of common roofs to the footprints and elevation points while Elberink and Vosselman (2009) reconstructed the roof model by segmenting the LiDAR points using a graph-based approach. Due to the limited accessibility regarding to extra data source such as terrestrial laser scanning survey and airborne sensors, most of the studies on LoD3 CityGML development was done semi-manually, which was usually time-and-labour-consuming.

## 2.3 BIM and GIS integration

Attempts have been made to realize the integration of BIM and GIS. The way of categorizing existing BIM-GIS integration methods is adopted from a study by Amirebrahimi *et al.* (2015). According to Amirebrahimi *et al.* (2015), these methods can be divided into three different levels as: data level, process level and application level.

### 2.3.1 Data Level

At data level, the integration regards to the revision of standards, creation of new

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standards or the translation of data format. An example of BIM-GIS integration on data level would be the use of Unified Building Model (UBM) as an intermediate model. In this case, UBM encapsulates information from both BIM and GIS models, thus protecting information integrity and avoiding translation. In construction of the UBM, classes together with their concepts are collected from both models, concepts that overlap are merged and new objects are created to preserve both indoor and outdoor objects. Also, relationships between objects are rebuilt in the framework of UBM (El-Mekawy *et al.*, 2012a).

Another perspective for data level integration focuses on the conversion, translation and extension of existing standards. For the fact that the current CityGML and IFC standards do not provide adequate support for urban and infrastructure projects, further steps are taken to resolve data exchange problems. Recently a semi-automatic approach was implemented with the ETL process, which Extracts homogeneous data from the source systems, Transforms them into proper format or structure and then Load them into data warehouse. First, ETL converts IFC geometry to vector geographic geometry and assigns Global ID of objects in IFC to corresponding vector objects. Second, a semantic conversion is conducted from BIM to GIS, relating IFC semantics to corresponding vector object as attributes. Finally, the dataset is geo-referenced based on a transformation mechanism while the centroid of the entire BIM model is assumed as the reference point of the IFC model (Rafiee *et al.*, 2014). The methodology in this study is developed under the concept of this ETL approach.

### 2.3.2 Process Level

An integration at process level does not change the format or structure of data, instead it uses a reference ontology as part of the semantic web or takes advantages of the Web Services in order to store and represent the differences of objects (Liu *et al.*, 2017). Semantic web has the intrinsic capacity to integrate data from different sources and promote interoperability. A reference ontology is supposed to offer a global view for high-level ontologies in extended and specialised domains rather than to create a new set of ontology. While remaining the semantic information in different domains, the integration is still allowed on semantic level. It also allows bidirectional conversion between BIM and GIS. Semantic web-based integration methods are more flexible in the way that ontologies defined within the framework can be applied for future use. However, the semantic web technology is still evolving and awaiting for the enrichment of the internationally approved ontology definition.

The Web Services test bed phase 4 (OWS-4) project by Open Geospatial Consortium (OGC) attempted to use Service Oriented Architecture (SOA) to promote the integration of BIM and GIS at a process level without addressing the integration issues or implementing new web services. And a compromised Transactional Web Feature Service was finally achieved to serve both IFC and CityGML features (Amirebrahimi *et al.*, 2015).



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### 2.3.3 Application Level

At application level an integration method is designed to fit specific use cases while maintaining the source data as well as object data. A study of noise mapping demonstrates the possibility of integrating BIM and GIS information in a specific use case by analysing traffic noise in both indoor and outdoor environments in a BIM-GIS integrated platform (Deng *et al.*, 2016b).

Irizarry *et al.* (2013) proposed another possibility of integrating GIS and BIM for manifesting the flow of materials, where GIS served as tool to estimate the cost of possible solutions with regard to the material layout and BIM served as a platform to accurately present the information concerning the status of the material.

### 2.4 IFC to CityGML LoD3 conversion

Reviewing the BIM and GIS integration possibilities helps to understand the applications and characteristics of the two. In this study we have only IFC as source data and want to derive properties of buildings out of it, thus the data level ETL process is adopted and a method is specifically designed with regard to the aim of the study.

Since IFC and CityGML are developed for different purposes, there are major differences in the geometric representation. For CityGML lower than LoD4 only the visible surfaces can be modelled. While it is acceptable for IFC to not only construct a space surrounded by solids, but also fill the space with other components. As shown in Figure 6, the solid wrapped by exterior and interior surface along with the pyramid representing indoor facilities are typical geometry represented in IFC while in LoD3 CityGML only the exterior surface is desirable. It basically takes two steps to deliver information from IFC to CityGML: semantic mapping and geometry transformation. Confusions between the two models sometimes occur because of similar terms. For example, the acronym of LOD (compared with LoD for Level of Detail in CityGML) in BIM terminology (capital O) refers to Level Of Development/ Detail of a project from conceptual (LOD100) to as-build (LOD 500). LOD of a BIM has no indication of whether it has the potential to be transformed into CityGML, although a higher LOD is often recommended since it contains more detailed description (Donkers, 2013).

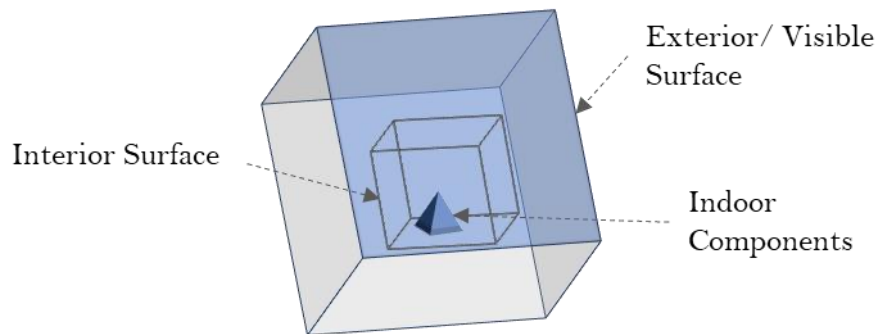


Figure 6 IFC representation versus CityGML of 3D features

A few characteristics of IFC models have to be highlighted and discussed here in comparison with its GIS counterparts. Firstly, there are about 900 IFC object classes in total, yet only 60 to 70 of which can be transformed to GIS. The remaining classes are mainly used to describe distributed elements such as ventilation and electrical elements. Therefore, only a small part of IFC is used for the representation of buildings and their architectural compartments. Secondly, there are three allowed types of representation for 3D geometries:

- 1) Constructive solid geometry (CSG): Boolean operations (union, intersection and difference) of simple shapes such as cylinders, spheres and pyramids (Requicha, 1980);
- 2) Sweep volumes: representing a solid feature by a 2d surface and the path it is extruded (Wang & Wang, 1986);
- 3) Boundary representation (b-rep): replacing a complex feature by its bounding surfaces, which is relatively rare in IFC, only sometimes used to represent complex features such as *IfcWindow* and *IfcDoor*.

Most IFC models in use today are using CSG and sweep volume (El-Mekawy & Östman, 2010), which determines that IFC objects usually have a solid representation.

In LoD3 CityGML only the surfaces are used to represent the geometry. The façade of the building is taken and different parts of the façade are implemented under one aggregated class *\_BoundarySurface*. Surfaces under *\_BoundarySurface* are divided into different explicit classes such as roof surface, wall surface, ground surface and closure surface.

A few programs provide the possibility to handle IFC-CityGML transformation. In practice, it is mandatory that the software be able to handle complex geometrical transformation from IFC to CityGML. The same software should also be able to manage geo-referencing and change of coordinate systems. Building Information Modelserver (Laat *et al.*, 2018), *IfcExplorer* and Feature Manipulation Engine (FME) by Safe Software (Safe, 2018) all provide the functionality for users to convert IFC to CityGML from different levels of detail. FME is used in this study for its richness of geometry converting tools.

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## 2.5 BIM and GIS for building energy analysis

BIM models, as 3D representation of buildings, not only contains the complete geometry of walls, roofs, columns, doors, windows and other building components, but also contains attribute information such as building material and material property. Therefore, BIM models offer an ideal alternative to leverage the required information into existing energy auditing tools. To fill the gap between existing tools and 3D BIM models, Kim *et al.* (2012) developed an IFC Input Data File (IDF) converter to act as a middleware that transfers knowledge while minimizing the loss of information. Bazjanac (2008) described a semi-automated simulation method that promotes interoperability between building energy assessment tools and IFC-based BIMs where HVAC data were added manually to the input file of EnergyPlus. It is also noteworthy that HVAC data, as an indispensable part for building energy assessment, is not available from BIM today due to lack of accepted standards for the transformation of necessary HVAC data into BIM (Bazjanac, 2008). Sullivan and Keane (2005) proposed a user interface to allow manual input of HVAC system information into IFC-based energy simulations. Kim *et al.* (2013) developed a semantic matching library to map materials with their thermal property values. Arayici *et al.* (2011) summarized that the industry was experiencing enormous changes with the advent of BIM technology. Traditional workflows were renovated and new ways to model buildings were invented. BIM models have to be combined with other sources of data to get a holistic view of real-world tasks such as energy modelling (Katranuschkov *et al.*, 2014). Later, Kim *et al.* (2016) also tried out an object based approach to parse IFC data as input for energy simulation tools (DOE 2.2 in this case). Current virtual energy audits often take into account GIS mapping, weather information, empirical data from similar buildings, household information and other publicly available dataset, and thus compensate for not having an on-site inspection (Mcauley, 2013).

