THERMAL ENERGY SIMULATION OF BUILDINGS BASED ON THE CITYGML ENERGY APPLICATION DOMAIN EXTENSION

A. Geiger[1], J. Benner[1], K.-H. Häfele[1] and V. Hagenmeyer[1]

[1] Institute for Automation and Applied Informatics, Karlsruhe Institute for Technology, Karlsruhe, Germany

ABSTRACT

The present paper describes a semi-automatic process, in which a typical CityGML 3D building model is enriched with explicit thermal energy related information and stored in a CityGML Application Domain Extension (ADE). Special emphasis is given to the discussion of suitability of existing CityGML models for city-wide energy simulations. Possible conflicts between the requirements of urban energy simulation systems, the capabilities of the CityGML Energy ADE and the available data are presented, which can be partly resolved by specific geometric / semantic corrections of the model data. For testing and evaluating the approach, interfaces for two building energy simulation systems have been developed.

INTRODUCTION

Recent studies have shown that cities are responsible for more than 70% of greenhouse gas emissions (IEA, 2016), and therefore strongly contribute to climate change and air pollution. This calls for a new, holistic urban planning approach, considering all aspects of sustainable urban development. Reducing energy demand and CO_2 emissions, and increasing the share of renewable energy are crucial points in this context.

Therefore, the popularity of urban energy modelling (UEM) tools for assessing the thermal energy demand of buildings on urban scale has risen in recent years (Reinhard and Davila, 2016). UEM technology is used for planning energy efficiency measures like integrating combined heat and power plants (CHP), supporting balancing fluctuating renewable energies for demand side management, and providing indispensable information for planning energy related retrofitting measures of the building stock.

Most of the applications mentioned above require analysing time-varying energy demand profiles under dynamic external (e.g. weather) conditions. A number of building performance simulation platforms like CitySim (Robinson et al., 2009), Sim-Stadt (Nouvel et al., 2015), EnergieAtlas (Kaden and Kolbe, 2013) or TEASER (Remmen et al., 2018) have been developed, which can handle multiple buildings on urban scale. However, a common problem in the application of these tools is the lack of energy related information for the individual buildings. Furthermore, the available data is frequently inaccurate or at least unreliable.

Typical sources for urban wide building energy related information are 2D cadastre data or virtual 3D city models from public agencies and aggregated statistical data from population and housing censuses. Thus, besides the building's position, orientation and - more or less generalized - geometry, there is typically only very little information available for the derivation of input for energy simulations. Each of the urban energy simulation systems mentioned above therefore implements specific strategies for checking, correcting and enriching the available information and transforming it into a usable simulation model. Therefore, the existing enrichment processes are tool specific and opaque to the user. This is one reason why simulations of the same urban situation - performed with different tools - can lead to strongly differing results.

The present paper therefore proposes a transparent enrichment process, which

- uses virtual 3D building models in the standardised data format CityGML, which are geometrically and semantically checked and corrected,
- enables control and correction of the attributive data being generated in the enrichment process, and
- explicitly stores the generated simulation model in an Application Domain Extension (ADE) "Energy" of CityGML.

The Energy ADE data model is considered a "neutral" interface between Building Information Modelling (BIM) tools and Geographic Information Systems (GIS) on the one hand and building energy simulation tools on the other hand. In the following, this approach is tested and evaluated by implementing Energy ADE interfaces for two specific simulation systems. First results prove the general applicability of the approach, but also reveal some technical difficulties in its realization and deficiencies in the current version of Energy ADE.

URBAN ENERGY RELATED DATA MODELS

At present, there are only a small number of open data formats for modelling the built environment, which primarily aim to support the interoperable data exchange in heterogeneous software architectures. In the BIM area, especially the standards IFC (Industry Foundation Classes) and gbXML (green building XML) are to be mentioned. The latter has explicitly been designed as interface between modelling and simulation systems for buildings (Casper et al., 2014). This interface is also supported by IFC as comprehensive product data model for buildings. However, at present there are no economic tools or methods for the derivation of BIM data for larger groups of buildings or a whole city.

