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USAGE PROFILE ENRICHMENT OF CITYGML MODELS FOR URBAN BUILDING ENERGY MODELING

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Abstract

In Germany, CityGML data is available nationwide either as open data or commercially. In order to be able to use this data for energy modelling of a city district or a campus, the CityGML data must be supplemented with information on building physics, usage behaviour and operational information.

This contribution describes a workflow, and its corresponding implementation, for CityGML data enrichment with building usage profiles. Once the required parameters are assigned, the enhanced data is saved together in a single CityGML Energy ADE file. Further, a simulation is performed with EnergyPlus, which serves to demonstrate that the CityGML Energy ADE store all simulation-relevant data.

Introduction

In Germany, the proportion of energy consumption for space heating in private households fell slightly between 2008 and 2018, but still accounts for around two-thirds of final energy consumption (Umweltbundesamt, 2020). One approach to quantify the behaviour of buildings and to be able to investigate different scenarios at district or city level is Urban Building Energy Modelling (UBEM).

UBEM applies many of the methods and techniques of Building Energy Modelling (BEM) on a larger urban scale. The United States Office of Energy Efficiency and Renewable Energy (EERE) defines BEM as a physics-based software simulation of the energy consumption of a building (Energy.Gov). However, physics-based simulation of the thermal performance of a building is only one method of simulating or estimating the heating demand of a building in the field of UBEM. In (Ferrando, et al., 2020) different UBEM approaches are described and classified upon the spatial scale, methods and parameters they use.

When planning a new building, the input parameters necessary for thermal simulation, such as the geometry, building physics and building services, are largely known. In contrast, the data situation in the building stock at city level is considerably more difficult. In addition, not all data is publicly available and may be subject to data protection.

Within the context of Open Data initiatives, more and more data is freely available in Germany. The GOVDATA data portal (GOVDATA) offers an entry point to find open data provided by federal states and local governments. This portal also hosts 3D city models that are made freely available to the public by state offices and individual city administrations.

3D city models in CityGML format provide an initial data basis for UBEM, (Biljecki, et al., 2015). When this spatial models are available in Level of Detail 2 (LoD2), the building envelope is simplified and usually semantically subdivided into wall, roof and floor areas, which in turn facilitates its use in UBEM. In addition, buildings can contain energy relevant properties such as year of construction, function or number of floors. Since the CityGML model does not have any energy-specific features and properties, the CityGML Energy ADE (Application Domain Extension) was developed as a model extension that integrates the information required for thermal simulation into the CityGML model. The CityGML Energy ADE allows to store information for a thermal building simulation in a transparent and interoperable way and to make it available to different simulation systems, (Agugiaro, et al., 2018).

In order to enrich a CityGML model and thus produce a valid CityGML energy ADE model that can be used for simulation, a proof of concept of an enrichment workflow is presented. In this workflow, the CityGML is first analyzed, revealing to the user statistics regarding the spatial model, including errors. If the data is suitable for further processing, in the simplest and most time-consuming case, the user can manually enter all missing parameters. To simplify this task, a module containing pre-defined templates of building parameters was created. This library is also used to automatically enrich CityGML depending on building function. In the current software application version, the enrichment process is completed by converting the building envelope into one thermal zone and assigning default materials. Afterwards, the enriched model can be exported as a CityGML Energy ADE file.

Finally, the enhanced building model stored in CityGML Energy ADE is converted into the EnergyPlus format IDF and a thermal building simulation is performed with EnergyPlus. This also serves to verify the workflow.

CityGML Data of German Federal States

CityGML (City Geography Markup Language) is a worldwide used 3D city model for different application fields. Currently, the conceptual model for CityGML version 3.0 (Kolbe, et al., 2021) is available and the encoding standards are in progress. In Germany, mainly CityGML version 1.0 (Gröger, et al., 2008) is made available by the federal states (see Table 1). CityGML version 2.0 (Gröger, et al., 2012) made minor changes to the building model, and is less widespread, as the aforementioned table indicates. As the CityGML model and its areas of application have already been described in detail in several articles (Gröger, et al., 2012), (Saran, et al., 2018), (Biljecki, et al., 2015), this paragraph focuses on details of CityGML Level of Detail 2 (LoD2) data available from German federal states.