On the other hand, the project “The Energy Atlas of Berlin” promoted an approach that derived key indicators for energy planning from a virtual CityGML model of Berlin in a holistic view (Krügerah & Kolbe, 2012). The challenge was to determine which indicators that are most important for different decision making levels. There are also considerations about whether the chosen indicators and method can be generalized and applied for other cities. Nouvel *et al.* (2014) conducted another study aiming to manage energy analysis on the national scale by calculating the heat demand using the quasi-static monthly energy balance under some adaptations of the DIN 18599 standard in Germany. Based on the scale of the study, every building was treated as a single thermal zone and with a fixed air change rates to living area ratio depending solely on the usage and age of the building. Geometrical details such as building storeys and window-to-wall ratio were ignored due to the low level of detail in the available data. Since May 2014, a group of urban energy simulation developers and users around the world has been trying to develop a common model standard for urban energy modelling. The CityGML Energy Application Domain Extension (Energy ADE) emerged with these efforts. It is a technical extension of CityGML schema for the existing CityGML schema does not support immediate access to energy related attributes. Energy ADE was originally developed for calculating building heating demand on the SimStadt platform by University of Applied Sciences Stuttgart. It aimed to deal with different levels of data quality and model complexity.

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The core of Energy ADE is the building elements that influence the energy flow in the building. These thermal building elements are linked to the CityGML building elements through the CityGML abstract classes *\_AbstractBuilding*, *\_BoundarySurface* and *\_Opening*. The schema of Energy ADE aims to comply to different levels of detail in CityGML while focusing on thermal zone extraction. Depending on different storeys and function partitioning, a building element can have one or multiple *Thermalzone* elements. These *Thermalzone* elements are either purely semantic elements such as building storeys for a LoD lower than 4 or corresponding classes to CityGML elements such as *Building*, *BuildingPart* and *Room* in LoD4. Likewise, *ThermalBoundarySurface* can be linked to CityGML *\_BoundarySurface* (e.g. roof, outer wall) under the condition that no internal separation (an attic floor, for example) accounts for the boundary of a thermal zone. The extended *\_AbstractBuilding* class is designed to support energy modelling with energy-related attributes with partial credits to the European INSPIRE data specification. As shown in the UML for defining Energy ADE (Figure 7), openings (denoted as *\_CityObject* type *Building::\_Opening* in CityGML) is taken as an essential type of object related to the thermal analysis and is extended with domain-specific details. In this context, one of the aims of this study is to extract opening information from BIM as an input to the energy simulation process.

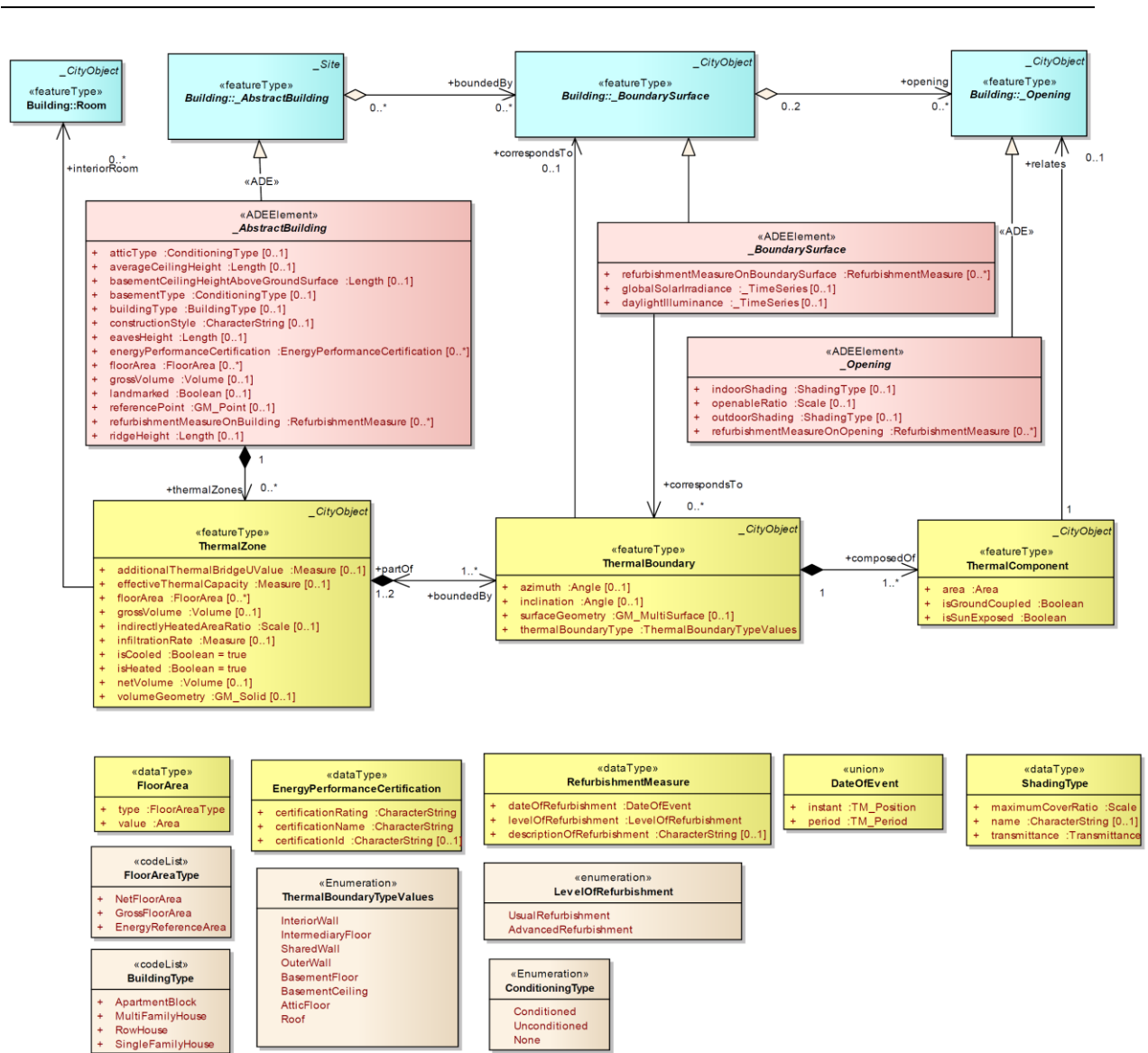


Figure 7 UML of the Energy ADE explaining building physics (OGC & SIG3D, 2016)

Currently, energy simulation with CityGML as a source of input is more general in scale compared to direct energy audit from construction models such as BIM. Sources of inputs are usually virtual 3D city models and LoD1-2 city models generated by airborne laser scanning. Airborne laser scanning facilitates the automatic generation of CityGML throughout a large region (citywide, for example) with a relatively affordable cost, but they are also lacking in semantic information. Lower than LoD2 CityGML does not include information of the semantic openings such as windows and doors that are valuable inputs in the energy simulation process.

Typically, windows occupy 10 to 30 percent of the surface area of building walls (Nouvel *et al.*, 2014). Basically, energy flow from windows comes in 2 major forms. One is thermal conduction (which causes heat loss in Winter and heat gain in Summer) and the other is the intake from solar radiation. Considerations of building energy demands are related to the location, climate and consumption demands. According to the report of the US department of energy in 2012, 37% of the energy consumption of buildings (residential and commercial) are accounted for by space heating (28%) and cooling (15%). As is shown in Table 2 (unit in Quad, an energy unit equal to  $10^{15}$  BTU, or  $1.055 \times 10^{18}$  Joules), for both

residential and commercial sectors the 3 most dominant factors of space heating are window conduction, wall conduction and infiltration while the biggest factor for space cooling is solar heat gain from windows (DOE, 2012; Sawyer, 2014).

Table 2 Energy consumption accounted by fenestration and building envelope components 2010 (DOE, 2012) ( 1Quad =  $1.055 \times 10^{18}$  J)

Building component	Residential		Commercial	
	Heating	Cooling	Heating	Cooling
Roofs	1	0.49	0.88	0.05
Walls	1.54	0.34	1.48	0.03
Foundation	1.17	-0.22	0.79	-0.21
Infiltration	2.26	0.59	1.29	-0.15
Windows (Conduction)	2.06	0.03	1.6	-0.3
Windows (Solar radiation heat gain)	-0.66	1.14	-0.97	1.38

### 3. Method

Since one of the objectives of the study was to convert IFC models to semantically rich and geometrically correct CityGML models, we developed the methodology with one of the IFC models available and tested it upon models from other two sources. Then the information derived from the model conversion was used to do preliminary energy analysis. The general workflow of the method is shown in Figure 8.

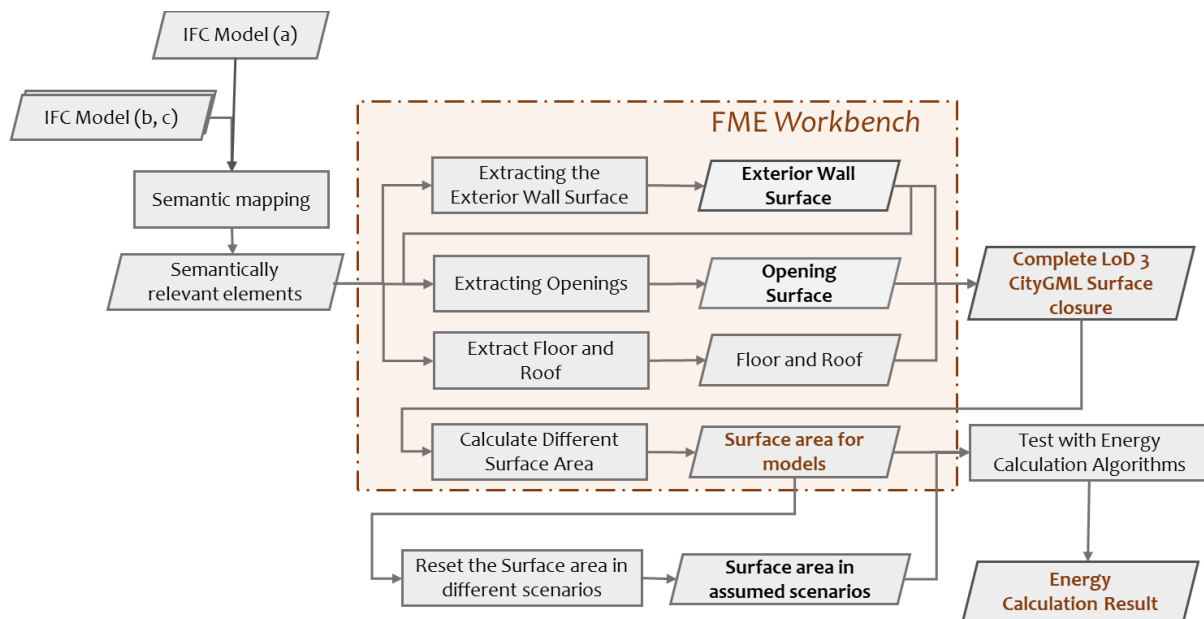


Figure 8 General workflow methodology used in the study

#### 3.1 Data

In this study, conversions and analysis are done for 3 building models (Figure 9):

- KTH building model which is an institutional demonstration data of an old building in Norway,
- FZK-House from GitHub OpenBIM community (Laat, 2015), and
- Nyvångskolan building model of a school building in the municipality of Lund, Sweden.