Furthermore, the building related information available on urban level differs significantly – in structure and content – from the above mentioned BIM models. They are geometrically limited both to the representation of the footprint or exterior shell of the building, representing geometry by explicit surfaces instead of (parametric) volumes, and to support only few non-geometric properties like building function or year of construction. However, 2D cadastre data and especially virtual 3D city models still represent the most comprehensive data source for urban energy modelling. Hence, the available information needs to be checked, corrected and enriched to allow for energy related simulations, and a suited extension of the 3D city model is needed for its storage and exchange.

CITYGML DATA MODEL

The OGC (Open Geospatial Consortium) standard CityGML (OGC 2012) is the most frequently used data format for 3D city models. In the current version 2.0 a building may either be represented by a single object (class *Building*), or separated into one main part modelled as *Building* and several building parts (class *BuildingPart*), differing structurally (number of storeys, roof type) or functionally (function, year of construction) from the main part. *Building* as well as *BuildingPart* objects can be represented both geometrically and semantically in up to 4 different Levels of Detail (LoD1 – LoD4, the two-dimensional LoD0 representation is irrelevant in the present context). This concept, including its strengths and weaknesses has been extensively discussed elsewhere (Benner et al., 2013), (Löwner et al., 2016). Therefore, in the present paper we discuss and rate only the suitability of different LoD representations for building simulations (see Table 1). The qualitative rating (from "++" (very good) to "--" (very bad)) uses the following criteria:

- Accuracy of the geometric representation of *building volume.*
- Separation of the building's exterior shell into classified (wall, roof, base slab) *boundary surfaces* suitable for thermal simulations.
- Geometric and semantic representation of *openings* (windows, doors) in the exterior shell suitable for thermal simulations.
- Geometric and semantic representation of *interior* building *structures* (e.g. rooms, inner walls, ceilings) suitable for thermal simulations.
- City-wide availability of data.

It turns out that the most frequently available LoD1 models provide no directly energy relevant information, besides an approximate representation of the overall building volume. Models of category LoD4 have the highest information content and could, potentially - after an adequate geometric processing - even represent different thermal zones within a building. However, such models do not exist in practice. Hence, the enrichment process described in this paper focusses on LoD2 and LoD3 models.

Table 1: Rating of CityGML LoD for building simulations

	LoD1	LoD2	LoD3	LoD4
Building volume	-	+	++	++
Boundary surfaces	n. a.	++	+	+
Openings	n. a.	n. a.	+	+
Interior structure	n. a.	n. a.	n. a.	+
Availability	++	+	-	--

Most building energy simulation systems work with simplifying assumptions about the thermal energy exchange between the building's interior and the outer environment. Therefore, the generalised boundary surface geometry provided by LoD2 models is typically better suited than the (geometrically more detailed) LoD3 version. However, the central disadvantage of LoD2 models is their lack of explicit opening information, which needs to be added in the enrichment process.

On an attributive level, CityGML 2.0 only provides the building's year of construction, different functional classifications of the building, and the building height and/or number of storeys. Many approaches for city-wide building energy simulation use these parameters in combination with building typologies – as, e.g. Tabula (Ballarini et al., 2014) - to derive real physical parameters like heat resistances or heat capacities of walls. Furthermore, based on the functional building classification and statistical data, the energy relevant behaviour of the building's occupants is assessed and quantified. Unfortunately, in the CityGML or cadastre data currently available, the attributive information, in particular the year of construction, quite often is missing or unreliable. This pertains especially to the year of construction, which may represent either the actual year of construction or the date of the last building modification (e.g. an enlargement) requiring an official approval.

CityGML Application Domain Extension Energy

Our approach follows the general workflow of enriching and extending the available building information. One of the main differences to other approaches is that the data enrichment process and building simulation process are decoupled and that the enrichment results are stored in a new data format. In principle, this allows running simulations with different tools based on the same input data set.

The new data model for building energy simulations is defined as Application Domain Extension (ADE) of the CityGML standard. According to the general ADE mechanism (van den Brink et al., 2013), the Energy ADE defines a number of new feature classes and extends the existing classes *Building* and *BuildingPart* with additional, energy relevant properties. Version 1.0 of the new data model is comprehensively introduced in (Agugiaro et al., 2018). Therefore, the present paper focuses only on a rough overview of the model (see Figure 1).

