

Virtual 3D City Model Support for Energy Demand Simulations on City Level – The CityGML Energy Extension

Joachim Benner, Andreas Geiger, Karl-Heinz Häfele

(Dr. Ing. Joachim Benner, Karlsruhe Institute of Technology, Institute for Applied Computer Science, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, joachim.benner@kit.edu)

(Dipl. Ing. Andreas Geiger, Karlsruhe Institute of Technology, Institute for Applied Computer Science, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, andreas.geiger@kit.edu)

(Dipl. Ing. Karl-Heinz Häfele, Karlsruhe Institute of Technology, Institute for Applied Computer Science, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, karl-heinz.haefele@kit.edu)

1 ABSTRACT

Due to the transition from fossil energy carriers to more renewable energy resources, the availability of energy in future will be fluctuating. Under these conditions, an accurate energy demand simulation for buildings is strongly needed as planning instrument on district or city level. This paper introduces a new data model for the energy relevant properties of buildings. It extends the existing standard CityGML for 3D city models by energy relevant properties like, e.g., physical materials, thermal zones and thermal boundaries, and building occupant's behaviour. The energy extension of CityGML is designed as system-independent interface to energy simulation systems and shall support detailed simulation on the level of single buildings as well as energy demand assessments on district and city level.

2 INTRODUCTION

Actually, one of the biggest challenges for cities is the implementation of the German energy transition process. In future, energy will more and more be produced by fluctuating, renewable sources like solar or wind energy. Under these conditions, an accurate energy demand simulation for buildings is strongly needed as planning instrument on district or city level. Potential application areas for such simulations are the planning of energetic renovation measures or of infrastructures like district heating systems.

For simulating or estimating the energy demand on district or city level, normally the same techniques and software tools are used as for single buildings. Simulation systems like TRNSYS (TRNSYS 2016) or EnergyPlus (ENERGY+ 2016) are based on a physical model of a building, describing the heat or energy exchange and conversion within the building and between the building and its environment. In order to apply such a model on a concrete building, a number of input data must be available. They can roughly be separated into four categories:

- Parameters describing the building geometry and its location in the 3D world;
- Parameters describing the physical condition of the building, especially heat capacity and thermal transmittance of exterior and interior building elements (walls, slabs etc.) and optical properties of windows;
- The weather conditions (e.g. temperature, solar radiation, wind speed) on the building's location;
- The behaviour of the buildings occupants.

An exact determination or prediction of all these parameters and influence factors is difficult and sometimes (e.g. for future weather conditions and occupants behaviour) only possible in a limited way. For the generally needed model simplifications, national regulations like the German norm DIN V 4108-6 (VDI 4108-6 2003) exist. The usage of such norms shall ensure that building energy estimations performed by different persons, eventually using different software systems, result in comparable results. All national norms try to minimize the needed effort to determine the input parameters of the simulation. Thus, one must be aware that the calculated energy amount may under- or over-estimate the actual situation significantly.

In using such systems for simulating groups of building, additional problems occur. On the one hand, in this case also the mutual influence of neighbouring buildings (e.g. shadowing, closed development) should be taken into account, which normally is not possible with existing simulation tools. The most significant problem normally is the availability of reliable input data. In the case of single buildings, missing information in principle can be collected by measurements or by interviewing the building owners / occupants. For simulations on district or city level, this is normally impossible due to effort reasons and privacy protection restrictions.

To enable software systems to perform energy simulation under these conditions, a number of methods have been developed (Carrion 2010) to estimate missing parameters on base of a few existing data like, e.g., the year of construction of a building, its function, or statistical data from a census. For these estimations and derivations no standards exists, they normally are performed heuristically by the user of the simulation system or even automatically by the software. In consequence, the reproducibility of energy simulations for groups of buildings is poor, which strongly reduces the reliability of the results.

This paper describes a new approach for enhancing quality and reproducibility of energy simulations for single buildings, city quarters or whole cities. Central approach is the specification of a system-independent ("neutral") data model, being able to represent all input data for a simulation as well as the generated simulation results. The possible usage of this data model shall be independent from quality and amount of available input data and the used physical building model. By a standardized description of simulation parameters, it becomes transparent which data are actually used in a specific simulation, and the influence of model simplifications and estimations of unknown parameters on the simulation results can be examined.