The results of extracted opening information are studied to promote the use of LoD3 CityGML in large scale urban energy studies.

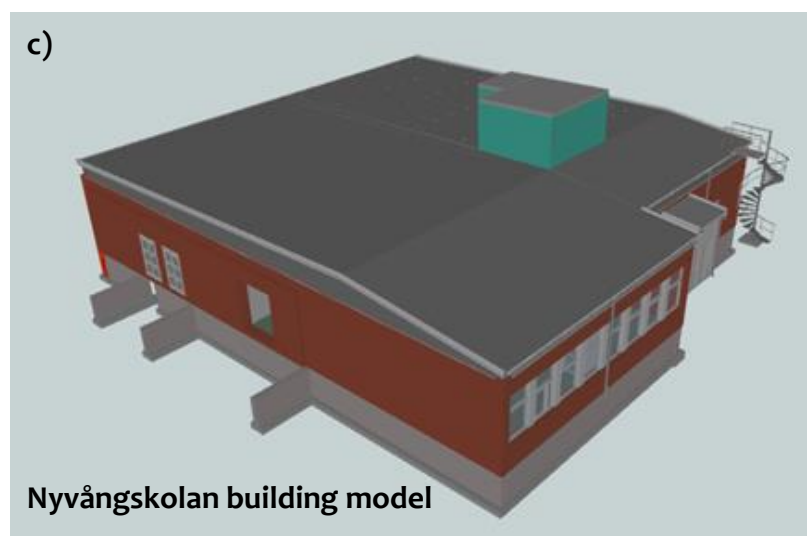
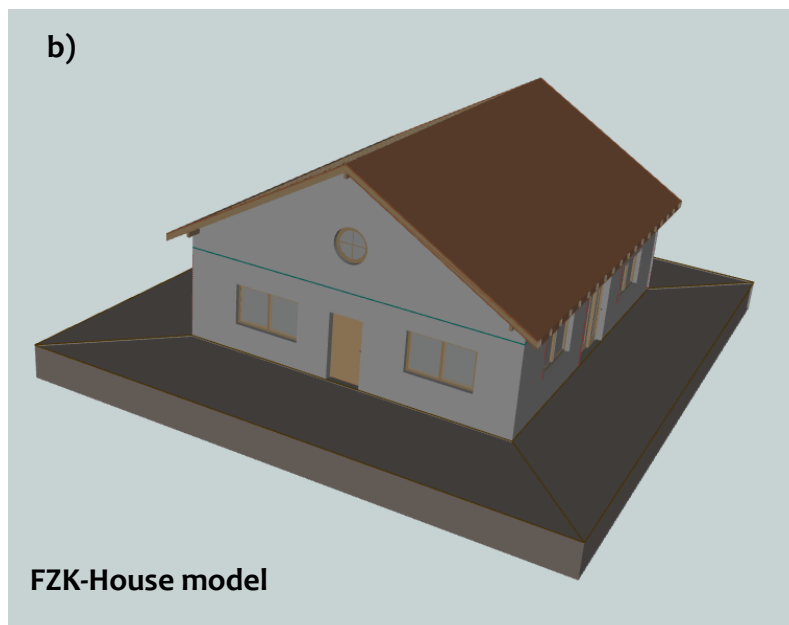
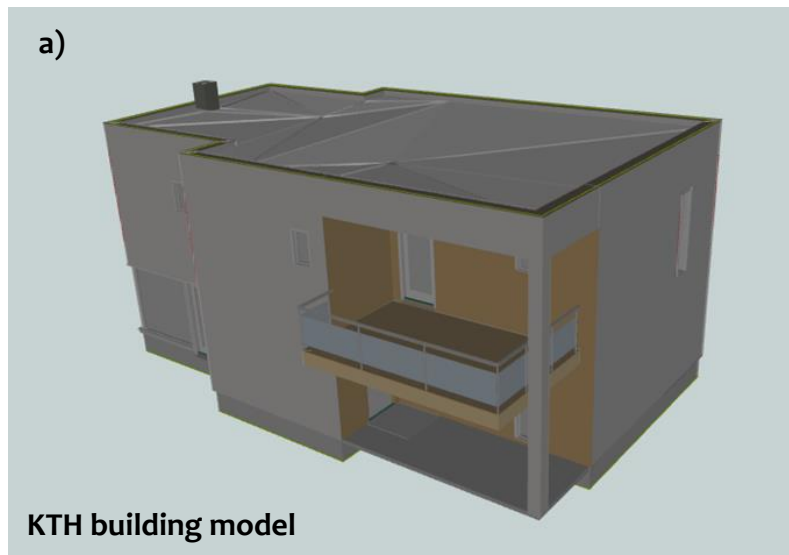


Figure 9 IFC datasets used in this study :a)KTH building; b)FZK House and c) Nyvångskolan building model



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## 3.2 Software

In this project, the Safe FME package is used to do geometric transformation on the BIM datasets, visualize the result and output LoD3 CityGML models. FME Workbench allows the IFC datasets to be read in the workspace by separate entity classes and the transformation result to be saved in CityGML format. All inputs, outputs and intermediate results can be shown in 3D space using the FME Data Inspector.

## 3.3 Workflow

The general idea of this study is to extract information from BIM and CityGML so as to support city energy planning and estimate the energy consumption of individual. For CityGML LoD2 to LoD3 models, it is practical to take a simplification of existing IFC models to account for the façade of a building. The main structure of the walls normally takes *IfcWall* and *IfcWallStandardcase* as the primary information source. Semantic mapping and geometric conversion are done subsequently for a full conversion. In order to grasp the semantics of different building components, semantics are mapped for all three IFC models together while the geometric transformation was done individually. A geometric transformer to extract the outer wall surfaces developed from model a in FME workbench was used and modifications were made with respect to specific IFC models of different building characteristics. The transformer was further developed to obtain complete LoD3 CityGML surface structure based on all the three IFC models.

### 3.3.1 Semantic matching

For the determination of types of surfaces in the CityGML, it is necessary to map the surfaces of IFC objects to CityGML components. Due to different sources of material, the semantics in IFC models are slightly different from one another. In this study we partly adopted the mapping method from El-Mekawy and Östman (2010) to map IFC classes with CityGML and proposed some new ideas based on the specific models analysed. Attempts were made to include all the versions of modelling encountered in the IFC models we worked with.

For semantic mapping first we decide on what features should be included for mapping. Because the purpose of semantic mapping is to get the IFC classes relevant for the geometry conversion, the first thing to do is to filter out the entity classes that have no geometry. In some cases *IFCsite* which contains no valid geometry in the real world also has geometry, so it is also ignored in the filtering process, the filtering and mapping process is combined in Figure 10.

Filtered IFC classes are processed through the semantic mapping. In this step we identify 1) if the class has distinguishable semantics as a building part, 2) if the element has a *PreDefinedType*, 3) if the element is composed of other elements and 4) the normal vector of the element. IFC entities that exist in the IFC models (a, b and c) were read by FME transformers and a filtering process was performed to extract the entities with both geometry and semantic. Since there are cases where the semantics of the object are not available either from entity type or *PreDefinedType*, some semantics are extracted from

the attribute values of a group of entity types. For example, *IfcDistributionFlowElement* in model b does not decompose any other *IfcBuildingElement*, nor does it get any semantic from *PreDefinedType*. Still, the *Name* of the object from attribute table suggests that it is a fireplace and is thus mapped as *BuildingInstallation* in CityGML. For LoD3 CityGML a fireplace might not be interested, but the geometry with semantics may offer more possibilities for conversions with higher level of detail. The final mapping are presented in Table 3. Highlighted rows are classes interested for LoD3 CityGML.