The CityGML classes *Building* and *BuildingPart* are extended by properties to represent size (*volume*, *floor area*) and location (*referencePoint*, *heightAboveGround*) of a building. In addition, the properties *buildingType* for an architectural classification (e.g. *singleFamilyHouse* or *terracedHouse*) and *constructionWeight* for classifying the construction status (e.g. *lightConstruction*, *heavyConstruction*) are introduced.

Core of the new data model is a thermal building model, separating the energetically relevant building volume (thermal building hull) into one or more thermal zones (class *ThermalZone*) with homogeneous thermal conditions. All *ThermalZone* objects may contain volumetric geometry (property *volumeGeometry*). Different *ThermalZone* volumes are non-overlapping and unite to the complete thermal building hull. A *ThermalZone* can also be related to one object *UsageZone*, specifying the thermal needs of the zone's occupants (schedules for heating, cooling and ventilation), as well as data to estimate the internal heat gains due to lighting or electrical facilities (class *Facilities*) and the occupants themselves (class *Occupants*).

ThermalZone objects are completely bounded by specific boundary surfaces (class *ThermalBoundary*), enabling the exchange of energy between adjacent thermal zones as well as thermal zones and the outside environment.

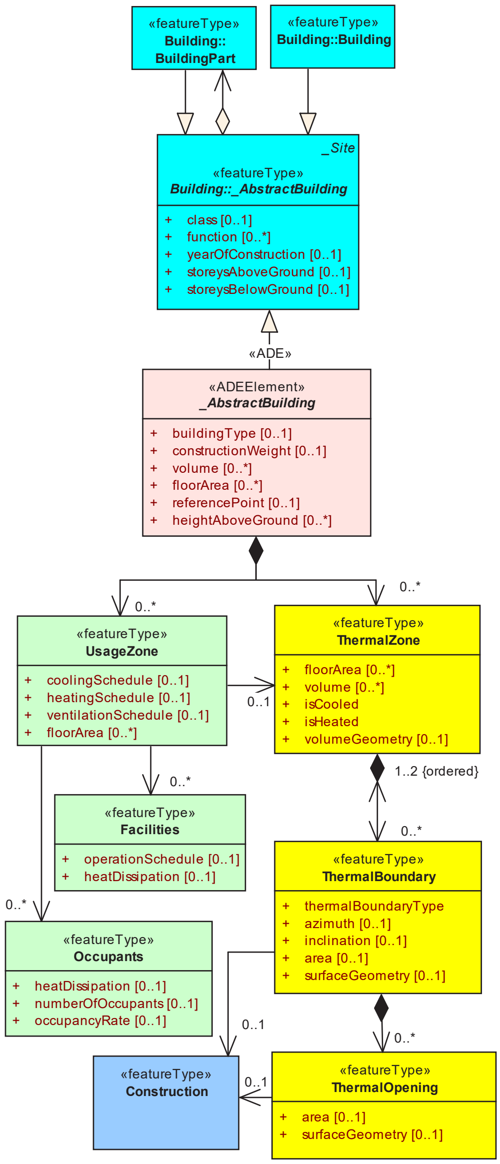

Figure 1: Simplified UML model of the CityGML Energy ADE

Thus, a *ThermalBoundary* relates either to exactly one *ThermalZone* object (in case it corresponds to the exterior building shell) or it relates to two *ThermalZone* objects (in case it corresponds to an interior wall or ceiling). Geometrically, *ThermalBoundary* objects are represented by a simply connected and (within certain limits) planar *surfaceGeometry*. Orientation of this plane (*azimuth*, *inclination*) and surface size (*area*) may also be specified by attributes, together with the mandatory boundary condition (*thermalBoundaryType*) of the surface (e.g. *outerWall*, *intermediaryCeiling*, *sharedWall*).

It is assumed that a *ThermalBoundary* object has homogeneous thermal and optical properties, aggregated in a related *Construction* object. If the corresponding real building element has openings (doors or windows) with differing physical and optical properties, the openings must be separately represented by *ThermalOpening* objects with their own *surfaceGeometry*, *area,* and associated *Construction*.

ENERGY RELATED ENRICHMENT OF CITYGML DATA

The new general workflow to enrich CityGML LoD2 or LoD3 building models is depicted in Figure 2. The process starts with importing the CityGML data into the new enrichment tool, which at present supports only a file-based import. In case the input data contains several CityGML *Building* objects, the enrichment is performed individually for each object.