In chapter 3, the needed input data for a reliable energy demand simulation are described, and the city-wide availability of these data is analysed. It turns out that virtual 3D city models, frequently available in the internationally standardized data format CityGML (CityGML 2012), are the most important input sources. Chapter 4 therefore gives a short overview on this data model and the availability of corresponding data, depicting that CityGML represents location and geometry of the building and its components (e.g. walls, roof, and ground slab), but lacks the representation of most other energy relevant building parameters. CityGML inherently supports a mechanism for application specific extensions (van den Brink et al. 2014) of the base standard called "Application Domain Extension" (ADE). This mechanism is actually used by an international consortium to specify the "Energy ADE" as standardized data model for energy relevant building data. The actual version 0.6.0 of this model (Nouvel et al. 2015 a, Nouvel et al. 2015 b) is introduced and discussed in chapter 5. Chapter 6 summarizes the paper, and gives an outlook to the next versions of the Energy ADE.

3 INPUT DATA FOR ENERGY SIMULATIONS ON BUILDING AND CITY LEVEL

In the following, the different types of input parameters needed to simulate the energetic performance of a single building are described.

3.1 Building geometry, location and orientation

Geometry, location and orientation of a building are important parameters influencing its energetic performance. The building's position determines the anticipated weather or climate conditions (see chapter 3.5) as well as additional effects of the neighbourhood like, e.g., shadowing. For incorporating effects of solar radiation, the orientation of the outer shell, especially of windows is essential.

An additional set of parameters is determined by the building geometry. The overall heating and cooling demand of a building is essentially determined by the occupied building volume. In many cases, the whole building is assumed to be thermally homogeneous ("one-zone model"). For more detailed simulations, it is necessary to regard multiple, (thermal) variably used regions ("thermal zones") within the building ("multi-zone model"). It is assumed that a thermal zone is isotherm, which means that heat exchange can only occur via its boundaries ("thermal boundaries"). These boundaries can be internal (between two adjacent zones) or external (between a zone and the outside world). In order to simulate the energy exchange, the volume of the zones as well as size, orientation and topology of the thermal boundaries must be known.

3.2 Building physics

The most important physical parameters determining the energetic behaviour of a building are the overall heat capacity of the building structure and the thermal transmittance of the outer shell. For taking into account heat losses and gains due to radiation, the optical parameters of the windows (reflectance, transmittance and emittance for different spectral regions) are needed as well. For multi-zone models, the same information is required for internal thermal boundaries.

3.3 Building occupants behaviour

Though the behaviour of the building's occupants significantly influences the energy demand, it is quite difficult to determine it in an objective way. In principle, at least the following effects must be considered:

- The temporally varying usage of the whole building or the different thermal zones. This can for instance be expressed by time-dependent schedules of the nominal temperature, ventilation rate, or the shading of windows.
- Energy consumption due to building systems different from heating and cooling, e.g. hot water production, cooking, usage of electrical appliances or lighting.
- Occupant dependent energy gains (internal gains).

3.4 Energy relevant building systems

For very detailed simulations, also the different energy conversion systems of a building need to be taken into account. The following effects influence the overall energy balance:

- Many systems are simultaneously energy producers and consumers. For example, a heat pump consumes electricity to produce thermal energy.
- Every energy transmission system has always an efficiency factor of less than 100%.

3.5 Weather and climate data

The meteorological conditions at the building position strongly influence the needed amount of heating and cooling energy. Most simulation systems use the following parameters: Air temperature, wind speed, humidity, direct and indirect solar radiation (Hensen & Lamberts 2011).

Depending on the type of simulation (static or dynamic), the meteorological parameters must be available as long term averages (e.g. monthly or yearly values), or as series of time-dependent values for one year. In the latter case, the time resolution typically is one hour. It is possible to use either "real" values based on measurements in a certain year in the past, or "typical" values, representing average climate conditions (Meteonorm 2016).

3.6 Data availability on city level

Table 1 shows in an overview the availability of the different input data categories and denotes the most important data sources for city-wide data. Best available are weather and climate data. National agencies like the Climate Data Center (CDC) of the German "Deutscher Wetterdienst" (DWD) provide several meteorological parameters with high temporal resolution (CDC 2016). It is possible to get "real" measurements related to concrete time periods, as well as data sets for "Test Reference Years" (TRY) (BBR 2014). These are specially compiled data sets containing various meteorological parameters for every hour of a year. They represent average, but for a year typical weather conditions. In addition, time series representing an exceptionally cold winter half-year and an exceptionally warm summer half-year are available. Measurement and TRY data sets are available for a number of sites representing different German climate regions.

