A proposal to update and enhance the CityGML Energy Application Domain Extension

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Abstract

The CityGML Energy Application Domain Extension (ADE), released in 2018, offers an open and standardised data model to facilitate multi-scale Urban Energy Modelling applications. The Energy ADE is based on and extends CityGML 2.0 and has been already used in several national and international projects, mainly focusing on the simulation and computation of the building energy performance based on the integration of semantic 3D city models and other sources of information. The technological innovations (e.g. the release of CityGML 3.0 in 2021) and experiences and feedback collected since its release have contributed to forge several new ideas to improve and update the Energy ADE. Since 2024, work has been going on to harmonise and implement such ideas, towards a so-called Energy ADE 2.0. This paper provides an overview of the development process of the conceptual model so far, and presents a selection of the major changes and improvements that have been made to the original data model of Energy ADE.

1. Introduction

In the last 15 years, semantic 3D city models have been steadily growing in terms of world-wide adoption and number of associated geospatial applications that take advantage of them as source of harmonised spatial and non-spatial data. A semantic 3D city model can represent all most relevant urban objects in terms of their spatial (1D, 2D, 3D geometries) and non-spatial characteristics (attributes), as well as their relations and dependencies. Additionally, if a semantic 3D city model is based on an international standard, there are intrinsic advantages in terms of (reduced) effort to prepare and distribute data, as standardised ontologies, semantics and data structures will ease the exchange of information between different applications and domains.

In terms of existing standards at urban scale, CityGML is an *open* data model and information exchange format by the Open Geospatial Consortium (OGC). CityGML defines classes and relations for 3D urban objects such as buildings, infrastructures, water bodies, vegetation, etc.). Such objects are represented not only in terms of geometry but also topology, semantics, and appearance. For example, a building can be represented by means of semantically distinct geometries for roof, wall, and ground surfaces, as well as attributes specifying the roof shape, the year of construction, the building usage, the number of storeys, etc. CityGML 2.0 was released in 2012 (OGC, 2012), while CityGML 3.0 was released in 2021 (OGC, 2021) and contains several enhancements to the conceptual data model.

When it comes to modelling energy-related objects and properties, however, even CityGML (no matter which version) partially falls short, as it has been *intentionally* conceived as an application-independent information model: some attributes like the year of construction, the building class and usage are provided, but, overall, they are still too few. Additional attributes can indeed be defined as generic attributes by means of the so-called *Generics module*, but they cannot be stored in a systematic and semantically standardised way. Nevertheless, CityGML can be extended by means of so-called Application Domain Extensions (ADE): depending on the specific needs, new features or properties can be added, hence greatly increasing CityGML modelling capabilities.

1.1 The Energy ADE in a nutshell

In order to overcome the aforementioned shortcomings and provide a standardised data model to deal with energy-related data required for Urban Energy Modelling (UEM), the CityGML Energy ADE was released in 2018 as a result of a 5-year-long development carried out by an international consortium that included specialists from different disciplinary fields ranging from computer sciences to energy (Agugiaro *et al.*, 2018). Since its release, the Energy ADE has offered a standard-based data model to allow for both detailed single-building energy simulation and city-wide, bottom-up building energy assessments. As a result, it has been tested and used in several national and international projects and in different cities (Geiger *et al.*, 2018; Bruse *et al.*, 2019; Malhotra *et al.*, 2019; Pasquinelli *et al.*, 2019; Rossknecht and Airaksinen, 2020; Schildt *et al.* 2021; Widl *et al.*, 2021; León-Sánchez *et al.*, 2022; Malhotra, 2023).

The Energy ADE is based on the CityGML 2.0 *Core* and *Building modules*. It is composed of six thematic modules. The modules contain either new classes or classes extending CityGML classes, together with additional data types, several codelists, and enumerations. Although a comprehensive description of the structure and the characteristics of the Energy ADE is beyond the scope of this paper and can be found in Agugiaro *et al.* (2018), the thematic modules are briefly listed here:

- The *Core module* defines additional attributes for the CityGML core::*_CityObject* and bldg::*_AbstractBuilding* classes. It also provides new abstract base classes for the other modules and establishes additional data types and enumerations;
- The *Building physics module* defines classes for thermal zones, thermal boundaries and thermal openings to model the thermal hull of a building;
- The *Occupants behaviour module* defines classes to model different usage zones and how they are used by occupants and facilities such as domestic hot water and lighting devices. Their behaviour over the day, year, etc., can be modelled via schedules;

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- The *Energy systems module* contains classes to represent the energy storage, emission, distribution, and conversion systems of a building;
- The *Materials and construction module* helps model construction elements by combining different layers and their physical properties;
- The *Supporting classes module* includes classes for schedules and time series, which helps to temporal values to the parameters of other modules.

