AN OPEN-SOURCE CITYGML ENRICHMENT TOOL (CITYENRICH)

Avichal Malhotra[1], Maxim Shamovich[1], Simon Raming[1], Jérôme Frisch[1], Christoph van Treeck[1]

[1] *Institute of Energy Efficiency and Sustainable Building (e3d), RWTH Aachen University, Deutschland*

Abstract

Urban Building Energy Modelling (UBEM), an analytical method to comprehensively represent buildings on an urban scale, incorporates multiple data formats, modelling techniques and simulation methodologies. Though widely used, UBEM-based formats (such as CityGML) often lack the essential information required for energy performance simulations. An archetype-based enrichment technique suffices for the lack of required parameters, but their reliance on statistical data often restricts precise enrichment for a building's energy-specific parameters. Therefore, this paper presents an open-source CityGML Enrichment Tool (CityEnrich), enabling users to manually enrich CityGML building models and exchange enrichment data in the form of Energy ADE. The presented paper highlights CityEnrich's technical implementation and demonstrates the tool's applicability in UBEM.

Introduction

Urban Building Energy Modelling (UBEM) facilitates the modelling of urban buildings for energy-related applications. The applications include city-wide use cases such as energy demand estimates, retrofitting requirement identification, and energy-saving potential recognition (Reinhart & Davila, 2016). UBEM includes virtual 3D heat and mass flow models for predicting a building's energy requirements, and its incorporating methods help urban planners develop energy-efficient urban areas. The modelling techniques in UBEM have become a novel strategy for supporting and enhancing sustainable development measures within urban buildings. For energy analysis, UBEM requires input data such as the building's geometry, construction & material information, building physics data, occupancy profiles, weather data, and the incorporated system descriptions (Moncef, 2018; Ferrando et al., 2020; Chen et al., 2018; Hong et al., 2020; Malhotra et al., 2021a).

Within UBEM, data models or formats help represent individual buildings virtually by storing a building's geometry definition within standardised exchangeable information structures. One such data format, the City Geographical Markup Language (CityGML), is an official Open Geospatial Consortium (OGC) standard that allows representing city-wide buildings collectively. In recent years, CityGML has been one of the most prominently employed data formats in UBEM-based energy simulations (Malhotra et al., 2021a).

CityGML and the Energy ADE

CityGML, an open XML-based data format, enables the representation, storage and exchange of geometric information for buildings at an urban scale (Gröger et al., 2012). CityGML models include a building's semantic and topological information and allow geo-referencing of building models in a uniform spatial reference system (Malhotra et al., 2021b). In CityGML, the 3D model representation incorporates the information of a building's geometry, footprint, number of floors above or below ground, construction years, roof type and surface information. For building usages and roof types, CityGML uses ALKIS codes that are defined within individual, extendable and re-definable code lists (Gröger et al., 2012). Based on the amount of geometrical information present in a model, the data format explicitly describes individual building models in five varying Levels of Detail (LoD). Figure 1 demonstrates the five CityGML LoDs, i.e. LoD0-LoD4.

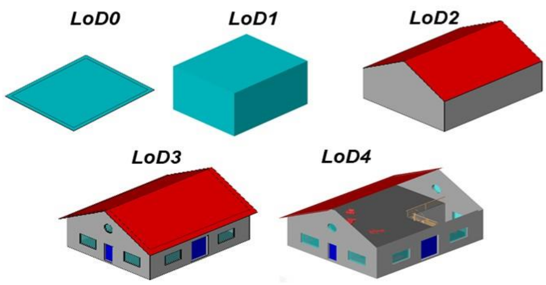

Figure 1: CityGML Levels of Detail (LoD)0-4

CityGML building models vary in their respective granularities according to their LoD definitions. Based on the intended use case, each LoD has its advantages and shortcomings. For energy simulations, CityGML LoD2 models are most commonly used. This results mainly out of the model's higher availability as open-source data (Malhotra et al., 2021b), inclusion of adequate geometric information (Malhotra et al., 2022), and its input and output support within many available simulation and validation workflows (Malhotra et al., 2021a). Although widely employed, the CityGML model architecture (in all LoDs) does not allow an inclusion of energy-specific information in the model but facilitates extending it with the required information. One way to extend the core geometric models is by using a CityGML Application Domain Extension (ADE). For energy-related applications, the Energy ADE was developed first in 2015 (Nouvel et al., 2015) and is generally employed.