Aspect	Availability	Data source
Building geometry, location and orientation	+	3D city models
Building physics	-	Year of construction Building typology
Building occupants behaviour	-	Building function Statistical demographic data
Energy relevant building systems	--	Not available
Weather and climate data	++	Weather agencies like "Deutscher Wetterdienst"

Table 1: Data sources and availability of energy relevant building properties

The city-wide availability of geometry-related building data is also quite good. Central data source are virtual 3D city models, which in many German municipalities are area-wide available in the CityGML format. However, as it is further discussed in chapter 4, the actually existing CityGML models do not use the full functionality of the data model and do not fulfil all requirements of a detailed energy simulation.

For all other relevant aspects of a building energy simulation, the city-wide availability is poor. Information concerning the physical characteristics of the building, the equipment of a building with energy consuming or producing systems, the number of occupants and their energy relevant behaviour is, if any, only available in exceptional cases. In some cases, procedures are known to estimate the needed information on base of available data. In particular, the heat transmission coefficients of the building facade and optical parameters of windows are often derived from the building's year of construction and its form typology. The occupants influence can (very roughly) be estimated from the building function, normally documented in the cadastre, and global demographic data taken from a census or microcensus.

4 THE CITYGML STANDARD FOR VIRTUAL 3D CITY MODELS

As discussed in chapter 3.6, virtual 3D city models in the CityGML format are an important source for energy simulations on district or city level. CityGML is an international data exchange standard of the Open Geospatial Consortium (OGC), based on Geography Markup Language version 3.1.1 (Cox 2004) for exchanging spatially related data. CityGML claims to represent all aspects of a city geometrically and semantically. Besides buildings, this also includes the terrain, traffic areas, infrastructure objects like bridges, tunnels or city furniture, and natural city objects like vegetation or water bodies. Furthermore, CityGML implements a methodology for application specific extensions called Application Domain Extension (ADE). An ADE, which is represented by one or more XML-schemata, not only allows to specify new classes in extension of existing ones, it is also possible to extent the attributes and relations of existing CityGML classes.

4.1 The CityGML Building module

This paper concentrates on buildings, because energy consumption of the traffic sector is not regarded and other kinds of city objects only indirectly influence the city-wide energy balance, e.g. by shadowing effects or influencing the micro climate. The CityGML module "Building" allows to represent buildings in 5 Levels of Detail (LoD), differing in the geometrical resolution and the semantic modelling depth (see Figure 1). In all LoD, a complex building may be separated in different building parts. Because the data models for buildings and building parts are identical, in the following the term "building" is used for both.