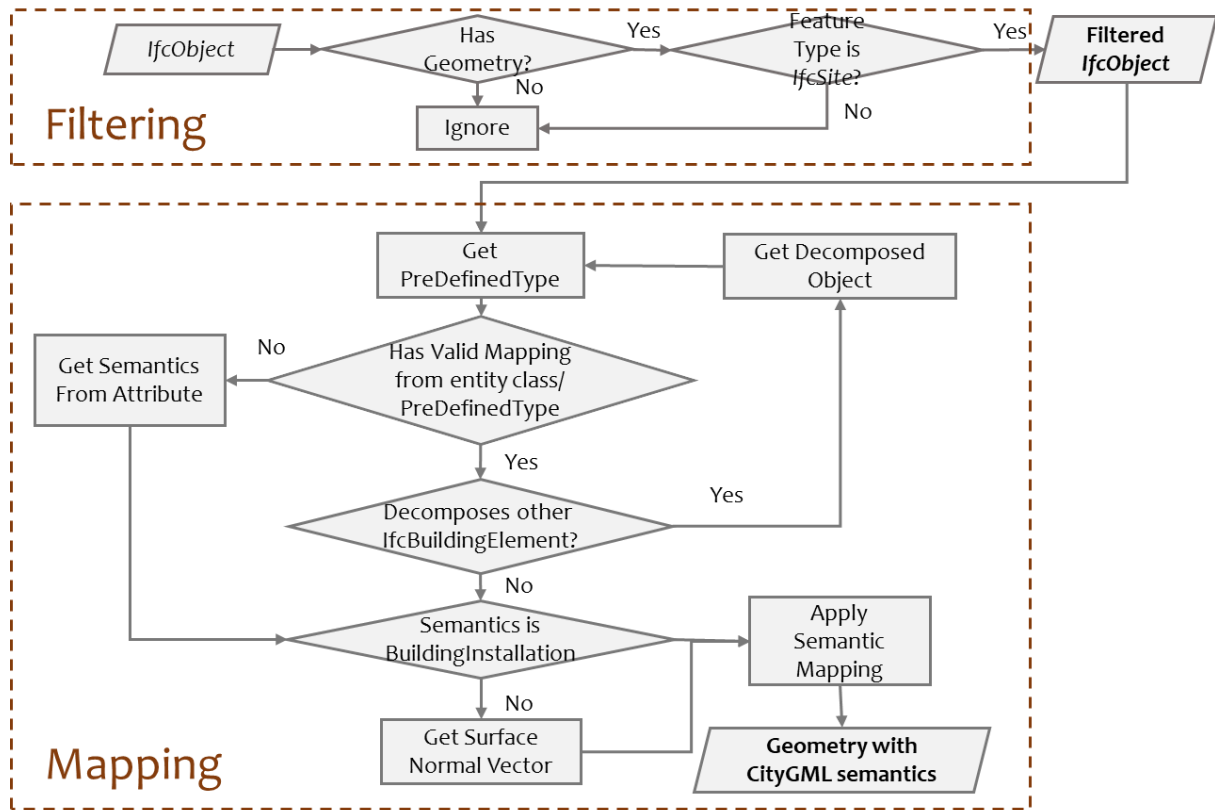


Figure 10 Workflow of filtering and semantic mapping process

Table 3 IFC to CityGML semantic mapping

IFC entity type	IFC PreDefinedType	Semantic from attribute	CityGML class (based on normal vector)		
			Up	Horizontal	Down
IfcBeam (a, b, c)		Beam	BuildingInstallation		
IfcBuildingElementProxy(c)		--	BuildingInstallation		
IfcColumn (a, b, c)		Column	BuildingInstallation		
IfcCovering (c)		CEILING	BuildingInstallation		
IfcDoor (a, b, c)			Door	Door	Door
IfcDistributionFlowElement		Fireplace	BuildingInstallation		
IfcFlowSegment (c)		Cutter	BuildingInstallation		
IfcFlowTerminal (b, c)		Water terminals	BuildingInstallation		
IfcFooting (c)		STRIP_FOOTING	BuildingInstallation		
IfcFurnishingElement (a, b, c)		Furnishing	BuildingInstallation		
IfcMember (c)		Assembled stair	BuildingInstallation		
IfcPlate (a)		Railing	outerFloorSurface	WallSurface	OuterCeilingSurface
IfcRailing (a, b, c)		Railing	BuildingInstallation		
IfcRoof (c)		FLOOR (a, b, c)	RoofSurface	RoofSurface	RoofSurface
IfcSlab (a, b, c)		FLOOR (a, b, c)	FloorSurface		
		ROOF	Roof (a, b)	RoofSurface	
			Vent roof (c)		
		BASESLAB (c)	OuterFloorSurface	WallSurface	OuterCeilingSurface
		LANDING (c)	BuildingInstallation		
IfcStair (a, b)		Straight run stair (a), Spiral stair case (b)	BuildingInstallation		
IfcStairFlight (c)		Assembled stair	BuildingInstallation		
IfcWall (a, c)			WallSurface	WallSurface	WallSurface
IfcWallStandardCase (b, c)			WallSurface	WallSurface	WallSurface
IfcWindow (a, b, c)			Window	Window	Window

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### 3.3.2 Wall Finder in FME (KTH building model, model a)

After relating the semantic source with desired CityGML classes, the first step for the practical conversion is to read all relevant features in FME. According to the revealed semantic relationship, the outer wall should be extracted from either the *IfcWall* or *IfcWallStandardCase* object class.

Since the geometries of IFC models we are dealing with is CSG, connected 3D blocks are to be disassembled and surfaces of disassembled parts are taken to extract a b-rep of the wall. In this process, a method developed by Olsson (2018) in FME environment is used to find the exterior wall surface from *IfcWall* class (referred as FME Wall Finder).

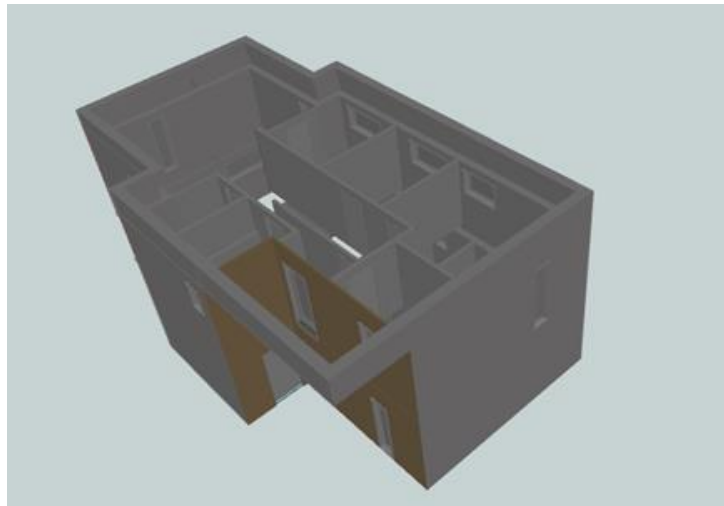


Figure 11 Opening-related objects in KTH building model (*IfcWall*, *IfcPlate*, *IfcWindows* and *IfcDoor*)

The FME Wall Finder was first developed based on the geometry characteristics and semantics of IFC dataset of model a (Figure 11). In this model Olsson (2018) used *IfcWall* to account for a complete wall structure (no *IfcWallStandardcase* elements were present) and Figure 12 illustrates the main steps performed in FME Wall Finder.

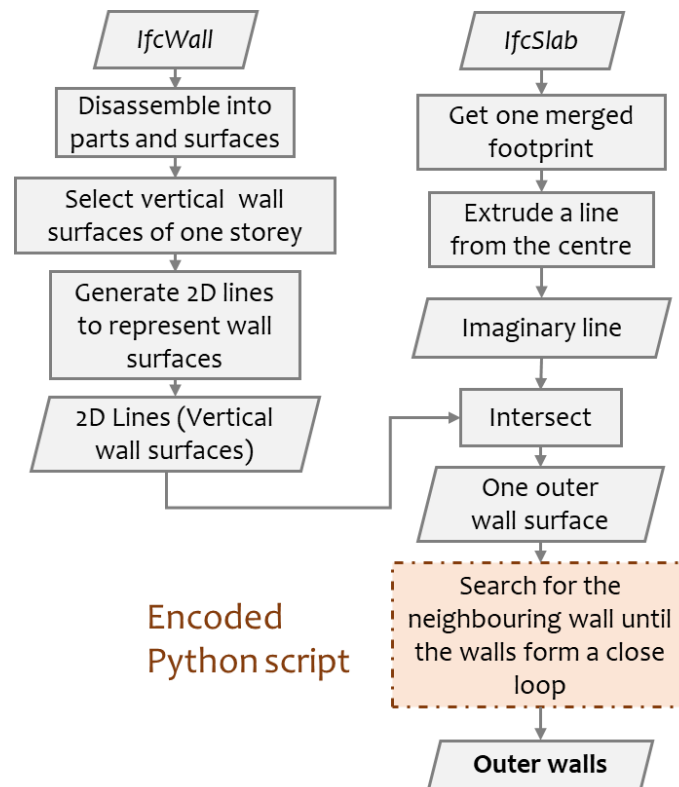


Figure 12 Workflow of the FME wall finder by Olsson(2018)

First of all, the wall features are disassembled from solid parts into surfaces with the semantics retained. This step results in duplication of a wall with both the exterior faces and the interior ones. Vertical walls belonging to the first floor are filtered out as a source of input for the outer shell. Since it is hard to model the geometrical connection between physically connected blocks from different storeys, the current transformer handles different storeys separately.

Connected walls in 3D dimension normally have 2 or more common conjunctions and one to many common line segment. To ensure that the exterior surface of the building is found and the inner walls ignored, the angle between faces need to be calculated and compared. For the fact that it is not yet supported in FME workspace to calculate the angles between 3D faces, an expedient solution is to take the overhead projection (i.e. footprint) of the surfaces as a compressed 2d representation of the walls and calculate angles between the lines instead (Note: this method does not work for building models that have curvier or non-vertical exterior surfaces). All 2D lines taken from the footprint are normalized into clockwise direction to facilitate the subsequent search of exterior walls in sequence based on the outer angle.

For the complete exterior wall surface to be found, the first exterior wall surface need to be detected. The idea of this work is to find an imaginary line that starts from inside the building and extends to the outside of it, which guarantees that the line intersects with at least one of the outer walls. Taking the footprint of one dissolved biggest slab (supposedly covering the footprint of the entire building) from *ifcSlab* class and extruding a line from the centre point of it ensures that the line starts from the inside of the building. Forcing

the line on the x axis and set the length as the extent of the building in x-axis ensures that the line extends to the outside of the building. All 2D lines representing wall surfaces along with the imaginary line are intersected using FME *Intersector*. When two lines intersect or one line terminates, the *Intersector* outputs the point as a node. From all nodes those belong to the imaginary line are taken and sorted. With the last node being the end node that is out of the building, the last but the end node should be the indicator of the last time the imaginary line intersects with the walls. This node is thus used to identify one of outer wall surfaces (see Figure 13).