The Energy ADE extends CityGML building models and defines an adaptable structure for storing and exchanging energy-relevant parameters, such as construction data and building physics information. The Energy ADE includes four functional modules, namely Building Physics, Materials and Constructions, Occupant Behaviour, and Energy Systems. For modelling time series, operation schedules (such as heating or cooling) and weather data, the Energy ADE defines some supporting classes in its extension architecture (Agugiaro et al., 2018). As the Energy ADE allows extending geometrical models with energy-related information, it forms the base as the (extension) structure for the CityGML Enrichment Tool (CityEnrich). Its usage (in CityEnrich) facilitates the storage of the necessary parameters in a well-defined structure allowing research communities to store, exchange and simulate enriched CityGML building models.

Energy-Specific Data Enrichment

For enriching CityGML models, it is common to use a bottom-up UBEM-based archetype enrichment approach or a manual enrichment approach (Ferrando et al., 2020). Both approaches enable modelling experts to assign energy-related information to the individual building models. The archetype-based approach relies highly on statistical data estimations and defines a building-specific archetype by selecting a sample building with measured or statistical building-related data (Ballarini et al., 2014). Using a building's construction year and usage, the defined archetype characterises each model and assigns the appropriate energy-specific parameters to the model. The archetype-based enrichment approach is highly beneficial in case the required energy-relevant data is unavailable. The method, however, might also inherit simulation errors and imperfections in case of inaccurate statistical data. Therefore, to reduce the errors in simulation results, it is necessary to enrich virtual models with precise information using manual enrichment methods. The methods help simulation experts quantify precise energy demands and develop energy-efficient strategies for cities and city-quarters. Currently, only a few workflows exist to enrich models manually. Some tools (such as FME (Safe Software, 2020) and GML ToolBox) allow the enrichment of energy data into geometric models; however, the tools are either not available as open-source or have certain licensing restrictions. If openly available, a manually enriched geometric model would also help store and exchange energy-relevant parameters within research and industrial domains. Therefore, this paper presents an open-source CityGML Enrichment Tool, allowing modellers to enrich CityGML LoD2 models manually and store enrichment data in the form of Energy ADE. CityEnrich envisions to support the UBEM community by providing an open workflow for manual enrichments of the CityGML models with energy-specific information. The presented paper highlights CityEnrich's technical implementation and explains the tool's functionalities for urban energy applications.

The remainder of this paper is structured as follows: The Section "CityGML Enrichment Tool" highlights CityEnrich's implementation and explains its incorporated functionalities; the Section "Tool Application and Validation" demonstrates an application use case and highlights the simulation results for an enriched model. It is followed by the "Conclusion and Future Work" section.

CityGML Enrichment Tool (CityEnrich)

As previously mentioned, CityEnrich enables users to manually enrich CityGML building models with energy-specific information. The tool lets users import CityGML LoD2 models and exports the enriched building models as a CityGML Energy ADE dataset. The enriched model comply with the CityGML's version 2.0 and Energy ADE's version 1.0. The CityEnrich tool enriches the LoD2 building models specifically for the 'Thermal Zones' and 'Construction Materials'. The tool incorporates a user-friendly and self-explanatory GUI for users from all domains and expertise levels. The authors developed the GUI using the Python library PySide2 (PySide2, 2019). In addition, the tool's modular architecture will allow its inclusion in other simulation workflows and tool chains. The CityEnrich tool is updated regularly and is available open-source under the MIT License (**https://gitlab.e3d.rwth-aachen.de/e3d-software-tools/cityenrich**). The following sections briefly highlight CityEnrich's functionalities in enriching the building models for thermal zones and materials.

Import

CityEnrich allows users to select a single CityGML dataset or several datasets by selecting a single folder. The tool enables the selection of individual building models and facilitates the selection of all models present in a dataset. In CityEnrich, the import window highlights the LoDs of input models for a consistent and simplified building selection. Currently, CityEnrich considers both buildings and building parts as single buildings and does not allow the enrichment of building parts separately. However, the enrichment of building parts separately is foreseen as future work. Once the tool imports the input CityGML data, it allows users to enter the building's years of construction and storeys above ground (if missing) into the tool. After inputting the information, users can select either the 'Thermal Zones Enrichment' or the 'Construction Enrichment'. Figure 2 demonstrates CityEnrich's selection window for selecting the desired type of enrichment.