In order to assess the availability and quality of CityGML models provided by the 16 German state authorities, 16 CityGML data sets have been downloaded and analyzed in terms of their suitability for thermal energy simulation. Currently, half of the federal states provide CityGML models as open data. Another five federal states offer CityGML test data for download on their website while three states delivered test data upon request.

All data sets contain a valid schema location and can be easily checked with an appropriate XML schema checking software. During the schema check, slight errors are found in two data sets (missing namespaces), but these do not affect the further processing of the data sets.

The structure of the CityGML building model in the data sets varies from federal state to federal state. Some federal states produce CityGML building models without subdivision into building parts. Other state subdivided the building model into building parts and the majority create corresponding closure surfaces as contact surfaces between the building parts (see Table 1). Only two federal states do not calculate contact surfaces between the building parts, making it difficult to determine the real building envelopes. The data sets of two federal states contain LoD2 buildings and building parts as well as LoD1 buildings or building parts, which can complicate further processing steps.

The data sets of all federal states contain the respective LoD 2 boundary surfaces and, with the exception of two federal states, also the solid geometry of the buildings (see Table 1). The exhaustive analysis of the geometry is beyond the scope of this article, but rather its use in thermal building energy simulation. As such, only the most common problems of the data sets, the ones that impact the presented goal are mentioned in this article. In many cases, polygons of boundary surfaces (mainly roof surfaces) are not planar. The deviations of such polygons from the best fitting plane can be up to 2 m. Only a few data sets pass the edge topology check for solid geometries without errors. The most common reasons for this are topologically incorrect surface compositions of wall- and closure surfaces. Furthermore, the sample data often contains small gaps in the building geometry meaning that the building is not sealed (not closed correctly). Almost all data sets contain point coordinates with three decimal digits, so that no edges shorter than 1 mm can arise. Analyses have shown that almost all test data contain very short edges in the lower millimeter range.

In addition to various generic attributes, the data sets also contain the standardized building attributes *function*, *roofType* and *measuredHeight*. However, the attribute *storeysAboveGround* is only included in about half of the datasets. Unfortunately, the reference to the code lists used for the attributes *function* and *roofType* is not given in any data set. In Germany, the code lists proposed by the CityGML standard are not used, but the code lists of the Arbeitsgemeinschaft der Vermessungsverwaltungen, AdV (AdV, 2022), are used. All buildings in the datasets have unique identifiers, which are also unique throughout Germany thanks to unique prefixes of the federal states.

Table 1: LoD2 CityGML models in Germany

German federal state (with link to official datasets)	**Open Data**	**CityGML Version**	**Only LoD 2**	**Building Part**	**Closure Surface**	**Building Solid**
Baden-Württemberg	✗	1.0	✓	✗	✗	✓
Bayern	✗	1.0	✓	✗	✗	✓
Berlin	✓	1.0	✓	✓	✓	✓
Brandenburg	✓	1.0	✓	✓	✓	✓
Bremen	✗	1.0	✓	✗	✗	✓
Hamburg	✓	1.0	✓	✓	✗	✓
Hessen	✗	1.0	✓	✓	✓	✓
Mecklenburg-Vorpommern	✗	2.0	✓	✗	✗	✓
Niedersachsen	✓	1.0	✗	✓	✓	✗*

Nordrhein-Westfalen	✓	1.0	✓	✓	✓	✓
Rheinland-Pfalz	✗	1.0	✗	✓	✗	✓
Saarland	✗	2.0	✓	✗	✗	✓
Sachsen	✓	1.0	✓	✓	✓	✗
Sachsen-Anhalt	✓	1.0	✓	✓	✓	✓
Schleswig-Holstein	✗	1.0	✓	✓	✓	✓
Thüringen	✓	1.0	✗	✗	✗	✓

* LoD1 only

The analysis of the data sets from the different federal states has shown that the use of the CityGML data as input for a physically based thermal building simulation is not possible without strict verification, structural and geometric modifications and tolerant enrichment methods. The different modelling methods and the partly incomplete data of the federal states are aggravating factors.