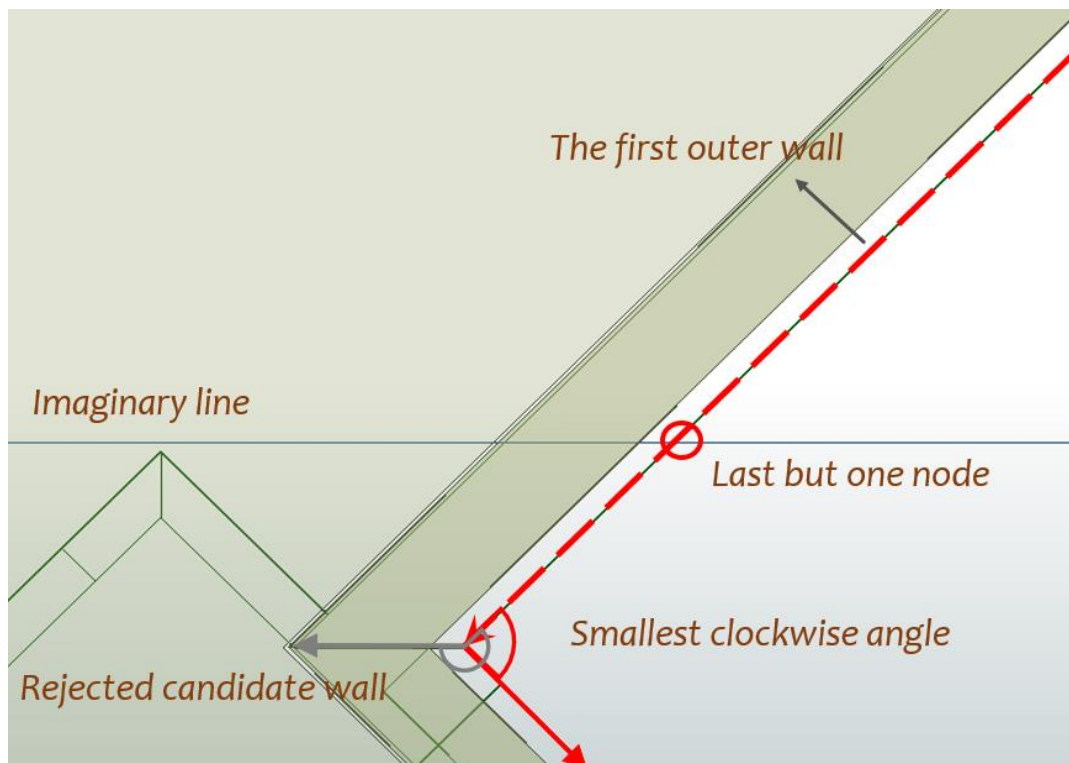


Figure 13 Illustration of the process done in FME Wall Finder

Once the first outer wall surface is found, a clockwise search starts from the 2D line that represents the wall surface. The end point of this line is compared with the start point of other lines. The lines starting at the end point or a point within a small range (10 millimetre is set here) are taken as candidates. Among all candidates within the range, the one with smallest clockwise angle is stored and taken as the next line while the binary attribute describing whether the wall is external (default 0) is changed. Then the search continues with the end point of that line until the next match is the starting line. This searching process is programmed in python and embedded in the FME transformer. The inputs are the unique id, start and end coordinates of walls. When the search is complete, the 2d lines which are detected as external should form a complete exterior boundary. The 2d lines are then used to merge with the wall surfaces by the unique id.

For a complete closure of surfaces the entity class *IfcPlate* that is unique in model a is also included to account for the wall surfaces and of the CityGML structure. However, *IfcPlate* on its own can account for various semantic meanings. In this model two separate parts of the class serve as the topping and foundation wall respectively. The part for foundation wall is used to vertically connect the wall surface of the first floor to the ground and the

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part for topping is used to connect the wall surfaces to the roof. The surfaces with horizontal normal vectors are treated the same way as wall surfaces and are processed with the Wall Finder to obtain the outer shell.

### 3.3.3 Extraction of the Openings

One of the objectives is to extract the opening elements from IFC and convert them to CityGML accepted representation form, the merged outer walls are used to extract openings in the walls as plain surfaces. Windows and doors in the IFC model (saved in *IfcWindow* and *IfcDoor* object types) are used to match and validate the walls found by the process.

The expected output of this transformer is the openings (doors and windows) as surfaces that seamlessly match with the outer walls of the building so that the walls and openings together account for a major part of the building envelope.

For the extraction of opening elements, two approaches were tried out in the methodology development process. One approach is using a transformer in FME called *DonutHoleExtractor*, which is actually one of the few transformers in FME that supports morphological operation of 3D features. But the result of this transformer is not satisfactory for several reasons. Since different storeys are processed separately, problems occur when the door reaches the bottom of the wall and touches the ground. The pre-installed transformer is not able to extract a geometry that does not belong to the input feature. Also, when a wall is made of different materials and modelled separately, the walls with different materials may be mistaken as openings. With this approach the donuts taken from the wall do not necessarily match with the window and door objects, thus it is problematic to match them with the correct attribute information.

The other approach is to get the projection of the original *IfcWindow/IfcDoor* objects. As explained in chapter 2, doors and windows are interconnected with walls by the intermediate class *IfcOpeningElement*. Thus it is possible to refer to the implicit geometrical container of a door/ window tracing back the parent ID of the elements. To match the doors and windows with the walls, the ids of the selected walls are matched with the parent id of the openings and the openings of the outer walls are used to further match with the doors and windows.

By matching the ids the doors and windows attached to the outer wall surface are selected. The next step is to convert CSG solid and fragmented windows/ doors to surfaces that match with the wall surfaces. Because windows are often modelled with frames and are sometimes attached to the inner side of the wall, surfaces that match the outer wall surfaces can only be obtained using projection. A projection on the vertical surface requires the correct position and normal vector of the wall surfaces, which are complicated to define in FME. The shortcut taken here is to derive the projected surfaces from rotated windows and doors, during this process the surface area is also obtained (for FME does not calculate 3D surface area). The footprints of slabs were derived and dissolved into one feature. In this case the footprint of the wall that a window belongs to performs as an anchor to get the perpendicular projection of the openings onto the wall surface. For each window and door that is found to match with the outer wall surfaces, all parts of the windows and doors are rotated 90 degrees relative to the footprint of the wall

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surface it belongs as the axis. Then the overhead projection of the rotated windows is recorded. Because both the footprint of the wall and the rotated windows and door are forced to the plain  $z=0$ , when the footprint of the windows/ doors are rotated back with the same axis 270 degrees, there is no horizontal gap between them. The total area of the outer windows and doors are available from the 2d footprints.

### 3.3.4 Forming a complete CityGML LoD3 geometry

From previous steps a horizontal closure of model a is obtained, yet the horizontal surfaces still needed to be extracted to get a complete LoD3 CityGML geometry. From Table 3 it is known that the semantic roof of this building is the *IfcSlab* with *PreDefinedType* "ROOF". The slab for the roof is placed horizontally but the upper surface is constructed with artistic design, which leaves an uneven surface for the roof. In order to generalise the roof surface, an overhead projection of the roof slab is taken and placed back at the highest point of the slab. Since the roof slab is only connected with the inner surfaces of the walls, there is still a gap between the roof and the outer wall surface. In this case the *IfcPlate* comes in as the bridge between the outer wall and the roof. The upper section of *IfcPlate* is vertically projected onto the highest point of the wall

## 3.4 Testing with other models

The workflow was applied to model b and c with the aim to test the generality of the method. Modifications were made with respect to characteristics of different models.

### 3.4.1 FZK-House (model b)

Building model b (see Figure 14) is slightly simpler in spatial structure than model a. However it still has 2 floors that have to be processed separately. In this model the entity class used to account for the wall is *IfcWallStandardCase*. A difference detected while conducting the same process was that the pre-defined unit of this model is one meter compared to one millimetre in model a. Therefore the threshold used in python code (since the python code handles values without unit) for searching outer wall segments was set 1000 times smaller (still 10 millimetres).

The roofs of this model are taken directly from *IfcSlab* objects which have the *PredefinedType* "ROOF" and the floor is extracted by taking the footprint of the base slab.



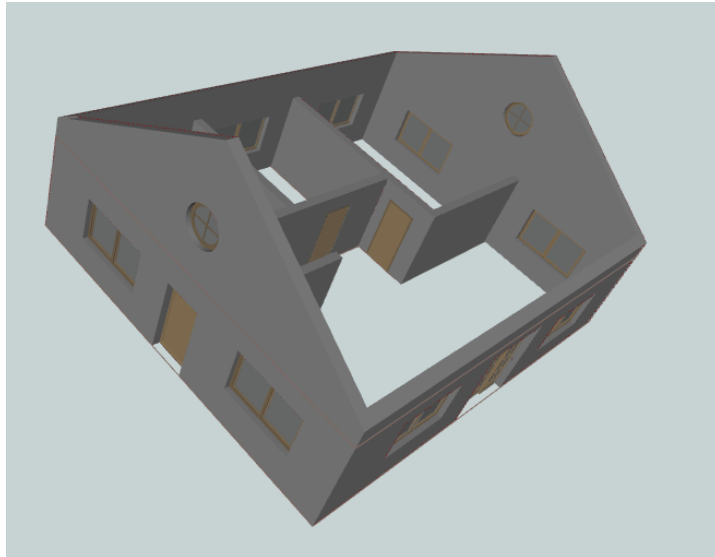


Figure 14 objects related to openings in model b (*IfcWallStandardCase*, *IfcWindows* and *IfcDoor*)

### 3.4.2 Nyvångskolan building model (model c)

Rather than *IfcWall* or *IfcWallStandardCase* accounting for the complete wall structure alone, the dataset of model c contains both entity classes as complementary for each other because a few walls of the building have varying thickness. According to IAI's definition, *IfcWallStandardCase* is for walls with a static thickness along the path and the thickness as a parameter can be described with an attached material layer set; on the other hand, *IfcWall* supports walls of any case, particularly those with varying thickness, non-rectangular cross-sections and walls that are non-vertical (BuildingSMART, 2008). To retrieve a complete closure of walls from separating levels from these classes the encoding method and attribute table were examined. The filtering for different levels of walls was done with *Name* and *ObjectType* from attribute table because different levels of construction of the walls were specified in these columns and thus making them separable. Using Revit© reader can also give a uniform feature type *Wall* that contains all features from *IfcWall* and *IfcWallStandardCase*, but the encoding method is different and feature reading takes considerably more time.