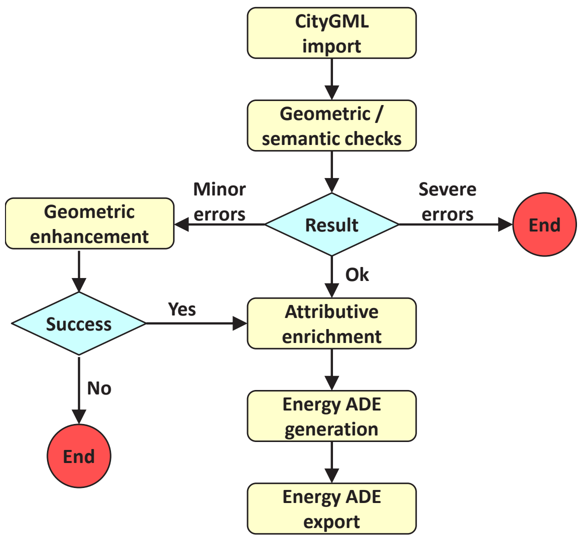

Figure 2: Enrichment process

In the first step, a number of geometric checks is performed. If none of these checks reveals significant errors, the process directly continues with the attributive enrichment. In case minor errors are detected, the algorithm tries to correct the data and afterwards to continue with the attributive enrichment. Finally, if one of the checks detects severe, not easily correctible errors, the enrichment process for this *Building* object stops.

Geometric checking and correction are performed without any user interaction. In the attributive enrichment process, however, where missing physical parameters and occupant behaviour information is added, user interaction is required. Finally, an Energy ADE representation of the corrected and enriched CityGML model is generated and stored externally. Since LoD2 and LoD3 input data contain no information on internal building structures, the process always generates one *ThermalZone* and one *UsageZone* object for each *Building and BuildingPart* object.

Geometric / semantic checking and correction

The relevance of application specific checking and validating CityGML models has been indicated by (Wagner et al., 2014). Simulations, in which the building's interior is assumed as thermally homogeneous (single zone models), require firstly a correct value for the building volume. Secondly, correct sizes, orientations and geometric representations of the different parts (boundary surfaces) of the building's exterior shell are necessary. Thirdly, correct boundary conditions for all boundary surfaces are crucial. The latter conditions indicate whether a specific surface is exposed to air, to the ground or to a neighbouring building.

Concerning boundary conditions, many existing LoD2 and LoD3 CityGML building models show deficiencies. Usually, this occurs when a CityGML *Building* relates to *BuildingPart* objects. Normally, *Building* as well as *BuildingPart* objects are completely enclosed by _*BoundarySurface* objects with significant overlapping surface geometry (see Figure 3).

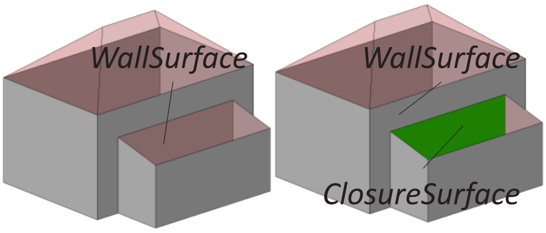

Figure 3: BuildingParts with overlapping WallSurfaces

The overlapping surface parts are then confined to the building's interior and normally do not correspond to real building elements. Thus, for a correct model they need to be separated and classified as CityGML *ClosureSurface*, which are ignored in the thermal model.

There are similar issues with closed building structures, which are frequently occurring in city centres. For correctly simulating the thermal behaviour of adjacent buildings, the parts of _*BoundarySurface* objects, where adjacent buildings touch, need to be separated and modelled as new _*BoundarySurface* objects of the type "SharedSurface" (see Figure 4). Unfortunately, CityGML has no standardised concept to express this situation.

