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Concept and Evaluation of heating demand prediction based on 3D city models and the Energy ADE – case study Helsinki

by
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A dissertation presented in partial fulfillment of the requirements for the degree of Master of Science in the Department of Geomatics, Computer Science and Mathematics, Stuttgart University of Applied Sciences.

Declaration

The following Master thesis was prepared in my own words without any additional help. All used sources of literature are listed at the end of the thesis.

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Stuttgart, 31.07.2020

Maxim Rossknecht

Approved by:

Prof. Dr.-Ing. Volker Coors

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Abstract

The City of Helsinki aims to be carbon neutral by 2035. As the heating of buildings causes the greatest portion of greenhouse gas emission in Helsinki, more energy-efficient buildings may be the key to achieving this goal. [1] In this work, the developed concept enables the simulation and further prediction of the heating demand and resulting CO2 emissions based on a 3D city model in various scenarios under the consideration of a changing climate.

The Helsinki 3D city model in CityGML format provides, together with the Helsinki Energy and Climate Atlas, detailed information about individual buildings (e.g. areas of different uses, refurbishments, or heating systems).

To utilize the information during the simulation, it is integrated into the 3D city model using the Energy Application Domain Extension (Energy ADE) for CityGML. The aim of the Energy ADE is to provide energy-relevant information together with the 3D city model based on a standardized data model. The enriched city model is stored in a database for 3D city models, called 3DCityDB. The simulation environment SimStadt is extended to retrieve the information stored with the Energy ADE, use the information during simulations, and write the simulated results back to the 3DCityDB.

Due to the climate change, a heating demand reduction of 4% per decade is predicted. By 2035, a reduction of 0.7 TWh is calculated in the normal and of 1.5 TWh in the advanced refurbishment scenario. Including the proposed improvements of the district heating network in Helsinki, CO2 emissions caused by heating are predicted to be reduced by up to 82% by 2035 compared to 1990.

Keywords

3D city model, CityGML, 3DCityDB, EnergyADE, SimStadt, CO2 emission, energy demand prediction

Table of Content

List of Figures

List of Tables

List of Abbreviations

ALKIS	Amtliches Liegenschaftskatasterinformationssystem (Engl.: Administrative cadastral property information system)
BAU	Business as usual
CSV	Comma separated values
DHW	Domestic hot water
EPBD	Energy performance of buildings directive
GML	Geography Markup Language
GUI	Graphical user interface
HEKA	Helsingin kaupungin asunnot Oy (Engl.: Helsinki owned building)
JDBC	Java database connectivity
LoD	Level of Detail
OGC	Open Geospatial Consortium
TMY	Typical meteorological year
TRY	Test reference year
WFS	Web Feature Service
WMS	Web Map Service
XML	Extensible Markup Language
XSD	XML schema definition

1 Introduction

"The goal of Helsinki City Strategy 2017–2021 is to create a carbon-neutral Helsinki by 2035" [1, p. 2]. To achieve this goal, a strategy plan containing more than 100 actions was developed. The target has been set to reduce CO2 emissions in Helsinki by 80% compared with the emissions in 1990. The remaining 20% should be compensated by emission reductions outside the city. As presented in Figure 1, the share of greenhouse gas emissions in Helsinki is dominated by heating.