Similarly with model b, model c also contains roofs that cannot be simplified by horizontal surfaces, so the roof is also taken directly from the IFC semantic roof (*IfcRoof*). A special case with model c is that it has a ventilation structure opened on top of the primary roof and the ventilation itself has a separate roof (contained in *IfcSlab*). The sides of the ventilation structure are recessed as another level of the walls and the auxiliary roof is picked out from *IfcSlab* with the *PredefinedType* "Roof".

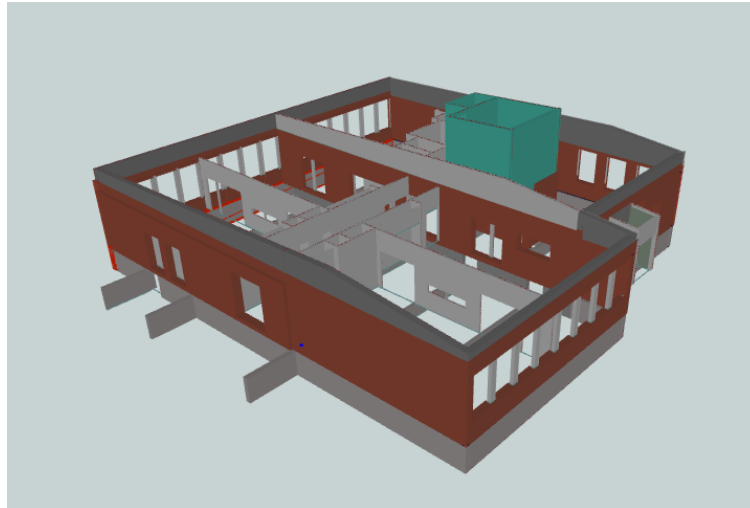


Figure 15 objects related to openings in model c (*IfcWall*, *IfcWallStandardCase*, *IfcWindows* and *IfcDoor*)

Minor geometry mismatch are found in this dataset. First, because of varying thickness of the wall, 2d segments that represent the walls are not always connected with conjunctions. This stops the search of outer wall when the end point of one wall segment does not find the starting point of the neighbouring segment within the threshold defined. The solution we figured out was to split the walls into segments using intersections between them. Coordinates of the start and end point are re-entered by extracting the coordinates from the new segments. Next, the computer storage method of real numbers causes the coordinates to alter every time they are saved. The range of this kind of variation is usually on the magnitude of  $10^{-6}$ . Line segments with length at such magnitude are treated more as points than lines. The computers fail in calculating the angle between line segments too small and another line segment therefore the loop to search the next candidate fails to continue. In this case we tried to continue search on the next neighbouring wall within the threshold by simply ignoring segments that are smaller than one millimetre. Another troublesome issue is with the partitioning of the walls with multiple windows. The gaps between windows are filled with columns of different material. The columns are still taken as *IfcWallStandardCase* class while physically filling the opening on the primary wall. According to our method, as long as the primary wall is taken, no attention would be paid to the detailed structure, which means such structure is prone to be missed. More concerns with the limitation of the method will be discussed in Chapter 5.

### 3.5 Energy Simulation with Openings

In an attempt to build energy simulation based on the LoD3 surfaces after conversion, the area of different types of surfaces are summed for all three models. Considering that FME workspace only supports area calculation on 2D, all surfaces obtained for LoD3 CityGML need to be transformed to get the actual area. For doors and windows since the surfaces are derived from the projection of original opening elements when they are rotated to the horizontal plane, the area is calculated before the surface is rotated back onto the wall. Similarly, the wall surfaces are rotated 90 degrees with the 2D projection of their own as axes so that the area can be calculated. For the roofs that have horizontal structures (model a), the footprints are directly taken as the area assumed for them. For those that are slanted (model b and c) the angle of inclination is obtained from the surface normal

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vector of the roof top surface and the surface area is retrieved by taking the arccosine ratio of the footprint area.

The primary energy flow from the building envelope can be expressed by the equation:

$$E = qc + qs$$

Where  $E$  is the total energy flow (kWh/m<sup>2</sup>),  $qc$  the energy flow through conduction and  $qs$  the energy flow through solar radiation.  $qs$  as the solar radiation onto the building envelope is always positive, while the sign of  $qc$  depends on the internal-external temperature difference.

Thermal conduction flow per unit area can be calculated by the equation:

$$qc = \sum UT \Delta t$$

where  $U$  is the thermal transmittance of the surface (W/m<sup>2</sup>K),  $T$  is the difference of temperature in Kelvin and  $\Delta t$  is the time difference in hours. In most countries where the annual temperature average is below 20 degrees Celsius, the thermal conduction flow is generally outwards, so thermal conduction flow is also called conduction heat loss in the coming text.

As for solar radiation, the simulation requires a lot more inputs. The solar radiation angle needs to be simulated per minute and weather conditions are very relevant. Since IFC models used in this study do not supply us with the orientation of the buildings, it is not possible to conduct a simulation of solar radiation gain based on the material. Still, from the original IFC dataset, the location (Coordinates: longitude, latitude) of the building models are provided and can be read from attributes of IfcSite/ IfcProject entities, which left us with possibilities on predicting how much energy is lost with the window size and the yearly weather statistics of the location.

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## 4. Result

### 4.1 CityGML conversions from different datasets

#### 4.1.1 The KTH building model (model a)

The outer walls along with the openings (doors and windows) extracted from model a model are found as shown in Figure 16. The transformation process was done separately with regard to wall objects from two floors. The result was combined in the final representation to account for the CityGML demanded format of objects. The grey faces are the external wall surfaces. The light blue faces are the windows attached to the outer walls, the pink faces are the outer doors, the olive green face is the ground floor and the brown surface is the roof. In 3D physical structure sometimes the windows are attached to the inner side of the wall, but the representation in CityGML requires them to match with the walls they belong to. Frames and glazing of a window are simplified in LoD3 CityGML models.

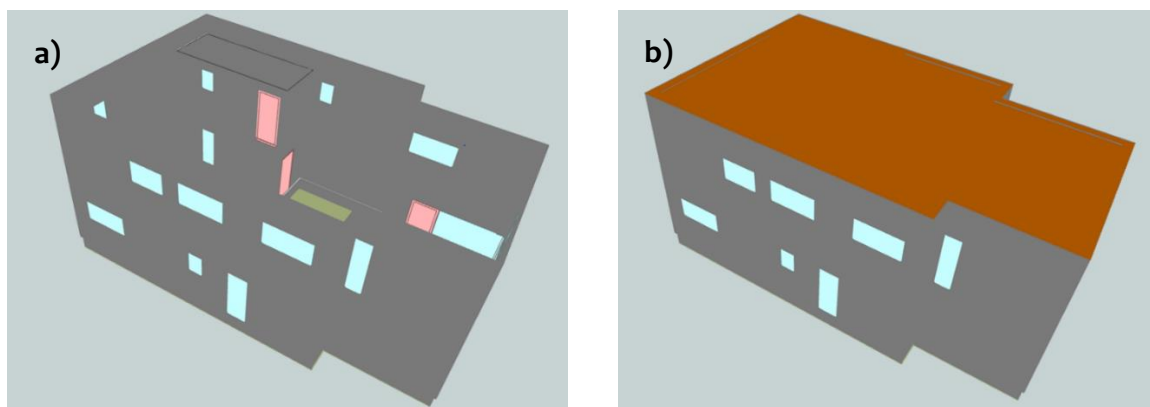


Figure 16 The complete CityGML LoD3 representation of KTH Building model: a) without roof; b) with roof

In the reformed 3D model of this building, a few glitches are found. The first noticeable error is the small gap found at conjunction of the corner windows. It exists there because both windows at the corner are sunken into the walls. The concave windows along with the frames have a smaller size than the space when casted on the wall surface. The second problem is that the doors converted from IFC are not exactly one piece. The crack between the door and its frame is still visible, which is not complying with LoD3 CityGML standards.

#### 4.1.2 The FZK Building Model (model b)

The conversion tool that worked for finding the outer walls in model a worked well for model b with the threshold values adjusted (Figure 17). The wall surfaces and openings are successfully converted. The inside of the walls sometimes look striped because the wall surfaces are one sided. The only thing that remains unsolved is the extraction of the outer surface of the roof. Since we need both the shape and thickness of the roof, surfaces of all directions are required. It is difficult to distinguish when the roof surface is separating from indoor to outdoor he substitute here is to keep all the surfaces of the roof even

though the inner side of the roof surfaces undesirable.

