

CityGML Data Preparation for Thermal Building Simulation at District Level

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Abstract

More and more cities and countries around the world are providing CityGML LoD2 (Level of Detail) building models, either commercially or as open data. Although these models divide the outer shell of buildings into walls, roofs and floor areas, most of the input parameters required for thermal simulation are missing. In addition, CityGML allows different modeling approaches, so that the geometry of the models must also be checked, the neighborhood relationships analyzed and the models modified if necessary.

The present article describes the analysis of CityGML models regarding the model structure and geometry. This includes checking the buildings geometry to be a closed volume, considering neighboring buildings as shading objects, and enriching building physics parameters depending on the year of construction. The geometry processing for buildings with several building parts, the calculation of shared surfaces in the case of closed constructions and the determination of neighboring buildings are described in detail. The enrichment of the building models with building physics and building usage parameters is introduced. All concepts are implemented in software and tested with the EnergyPlus simulation kernel. The software, which can be used to convert basic CityGML models into comprehensive CityGML Energy ADE models, will be available to the community as freeware.

1. Introduction

Urban Building Energy Modeling (UBEM) broadens the **Building Energy Modeling (BEM)** approach from the single building scale to the city, regional or national level. UBEM is much more than the simple aggregation of individual building energy models, as it takes into account the design of the building stock, the microclimate and the mutual influence of energy loads (Malhotra et al., 2022a).

There are basically two approaches to UBEM: top-down and bottom-up. While the top-down approach works mainly with historical time series at a high aggregation level, the bottom-up approach operates at a disaggregated level and requires a lot of information to describe individual components. The building physics based bottom-up approach requires the most detailed information possible about the building stock (Kavgic et al., 2010).

CityGML (Gröger et al., 2012) as a comprehensive semantic city model provides a standardized data model for buildings in an urban context. The data model allows buildings to be represented at different levels of detail and facilitates a decomposition of buildings into individual boundary surfaces (e.g. wall, roof, and ground). The extensive availability of CityGML building models in many countries around the world provides a good basis for building physics based thermal simulations. Although CityGML as a general semantic city model does not provide energy and simulation relevant features and properties, it offers a mechanism for schema extensions (**Application Domain Extension - ADE**) (Biljecki et al., 2018). The CityGML Energy ADE is one such schema extension, defined by an international working group to meet the requirements of UBEM (physics based bottom-up approach).

Several tools are available for using public available CityGML data for thermal simulation. SimStadt (Coors et al., 2021) is designed to simulate and analyze the energy performance of buildings at the district or city level. It supports CityGML and EnergyADE as the data format for input of the simulation. Enrichment of CityGML data and the generation of an EnergyADE dataset is not supported. Another energy urban modelling and simulation tool is CitySIM (Rosser et al., 2019). A simulation based on CityGML and EnergyADE data is also possible here. However, it is unclear to what extent this information can also be stored in EnergyADE and whether geometric adjustments are supported.

However, apart from the tool presented here, only CityEnrich (Malhotra et al., 2022b) is currently available for an enrichment of CityGML datasets with energy relevant parameters. CityEnrich allows the manual assignment of parameters per element type and usage profile, but it is not possible to assign them automatically on the basis of a building age class and building function. None of the tools mentioned above seem to check the input data both structurally and geometrically and adapt the structure, semantics and geometry if necessary.

The present paper introduces a process for enriching differently structured CityGML building models with features and properties necessary for thermal simulation. Although CityGML provides a standardized building model, it allows different geometric and semantic variations, so that the model has to be analyzed in a first process step. Depending on the results of the analysis, building parts are merged into a single zone model in a further process step. In the following process step, neighborhood relationships are then established between the individual buildings in order to identify and process a closed construction and to determine buildings for shading assessment. In the final process steps, the building model is then completed with information on building usage (e.g. user behavior) and building physics (e.g. thermal conductivity) using CityGML Energy ADE features and properties.

The resulting building models can be exported as a CityGML EnergyADE dataset and shared with other applications. In the in-house application KITModelExplorer, the CityGML EnergyADE models can be converted into EnergyPlus (EnergyPlus, 2024) input data and simulated.