It is worth mentioning that the Energy ADE, although initially developed for CityGML 2.0, has been recently mapped to CityGML 3.0. Further details can be found in Bachert *et al.* (2024). Please note that, from now on, the Energy ADE will be referred to as Energy ADE 1.0 in order to differentiate it from the Energy ADE 2.0, which represents the main subject matter of this paper.

1.2 A proposal for the Energy ADE 2.0

This paper presents and describes some proposed updates and enhancements to the Energy ADE 1.0 resulting from the experiences gathered since its release in 2018, thanks to its adoption in projects, but also due to the new technological advancements of recent years. For example, more CityGML ADEs have been developed since 2018, and, as already mentioned, CityGML 3.0 has been released. For practical reasons, we have started to refer to the improved version of the Energy ADE as Energy ADE *2.0*. Active development of the Energy ADE 2.0 started in 2024, driven by four main objectives. The first two coincide with those of the previous version, while the latter two take into account what has happened since 2018. The four goals are:

1) The Energy ADE 2.0 must support storing and handling energy-related data gathered at an urban scale, like building use, construction year, number of dwellings, and residents;
2) The Energy ADE 2.0 must supply data for evaluating building energy performance through various methods and software tools, such as standard energy balance techniques from ISO 13790 or detailed sub-hourly dynamic simulations using specific simulation programs;
3) The new data model must incorporate the knowledge gathered since 2018. For example: new classes may be added, while other classes will be simplified or removed. Additionally, other ADEs that may contain energy-relevant concepts can be a source of inspiration;
4) The lessons learned from mapping the Energy ADE 1.0 to CityGML 3.0 must be considered: changes to the data model should allow the future conversion of the Energy ADE 2.0 to CityGML 3.0 to be facilitated. Given the expected slow but steady transition of data and tools from CityGML 2.0 to CityGML 3.0, it is reasonable to conceive a new data model that can be ported to CityGML 3.0 without major issues.

In the remainder of the paper, first, a very short overview of the methodology is given (section 2), followed by an overview of the Energy ADE 2.0 conceptual data model, a description of the main changes, and some detailed information on a selection of 3 modules (section 3). Information about the current implementation status is provided in section 4, while section 5 contains the conclusions.

2. Methodology

The Energy ADE 2.0 has been developed following a well-known and established approach, which has already been described and published by van den Brink *et al.* (2013) and already used in other ADEs For this reason, it will be only briefly summarised here.

First of all, the data model of the Energy ADE 2.0 has been described at the conceptual level covering its necessary classes, properties, and relationships. UML has been used as the modelling language. The second step consists in deriving the transfer format from the UML data model. In our case, based on the target encoding (i.e. GML), an XSD file has been created, which contains the computer-readable rules on how to correctly read, write and validate Energy ADE 2.0 GML instance files for CityGML 2.0. The third step consists in creating test datasets, which will be used to test the conversion tools developed successively. Such test datasets, containing data in CityGML 2.0 with Energy ADE 2.0, have been created using Safe Software FME Form and the XSD file previously obtained. Finally, the development of the conversion tools encompasses also the development of Java-based libraries to load and save XML-based CityGML files with Energy ADE 2.0 content, and to convert such XML-based files to a SQL-based encoding, therefore allowing to import and export data from/to the CityGML 3D City Database (Yao *et al.* 2018). At the time of writing (spring 2025), the Java libraries are still in active development. Further details will be provided in section 4.

3. Conceptual data model

3.1 Overview

Just like its predecessor, the Energy ADE 2.0 builds upon CityGML 2.0 modules (namely, the *Core*, *Building*, and *CityObjectGroup* ones) by extending some of their classes, while also adding its own classes, enumerations and codelists. Similarly to the Energy ADE 1.0, it has a modular structure, as depicted in Figure 1. Some modules are indeed very similar to those of the Energy ADE 1.0. In other cases, classes have been reordered in different packages. In short, the modules of the Energy ADE 2.0 are:

- The *Core module* defines additional attributes for the CityGML core::*_CityObject* and bldg::*_AbstractBuilding* classes. It also provides new abstract base classes for the other modules;
- The *Building physics module* defines additional attributes for the CityGML bldg::*_BoundarySurface* and bldg::*_Opening* classes. Additionally, it defines new classes to model the thermal hull of a building;
- The *Occupancy module* defines classes to model different usage zones and how they are utilised by occupants;
- The *Devices module* provides classes to model different types of energy-related devices that are responsible for transforming or storing energy (e.g. solar collectors, storage devices, etc.);
- The *Layered construction module* enables the modelling of the composition of construction surfaces through different layers and their physical properties;
- The *Resources module* is new and allows to model resources (energy, water, food, etc.) that an urban object may need, produce or store;
- The *Urban function areas* module is new and allows to define spatial entities that allow to aggregate values;
- Finally, the *WeatherStation module* contains just a single class to model weather stations;
- The *Schedules module* includes different types of schedules, the *TimeSeries module* contains classes for time series;
- The *CodeLists, Enumerations* and *DataTypes modules* contain support classes that are needed by all other modules.