CityGML Energy ADE

The CityGML standard was conceived as an application independent information model (use case agnostic). This is why it is insufficient when it comes to energy specific entities and attributes used in urban energy modeling. To cover this use case, the Energy Application Domain Extension (ADE) was developed, (Agugiaro, et al., 2018). Ensuring interoperability with CityGML is the fact that the ADE has its own XML-schema with an associated namespace. The extension facilitates work in the field of UBEM, where data quality and interoperability are an essential part of any simulation. The Energy ADE provides a standardized way of describing building energy information and allows for both detailed single-building energy simulation (based on sophisticated models for building physics and occupant behaviour) and city-wide, bottom-up energy assessments, with particular focus on the buildings sector, with multiple tools using it, (Malhotra, et al., 2022).

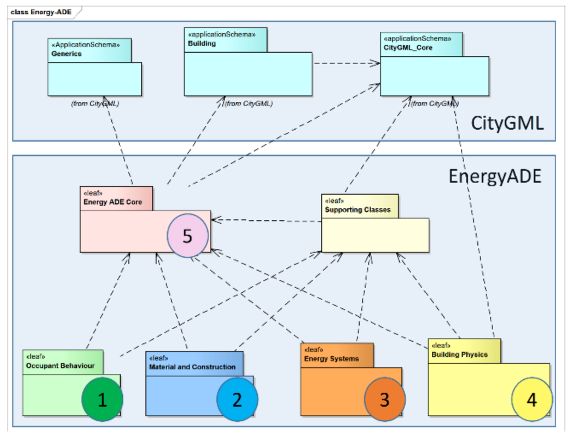

Figure 1: Schematic diagram of EnergyADE

Figure 1 shows the dependencies to CityGML feature and the five modules of the Energy ADE. These modules, first published in (Nouvel, et al., 2015) are: (1) occupant behaviour, describing building operation and respective schedules, (2) material and construction, which contains parameters regarding the thermal and optical properties of buildings materials, as well as material layers, (3) energy systems, where energy sources of are described, (4) building physics, that contains the description for thermal (single- or multi-) zones representing the building and its envelope, and (5) the core, which defines abstract base classes and generally used data types, allowing for schedules, physical and weather data to be stored.

The CityGML ADE, currently in version 2.0, has been used successfully in simulations, in different spatial contexts and at different scales, such as (Agugiaro, et al., 2018), (Geiger, et al., 2020), (Remmen, et al., 2018). To achieve this, the Energy ADE is very flexible. With simplified energy assessments, a building can be modelled as a single-zone with simplified thermal properties (U-values, g-values, etc.) and then be further detailed for complex dynamic simulations with multi-zone models, detailed associated geometries, layered constructions and complex occupancy schedules included, (Agugiaro, et al., 2018).

Usage Profile Enrichment Workflow

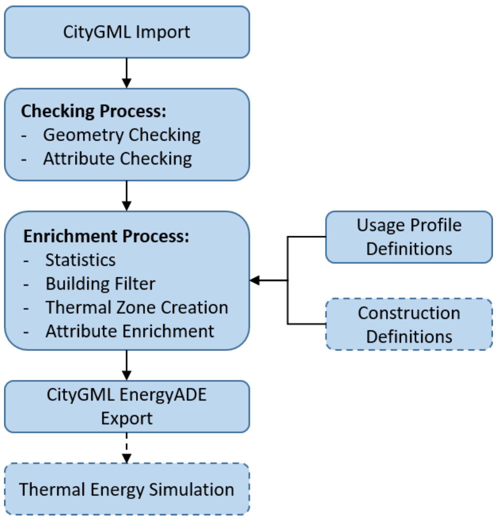

Figure 2: Diagram of the enrichment workflow

As already described in the previous sections, standard CityGML does not include the required parameters for thermal building simulation. For this reason, an enrichment process was developed, presented in Figure 2. The process is divided into two main steps. In the first step, the imported CityGML building models are analyzed and checked before they are enriched in the second step.