2. CityGML and CityGML Energy ADE

CityGML as a comprehensive city model represents many aspects of a city, such as buildings, vegetation and transportation infrastructure. The data model is therefore subdivided into individual thematic modules. As the work described in the following relates to thermal building simulation, the focus is on the building module (Gröger et al., 2012).

CityGML and the CityGML extension Energy ADE have often been described comprehensively in several publications, so that only special modeling aspects are addressed here. The latest CityGML version 3.0 (Kolbe et al., 2021) offers few relevant innovations with regard to the requirements of thermal building simulations, meaning that the work described here relates to CityGML version 2.0. In addition, in practice only a few data sets are available in

CityGML version 3.0. Although CityGML can provide several levels of detail, the description here focuses on Level of Detail 2 (LoD2), as most of the datasets are available at this level of detail (Geiger et al., 2022). In principle, the considerations listed in the present article also apply to LoD3 building models.

2.1. CityGML

A CityGML building model can have several levels of detail and can be composed in different ways. The subdivision of a building into building parts is based on various aspects (e.g. roof shape or building function) and is therefore not standardized. The use of building installations (e.g. winter gardens and dormers) is also not clearly defined. The building, building part and building installation feature can be represented optionally as a surface model and as a volume model. Additionally, these features can also be semantically subdivided into boundary surfaces such as wall, roof and ground surfaces (SIG3D 2017). This variety of possible combinations requires a structural and geometric analysis of the CityGML building models in order to be able to use the model for thermal building simulations. In most cases, the models have to be modified semantically (e.g. creation of shared walls) and geometrically (e.g. merging of building parts) after the analysis.

The outer boundary surfaces usually form the building envelope. Simulation kernels for a thermal simulation require certain construction properties (e.g. layer thickness, thermal conductivity), which are assigned to the boundary surfaces. Since CityGML does not define any standardized attributes for boundary surfaces and the CityGML material concept only contains visualization properties, material constructions, e.g. for walls, are difficult to implement without a CityGML extension.

Since the CityGML is a general-purpose model but provides a schema extension mechanism (ADE) for domain-specific applications, features for modeling energy-relevant information are not included in the CityGML schema and must be defined in an ADE.

2.2. CityGML Energy Application Domain Extension (ADE)

As mentioned in the previous chapter, domain-specific CityGML features must be specified in a schema extension. In 2015, an international group of urban energy simulation developers was established to define a common CityGML Energy ADE. The aim was to close the gap between the general use of city models and urban energy modeling by extending the schema with

additional features and attributes. For thermal building simulation, the CityGML Energy ADE can extend a CityGML building model without interfering with the original CityGML model structure. This has the advantage that a relationship between the CityGML building model and the CityGML Energy ADE building model exists only on a common building feature level.

For thermal building simulation, the extensions for describing the thermal zones and their usage are particularly relevant. The thermal zone is bounded by LoD-independent thermal boundaries and owns further energy-relevant attributes. The thermal boundaries can be described with geometry as well as with alpha-numerical properties and are further classified into outer wall, interior wall, shared wall, ground slab, roof, floor and ceiling. Furthermore, thermal boundaries can refer to openings. The physical building parameters that are particularly important for a thermal simulation, such as composition, thermal conductivity and heat capacity, can be specified in detail with the construction, layer and material features (Nouvel et al., 2015).

A thermal zone can contain several so-called usage zones. The usage zone defines the user behavior and the characteristics of other energy-related factors, such as heating and cooling profiles, air change rates and internal heat loads. In order to model these behaviors, new features have been introduced that support schedules and time series (Benner et al., 2016).

The CityGML Energy ADE has other modules, but these are not relevant to the process described here and will therefore not be discussed further.

3. Data Preparation

In more and more countries, CityGML building data is provided by official bodies. In Germany, the federal states provide CityGML LoD2 data mostly as open data or commercially (CityGML Wiki, 2024). However, the available LoD2 CityGML building data provided is not uniform (Geiger et al., 2022). For this reason, it is necessary to analyze and harmonize the building geometry. In principle, the checking and analysis of semantic data can be classified into three categories: consistency, correctness and completeness (Geiger, et al., 2021). Consistency means the syntactic and semantic correctness of the data, in this case a validation against the corresponding CityGML schema. If this is not fulfilled, there are already errors when reading and interpreting the data. The checking process takes into account the correctness and completeness of the building data. Checking for

correctness is currently restricted to geometrical analysis like checking for closed volume or surface planarity. This is essential for buildings and building parts where the geometry can be represented by a volume geometry or by a volume resulting from the individual boundary surfaces. During the completeness check, the required features and attributes are analyzed and with the correctness check, specified values are checked to ensure the used values are within a valid range.