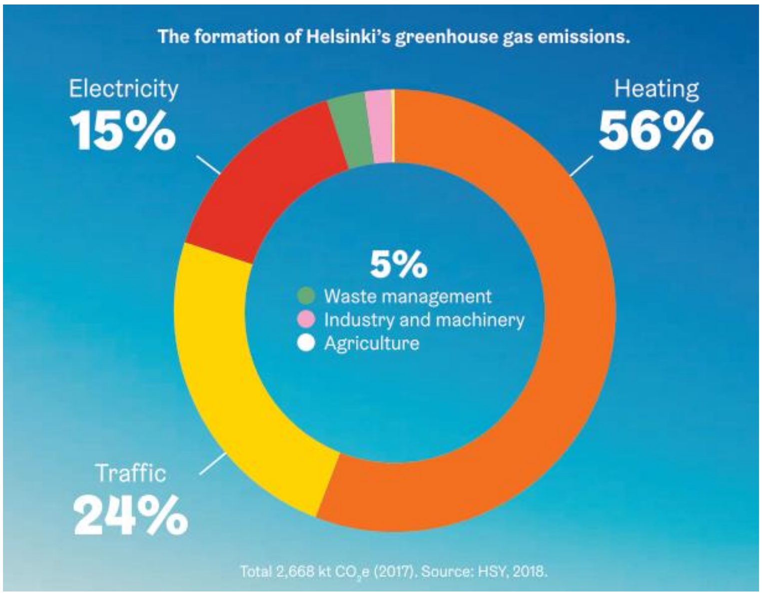


Figure 1: Share of greenhouse gas emissions in Helsinki by sectors [adopted from: 1, p. 3]

Here, energy renovations provide the greatest potential in reducing CO2 emissions. [1] According to the action plan, the buildings' emissions could be reduced by 80%. A small part of the building stock in Helsinki is owned by the city, and these buildings hold only 11% of the reduction potential; therefore, the owners must be motivated through financial support for building renovations. [1] One way to develop efficient renovation strategies is to more strongly support the owners of buildings with greater reduction potential than others.

The City of Helsinki seeks to provide all available data related to the energy of buildings with the Helsinki Energy and Climate Atlas. [2] This is a web visualization of the Helsinki 3D city model which allows for virtually exploring Helsinki in a web browser and retrieving information for each building. However, measured heating energy consumption are available only for Helsinki-owned buildings (fin.: Helsingin kaupungin asunnot Oy, HEKA buildings). The energy consumption of other buildings is categorized by the year of construction and the usage class of the building, which allows only a rough assessment of the energy demand of a building. Additionally, the information of the Helsinki Energy and Climate Atlas is provided as an Excel file, which can be connected to the 3D city model buildings via a permanent building code, but the data is not directly integrated into the city model. This integration is achieved using the Energy Application Domain Extension (Energy ADE). The Energy ADE is an extension of CityGML for 3D city models and aims to extend a 3D City model stored in CityGML format with a standardized data model for energy-relevant data.

2 Research Questions

2.1 Objectives

The aim of this thesis is to predict the heating demand of Helsinki's building stock in different scenarios on the urban scale and calculate the heating-demand-saving potential on the building scale. Based on the energy demand for heating and information about the heating systems, the CO2 emissions caused by heating can be calculated.

As the data basis, the 3D city model is used together with information of the Helsinki Energy and Climate Atlas and additional information of the Helsinki city register and long-term predicted weather data. Information which conduct the energy demand of a building are integrated into the 3D city model using the Energy ADE.

2.2 Hypothesis

With a heating demand simulation and prediction based on 3D city models,

a) The heating demand can be simulated with an accuracy of 20% deviation from measured values.
b) The yearly refurbishment rate for achieving the needed reduction of CO2 emissions caused by heating can be calculated.

3 Related research

Heating demand prediction can be achieved using various approaches on different scales. Chalal et al. [3] differentiate possible approaches on the urban and building scales. As illustrated in Figure 2, the building scale is further divided into engineering, artificial intelligence, and hybrid approaches, while the urban scale approaches are further classified into 2D-GIS-based, CityGML-based, and bottom-up statistical approaches.