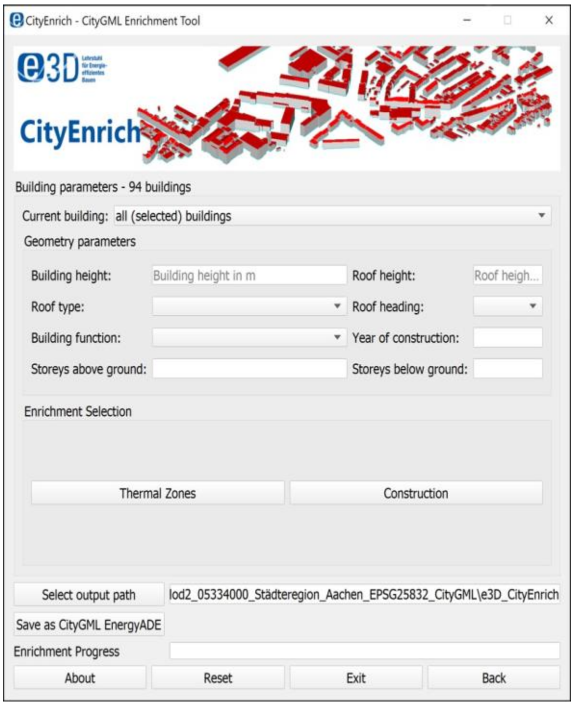

Figure 2: Overview of CityEnrich's selection window for selecting the required enrichment.

Thermal Zone Enrichment

CityEnrich uses the Energy ADE's structure for storing enrichment parameters. The Energy ADE includes a thermal zone within its *BuildingPhysics* module and the zone definitions are essential for building heating and cooling demand calculations. A thermal zone defines the smallest spatial region for energy demand calculations and includes energy-related attributes characterising its geometry, conditioning status and building physics properties. In CityGML, building models can associate with several thermal zones. Currently, CityEnrich only supports the energy-specific enrichment for a single thermal zone and does not allow users to select more than one zone in a building model. Developing a multi-zone CityGML model enrichment is planned in the future. Moreover, CityEnrich also allows users to input and select parameters from its thermal zone enrichment interface and includes the following parameters:

- **Floor area (m^2):** Refers to the floor area of the selected thermal zone. Users can select gross floor area or net floor area as the calculation methods.
- **Volume (m^3)**: Refers to the volume of a thermal zone. The tool allows users to select gross volume or net volume as the calculation method.
- '**Is heated**' or '**Is Cooled**': Is a Boolean selection option which allows users to select if a thermal zone is heated or is cooled.
- **Usage Zone - Schedules**: The tool connects the schedules to Energy ADE's base class 'Abstract Schedule'. It defines all the schedules related to a building's usage and includes:
- **Heating**, **Cooling** and **Ventilation:** The three schedule definition types include:
    - **Beginning and End Date**: It defines the starting and ending date for the schedules. The tool allows users to enter the date in a 'YYYY-DD-MM' format.
    - **Beginning and End Hour**: It defines the starting and ending hours for the schedules. The tool allows users to enter the hour in a 'HH:MM: SS' format.
    - **Acquisition Method**: It refers to the method used to acquire the schedules. It includes 'measured data', 'simulated data', 'data of a calibrated simulation', 'estimated data', and 'unknown acquisition method' as the selection options.
    - **Interpolation Type**: A mathematical rule defined in (SIG3D, 2017) and connects to a separate code list. In CityEnrich, the interpolation types that are previously specified within the EnergyADE (such as continuous, discontinuous, instantaneous Total, preceding Total, succeeding Total) are pre-defined for user selection.
    - **Thematic Description**: It defines a thematic description of the selected schedules.
    - **Day type selection**: Schedule representation consisting of associated recurrent day types, i.e. weekdays and weekends.
    - **Schedule Selection**: A '.csv' import function for users to select the desired schedule.
    - **Unit of Measurement**: The unit of measurement for the selected schedules.
- **Occupancy**, **Lighting** and **Appliances:** The three schedule types include the previously

mentioned attributes (in heating schedules) along with additional parameters, such as:

- **Convective Fraction**: The fraction of the total power given to the environment through convection.
- **Radiative Fraction**: The fraction of the total power given to the environment through radiation.
- **Total Value**: The sum of convective fraction and radiant fraction.
- **Number of Occupants**: It is defined only for the occupancy schedules and refers to the occupant number for the considered thermal zone.