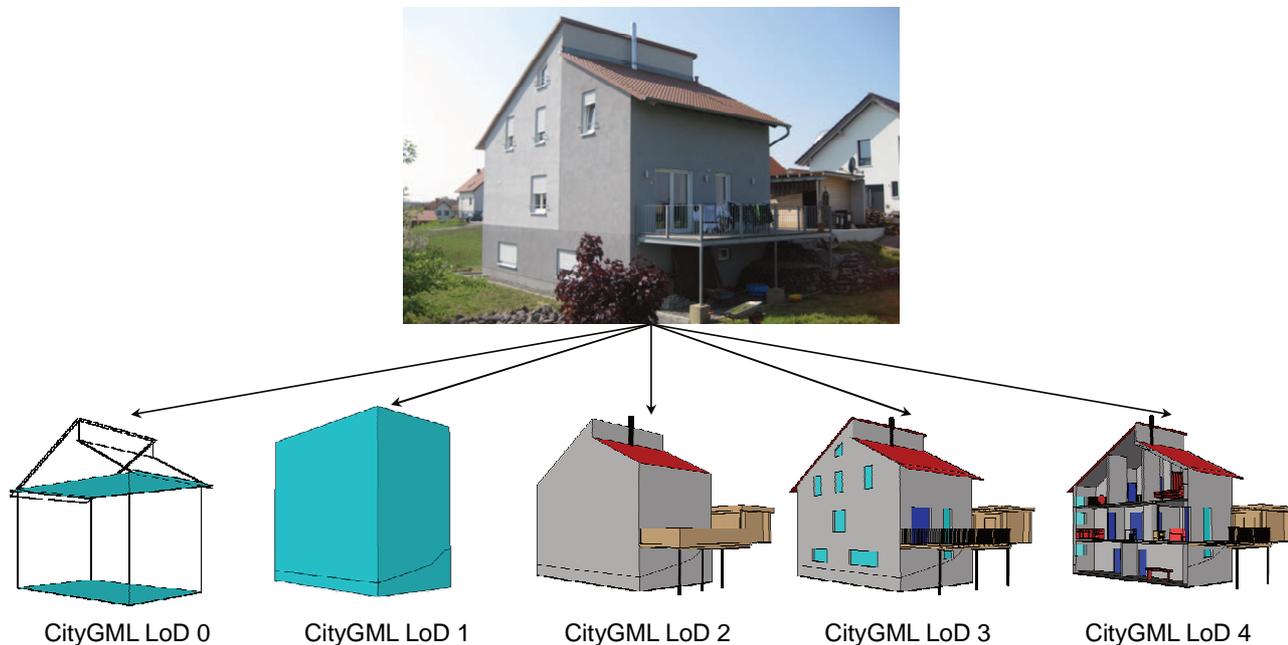


Figure 1: Representation of a building in 5 different Levels of Detail

Each building optionally has a number of attributes, allowing to specify its function, actual usage, year of construction, roof type, overall height, number and height of storeys. The five supported LoD of a building differ in quality and resolution of the geometric representation and the semantic structuring of the geometry. In LoD 0, the footprint or roof edge of the building are geometrically represented as horizontal surfaces. LoD 1 supports a fully 3D representation of a building as block model, where the building's footprint is vertically

extruded to, e.g., the eaves or ridge height. In LoD 2 and higher LoD, the exterior shell of a building is not only represented geometrically, but can also be composed of semantic objects like wall-, roof- or ground surfaces. These "boundary surfaces" are geometrically represented as surfaces and carry no thickness or material information. Smaller features of the building significantly affecting its characteristics can be separately represented as "outer building installations".

LoD 2 realizes a geometrically generalized representation of the exterior shell, while LoD 3 calls for a geometrically exact representation. Furthermore, an explicit geometrical and semantical modelling of openings in the outer building shell (doors or windows) is possible from LoD3. As for the exterior boundary surfaces, it is not possible to attach energy relevant properties like a glazing ratio or optical parameters to openings. In LoD4, also the representation of interior rooms is possible. The volumetric geometry of a room can be subdivided into boundary surfaces (floor, interior wall and ceiling surfaces), and interior equipment (installations, furniture) of a room can also be modelled.

4.2 Availability of CityGML building models

Though CityGML principally supports 5 different LoD, city-wide available data mostly fall into the categories LoD1 and LoD2. The reason is that for these models an automatic generation based on existing cadastre data and (in the case of LoD2) airborne laser scanning or photogrammetric measurements of roof surfaces is possible. The generation of LoD3 and LoD4 models needs much more effort, and corresponding data are only available for some landmarks.

5 THE CITYGML ENERGY EXTENSION (CITYGML ENERGY ADE)

In this chapter, the CityGML extension supporting energy simulations is discussed in detail. Functionally, the following components can be identified in the data model:

The extension of CityGML base classes by energy relevant properties and relations to new energy related classes (see chapter 5.1).

- Classes to represent thermal zones and corresponding thermal boundaries (see chapter 5.1).
- Classes to represent physical materials and layered wall constructions (see chapter 5.2).
- Classes to represent the energy relevant behaviour of building occupants (see chapter 5.3).
- Classes to represent the building's energy demands and energy conversion systems (see chapter 5.4).

Furthermore, the Energy ADE implements some technical concepts, e.g. to represent schedules and time series, which are not discussed here.

5.1 General structure of the CityGML Energy ADE

Figure 2 depicts the general structure of the new data model, especially documenting the relations between the central classes. For better readability, the attributes of these classes are not shown. The different colours of the UML (Unified Modeling Language) elements in Figure 2 indicate the corresponding ADE module (see Table 2).

Four different CityGML classes have been extended with additional attributes:

- The extension of the CityGML base class (class `_CityObject`) enables that all derived classes can refer to energy demand information (class `EnergyDemand`, see chapter 5.4) and material information (class `Construction`, see chapter 5.2).
- The CityGML base class for buildings (class `_AbstractBuilding`) is extended by a number of energy related properties. Among others these include some specific building height values (ridge height, eaves height, average ceiling height), information on the conditioning of attic and basement, the building typology (e.g. single or multi family house), and information on refurbishment measures performed. The extension also allows relating a building with the new classes for energy conversion systems (class `EnergyConversionSystem`, see chapter 5.4) and occupant behaviour (class `UsageZone`, see chapter 5.3).

- Refurbishment information is also added to the CityGML base class for boundary surfaces (class `_BoundarySurface`). Furthermore, time series for the global solar irradiance and the daylight illuminance can optionally be specified for any boundary surface.
- The CityGML base class for doors and windows (class `_Opening`) is extended with refurbishment information and shading parameters.