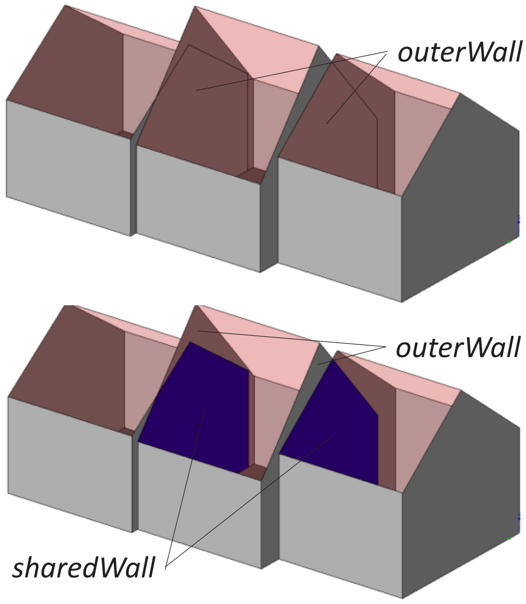

Figure 4: Building objects with overlapping surfaces

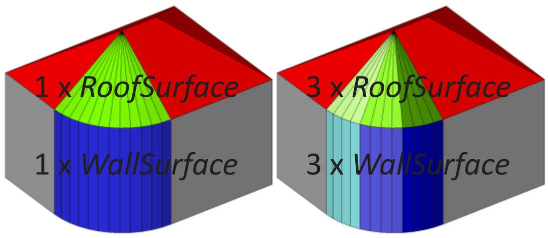

Figure 5: Separation of curved boundary surfaces

In the current state of implementation of the enrichment tool, all geometry errors like non-planar polygons, overlapping surface patches in multi-surface geometries or faulty volume geometry are classified as "severe", and result in an abortion of the enrichment process. Approaches to heal such errors under certain conditions (Wagner et al., 2013) may be incorporated in the future. A geometrical correction is performed in the following cases:

- The overlapping parts of *Building* / *BuildingPart* objects belonging to the same

Building are geometrically identified and classified as “virtual wall” (see Figure 3).

- The overlapping areas of *Building* / *BuildingPart* objects belonging to different Building Objects are geometrically identified and classified as “shared wall” (see Figure 4).
- A *_BoundaySurface* object is composed of surface patches with differing orientations, patches with (within certain limits) identical orientation are clustered, and a new *_BoundarySurface* object is generated for each cluster (see Figure 5).

Attributive enrichment

In this step of the enrichment process, the attributive information missing in the CityGML data is added. At present, this step is entirely performed by the user. However, for future implementations the automatic generation of realistic proposals is planned, which only necessitates checking and correction by the user.

The added information covers three different areas: (1) Thermal and optical properties of the different *_BoundarySurface* objects (*WallSurface*, *RoofSurface,* and *GroundSurface* objects), (2) set-point data for heating, cooling and ventilation, and (3) parameters to assess internal heat gains. For LoD2 models, percental "opening ratios" can be assigned to *WallSurface* and *RoofSurface* objects. The ratio indicates the size of an opening without determining its shape and location on the boundary surface.

Altogether seven sets of material parameters must be defined for *WallSurface*, *RoofSurface* and *GroundSurface* objects, and for openings (*DoorSurface* and *WindowSurface*) in walls and roofs. It is possible either to choose complete constructions - being composed of one or more layers - from a predefined construction list, or to specify physical parameters directly. In the latter case, a corresponding construction with one or two layers is generated automatically. For every layer, thermal conductivity, density, specific heat capacity, and layer thickness need to be specified. For openings, transparency and glazing ratio must be defined.

Set point information is defined in form of daily profiles, i.e. 24 hourly values for the needed temperatures and ventilation rates. For this, different schedules for specific days of the week (e.g. weekdays and weekends) and specific time periods within a year can be defined.

Internal heat gains are composed of the thermal energy emitted by the occupants, illumination and other electric devices. Again, daily usage or attendance schedules have to be defined, together with floor area or person-related constants to assess the emitted energy.

INTERFACING ENERGY ADE DATA WITH SIMULATION SYSTEMS

As already mentioned, the extended CityGML data model shall establish a "neutral" interface between modelling and simulation systems in the building area. For testing and evaluating this approach, two different simulation systems are used: The commercial system "Gebäude-Simulation 3D Plus" (Geiger et al., 2016), and the open source system EnergyPlus (Crawley et al., 2001). The goal of this research is the automatic derivation of input data sets for the dynamic simulation of a building's heating and cooling demand.