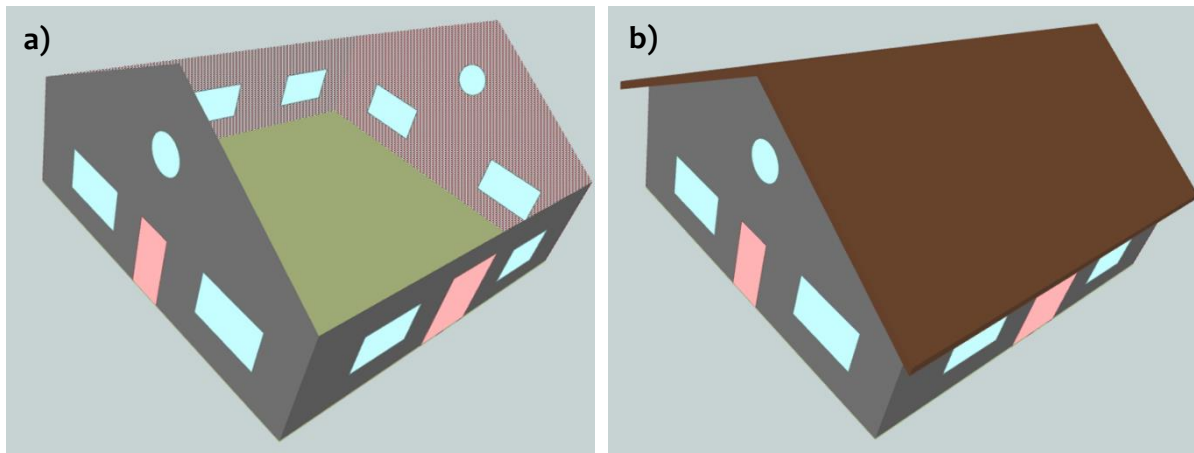


Figure 17 The complete CityGML LoD3 representation of FZK-House model: a) without roof; b) with roof

#### 4.1.3 The Nyvångskolan Building Model (model c)

As for applying the method to model c, a few problems occurred. Figure 18 shows the result and Figure 19 points out the different types of errors present in the result. Type 1 error is where an inner surface is also counted as an outer wall, which happens when one part of the wall is external and the other not and it is not possible to split a surface in FME. Type 2 error is absence of outer wall parts where there should be, which in most cases are caused by inner structure of walls with different material or functionality. Type 3 error is the columns between windows on the same wall, which is a special modelling structure not often seen in other IFC models. Type 4 error is the gap between different levels of construction because of varying wall thickness. Type 5 error is a special entrance area where the door is attached to an inner wall instead of the opening on the outer wall. The major problem here is that CityGML standards do not support an opening that is filled by objects other than windows and doors (Isikdag & Zlatanova, 2009). Filling these blanks by either opening surfaces or wall would cause semantic paradox, therefore they are knowingly left blank.

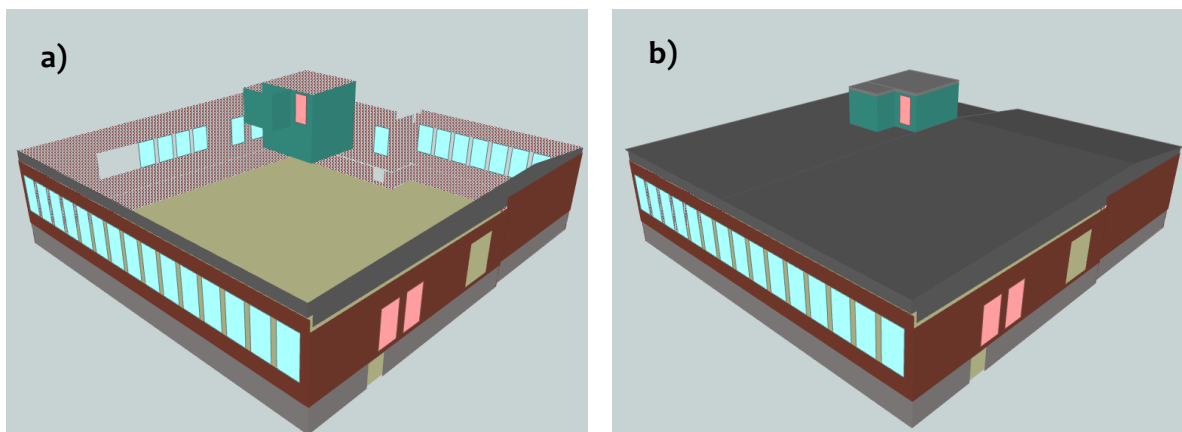


Figure 18 The complete CityGML LoD3 representation of Nyvångskolan Building model: a) without roof; b) with roof

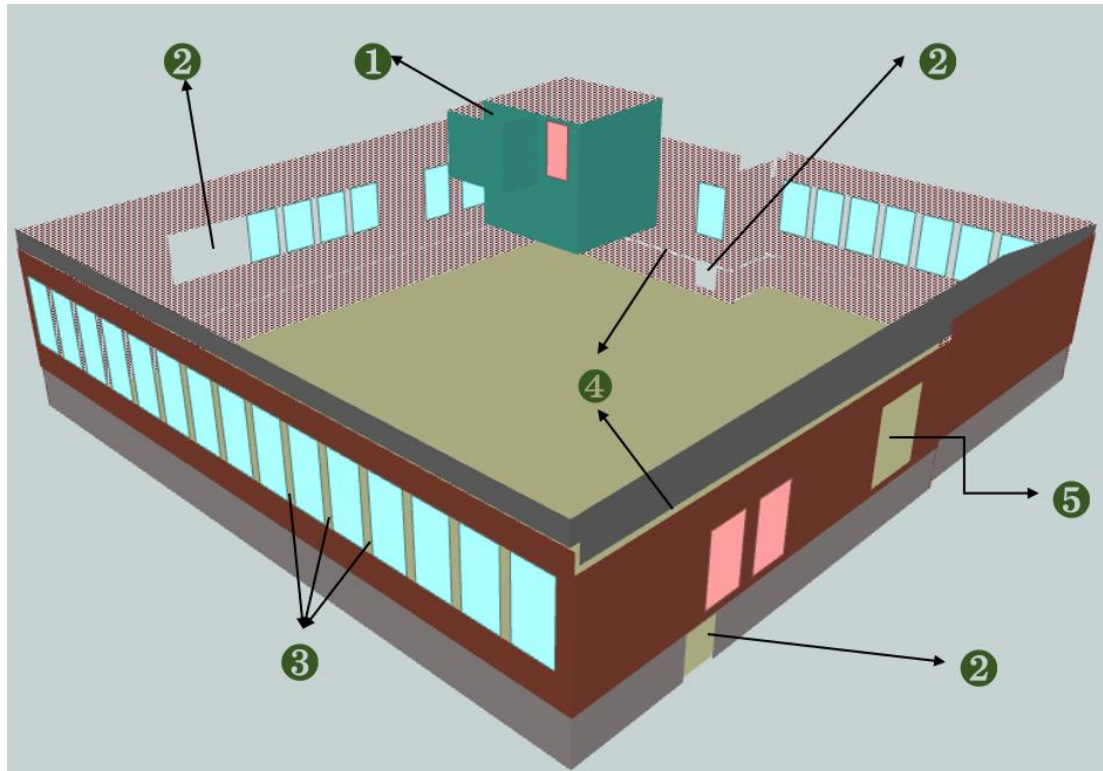


Figure 19 Types of errors in the CityGML LoD3 conversion for Nyvångskolan Building model

## 4.2 Extraction of energy simulation parameters

As defined in BBR the Swedish building regulation, the buildings should be designed in a way that limits energy use by lower heat loss, lower cooling demands and efficient use of heat, cooling and electricity (Boverket, 2016).

From the LoD3 CityGML models we converted, the area of walls, windows, doors and roofs are collected from all three models (shown in Table 4).

Table 4 Surface area (m<sup>2</sup>) derived from IFC-converted CityGML model

Surface Type	Model a	Model b	Model c
Wall	256.374	162.864	515.091
Window	23.362	20.769	80.462
Door	6.587	6.804	9.546
Roof	97.576	165.122	543.099
Floor	81.549	120.00	525.833

From the original IFC dataset, the location (Coordinates: longitude, latitude) of the building model can be read from attributes of *IfcSite/IfcProject* entities. For all the given locations the weather information is taken from the closest weather station (see Table 5).

Table 5 Weather information of model sites from nearest weather station (Meteonorm, 2018)

Model	Coordinates (IfcSite)	Weather Station	Coordinates (weather station)	Temperature Average (2000-2009)
a	59.3N, 18.5E	Stockholm	59.3N, 18.1E	7.7
b	52.5N, 13.4E	Berlin- Dahlem	52.5N, 13.3E	5.0
c	55.7N, 13.3E	Lund	55.7N, 13.2E	8.7

Since the thermal transmittance value (U-value) of different materials are absent for all datasets, we take the recommended U values from Swedish building regulation (see Table 6) to assess how much influence the opening has on the heat loss calculation from the building envelope.

Table 6 BBR recommended U-values of different building envelope surfaces (Boverket, 2016)

$U_i$	[W/m <sup>2</sup> ,K]
$U_{\text{roof}}$	0.13
$U_{\text{wall}}$	0.18
$U_{\text{window}}$	1.2
$U_{\text{exterior door}}$	1.2
$U_{\text{floor}}$	0.15

Three scenarios of opening-to-wall ratio are considered for the analysis:

Scenario 1: Surface area taken straight from the surface area calculated from the LoD3 CityGML model;

Scenario 2: 0% opening is considered in the estimation of conduction heat loss, all opening surfaces assumed as wall surfaces (LoD2 CityGML representation);

Scenario 3: 20% opening surfaces is assumed for all models. The area of opening and walls is redistributed while the sum of area (wall and opening) is remained (LoD2 CityGML with assumed opening ratio).

These three scenarios are designed to intuitively compare the building energy simulation cases. Scenario 1 represents the case where opening information of individual buildings are taken from the actual openings and thus assumed as the correct value. Scenario 2 represents the case where opening information is ignored, which is true for most simulations based on LoD2 CityGML. And scenario 3 represents the case where the opening area is assumed to take the average or uniform ratio, which is also seen in the work of Nouvel *et al.* (2014). The number 20% is also taken from the median of what they claim as typical range of window to wall ratio (10% -30%) of residential buildings.

Annual conduction heat loss from different surfaces scenarios of the building envelope is calculated for the three scenarios assuming indoor temperature as 20°C (293.15K) and

results are shown in Table 7.