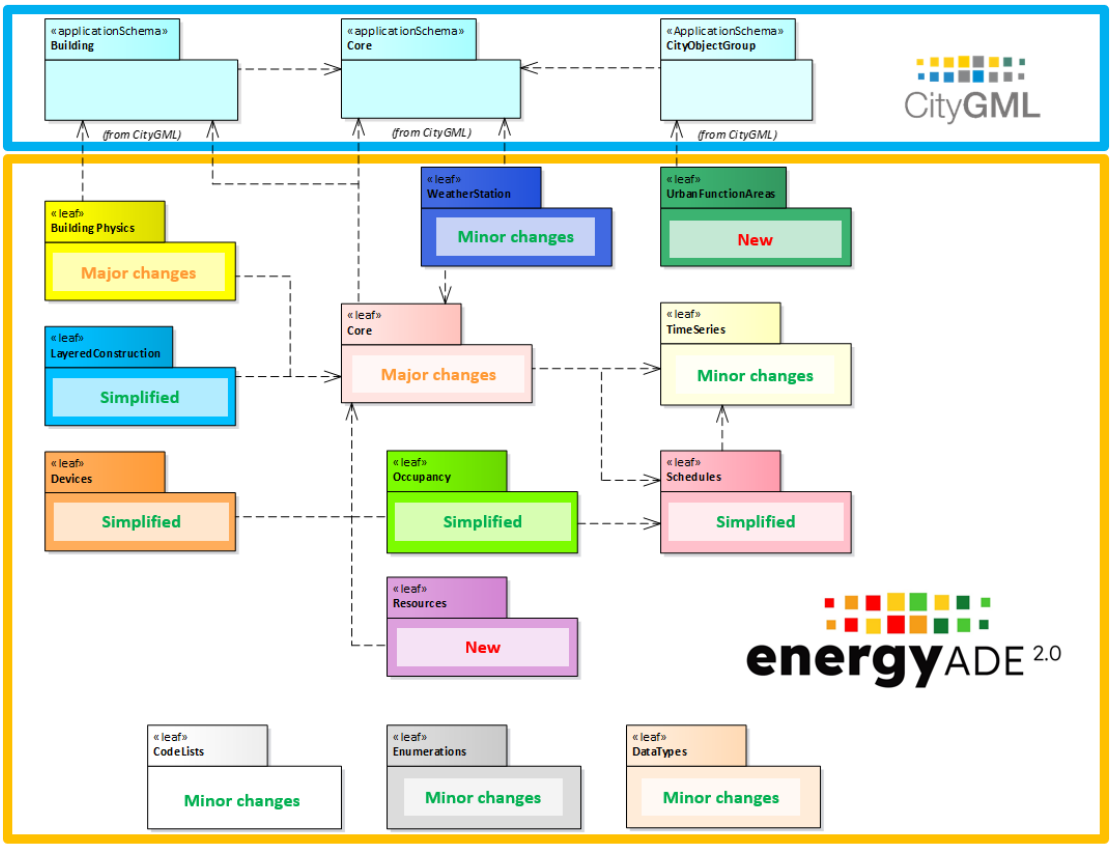

Figure 1. Energy ADE 2.0 packages and their dependencies represented by means of dashed arrows (omitted for packages *CodeLists*, *Enumerations*, and *DataTypes* for better readability). A simple label indicates the level of changes since Energy ADE 1.0.

3.2 Main changes

Compared to the Energy ADE 1.0, the Energy ADE 2.0 has gone through a series of overarching changes. For example, although it is designed for CityGML 2.0, some changes have been made to align it also to CityGML 3.0 and to simplify its future mapping to the latest version of CityGML. For example, all Energy ADE 1.0 classes belonging to stereotype «type» have been replaced with «featureType», as the former is not used anymore in CityGML 3.0. Additionally, some concepts from CityGML 3.0 have been "backported", as in the case of class *CityObjectRelation* (see Figure 2), which allows to define a relation between any city objects, and *de facto* contributes to simplifying several Energy ADE 1.0 relations. For example, it is now easier to model the adjacency relation between two buildings even in the (rather common) case that, due to geometrical errors, such spatial relationships cannot be computed directly from the footprint geometries. Additionally, the relation between the party walls of two buildings, or between two thermal zones can also be modelled using *CityObjectRelation*.