For the modelling of thermal zones, three new classes have been defined. A building can refer to an arbitrary number of thermal zones (class `ThermalZone`). Each thermal zone is characterized by geometric parameters (gross volume, net volume, floor area), and physical parameters specifying its thermal capacity, infiltration rate and thermal bridges. The information whether the zone is heated and/or cooled is provided. Optionally, also the volumetric zone geometry and the list of rooms related with the zone can be represented.

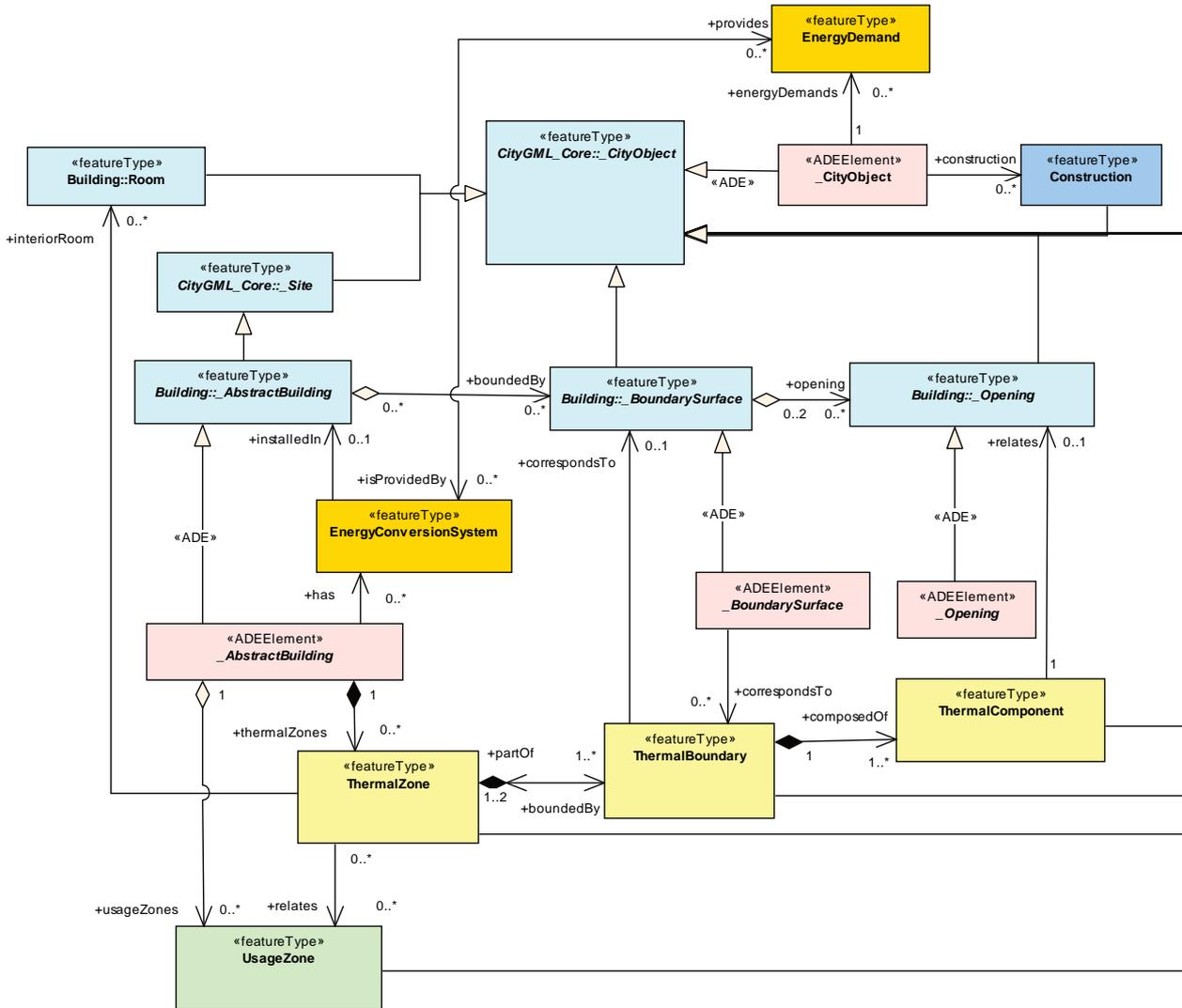


Figure 2: Energy ADE core model

	CityGML base classes
	Extension of CityGML base classes
	Thermal zoning
	Material
	Occupant behaviour
	Energy conversion systems

Table 2: Colour codes used in Figure 2 - Figure 5

It is mandatory to represent the boundaries of thermal zones by the class ThermalBoundary, which optionally can be related with a physical boundary surface. Attributes of ThermalBoundary are its orientation (azimuth and inclination angles), and the thermal boundary type. This type indicated whether the boundary represents an exterior wall, a roof, a shared wall between adjacent buildings, or some kind of interior thermal boundary. If a thermal boundary is composed of different components (e.g. solid wall parts and windows), these can individually be represented by the class ThermalComponent.