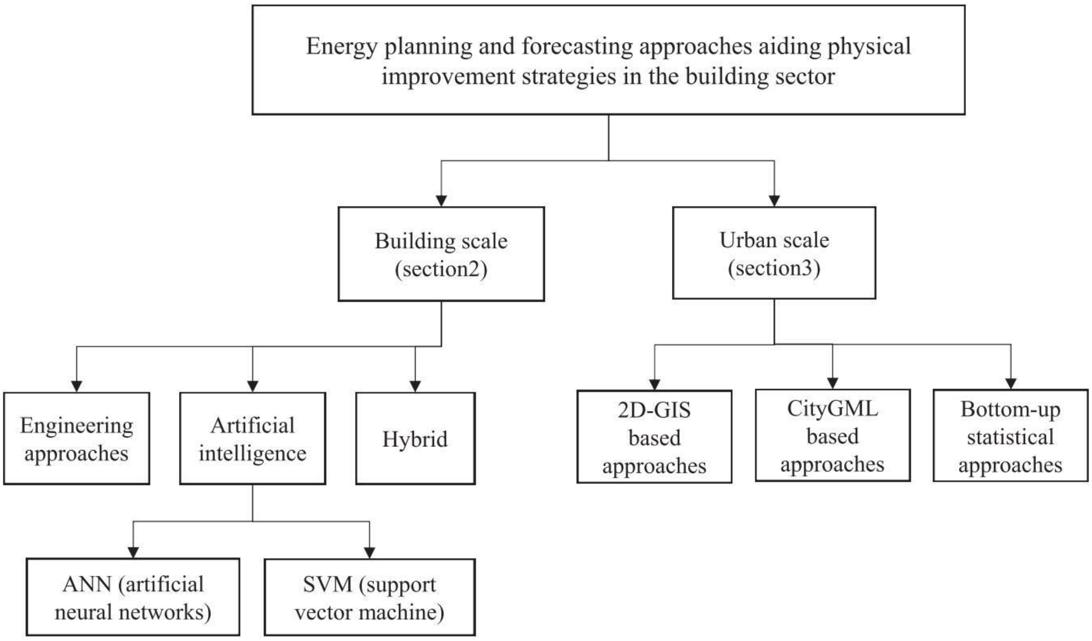


Figure 2: Building's energy predictions approach classification [adopted from: 3, p. 763]

Engineering approaches predict energy consumption based on physical and thermodynamic principles and relationships, whereas a statistical approach usually uses historical consumption data to perform statistical analysis, such as a linear regression on the available data sets. [3] The accuracy of statistical approaches depends on the significance and availability of historical consumption data, whereas engineering approaches based on 3D city models are primarily influenced by missing building information, such as refurbishments, window-to-wall ratio, the LoD, the heated area, and the behavior of its occupants. [4]

The energy consumption of the Finnish building stock has already been studied using a variety of energy models. An overview of the existing energy models is provided by Lounasheimo et al. [5]. The POLIREM energy model is developed by the Tampere University of Technology. The researchers developed this model after the EKOREM model, which is often used in published work. [6] Both models aim to assess the energy consumption and greenhouse gas emissions, primarily based on the building and energy statistics of Finland. [7]

Tuominen et al. [8] developed the so-called REMA energy model. Based on the representative building types and the simulation tool "IDA Indoor Climate and Energy" (IDA ICE), the energy consumptions of different sectors are estimated using a bottom-up approach. IDA ICE uses building models in CAD format to assess the energy consumptions in multi-zonal simulations. [8]

The same software was used by Jylhä et al. [9] to assess the energy demand of a detached house in Finland under the aspect of a changing climate with long-term predicted weather data sets for up to 2100. As a result, the simulated energy demand for heating will decrease by 2–4% per decade, whereas the energy demand for cooling will increase by 4–8% per decade. [9]

In 2009, the Laboratory for Solar Energy and Building Physics of the Swiss Federal Institute of Technology Lausanne (EPFL) introduced a software for simulating a building's energy flows based on 3D city models. Using the simplified building models, the software includes thermal interactions of buildings with their environment (i.e. shadowing, infrared exchanges, and light inter-reflections). The software is validated against the Building Energy Simulation Test approach (BESTEST). As a result, the energy demand for heating deviates by 1% from the expected values. [10]

The software used in this work is a simulation environment that includes physical building and usage models to perform energy simulations based on 3D city models. Several case studies reveal an accuracy in heat demand simulation of 5–21% compared with measured values. Furthermore, refurbishment scenarios can be applied to calculate the energy saving potential for each building on the urban scale. For the case study of the "Grünbühl" district in the city of Ludwigsburg, a refurbishment scenario based on standardized energy refurbishments in Germany was performed. As a result, the total energy reduction potential for heating is calculated to be 64%. Furthermore, a refurbishment strategy with 2% refurbishments per year for the district was calculated from 2010 to 2050. This refurbishment rate is needed to achieve the maximum heating savings up to 2050. [11]

4 Background

4.1 3D city models

One motivation for developing a 3D city model is to provide a virtual twin of a city that can be used as a geographical information system. The city of Helsinki provides two types of city models: Whereas the reality mesh model is primarily used for visualization purposes, the semantic CityGML model is used as the basis for a city information system.