3.1. Building and Building Parts

For the thermal analysis of buildings at city or district level, the workflow presented here is based on a single thermal zone per building. The calculation of buildings with multiple zones - if building parts are present - is possible in principle, but is not discussed in this article. If building parts are present, it is assumed that the building parts are connected to each other and form a single building envelope, although this is not explicitly required by the CityGML specification. The main requirement is to check and ensure that the building represents a closed volume and that the external thermal surfaces can be derived from this closed volume.

According to the CityGML specification, buildings can be modeled as single buildings or as buildings with one or more building parts. In most cases, the buildings and building parts are available in LoD2. However, it occasionally happens that a LoD1 building or building part without boundary surfaces is provided. A combination of LoD1 and LoD2 building parts is also possible (Figure 1).

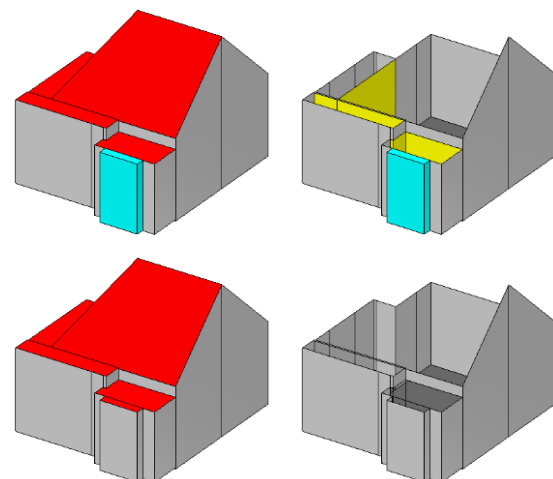


Figure 1: Building consisting of LoD1 and LoD2 building parts (upper row – original CityGML building; lower row the newly generate building envelope; roof surfaces are hidden on the right side)

Firstly, a closed volume is ensured for each part of the building and then the thermal surfaces for the LoD1 components are determined based on the surface orientation and semantically classified as wall, roof and ground surfaces. Vertical surfaces with a maximum slope of 10° are classified as *WallSurface*. Surfaces oriented in a positive Z direction and with an angle between 0° and 80° are classified as *RoofSurface* while all surfaces oriented in a negative Z direction with an angle between 0° and -80° are classified as *GroundSurface*. If building parts are present, they are geometrically united by Boolean operations to form a thermally homogeneous envelope. The contact surfaces between the building parts are calculated and classified as *ClosureSurface* if necessary. In some cases, the original CityGML data already contain *ClosureSurface* between the building parts.

When analyzing the geometry, it also revealed that some of the existing geometries of type GML *Solid* do not meet the requirements of a closed volume. This is due to an incorrect assignment of the LoD2 faces to the faces of a GML *Solid*. In these cases, collinear points that would be required for an edge check are missing. In this case, it is checked whether the collinear points can be supplemented by an edge analysis and thus a closed volume can be generated.

3.2. Neighborhood Relations

In addition to a closed single zone, the relationship to neighboring buildings is of particular importance for the thermal analysis of buildings. With CityGML it is possible to describe a building, but there are no relationships between the buildings. This means that this information must be derived geometrically. For this purpose, a respective Voronoi diagram is used.

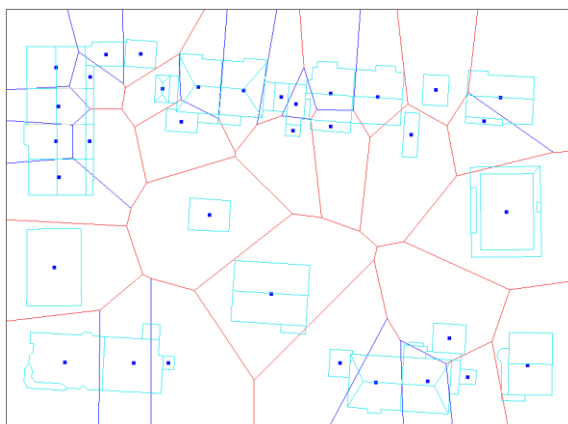


Figure 2: Voronoi diagram showing the neighborhood relations of the buildings (edges to touching buildings are colored blue; all other edges are colored red)