Some classes have been renamed to avoid future naming conflicts. For example, the Energy ADE 1.0 *Construction* class is now called *LayeredConstruction*, as CityGML 3.0 has already a class *Construction* which however yields a different semantics. More in general, classes, relation and the structure of the modules have been reorganised and, if necessary, simplified, following the feedback from the past years' experiences. It is the case of the former *Energy systems module* (now renamed to *Devices module*), which has been completely redesigned and simplified as the previous data model had turned out to be too complex to be used in a real-world context. At the same time, inspiration has been taken from other ADEs containing energy-relevant concepts – more details will be provided in the next sections.

3.3 Core module

The *Core module* has gone through some major changes, given its relevance for all other modules. Its UML diagram is presented in Figure 2. Similarly to the Energy ADE 1.0, the *Core module* extends two classes of the CityGML base standard with energy relevant properties (namely the *_CityObject* and the *_AbstractBuilding* classes). It provides abstract base classes for the other modules (*AbstractResource*, *AbstractDevice*, *AbstractLayeredConstruction*). Thanks to its structure, it is possible to avoid mutual dependencies between the modules.

The CityGML abstract base class *_CityObject* is extended via the ADE hook mechanism. In terms of geometry, the ADE *_CityObject* class adds the possibility to optionally represent any city object by means of a point geometry via the *referencePoint* property. This change "backports" what was introduced in CityGML 3.0.

As in the Energy ADE 1.0, every city object can have to an arbitrary number of *WeatherData* objects. Class *WeatherData* has been slightly updated. Each *WeatherData* object is characterised by the attribute *type* (e.g. temperature, wind, etc.). Actual values can be stored either as yearly values (attribute *yearlyValue*), or associated with a time-dependent object derived from class *AbstractTimeSeries* (attribute *timeDependentValues*). The *valueType* attribute can be used to further specify whether the weather parameter (e.g. temperature) is the maximum, minimum, etc. Additionally, via the *position* attribute, a point geometry can be also defined to specify the position the *WeatherData* object refers to.