A quality check of the building models can basically be subdivided into three categories, these are consistency, correctness and completeness and are explained in detail in (Geiger, et al., 2021). The consistency - correctness of the syntax and semantics - of the CityGML data is assumed, otherwise even importing the data would lead to errors. The checking process takes into account the correctness and completeness of the building data. For the correctness check of the building geometry, a closed volume is required. This volume can be represented either by a solid of the building or building part or by a resulting solid from the individual boundary surfaces. The solid check is done using an edge topology similar to the Winged-Edge data structure (Baumgart, 1974).

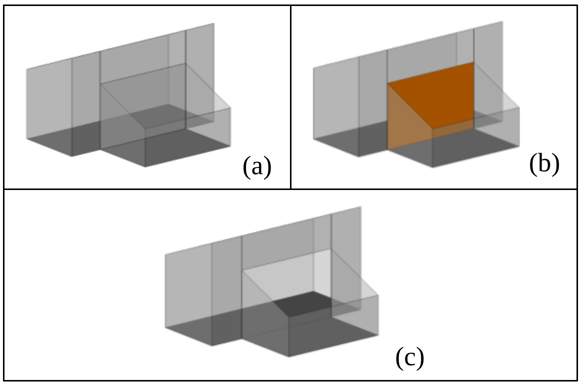

Figure 3: BuildingParts example

As explained in detail in the section CityGML Data of German Federal States, modelling of buildings is not uniform in the various federal states. This applies in particular to the building subdivision into building parts. In the current implementation, it is assumed that the building´s interior is one thermally homogenous single zone. This rule also applies to building parts. This means that the volumes of a building and its building parts are combined into one single building envelope (see Figure 3c). A distinction is made between adjacent building / building parts with *ClosureSurface* (see Figure 3b) and without *ClosureSurface* (see Figure 3a). If there are no *ClosureSurfaces*, the 2D intersection of touching surfaces is calculated. This represents the missing *ClosureSurface*. The newly calculated *ClosureSurface* is subtracted from the touching surfaces. An example for the resulting buildings envelope is shown in Figure 3 bottom side illustration. Finally, in order to ensure that the resulting zone forms a valid and closed volume, the described volume check is performed.

In most cases, the buildings are available in LoD2. However, it occasionally happens that LoD1 building or building part without boundary surfaces are provided. In this case, the thermal surfaces are simply determined based on the surface orientation. Vertical surfaces with a maximum slope of 10° are classified as exterior walls. Surfaces oriented in positive Z direction and an angle between 0 and 80° are classified as roofs while all surfaces oriented in negative Z direction and an angle between 0 and -80° are classified as ground surfaces.

Finally the attributes are checked for both completeness and correctness. This is done in particular, for the attributes year of construction (should exist and represent a valid year with 4 digits), building function (has to be a valid CityGML codelist entry), storeys above ground (should exist and is required for the correct floor area), storeys below ground (optional, also used for the floor area) and measured height (should be consistent with the height of the building solid and combined with the number of floors it should give a realistic floor height).

The spatial model produced in the checking process then goes into the enrichment process. First, an overview of all buildings, their geometry types and their parameters is presented in the form of a statistic. This helps the user get a quick overview of the buildings, which is especially usefull with larger data sets. In principle, the parameters of the thermal model can be defined separately for each individual building, a time consuming process, which is not practical for districts with a large number of buildings. Therefore, with the enrichment process presented here, the usage profiles are automatically assigned to each building. This is done by using the CityGML codes of the building function attribute. In order to complete the simulation parameters, default materials are currently used for the building envelope components.