With CityGML, the Open Geospatial Consortium (OGC) adopted an open data model for 3D city models with the aim of storing and exchanging virtual 3D city models in a common definition based on the XML encoding format. The implementation is done based on the Geography Markup Language (GML) standard of the OGC, an encoding standard for storing end exchanging geospatial information. [12] The latest version, CityGML version 2.0.0, has been valid since 2012, and the upcoming CityGML version 3.0.0 is currently in development. This work concentrates on CityGML version 2.0; for the purpose of simplification, the version number is omitted in the following chapters. The general structure of CityGML is visualized in Figure 3. With the modular concept of CityGML, it is possible to model several feature types of a city (e.g. buildings, transportation, relief, and land use).

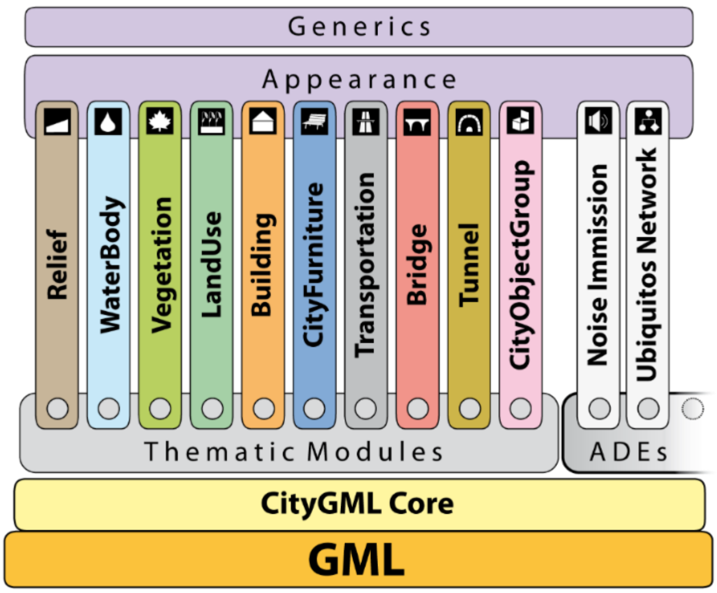


Figure 3: CityGML version 2.0 modular structure [adopted from: 13]

The feature types can be defined in different level of detail (LoD). LoD1 to LoD4 of a building are visualized in Figure 4. At the LoD1, the buildings are modeled as rectangular and flat-roofed. For a building in LoD2, different shapes and surfaces of roofs stand out. LoD3 includes openings such as doors and windows to the facades, whereas in LoD4, the interior is also modelled.

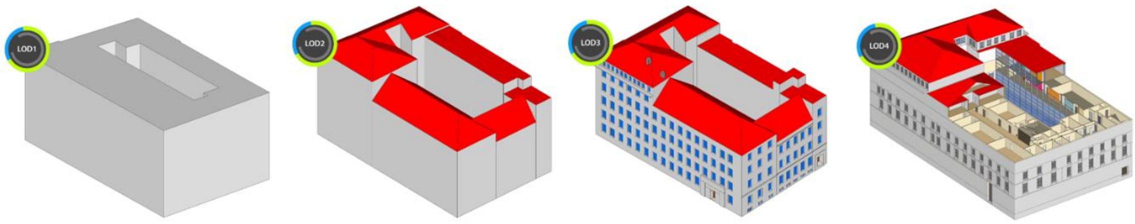


Figure 4: A building of the Hochschule für Technik Stuttgart in different Level of Detail [adopted from: 4]

This work focuses on the CityGML Buildings in LoD2, as those are used for heating demand calculation and prediction. Using 3D city models in CityGML provides the benefit of including known semantic information next to the geometry, as illustrated in Figure 5. Thus, it is known which geometric feature refers to which part of a building (e.g. the wall, roof, or ground).