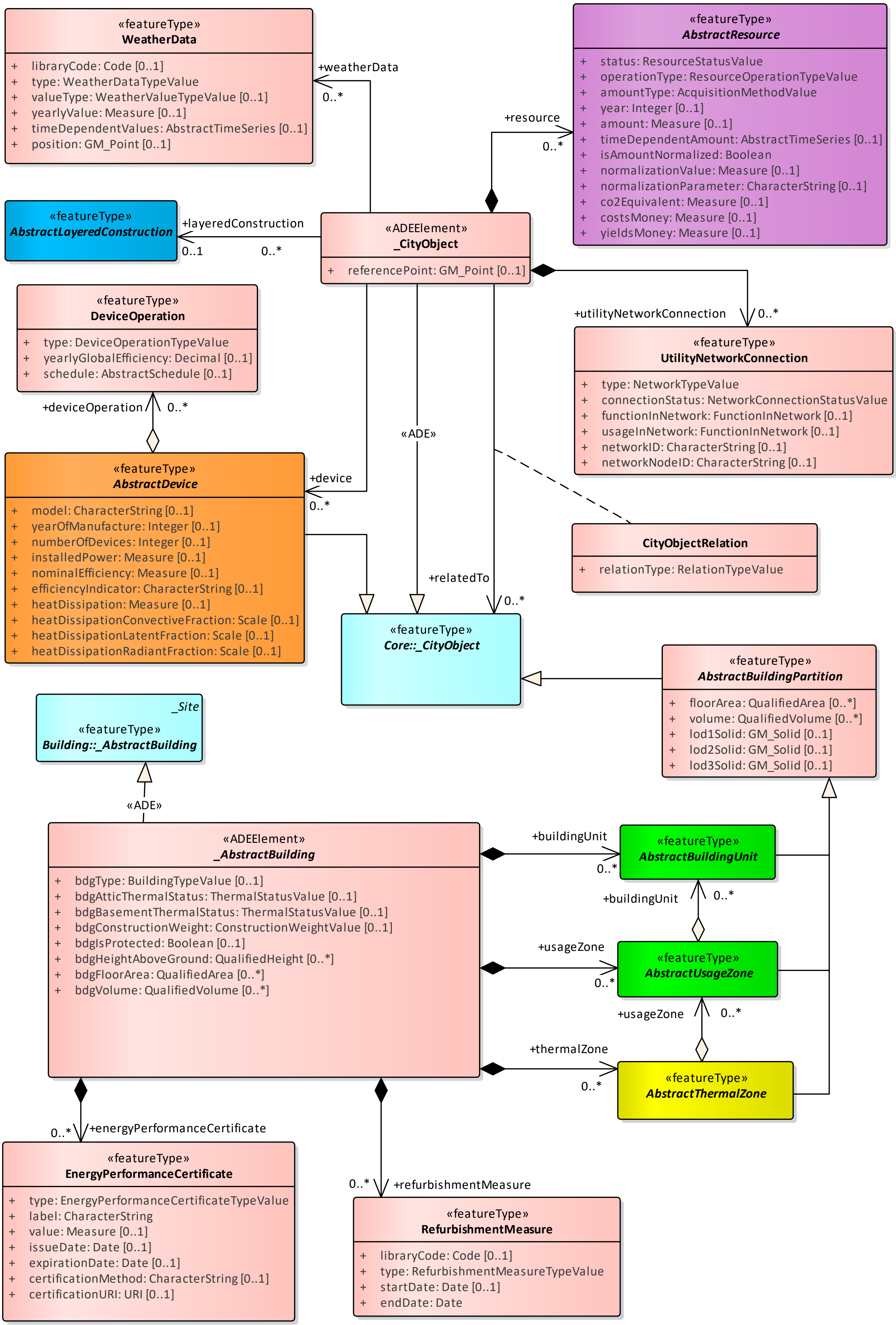

Figure 2. UML diagram of the Energy ADE 2.0 *Core module*.

Finally, the *libraryCode* attribute can be used to store a specific code for a weather parameters to be looked up in an external database.

Class *UtilityNetworkConnection* is a new class and is used to model the actual or potential connectivity status of a city object with regard to any utility network, be it gas, electricity, etc. By means of the attribute *connectionStatus*, not only the current connectivity status can be modelled, but also the future one in case, for example, the building is disconnected from the gas network and opts for a complete electrification. If specific information about the network is available, this can be stored using the *networkID* and the *networkNodeID* attributes. Finally, attributes *functionInNetwork* and *usageInNetwork* can be used to further specify the connection to the network. Many of these attributes are taken over from a conceptually similar class in the Utility Network ADE (Kutzner *et al.*, 2018). An advantage of using class *UtilityNetworkConnection* is that the connectivity status can be modelled regardless of the availability of actual network data (be it topological or geographical) – which is a very common problem with real-world datasets due to the complexity of collecting such data.

When it comes to the CityGML class *_AbstractBuilding*, this is also extended by means of the ADE hook mechanism. The ADE *_AbstractBuilding* class contains several energy-relevant attributes at building level. Please note that in the UML diagrams the prefix “*bdg*“ is used with class property names to avoid naming conflicts in the resulting XSD file, but – for the sake of readability – in this paper they are named without the prefix. In class ADE *_AbstractBuilding*, attribute *type* is intended to store information about the typology of the building (e.g. single-family house, terraced house, etc.). The thermal status of the attic and the cellar can be specified by means of the attributes *basementThermalStatus* and *atticThermalStatus*, as well as information about the rough classification of the building construction structure (*constructionWeight*), its protection status (e.g. in case of historical buildings), as well as relevant dimensional characteristics (*referenceHeight*, *floorArea*, *volume*). If a building possesses Energy Performance Certificates, or information is known about its refurbishment history, such information can be stored using the *EnergyPerformanceCertificate* and the *RefurbishmentMeasure* classes.

Finally, for more advanced energy simulations, concepts such as thermal zones, and usage zones must be introduced. For this reason, the ADE *_AbstractBuilding* class is related to the abstractbase classes *AbstractThermalZone*, *AbstractUsageZone*, and *AbstractBuildingUnit*. These three abstract classes are derived from the *AbstractBuildingPartition* class, which allows to store information about area and volume of each partition (attributes *floorArea* and *volume*) and up to three representations by means of solid geometries (in LoD1, LoD2, and LoD3, respectively). The *AbstractBuildingPartition* takes inspiration from CityGML 3.0’s *AbstractBuildingSubdivision* and adds a LoD concept to the possible representations of thermal zones, thermal boundaries and openings, as well as usage zones and building units. This is new compared to the Energy ADE 1.0, which allowed for only *one* representation for each object belonging to the respective classes. Class *AbstractThermalZone* is further specialised in the *Building physics module*, while classes *AbstractBuildingUnit* and *AbstractUsageZone* are further specialised in the *Occupancy module*. Finally, class *AbstractResource* represents the base class that is further specialised in the *Resource module*.