Construction Enrichment

In CityEnrich, the enrichment of construction material points to the Energy ADE's *AbstractConstruction* element. It defines a set of material layers for the corresponding building element, i.e. the walls, roof, ground surface and windows. For each building element, the related construction definition physically represents an element's opaque part by characterizing its structure and specifying its corresponding thermal and optical properties (SIG3D, 2017). The CityEnrich tool enables users to select the appropriate construction material for every building element and the tool incorporates over 450 pre-defined construction materials such as concrete, hardwood plywood and clay. The authors consider material definitions from the open-source TEASER tool (Remmen et al., 2017) where the material list includes attributes (such as such as name, density, and thermal conductivity) from the Energy ADE's *SolidMaterial* class. From the material list, CityEnrich allows users to select the appropriate material by the material name (such as 'concrete') and stores its corresponding attributes (such as 'heat capacity') into the output Energy ADE. The tool includes the following parameters for construction enrichment:

- **Outer walls**, **Roof** and **Ground:** CityEnrich allows users to enrich individual layers of a building element and enables the addition of supplementary layers within the tool. For simplicity, the tool includes the following selection options:
  - **Material Name**: It refers to the name of the selected material. The tool allows users to select a similar or separate material for each layer of a building element.
  - **Thickness (m)**: It defines the thickness of a material layer.
  - **U-value (W/m^{2}K)**: It is an overall heat transfer coefficient representing the heat flux through the construction surface at a steady state. The CityEnrich tool calculates the U-value for each selected material of the corresponding layer.
- **Windows**: For a building, the window definitions include the following parameters:
  - **Window to Wall Ratio (%)**: It is the measure of the total glazed area on a building relative to the total amount of exterior building's wall area.
  - **Transmittance Fraction**: It refers to the faction of the energy transmittance, and the value is between '0' and '1'.
  - **Glazing Ratio**: It represents the ratio of the glazing surface over the total surface of a building. The ratio's value lies between '0' and '1'.
  - **U-value (W/m^{2}K)**: Similar to the other building elements, the U-value of a window represents an overall heat transfer coefficient through a construction surface at a steady state. For windows, CityEnrich calculates the U-value and outputs it into the Energy ADE.

Export

CityEnrich allows users to export the building-specific energy-relevant information in the form of CityGML Energy ADE. Currently, CityEnrich exports the enrichment data in compliance with the Energy ADE version 1.0 schema definition; however, an adaptation to the export of Energy ADE version 2.0 is planned in future.

The current implementation of CityEnrich envisions supporting UBEM-based research studies and aims to enhance CityGML's usage in existing energy-related workflows and toolchains. The following section highlights CityEnrich's application by enriching a CityGML LoD2 building model using an archetype-based enrichment method and a manual enrichment method. The section compares heating demand simulation results for models enriched using the archetype-based enrichment and manual enrichment approach.

Tool Application and Validation

In order to validate CityEnrich, the authors developed a CityGML LoD2 building model (further referred to as 'B1') for enrichment and heating energy demand simulation. The authors employ CityBIT (Malhotra et al., 2022) for generating the model B1 and enrich it using (i) TEASER+ for an archetype-based enrichment and (ii) CityEnrich for manual enrichment. The building model B1 is modelled with a ground surface floor area of 225m^2 and has three above-ground storeys. The authors define each storey with a storey height of 4m and the complete model includes a flat roof configuration. For B1, the total building height is 12m, with a calculated volume of approximately 2,700 m^3. Figure 3 demonstrates a 3D representation of the CityGML building model B1 using the FZK Viewer (IAI/KIT, 2019).

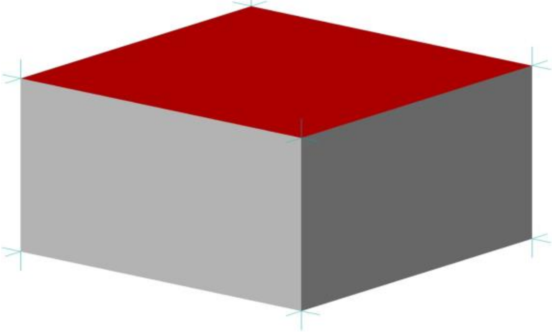

Figure 3: 3D representation of building model 'B1'.

The authors validate CityEnrich by using only one building model due to the current unavailability of precise district-wide energy-specific data. If available, precise enrichment of district-wide buildings might reduce inconsistencies in energy simulation results and help facilitate accurate energy demand predictions.