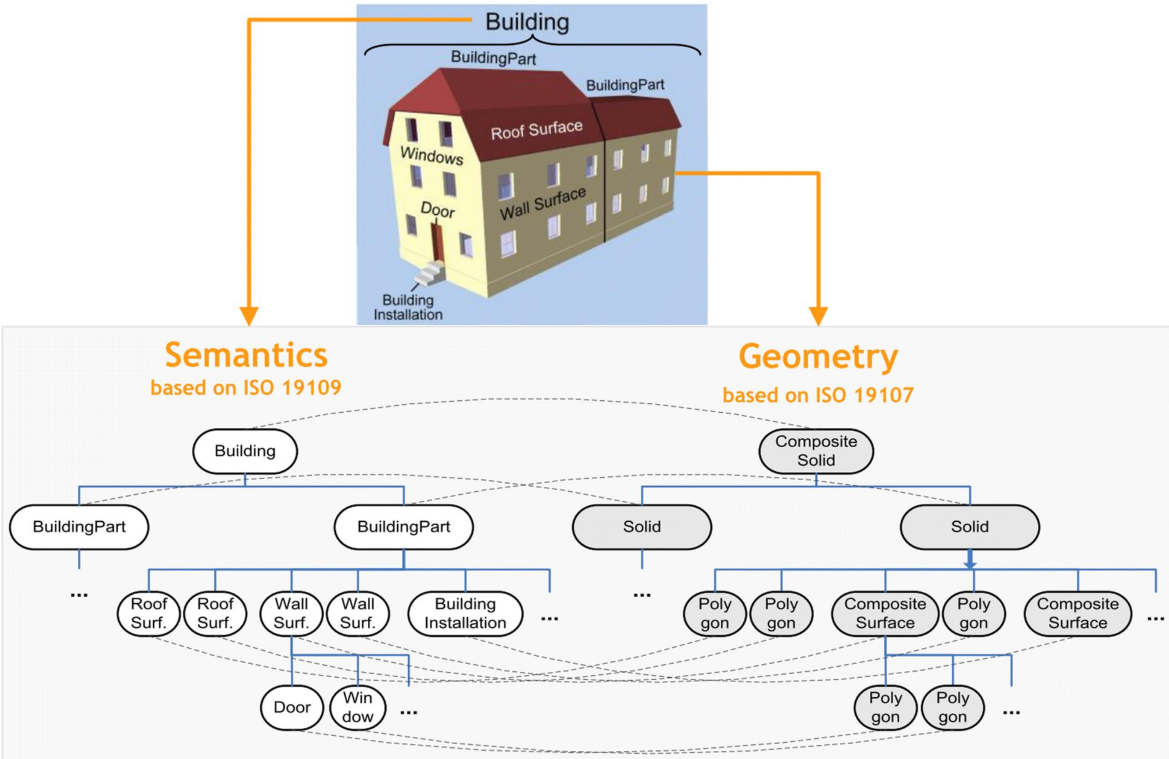


Figure 5: Semantics and geometry in CityGML [adopted from: 14]

4.2 Energy ADE

The Energy Application Domain Extension (Energy ADE) is an extension of CityGML. The purpose of the Energy ADE is to extend CityGML with a standardized data model for energy-relevant data. This enables interoperability, as it is used in different simulation software. [15]

4.2.1 Modular structure of the Energy ADE

As CityGML itself, the Energy ADE is structured in a modular way. These modules are presented in Figure 6 and described according to the Energy ADE version 1.0 specifications. [16]