3.4 Resources module

The *Resources module* is a new module added to the Energy ADE 2.0. It stems from the need to extend and generalise the concept of *EnergyDemand* of the Energy ADE 1.0, in which a *_CityObject* could only be related to different types of energy demand (for heating, cooling, cooking, etc.). However, neither the production of energy (e.g. via photovoltaic solar collectors or from geothermal energy sources) nor potential values of production or demands (or storage) could be explicitly modelled. Finally, the demand was limited to energy, but any other types of resources were left out (e.g. water, food, etc.). The resource module takes inspiration from and further elaborates on the Food-Water-Energy ADE (Padsala *et al.*, 2021), and largely extends the modelling capabilities of the Energy ADE, allowing to overcome the aforementioned shortcomings of the Energy ADE 1.0. The overview of the resources module in terms of UML diagrams is presented in Figure 3.

The main idea is that *every* city object can demand/consume, produce/generate, store/accumulate (this is expressed by attribute *operationType*) "something" (i.e. a resource). Thanks to the attribute *status*, it is now possible to deal not only with actual values, but also with *potential* values. The quantity can be expressed either as a yearly amount, or as a time series (or both), via the *amount* and *timeDependentAmount* attributes, respectively. Values can be expressed either as absolute or specific values providing additional information via the attributes *isAmountNormalized*, *narmalizationValue* and *normalizationParameter*. For example, value(s) of energy demand could be expressed in kWh/a. However, if the normalisation value is provided (e.g. reference heated area in m^2) then the value(s) in kWh/(a*m^2) can be obtained from the previous without the need to store two values or two time series. Finally, the CO_2 equivalent for each resource can be specified, as well as its costs for production or consumption.

Class *AbstractResource* is finally specialised in several subclasses, representing each a specific type of resource. i.e. *Energy*, *Water*, *Food*, *Waste*, *ConstructionMaterial*, or a generic *OtherResource*. For each of these subclasses, specific attributes are available, too. Finally, it is worth mentioning that the resources module may offer new possibilities to deal with circularity of materials at urban scale, as it allows to associate to each city object, which therefore acts as a node in a graph, it owns quantities of resources produced, consumed or stored.

3.5 Urban function area module

The *Urban function areas module* is a new module. It stems from the need to offer support for aggregated values (e.g. of energy demand, or of *any* other resource) at different geographical scales. Very often, values are computed and associated at building level, and must be then aggregated and presented at different scales, e.g. at block, quarter, district level, or even up to the whole city. On the other hand, sometimes certain values are available only at such aggregated levels, therefore a geographical object is required to “contain” them. The overview of the *Urban function area module* in terms of UML diagrams is presented in Figure 4. The Urban function areas module takes inspiration from, and nearly coincides with, the *UrbanFunctionArea* class found in the i-UR ADE (Akatoshi *et al.*, 2020), and it consists of just a class derived from CityGML class grp::*CityObjectGroup*. All properties of a *CityObjectGroup* class are hence inherited, i.e. attributes, the possibility to associate a geometry (e.g. a polygon representing

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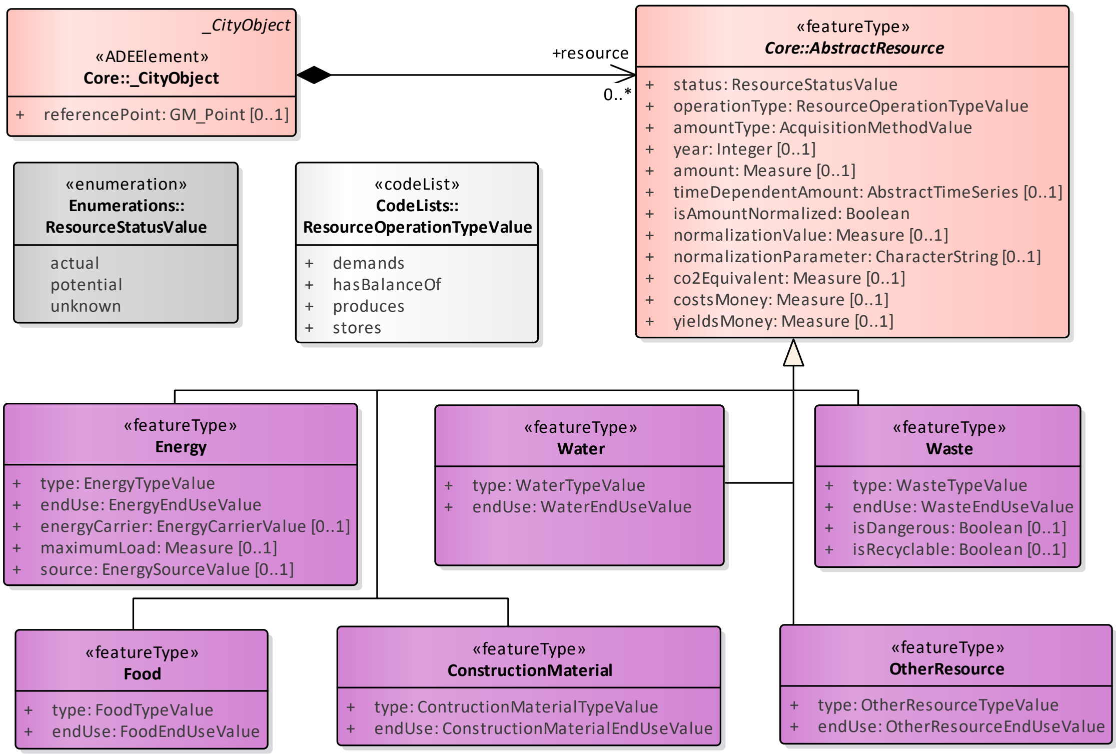