It turns out that this is principally possible for both target systems. Especially EnergyPlus has a very comprehensive and detailed data model for multiple applications, whose functionality is only rudimentarily covered by the CityGML Energy ADE. However, for both target systems it is possible to generate the necessary objects and mandatory properties to support thermal simulations. Transforming the building geometry is easier for the commercial simulation system “Gebäude-Simulation 3D Plus”, because this software only needs geometrical parameters (size und orientation) of the thermal boundary surfaces and openings. In contrast, EnergyPlus needs the explicit, geometrically generalised geometry of these surfaces. Multi surfaces and interior contours are not feasible and openings must have at most 4 contour points.

In the course of implementing the interfaces, some gaps and shortcomings in the current version of the CityGML Energy ADE become obvious. Among these are:

- Missing specification of underground soil temparatures;
- Missing class for "transparent" materials;
- Missing boundary conditions for walls in contact with the earth;

- Missing properties to limit the maximum available heating and cooling power.

SIMULATION RESULTS

Enrichment workflow and model transformations are tested with different CityGML models. One of these models is a typical office building (KIT Campus North building 445), whose CityGML LoD3 model is depicted in Figure 6. After finishing the enrichment process, which ignores all building installations (coloured brown in Figure 6), the model contains one *ThermalZone* object, referring to 12 *ThermalBoundary* and altogether 320 *ThermalOpening* objects. For heating and ventilation set-point schedules as well as usage parameters, the profile "Large Office" of "Schweizerischer Ingenieurs- und Architektenverein" (SIA 2015) is used. Typical weather data of the building site are provided by the Meteonorm software (Meteonorm 2018).

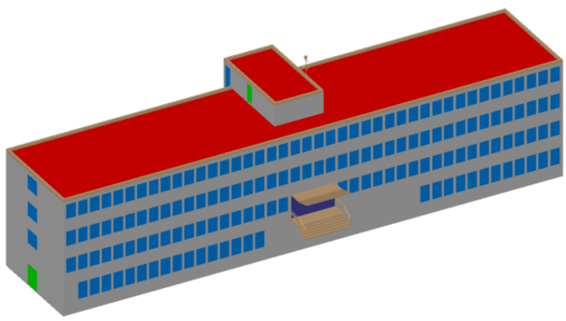

Figure 6: CityGML LoD 3 model of KIT building 445

For both simulation systems, it is generally possible to transform the ADE model into specific simulation models and to perform simulations without severe errors. Central results (calculated yearly heating energy demand as well as energy gains and losses) are depicted in Table 2.

Table 2: Simulated yearly energy demands, gains and losses in kWh

	EnergyPlus	GebSim
Energy demand heating	203.609,0	195.921,9
Energy gains occupants	12.199,1	10.861,8
Energy gains lighting	35.840,4	35.840,2
Energy gains devices	26.065,8	26.064,4
Energy losses ventilation	116.190,0	124.726,5

Considering the differences in the physical models of the simulation programs and the deficiencies of the Energy ADE model, the agreement between the results is very good, with a difference of only 3.8% of the overall heating requirement, as can be seen in Table 2. Only the difference in the ventilation losses is significantly higher, probably due to different models for the ventilation systems. However, the quality of the simulation can still be improved by an extension of the Energy ADE. Especially EnergyPlus uses and needs a number of parameters where presently only default values can be used, because they are not provided by the Energy ADE in its current version.

SUMMARY AND OUTLOOK

The paper presents a new approach to support building related thermal energy simulations on urban level. The suggested method builds on existing 3D building models in the CityGML format, which are geometrically enhanced and semantically enriched with energy relevant information in an interactive process. A central feature of this approach is that the result of the enrichment process is explicitly represented in a specialised extension (Energy ADE) of the CityGML data format.

A central goal for developing the Energy ADE data model is to support different building energy simulation systems. In order to test and evaluate this functionality, software modules for transforming Energy ADE data into input data sets for two different simulation systems are developed. By this, the principle ability of the Energy ADE to act as a "neutral" interface between modelling and simulation tools in the building area is demonstrated.

When transforming Energy ADE data into input data for the two considered energy simulation systems, a number of deficiencies of the current Energy ADE version become obvious, which need to be corrected in the future. In some cases, the ADE model structure is inappropriate to easily support existing simulation systems and some important physical parameters are not represented completely.

Additionally, the enrichment process itself has potential for further improvement. Central point will be to introduce a higher degree of automation of the process, which is indispensable for the simulation of larger groups of buildings. For this, statistical information will be used to automatically derive detailed energy related information (e.g. building material data of usage profiles) based on the available information (year of construction, building function).