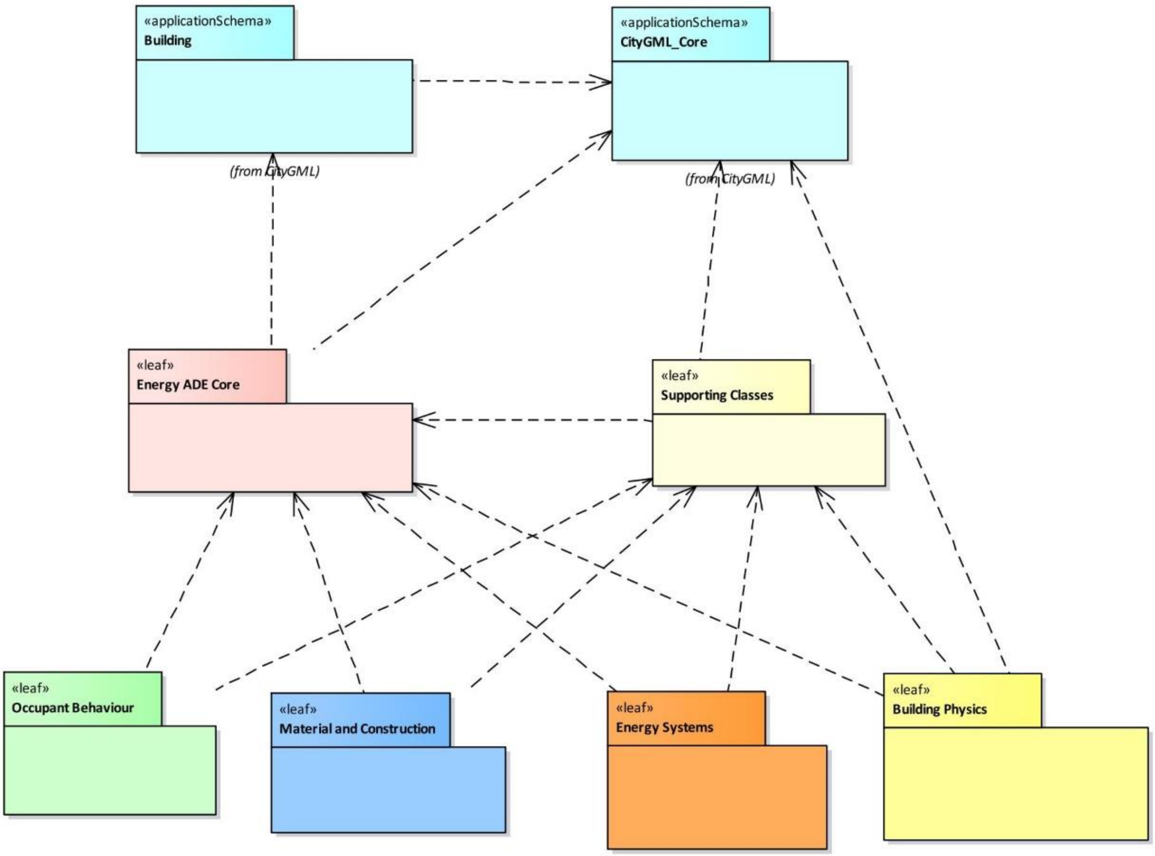


Figure 6: Overview of the Energy ADE modules [adopted from: 16]

Energy ADE Core module

The Energy ADE Core module extends the CityGML modules *CityGML_Core* and *Building* by energy-relevant properties, such as *EnergyDemand, floorArea,* and *volume.*

Supporting Classes module

The Supporting Classes module provides several classes for the representation of time series, weather data, and schedules used in the other modules.

Building Physics module

The Building Physics module extends a building by its physical properties. This is done by the definition of one or many (mono- or multi-zone) *ThermalZones*. A *ThermalZone* may be defined by geometry information (e.g. *volume* and *floorArea*); the conditioning information of whether a zone *isHeated*, *isCooled*, or both; and general physical properties such as the *infiltrationRate* or the *additionalThermalBridgeUValue*.

Occupant Behavior module

The aim of the Occupant Behavior module is to represent the usage of a building (e.g. the *UsageZones*). The occupancy of a *ThermalZone* is defined by a link to at least one *UsageZone*.

Material and Construction module

The Material and Construction module is used to define the thermal and optical properties of building elements for slabs, walls, roofs, and windows. Furthermore, it is possible to define a set of layers that contain different construction materials to represent a building element, such as a wall.

Energy Systems module

The energy flow of a *CityObject* from energy sources to its final energy demand is described within the Energy Systems module. Additionally, this module includes the energy conversion, distribution, and storage systems and the flow of energy between them.

4.2.1 Energy ADE profiles

In addition to the original Energy ADE, so-called Energy ADE profiles exist. A profile adopts and modifies the original schema, which is typically done to strengthen the schema rules, exclude classes or modules, exclude optional attributes, or declare optional ones as mandatory. Thus, the data model's complexity can be reduced. [17]

4.3 Heating demand simulation

The European directive for the energy efficiency of buildings declared in 2002 requires the states of the European Union to analyze the energy efficiency of their buildings. [18]

In 2005, the German standardization institute ("Deutsches Instut für Normung", abbr. DIN) released the DIN V 18599 standard, which defines the formulas to calculate energy demands for buildings. [19]

Figure 7 presents a simplification of the used building's energy model. The general concept is to identify the heat sinks and heat sources in a building zone. Heat sinks describe the heat losses of a zone (e.g. transmission, ventilation, internal, and solar heat losses), whereas heat sources are heat gains (e.g. trough transmission, solar radiation, ventilation, and internal gains).