Table 7 Annual conduction heat loss of building envelopes from different opening scenarios

Surface Area(m <sup>2</sup> )	Scenario 1 (data)			Scenario 2 (0% opening )			Scenario 3 (20% opening)		
	Model a	Model b	Model c	Model a	Model b	Model c	Model a	Model b	Model c
<b>Wall</b>	229.460	134.695	515.091	259.409	162.268	605.099	207.527	129.814	484.0792
<b>Window</b>	23.362	20.769	80.462	0.000	0.000	0.000	51.882	32.454	121.0198
<b>Door</b>	6.587	6.804	9.546						
<b>Roof</b>	97.576	165.122	543.099	97.576	165.122	543.099	97.576	165.122	543.099
<b>Floor</b>	81.549	120.00	525.833	81.549	120.000	525.833	81.549	120.000	525.833
<b>Conduction Loss(kWh)</b>	11007.4	12719.3	34666.0	7715.9	9023.8	25578.1	13417.9	13373.5	37797.2
<b>Bias</b>	0%	0%	0%	-30%	-29%	-26%	22%	5%	9%

As shown in Table 7, in scenario 2 where no openings are considered for a building, the conduction heat loss is underestimated for all three models. The biases say that the conduction heat loss estimation is 30% less than the result from LoD3 CityGML model where openings are represented for model a, 29% for model b and 26% for model c.

In some urban energy simulations based on CityGML LoD2 model, considerations are given to the openings by assuming a uniform opening ratio (Window-to-Wall Ratio, WWR) for all buildings. Scenario 3 is designed to represent this operation and compare how much the result alters from LoD3 results and the opening ratio is assumed as 20%. The result of conduction heat loss from 20% opening scenario is overestimated by 22% for model a, 5% for model b and underestimated by 9% for model c.



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## 5. Discussion

This study proposed a novel approach to access information from existing 3D building models and suggested that more detailed 3D city models can be used in urban energy analysis to enhance the accuracy.

### 5.1 Result Evaluation

#### 5.1.1 Surface extraction

The outer wall surface extraction results were generally satisfactory for model a and b in that they presented the complete visible outer surfaces of a building with minimal omissions. More errors were discovered when applying the workflow to model c. Omissions of wall surfaces occurred because of partitioning of the overall structure of the wall for various reasons, of which the most obvious were the construction of different materials and varying thickness. However, the algorithm aimed at identifying the wall surfaces that not only belonged to the visible facade of the building but also could link up to form a complete perimeter. Because of such nature of the method, though it might overlook the partitioning details on the wall structure, it also guaranteed that the primary walls were identified. Identifying the primary walls is crucial for identifying the openings that are linked to the building exterior surface because *IfcOpeningElement* is only related with primary walls by the relationship *IfcRelVoidsElement*. As long as the correct opening elements are discovered, all the windows and doors filling the openings will present in the result as 2D representation. Therefore, the final result of outer wall surface could be less complete than the result for the openings.

#### 5.1.2 Constructing complete CityGML geometry

Constructing the complete CityGML geometry in LoD3 requires not only walls and openings, but also roofs and the base floor. There are also suggestions on including generalised building installations in LoD3 CityGML. It is much simpler to get the floor than the complete roof surface because roofs often have inclinations and attachment structures such as chimneys and skylights. In this study, only model a has a roof surface that is completely explainable as exterior surface, whereas roofs of model b and (c) are both taken directly from all surfaces that form the solid roofs in the original IFC datasets. Though it is clear that the lower surface of the roofs that lies inside the buildings are not desirable in CityGML geometry, it is the least worst way we can take to remain the roof structure without sacrificing the correct geometry. In another study by Donkers (2013), the surface of the roofs are extracted by partitioning the Euclidean space using the union of the solids that construct the building and taking the 2-manifold with the largest volume. Artefacts are made to construct solid fills of a building when geometries are not perfectly connecting.

Another problem worth noticing is that when walls have varying thicknesses, the exterior surfaces are not matching to the same plane. If we want to close the surface by taking the upper/ lower side of the walls as part of closure surface, there would be much more

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manual selection which is against the initial purpose of the work. Also, ignoring such gaps does not have much influence on the energy calculations. Therefore, the gaps between different levels of walls were left with the original shape before we could figure out some general solution.

### 5.1.3 Heat loss simulation

Looking at the conduction energy loss calculation from different scenarios, it is evident that including opening areas in the energy calculation does have a significant impact on the result. Taking an appropriate uniform opening-to-wall ratio compensates the bias to a certain degree, yet the effect of such operation is unpredictable for individual buildings.

However, the heat loss simulation conducted in this study is more of a qualitative assessment than a quantitative measurement of the real energy performance. First of all, conduction heat loss only explains part of the overall energy flow of a building. Second, the U-values of materials are set as uniform values for absence of information. Third, of all the building models used in this study, only model c has evidence of existence as a real building, which means for the others the coordinates of buildings are just for reference.

## 5.2 Limitations of the study

### 5.2.1 Data Limitation

As for dealing with different building models designed by different companies/organizations, problems occur when specific changes need to be made to the method/workflow in order to get a satisfactory result. This case can be resulted from different standards of BIM development from different construction companies or intrinsic geometry difference of different buildings. In the building industry, IFC models are updated throughout the entire phase of designing and can therefore have many different versions. Discrepancy and difference in semantic/physical structure can be found between different versions of models. However, this is not desired as we were originally aiming at proposing a general solution for the energy calculation of buildings.

### 5.2.2 Algorithm Limitations

The method used to find outer walls of a building in this study proved its usefulness for simple structure IFC models. Yet it also has evident shortcomings. One that stood out as we proceeded with the study was that it relied very much on the consistency of the outer wall structure and its independence with other elements. When the exterior boundary, normally framed by walls, includes other elements such as French windows or columns, the Wall Finder described in 3.3.2 will not be able to find a complete perimeter of walls that surrounds the building. Also, the wall finder used to extract the outer wall has to deal with different storeys of a building respectively, which means there should be a way to distinguish the storeys and separate them. In the model a and (b) this separation was hardcoded using a filter to select the features of the same storey with the same unique parent id. In the model c the building was one storey, but the roof and ground conjunction

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still need to be filtered out otherwise a closing wall structure might not be found.

The floors and roofs were extracted from the original 3D geometry of the input model, which means all attachments and building installation component are taken as they were in the IFC model. This is certainly not desirable for a valid LoD3 CityGML representation.

### 5.2.3 Software Limitations

Since this study is based on IFC building models, the complexity of 3D building geometry is inevitable. In general, 3D transformations are more complex than 2d transformations. Although FME works fine for most transformations needed in this conversion method, some transformers and operations are only available for 2D. For example, the FME workspace does not allow bounding box extraction of polygons in 3D dimension. All inputs of BoundingBoxReplacer will be forced onto the plane  $z=0$ . Also, the Dissolver that is often used to merge polygons on the same plane into one single feature only works for 2d objects. It was used to merge the frames and glazing of the windows into a unity while the window was rotated and forced to 2d. Curvier shapes and non-vertical walls are not discussed here.

## 5.3 Suggestions for further research

### 5.3.1 Data openness

Although enriching semantic and geometry information of CityGML looks promising from the first sight, the openness of IFC models is still a problem. Construction companies would like to keep detailed information of buildings confidential due to market competition. Hence the development of a citywide LoD3 CityGML model using IFC model as input is still visionary. The idea here is that the conversion method, if fully developed, can be released to the public and used by the construction companies holding most existing IFC models in the market. Instead of releasing too much detail attached in IFC models, making LoD3 CityGML building models open to the public would sufficiently improve the analyses performed on a urban planning scale without sacrificing confidentiality.

### 5.3.2 Format standardisation

When dealing with IFC models, a substantial barrier is to extract the correct semantics of the models. As demonstrated in the study, we had to resort to the attribute table and get semantic information from individual objects. Sometimes the attribute tables are written in the language of model origins, which adds to the difficulty. A suggestion for the standardisation of object semantics is to include *ObjectType* as a mandatory attribute of all physical existence in an IFC model, which can strongly promote the semantic reading process. Also, none of the three models used in this study had information regarding to the orientation of the building. It is still a challenge to project IFC building models from a local coordinate system to the real world coordinate systems. For the sake of data interoperability and better alignment of the models, it is suggested that a standard orientation is defined in all IFC models.

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Since CityGML is a generic standard that allows implementers to experiment with different modelling structures, modellers are often confused about what can be managed and what to expect for the results. It is recommended that more rigid standardization be made and detailed illustrations of possible operations be provided. For example, when modelling building surfaces of a LoD3 model, it should be clear what features can be linked as which kind of surface type. Also, there should be a clearer specification to distinguish CityGML of different LoDs. Up to now, the standards for CityGML do not yet specify whether an attachment of the roof should be present in LoD3 and if so, how it can be generalised. There is ongoing work by Biljecki *et al.* (2014) to propose more restrictions on the geometric and semantic representations of CityGML, but the work is mainly focusing on how to model interior structure that are commonly recognised as LoD4 structure.

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## 6. Conclusions

In this study, an FME-based approach is developed to convert IFC building models into semantically rich and geometrically correct LoD3 CityGML models. The conversion was done with greater emphasize on the extraction of the building exterior envelope that consists of walls, openings, roofs and floors.

The conversion was successful with all three models with minor adjustments for specific buildings, although the quality of the result varies with the model structure and building characteristics.

The results of the conversion were tested with the calculation of conduction heat loss through the building envelope from different surface area, and comparisons were made in three opening to wall ratio scenarios. Including the opening surfaces in calculating conduction heat loss will introduce a considerable increase in the heat loss compared to no-opening scenario. Taking a uniform value as opening- to-wall ratio approximates the effect of real openings to a certain degree, although the effect on individual buildings was unpredictable (also influenced by the selected value and building structures).

Instead of sticking to existing surfaces in the IFC models, further research on the model conversion can focus more on the morphological operations on the IFC solids. Dealing with inconsistent and fragmented surfaces are tedious, therefore there might be a way to aggregate and generalise the model based on solids. Also, the method should extend its applicability in dealing with non-vertical structure which are common in modern buildings constructions.

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