LITERATURE

Agugiaro, G., Benner, J., Cipriano, P and Nouvel, R. 2018. The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations. Open Geospatial Data, Software and Standards (2018) 3:2 https://doi.org/10.1186/s40965-018-0042-y.

Ballarini, I., Corgnati, S. P., Corrado, V.. 2014. Use of Reference Buildings to Assess the Energy Saving Potentials of the Residential Building Stock: The Experience of TABULA Project." Energy Policy 68: 273–284. doi: 10.1016/j.enpol.2014.01.027

Benner, J., Geiger, A., Gröger, G., Häfele, K.-H., Löwner, M.-O. 2013. Enhanced LoD Concepts for virtual 3D City Models. ISPRS 8th 3DGeoInfo Conference & WG II/2 Workshop, 27 – 29 November 2013, Istanbul, Turkey.

Casper, E., Häfele, K.-H., Kaden, R. 2014:OGC standard CityGML opens up new applications in Energy simulation, J. Nat. Inst. of Building Sciences, Vol.2, No. 6.

Crawley, D., Lawrie, L., Winkelmann, F., Buhl, W., Huang, Y., Pedersen, C., Strand, R. 2001. EnergyPlus: Creating a New-generation Building Energy Simulation Program. Energy and Buildings 33 (4): 319–331. doi:10.1016/S0378-7788(00)00114-6.

Geiger, A., Reichenbach, I., Häfele, K.-H. 2016: IFC-Daten für die thermische Gebäude-simulation, 28. Forum Bauinformatik, 19.-21-Sept. 2016, Hannover.

IEA 2016. Energy and air pollution - World energy outlook 2016 special report. Organisation for Economic Co-operation and Development / International Energy Agency.

Kaden, R., and T. H. Kolbe. 2013. City-Wide Total Energy Demand Estimation of Buildings Using Semantic 3D City Models and Statistical Data. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences II- 2/W1: 163–171. doi:10.5194/isprsannals-II-2-W1-163-2013.

Löwner, M.-O., Gröger, G., Benner, J., Biljecki, F., Nagel, C. 2016: Proposal for a new LOD and Multi-Representation Concept for CityGML. ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci., IV-2/W1, 3-12, https://doi.org/10.5194/isprs-annals-IV-2-W1-3-2016, 2016.

Nouvel R., Brassel. K.-H., Bruse, M., Duminil, E., Coors, V., Eicker, U., Robinson, D. 2015. SimStadt, a new workflow-driven urban energy simulation platform for CityGML city models. Lausanne: CISBAT International Conference 2015.

Open Geospatial Consortium (OGC) 2012. OpenGIS®City Geography Markup Languale (CityGML) Encoding Standard. OGC 08-007r2, Version 2.0.0 (2012),

Reinhart, C. F., and C. Cerezo Davila 2016. Urban Building Energy Modeling – A Review of a Nascent Field. Building and Environment 97: 196–202. doi: 10.1016/j.buildenv.2015.12.001.

Remmen, P., Lauster, M., Mans, M., Fuchs, M., Osterhage, T., Müller, D. 2018. TEASER: an open tool for urban energy modelling of building stocks. Journal of Building Performance Simulation, 11:1, 84-98, DOI: 10.1080/19401493.2017.1283539

Robinson, D., Haldo, F., Kämpf, J.,Leroux, P., Perez, D., Rasheed, A., Wilke, U. 2009. CITYSIM: Comprehensive Micro-Simulation of Resource Flows for Sustainable Urban Planning." Proceedings of the 11th international IBPSA conference, 1083–1090.

van den Brink L, Stoter J, Zlatanova S. 2013. UML-based approach to developing a CityGML application domain extension. Trans GIS. 2013;17(6):920–42.

Wagner, D., Wewetzer, M., Bogdahn, J., Alam, N., Pries, M. and Coors, V. 2013. Geometric-semantical consistency validation of CityGML models. In Progress and New Trends in 3D Geoinformation Sciences (pp. 171-192). Springer Berlin Heidelberg.

Wagner, D., Coors, V. and Benner, J. 2014. Semantic validation og GML-based geospatial data. 9th 3DGeoInfo Conference 2014, Dubai, UAE, November 11-13, 2014.