For the archetype-based enrichment, the authors supplement B1 with statistical energy-specific parameters using TEASER+ (Malhotra et al., 2019). As B1 is modelled with a construction year of '2015' and a 'tenement' building usage, TEASER+ enriches the model with TABULA's Multi-Family House archetype. The (archetype-based) enriched model is later referred to as 'AEB1'. Using TEASER+ and the Modelica library AixLib (Müller et al., 2016), the authors convert AEB1 into a ready-to-simulate Modelica model. The authors simulate AEB1 using Dymola (Dassault Systems, 2020). Once simulated, the authors compute AEB1's aggregated heating energy demand per square meter of the net leased area (in kWh/m^{2}a) for one year.

For the manual enrichment, the authors input (partially) precise energy-specific parameters into CityEnrich. Due to the current unavailability of some of the energy-specific parameters for B1, the authors use the operational and occupancy schedules similar to the (previously mentioned) archetype-based enrichment. The authors consider the construction materials for B1 from the energy-efficient construction standard 'KFW40 Plus' (Beckmann, 2020; KfW 2022). The standard defines an energy efficiency house level for new building construction and provides threshold values for parameters such as the number of insulation layers, thickness, and others. As the considered building is also in the planning phases, it is foreseen to have an energy efficiency level 40. For enrichment, however, not all construction parameters are available to the authors, and therefore, some construction materials are assumed. It is also important to mention that this paper does not include detailed information over enrichment schedules and construction parameters due to data privacy policies of the acknowledged research project. The manually enriched model is further referred to as 'MEB1'. The authors convert and simulate MEB1 for comparing its simulation results to AEB1. Figure 4 compares the computed heating energy demand per square meter of net-leased area (kWh/m^{2}a) for buildings enriched using an archetype-based enrichment approach (in red) and a manual enrichment approach (in green).

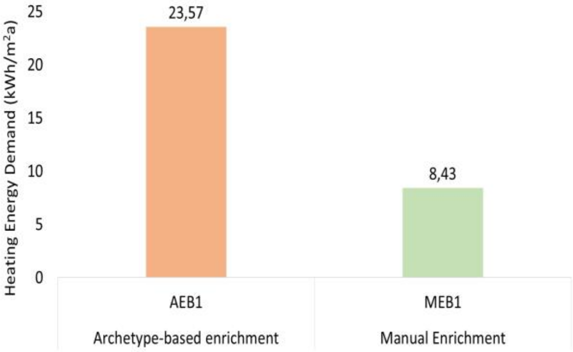

Figure 4: Comparison of heating energy demand per square meter of the net leased area (kWh/m^{2}a) for AEB1 (in red) and MEB1 (in green).

In Figure 4, a significantly large difference between the simulation results of AEB1 and MEB1 can be seen. As the actual building is planned to incorporate the KFW40 specifications, it will likely show simulation results similar to MEB1. Moreover, the difference in simulation results highlights the necessity of precise building-specific enrichment while predicting energy demands. If available, the precise data with manual enrichment techniques help store, exchange and simulate building models for energy performance simulations.

Conclusion and Future Work

The CityEnrich tool enables users to manually enrich energy-specific attributes of CityGML building models. CityEnrich supports the import of CityGML LoD2 models and exports the enriched model in the form of CityGML Energy ADE models. The tool is available as open-source and has a modular architecture incorporating a user-friendly GUI. The tool currently supports the enrichment of a building's thermal zone and construction. For now, it is limited to modelling a single-thermal zone; however, future version would include a multi-zone enrichment. The authors also envision the further development of the tool by incorporating enrichment functionalities for building's energy systems and other physical parameters. Future support with supplementary material-related databases and the flexibility to select pre-defined boundary conditions is planned. Moreover, an import functionality of all CityGML LoDs alongside its export as Energy ADE 2.0 is also foreseen.

Acknowledgement

Part of this work was funded by the German Federal Ministry of Economics and Energy (BMWi), promotional reference 03EWR010B.

References

Agugiaro, G., Benner, J., Cipriano, P., & Nouvel, R. (2018). The Energy Application Domain Extension for CityGML: enhancing interoperability for urban energy simulations. *Open Geospatial Data, Software and Standards*.

Ballarini, I., Corgnati, S., & 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*, S. 273-284.

Beckmann, N. (2020). Energiestandards im Bausektor. In *Energieeffizientes Bauen und wie es sich lohnt* (S. 89-111). Springer.