A Voronoi diagram is a mathematical concept that divides an area into regions based on the distance to a set of points (Burrough et al., 2015). The implementation is based on the Euclidian distance. In this case, the Voronoi diagram is used to determine the direct neighbors for each building (Figure 2). This is undertaken by first calculating the geometric center of gravity for each building and using it as the center point for calculating the Voronoi diagram. From the direct neighboring buildings identified in this way, the surfaces are then checked geometrically for connections. A subsequent step analyzes the list of direct neighbors to determine whether buildings intersect within a tolerance (e.g. 5 cm). Intersections between two buildings that consist exclusively of a point or an edge are ignored. For all other intersections, the actual intersection area is calculated using 2D Boolean operations and assigned to the respective neighboring buildings as shared walls (Figure 3).

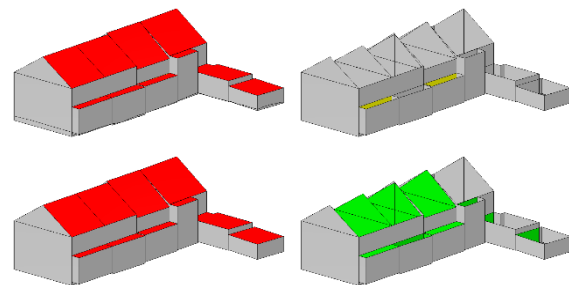


Figure 3: Closed construction (upper row: original CityGML model with outer walls (grey) between the buildings; lower row thermal boundaries with shared walls (green) between the buildings)

3.3. Openings

The heat loss and solar gain through windows is a significant influencing factor (Geiger et al., 2020) in the thermal simulation of buildings. However, the CityGML building models in LoD2 do not have windows. For this reason, there is an option in the enrichment process to specify a wall-window or a roof-window ratio. These window areas are calculated geometrically and assigned as a *ThermalOpening* to the corresponding wall respectively roof surface. For the window calculation process, some boundary conditions are defined. These include that the dimensions of the target surface must have least a length of one meter and the area must be larger than two square meters. This prevents openings being created in small surfaces (Figure 4).

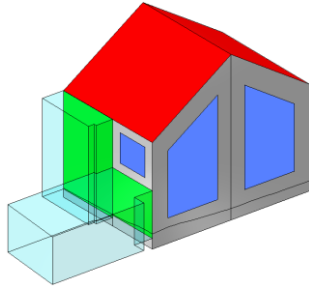


Figure 4: LoD2 building with calculated opening geometries (blue) (Shared walls (green) and small wall surface (below shared walls) are ignored)

3.4. Neighboring Buildings as Shading Objects

As already mentioned, UBEM considers not only the individual building but also the mutual influence of the buildings. Solar gains, for example, also depend on the mutual shading of the buildings. EnergyPlus therefore offers the option of defining shading objects in the building simulation. As the time performance of the simulation depends on the number of shading objects, only selected neighboring buildings should be considered as shading objects.

As previously described in Chapter 3.2, a respective Voronoi diagram provides the direct neighbors of a building. In the current implementation of shading objects, not only the direct neighbors are taken into account, but also their respective neighbors. Figure 5 shows the direct neighbors (dark grey) and their neighbors (light grey) for the selected green building.

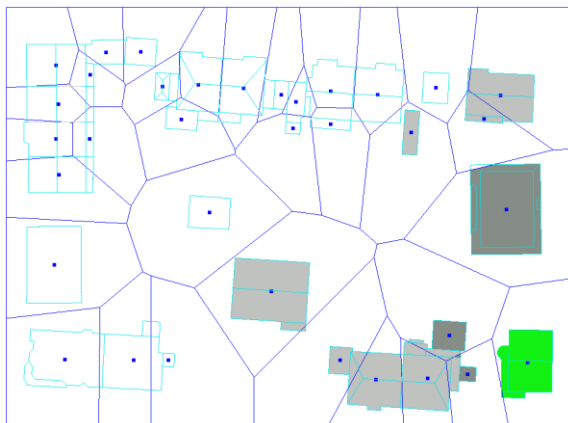


Figure 5: Voronoi diagram showing the neighborhood relations of buildings for shading

For each building in a district, a set of neighbors is determined and assigned to the building as shading objects. In order to keep the geometric complexity of these shading objects low, the original CityGML model with possible building parts is not used, but the newly calculated reduced thermal envelope of the buildings. The information regarding shading objects cannot yet

be mapped in the CityGML Energy ADE and must therefore be redetermined if required.