5.2 Materials

The new class Construction (see Figure 3) in the most general case describes the different material layers of a construction. If no layer information is available, the energetic performance of a building element can also be specified by a global thermal transmission coefficient (U-value) and a number of optical parameters. Each material layer (class Layer) can consist either of one homogeneous material, or a mixture of materials. The corresponding class LayerComponent carries a thickness value and is related to exactly one material. Actually, two different types of materials are considered. Solid materials (class SolidMaterial) are characterized by physical parameters like density, thermal conductivity and specific heat. Materials with negligible density and heat capacity (class Gas), are described by their thermal resistance (R-value).

If the layer order shall be applied in the reverse order (e.g. in case of interior thermal boundaries), the class ConstructionOrientation can be used.

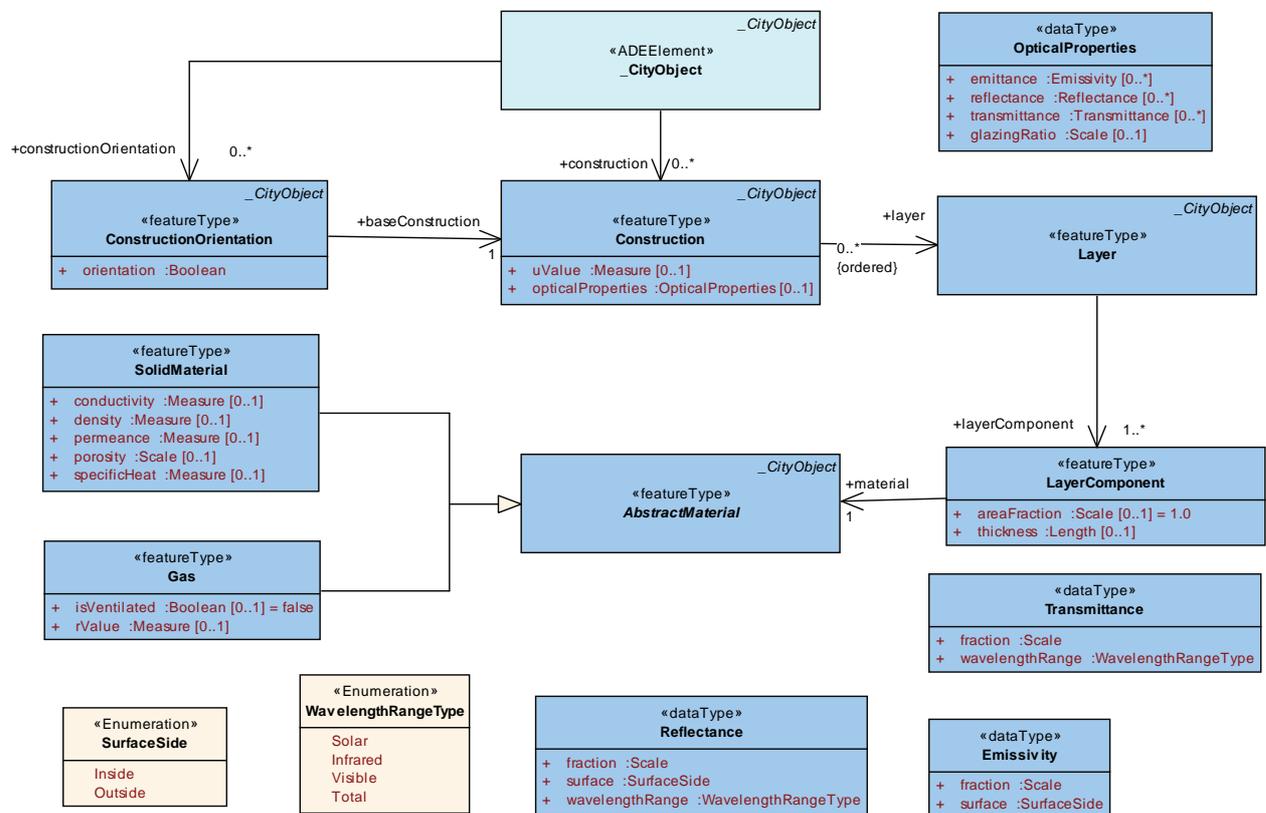


Figure 3: Energy ADE Material module

5.3 Building occupant behaviour

Figure 4 shows the classes to represent the occupants of a building and their behaviour, as far as it is relevant for an energy simulation. Central concept is to define regions of homogeneous usage (class UsageZone), which are referenced by the class ThermalZone. For each usage zone, arbitrary schedules for heating, cooling and ventilation may be prescribed, as well as the total internal energy gains due to the occupants. For more detailed simulations, the individual occupants of the usage zone and the corresponding households can be represented. The class Facilities allows considering the heat dissipation caused by hot water production, electrical appliances and lighting.