Earlier work in (Geiger, et al., 2020), have identified the largest influencers in terms of relative value to the estimation of thermal demand using UBEM methods – combined spatial and physical modeling. Out of the determined variables, building usage plays a significant role, determining a large variation in the final primary thermal energy demand. In order to populate the data set provided as input in the simulation the German standard DIN V 18599-10 was used, (DIN Deutsches Institut für Normung e. V., 2011). This document contains a total of 44 space usage profiles dedicated to describing typical building usage profiles (each with dedicated names “Einzelbüro”, “Lagerhallen”, “Logistikhallen”, …). Each profile contains scheduling and thermal specifications for heating, cooling, ventilation, lighting, person attendance and existing devices. There is however, no direct way of linking CityGML building function to these space usage profiles. As a substitute, a mapping in between CityGML building function codes and DIN 18599-10 was performed. The mapping makes use of an experience based relative ratio to estimate the proportion of a building occupied by a certain type of occupancy depicted in the 44 space usage profiles mentioned earlier. The relative values were tested against values calculated from public buildings. Trough this process the enrichment module allocates building use profiles to the newly enriched data, its associated profile production workflow being depicted in Figure 4.

For each building function a maximum of eight DIN 18599-10 profiles are used to calculate a new building use profile. In total, CityGML includes 302 standard codes that can be used to describe the building. These codes can be classified into ten comprehensive first tier categories (*31001_1000*, *31001_2000*, *31001_3000*, …), each with a unique code for identification..

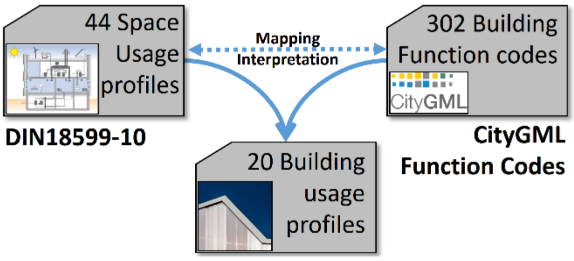

Figure 4: Building Usage profile creation workflow

In addition, the above mentioned categories can be further classified in 45 second tier sub-categories. For the scope of this publication it was decided to produce profiles that correspond to information matching the first tier categories (with the exception of *31001_9998* where no ratios could be allocated) and partly for the second tier (all residential building codes are allocated to the first tier *31001_1000*, while the eight sub-categories of *31001_2000* and the three *31001_3000* received distinct profiles). Together with the nine first tier categories it brings the total of building usage profiles to 20. These cover the relative vast majority of buildings in use in Germany.

Enrichment verification

The verification of the enrichment process is focused on the general applicability of a simulation and the completeness of the required parameters. This means that no statement is made as to whether the generated building models match their real world counterparts.

To validate the completeness of the generated EnergyADE data, both individual buildings as well as large number of buildings were simulated based on the available data sets. For this purpose, the EnergyADE file was converted into the data format IDF (Input Data Format) with the help of the application IFCExplorer and then transferred to the simulation tool EnergyPlus and simulated without errors.

Conclusion and Outlook

The paper presents a new approach for enriching a larger number of 3D building models by usage profiles for thermal building simulation. The results of the enrichment process are stored in the interoperable standardised CityGML EnergyADE format and contain all the necessary parameters for thermal building simulation using EnergyPlus.

The CityGML building models of the federal states, which are available nationwide, are used as the original source data. A detailed analysis of the available data sets shows that the building models differ significantly in the individual federal states. The enrichment module considers these differences and enables an automatic assignment of usage profiles as well as a manual assignment of default material information required for the thermal building simulation. The developed module analyses the data for correctness and completeness and creates a single-zone model independent from the original building subdivision.

For the enrichment of the usage profiles, the German specifications of DIN 18599-10 for space usage profiles are used for the current implementation. Further implementations will also consider the definitions of the Swiss standard SIA 2024, which provide additional detailed information for the usage profiles.

The current implementation uses default materials in order to guarantee complete parameter set for simulation. In future, the material parameters should be automatically derived from other sources, e.g. the CityGML attribute year of construction. In addition, if buildings have different functions or year of construction for their building parts, it should be possible to create multi-zone models.

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