3.5. Building Usage

Beside a correct building geometry, a thermal simulation requires usage profiles that describe the behavior of various influencing factors on a thermal zone in the form of time series (Geiger et al., 2020). These are profiles for the use of heating and cooling, profiles for additional heat sources within a thermal zone such as technical devices, lighting, but also the users and finally ventilation and shading devices. In Germany, the DIN 18599-10 standard describes a total of 44 space usage profiles. However, there is no direct link between CityGML building functions and DIN 18599-10 space usage profiles. As a replacement, a mapping between the CityGML building function codes and DIN 18599-10 has been created. The mapping uses an experience-based relative ratio to estimate the proportion of space use profiles within a building. One building usage profile was calculated for each ALKIS building function from a maximum of eight DIN 18599-10 room use profiles (Geiger et al., 2022). If no building function is available, the usage profiles must be selected manually.

3.6. Building physics

Finally, the material information is missing to perform a thermal simulation. In this last task, the automatic assignment is based on the building attribute *yearOfConstruction*. If this attribute is not available, a suitable construction must be selected manually. In order to obtain suitable material information for a year of construction, the data from TABULA, which was created as part of the Intelligent Energy Europe project, is used (TABULA, 2024). The data contains building typologies for the energy assessment of residential buildings that provides statistical building physics. These building typologies are based on a set of reference buildings representing certain size and age classes of the building stock within a country and data are provided for 21 European countries. Four building types are considered and eleven building age classes are covered for each building type. The data set contains typical component information for walls, floor slabs, roofs and windows. Unfortunately, the data is not stored in the form of a database; instead, EXCEL tables are offered for download. Therefore, the data had to be extracted and mapped in a separate data structure. Based on this new data structure, the material information can now be queried with the attribute *yearOfConstruction* by searching for the corresponding period in the construction age classes. As non-residential buildings are not

included in TABULA, it is planned to use data from the Institute for Housing and Environment – Institut Wohnen und Umwelt GmbH (IWU) – for this in future, although this will only take into account the German building stock (Hörner et al., 2022).

4. Implementation

The enrichment process for CityGML building models described above is realized as a plugin (KITModelViewer PlugIns, 2024) for the KITModelViewer application (KITModelViewer, 2024), formerly FZKViewer. The plugin will be available as part of the freeware version. Although all the process steps mentioned are already developed, the module is still in a prototype state and the results of the enrichment process still depend strongly on the quality (mainly the geometric quality) of the input data.

The requirements for the automated enrichment process and the possible user interactions are explained in more detail below.

After loading a CityGML dataset either as a file or via an OGC-compliant Web Feature Service (WFS), the enrichment plugin can be started. In the first step, all buildings to be processed are displayed and outlined on a 2D map in order to visually check their completeness and geographical location. In a second step, model statistics are generated to provide the user with an overview of the model structure, the model geometry, the correctness of the geometry, the presence of relevant properties and the number of thermal zones generated. If the model statistics meet the user's requirements, the building physics and building usage can be assigned.

Regardless of whether a building or a district is being processed, the module primarily attempts to interpret the GML standard attributes *function* and *yearOfConstruction* in order to perform automatic enrichment. The following requirements apply to automatic enrichment:

- The assignment of usage profiles relies on the ALKIS building code provided in the attribute *function*.
- The assignment of the material definitions results from the attribute *yearOfConstruction* and is obtained from the TABULA data.

Based on the parameters provided by the buildings, the enrichment process automatically assigns usage profiles and the material information. If this automatic assignment is not possible for one or more buildings, manual assignment to a corresponding ALKIS code or a corresponding building age class is also possible.