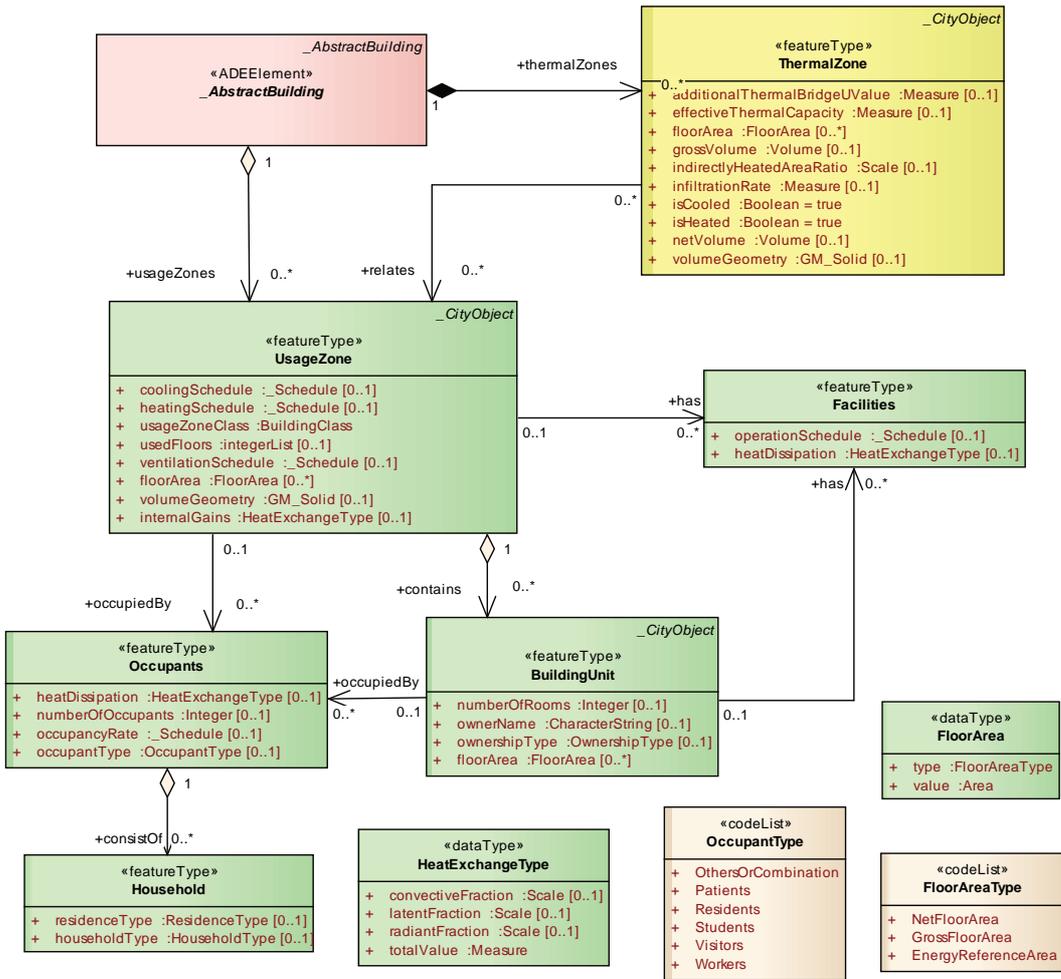


Figure 4: Energy ADE module "Occupants"