Figure 3. UML diagram of the Energy ADE 2.0 *Resources module*.

the administrative boundaries), the possibility to create hierarchies (groups containing groups), and the possibility to associate any type of *_CityObject* to a group. Additionally, class *UrbanFunctionArea* adds only few more properties. A property *type* associated to a CodeList (e.g. block, neighbourhood, district, city) and, optionally, a *code* to store specific existing codes associated with it (e.g. an ID used for a specific census area). It is worth keeping in mind that shape of the *UrbanFunctionArea*, i.e. its geometry, can be regular or not, e.g. a regular grid (as in the case of some existing datasets containing statistical data in some countries) or an administrative boundary, or any other user-defined shape.

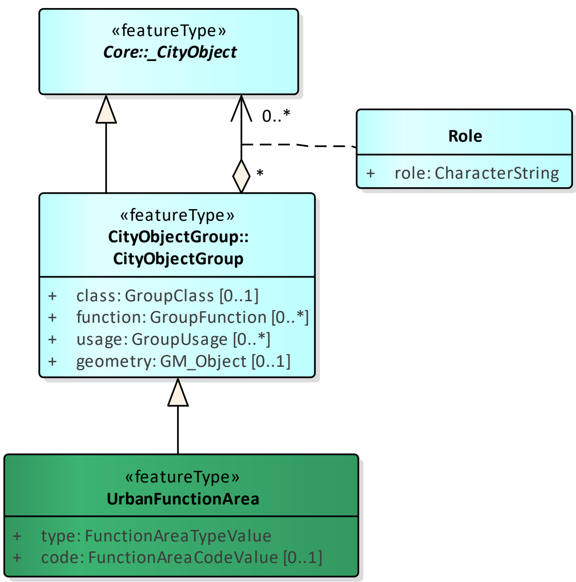

Figure 4. UML diagram of the Energy ADE 2.0 *Urban function area module*.

4. On-going implementation and testing

Whenever the UML-based modelling of the Energy ADE 2.0 reaches an acceptable status of stability (for example, at the time of writing, it is the beta 6), different follow-up development and testing steps starts (or build upon the previous beta). They will be briefly mentioned here for the sake of completeness, however it must be clear to the reader that, due to the circular and iterative nature of Energy ADE 2.0 development, all software resources must be considered as still work in progress. Nevertheless, the valuable experiences and feedback collected during these stages are used as well to further enhance the Energy ADE to the next (beta) version.

4.1 Additional software resources

First of all, the XSD file is derived to create and validate instance documents containing CityGML 2.0 and Energy ADE 2.0 data. The XSD is obtained using the software tool ShapeChange[1] 3.10. Additionally, the resulting XSD file is carefully checked also manually to ensure the correctness of the classes and properties. Additionally, the XSD file is then used in FME and in the KIT ModelViewer[2] for testing purposes, to generate and visualise test datasets. Finally, using the ADE Manager plugin of the 3D City Database Suite (Yao *et al.*, 2018), database DDL scripts are generated to extend the 3D City Database. At the same time, the development of two Java-based libraries is currently being carried out to ensure that the 3D City Database and its Importer/Exporter plugin completely support the Energy ADE 2.0. The first library is needed to extend the citygml4j API for CityGML[3] in order to be able to read and write CityGML data with Energy ADE 2.0 contents. The second library is needed to support the import and export of Energy ADE data to/from the 3D City Database. Finally, and as

[1] https://shapechange.github.io/ShapeChange
[2] https://www.iai.kit.edu/english/4561.php
[3] https://github.com/citygml4j/citygml4j

a temporary solution while the Java-libraries are still in development, an FME workbench has been developed that allows to import Energy ADE 2.0 into the 3DCityDB – which must have been previously extended using the above-mentioned DDL scripts. All the software resources mentioned in this section are available in the GitHub repository of the Energy ADE 2.0[4].