Biljecki, F., Kumar, K., & Nagel, C. (2018). CityGML Application Domain Extension (ADE): overview of developments. *Open Geospatial Data, Software and Standards*.

Chen, Y., Hong, T., Luo, X., & Hooper, B. (2018). Development of City Buildings Dataset for Urban Building Energy Modeling. *Energy and Buildings*, S. 1-36.

Dassault Systems. (2020). *3ds*. Accessed on 05. 12 2020 from https://www.3ds.com/products-services/catia/products/dymola/

Ferrando, M., Causone, F., Hong, T., & Chen, Y. (2020). Urban building energy modeling (UBEM) tools: A state-of-the-art review of bottom-up physics-based approaches. *Sustainable Cities and Society*, S. 102408. doi:https://doi.org/10.1016/j.scs.2020.10240

Gröger, G., Kolbe, T. H., Nagel, C., & Häfele, K.-H. (2012). *OGC Citz Geography Markup Language (CitzGML) Encoding Standard.* Open Geospatial Consortium.

Hong, T., Chen, Y., Luo, X., Luo, N., & Lee, S. (2020). Ten questions on urban building energy modeling. *Building and Environment*, S. 106508. doi:10.1016/j.buildenv.2019.106508

IAI/KIT. (2019). *FZKViewer (5.2)*. Accessed on 19. February 2020 from https://www.iai.kit.edu/1302.php

Malhotra, A., Bischof, J., Nichersu, A., Häfele, K.-H., et al. (2021). Information Modelling for Urban Building Energy Simulation - A Taxonomic Review. *Building and Environment*, S. 108552. doi:10.1016/j.buildenv.2021.108552

Malhotra, A., Raming, S., Frisch, J., & van Treeck, C. (2021). Open-Source Tool for Transforming CityGML Levels of Detail. *Energies, 12*, S. 8250. doi:10.3390/en14248250

Malhotra, A., Raming, S., Schildt, M., Frisch, J., & van Treeck, C. (2022). CityGML model generation using parametric interpolations. *Proceedings of the Institute of Civil Engineers*, S. 1-76. doi:10.1680/jsmic.21.00015

Malhotra, A., Shamovich, M., Frisch, J., & van Treeck, C. (2019). Parametric Study of different Levels of Detail of CityGML and Energy ADE Information for Energy Performance Simulations. *IBPSA Building Simulation*. Rome.

Moncef, K. (2018). Chapter 9 - Analysis of Large-Scale Energy Efficiency Programs. In *Optimal Design and Retrofit of Energy Efficient Buildings, Communities, and Urban Centers* (pp. 547-610). Butterworth-Heinemann.

Müller, D., Lauster, M., Constantin, A., Fuchs, M., & Remmen, P. (2016). *AixLib - An Open-Source Modelica Library within the IEA-EBC Annex 60 Framework.* BauSIM - IBPSA.

Nouvel, R., Kaden, R., Bahu, J. M., Kaempf, et al. (2015). Genesis of the CityGML energy ADE. *Infoscience EPFL scientific publications* (S. 931-936). Lausanne: CISBAT 2015.

PySide2. (2019). PySide Python Library.

Reinhart, C. F., & Davila, C. C. (2016). Urban Building Energy Modeling – A Review of a Nascent Field. *Building and Environment 97*, pp. 196-202.

Remmen, P., Lauster, M., Mans, M., Osterhage, T., & Müller , D. (2017). TEASER: an open tool for urban energy modelling of building stocks. . *Journal of Building Performance Simulation*, S. 84-98.

Safe Software. (2020). *FME - The Simple Solution for Complex Integration*. Accessed on 29. October 2020 from https://www.safe.com/

SIG3D. (2017). Accessed on 11. 05 2022 from SIG3D Documentation: Energy ADE TimeValuesProperties.

SIG3D. (2018). *Modeling Guide for 3D Objects: Part 2 Modeling of Buildings (LoD1, LoD2, LoD3).* Accessed on 20. 11 2020 from https://en.wiki.quality.sig3d.org/index.php?title=Modeling_Guide_for_3D_Objects_-_Part_2:_Modeling_of_Buildings_(LoD1,_LoD2,_LoD3)&action=info

KfW, Frankfurt am Main. (23. May 2022). Von Die Effizienzhaus-Stufe für einen Neubau. Accessed on 23.05.2022 from: https://www.kfw.de/inlandsfoerderung/Privatpersonen/Neubau/Das-Effizienzhaus/