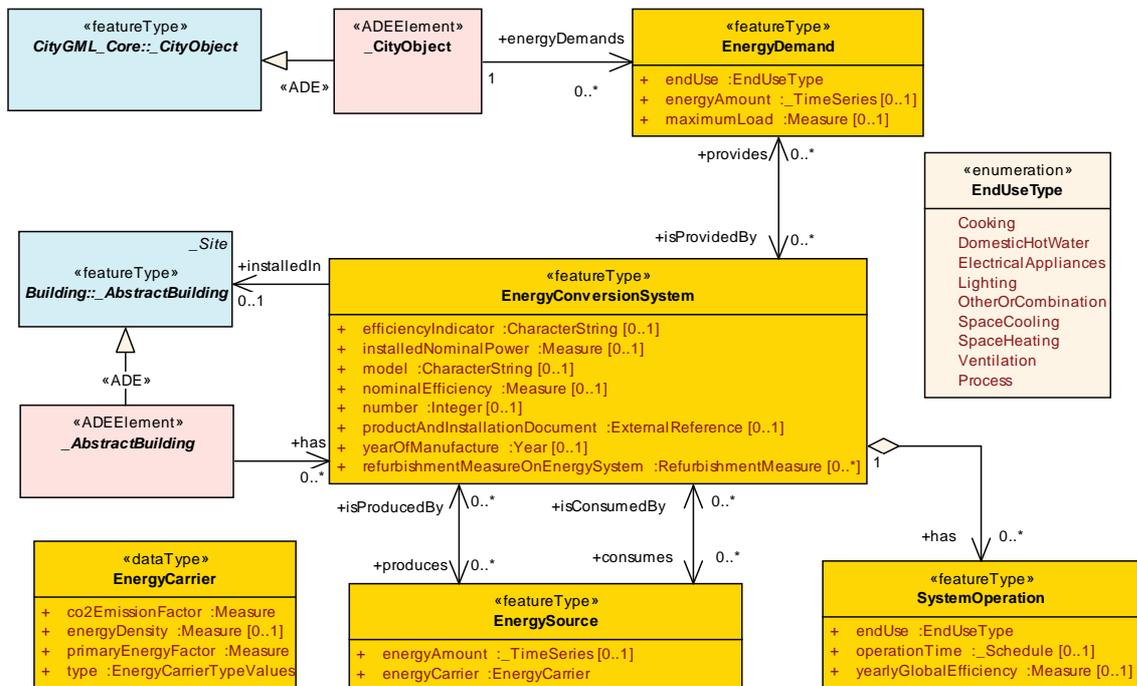


Figure 5: Energy ADE module "Energy system"

5.4 Energy conversion systems in buildings

In Figure 5 a very simplified UML model of the classes for the energy conversion systems of a building is depicted. The central class `EnergyConversionSystem` has properties for efficiency measures, for age, type and manufacturer of the system, and for refurbishment measures performed. Specific energy conversion systems like, e.g. boilers, heat pumps or district network substations are modelled by specific classes (not shown in Figure 5) derived from `EnergyConversionSystem`.

By using different energy sources (class `EnergySource`), it is possible to represent that a conversion system simultaneously produces and consumes energy. For each specific end use type (e.g. space heating, domestic hot water or cooking), it is possible to prescribe usage time schedules of the system. In combination with the properties of the energy carries (data type `EnergyCarrier`) this enables to calculate the total amount of consumed or produced energy and the CO₂ footprint.

The data model furthermore supports modelling the energy demand related with a specific end use (class `EnergyDemand`). The corresponding time series may contain either measured energy amounts or simulation results. The CityGML extension mechanism enables to attach energy demands either to the whole building or to a sub-structure like, e.g. a room, a thermal zone or a usage zone.

6 SUMMARY AND CONCLUSION

For the holistic consideration of the energy performance of buildings it is not enough to focus on the building itself but, also to examine the neighbourhood on district or even on city level. Neighbourhood buildings can influence the energy consumption of a building, and the given or planned infrastructure can affect the selection of the building services and therefore the energy efficiency.

CityGML, as an established 3D city model, provides a good basis for such comprehensive considerations. At least in Germany, CityGML models (LoD1 and LoD2) are widely available from official agencies. Another big advantage of CityGML is the ADE mechanism, which allows the data model to be extended by own properties and features.

This ADE mechanism was used to extend CityGML by properties and features, which are relevant for energy simulations and estimations. After identifying the gaps of CityGML regarding energy simulation, a new UML based data model was created. For clarity reasons the model was structured into four parts: Core, Materials, Occupant Behaviour and Energy Systems. An overview of these parts is given in this paper.

Finally, after discussions within the Energy ADE development group, the version 0.6.0 of the extension has been released. For this version, the CityGML ADE schema including an online feature catalogue was automatically generated. Details of the CityGML Energy ADE can be found in the Github of the development group (<https://github.com/cstb/citygml-energy>) and the CityGML Wiki (http://www.citygmlwiki.org/index.php/CityGML_Energy_ADE).

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