4.2 Documentation and test data

In addition to the above-mentioned software resources, particular care is paid to the documentation of the data model. For this reason, a rather extensive document containing the technical specifications is regularly updated and kept in sync with the accompanying UML model. Additionally, a set of modelling rules is also compiled and included in the same document. Such set of rules is meant to help the user in using the Energy ADE 2.0 and to provide examples of how certain classes must be used, and in which cases. Last but not least, a set of test datasets is kept up to date and made available for each beta version of the Energy ADE 2.0. As mentioned before, such test datasets play a pivotal role in the continuous testing not only of the conceptual data model, but also of the successive software resources that build upon it. Finally, the test datasets are also described in the specification document and used as examples for communication purposes. The documentation and the test datasets mentioned in this section are available in the GitHub repository of the Energy ADE 2.0.

4.3 Tests with real-world data

The Energy ADE 2.0 is being developed mainly within the framework of the European project DigiTwins4PEDs[5] which aims to exploit semantic 3D city models in order to facilitate urban transformation towards positive energy districts. As a consequence, first tests with the Energy ADE 2.0 are already being carried out with data from the partner municipalities of Rotterdam, Stuttgart, Vienna and Wroclaw. Providing a detailed insight of the experiences gathered in each study area goes beyond the scope of this paper, however further details can be found in Gao *et al.* (2025) and Padsala *et al.* (2025). Two screenshots from the Rotterdam (Figure 5) and Stuttgart (Figure 6) case studies show an example of the Energy ADE 2.0 being used to deal with multi-scale results of heating and cooling demand simulations (e.g. at building and urban function area level).

5. Conclusions

This paper has provided an overview of the development of the conceptual model of the CityGML Energy ADE 2.0, and, due to space constraints, has presented only a selection of the major changes and improvements that have been made so far. Nevertheless, full documentation of the Energy ADE 2.0 (beta 6) specifications, the UML diagrams, a set of modelling rules that explain and show examples of how to use the ADE, as well as test datasets, DDL scripts for database schema generation, and a still-in-development set of Java libraries are available on the projects GitHub for the reader that might be interested in learning more.

The Energy ADE 2.0, in its current status, represents a major improvement compared to the previous version and, although it is still in beta status, it is being already tested in 4 cities (Rotterdam, Stuttgart, Vienna and Wroclaw). Results from the first tests carried out on these cities confirm that the new data models performs as desired, although further testing with additional real-world data is of course needed. At the same time, thanks to the free and open-source nature of the Energy ADE 2.0, we look forward to further constructive feedback from additional testers, users and early adopters to further enhance it.

We expect that, once the Energy ADE 2.0 conceptual model and first tier of associated resources (XSD file, Java libraries, DDL scripts) are developed and sufficiently tested, they will allow to add full support for the Energy ADE 2.0 also in other software packages, such as for example SimStadt[6] or the QGIS plugin for the 3D City Database (Agugiaro *et al.*, 2023).

Figure 5. Example of specific cooling demand results presented at building level and annual values presented at urban function level from the study area in Rotterdam.

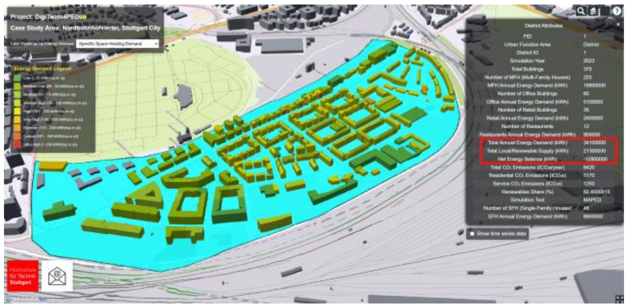

Figure 6. Example of specific heating demand results presented at building level and annual energy balance presented at urban function level from the study area in Stuttgart.

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[4] https://github.com/tudelft3d/Energy_ADE_2.0
[5] https://digitwins4peds.eu
[6] https://simstadt.hft-stuttgart.de/

suggestions and constructive feedback during the initial development of the Energy ADE 2.0.

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