The total number of buildings and the number of buildings to be enriched are automatically derived from the completeness of the parameter sets and presented to the user.

In addition to assigning the material structure of the building elements and the profiles for the building usage, the percentage ratio of window area to wall or roof area can be defined.

All information generated during the enrichment process is added only to the CityGML Energy ADE features *ThermalZone* and *UsageZone*. The original data and the geometry of the buildings remain unchanged.

Once all operations and checks have been made, the generated CityGML Energy ADE model can either be exported and made available to other applications or converted into EnergyPlus input data using our internal version.

5. Example

The KIT/IAI Institute has stored CityGML building models that are freely available from the German state offices (approx. 41 million buildings) in a GIS database and retrieves the CityGML data via a Web Feature Service (WFS). The implemented functions introduced in this paper were tested by selecting a small building block in Cologne, which contains both buildings with building parts (LoD1 and LoD2) and a closed construction (Figure 6). The test model consists of 35 building models, of which 10 building models are subdivided into building parts (28 building parts in total).

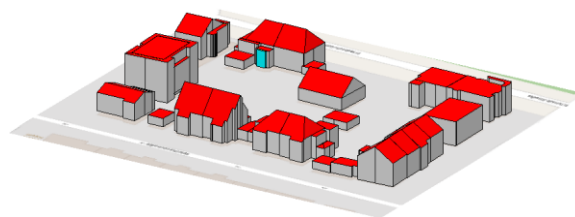


Figure 6: The selected building stock in Cologne retrieved from the CityGML database

The building parts are connected to each other by the *ClosureSurface* feature (see Figure 7) and are all classified by the attribute *function*: 21 x "residential building", 1 x "residential building with trade and services", 3 x "building for business or industry", 6 x "garage", 1 x "shed" and 3 x "roof". None of the building models have the year of construction attribute.



Figure 7: The *ClosureSurface* features (yellow surfaces) which separate the building part

In the first step, buildings that are not to be taken into account (e.g. garages, sheds and roofings) are ignored and the building parts are merged into a single zone (Figure 8).



Figure 8: The building stock after merging the building parts and removing the buildings which are not simulated (e.g. garages, sheds and roofings)

Then the neighborhood relationships are established, a closed construction method is detected and corresponding shared walls are created (Figure 9).



Figure 9: The calculated *SharedWall* featured for building in a closed construction

In the final step of the geometric generation of the single zone models, window elements are generated for a preset wall-window ratio (Figure 10).



Figure 10: The final building geometry including windows generated according to the preset wall-window ratio

In addition to the correct geometric calculation of the thermal zone, attributes for building volume and base area are derived from the generated building envelope. If the CityGML attribute *storeysAboveGround* is available, it is used

together with the base area to determine the heated area. Otherwise, the number of storeys is determined using a predefined average storey height and the building height. Depending on the building usage, schedules are generated in a further step, which describe the usage behavior in general terms. Specifically, schedules are generated for the set point temperatures (heating, cooling), presence of people, lighting and internal loads. And finally the material parameters are assigned based of the attribute *yearOfConstruction* and TABULA.

Conclusion and Outlook

The method introduced in the present paper allows a CityGML building model to be enriched in several subsequent steps for thermal building simulations. To ensure maximum transparency and interoperability, the enrichment is performed according to the model specifications of the CityGML Energy ADE. Both geometric and semantic modifications to the original CityGML building model may be necessary to generate the thermal building envelope. Enrichment with information for building usage and building physics is achieved with the use of customized libraries based on DIN 18599-10 and TABULA. The data derived from this is converted into CityGML Energy ADE time series and component structures and is therefore transparent for all subsequent processes. The method enables the widespread CityGML building models to be used for thermal building simulation and, the enriched CityGML Energy ADE building models to be shared with other applications in an open data model.

The enrichment process is prototypically integrated into the KITModelViewer software. The results of the geometric operations on the model are heavily dependent on the structure and quality of the input data and must be tested with additional different data sets and adapted if necessary. The libraries for assigning data for building usage and for component structures are implemented in a rudimentary way. Both the content and the use of these libraries must be easily and flexibly expandable in the future.

The functionality to enrich CityGML building models with energy-relevant information and the export to CityGML Energy ADE will be part of future versions of the freeware KITModelViewer.

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