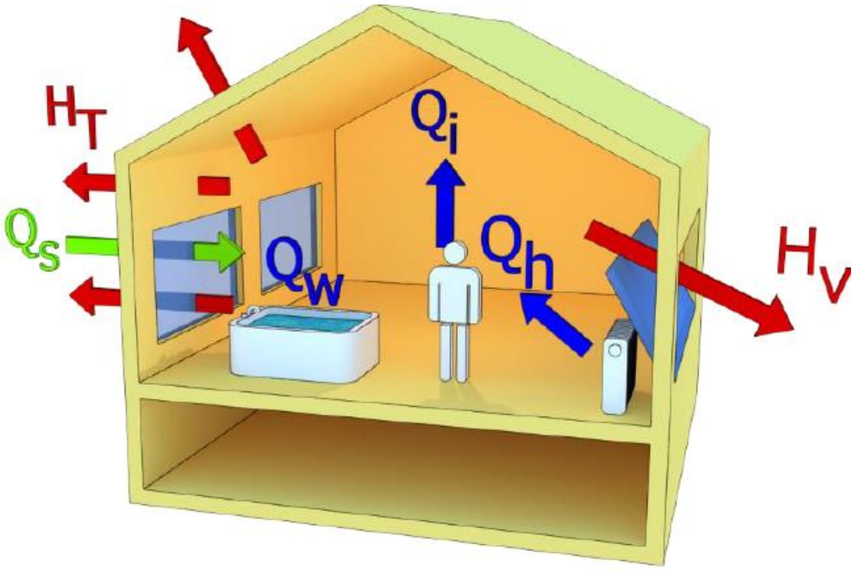


Figure 7: Simplified building's energy model [adopted from: 20]

The final heating demand of a building's zone $Q_{h,b}$ is then calculated by combining the sum of heat sinks Q_{sink} and sources Q_{source} with the "degree of utilization" η. [19, 21]

$$Q_{h,b} = Q_{sink} - \eta \cdot Q_{source}$$

The degree of utilization is calculated as follows:

$$\eta = f\left(\frac{Q_{source}}{Q_{sink}}, \tau\right)$$

where the time factor τ describes the needed time for heating a thermal zone

$$\tau = f\left(\frac{C_{eff}}{H_T, H_{V,Infiltration+Window}, H_{V,mechanical}}\right)$$

The function of τ depends on the

C_{eff} thermal zone's effective heat capacity [W/K], the

H_T heat transmissions coefficient [W/K] of the building's envelope, and the

H_V heat transmissions coefficients [W/K] for ventilation through infiltration, windows, and mechanical ventilation.

The heat transmission coefficients H_T can be calculated using the mean thermal transmittance [W/(m².K)] of the building's envelope and its area [m²]:

$$H_T = U_{mean} \cdot A_{envelope}$$

where the heat transmissions through ventilation is calculated by

$$H_V = c_{p,air} \cdot \rho_{air} \cdot V_{net} \cdot n_{air}$$

with

$c_{p,air} \cdot p_{air}$ air constant 0.34 [Wh/m³.K]

V_{net} thermal zone's net volume [m³]

n_{air} air change rate [1/h]

The thermal zone's volume and surface areas can be calculated by the geometry of the building; therefore, a 3D city model can be used. A particular advantage is offered by CityGML, as the LoD2 geometry is semantically structured into the wall, roof, and ground surfaces. This allows for example the calculation of the mean U-value of the building's envelope.

The simulation environment SimStadt implements this standard to calculate the monthly energy demand of a building based on the 3D city model in CityGML format and building typologies. A detailed description of the software is provided in Section 7.1.

4.4 3D city model visualization

The results of the heat demand analyses of this work are to be made available to the public. A 3D web application is suited for this purpose, as it would allow for visualizing the 3D city model via a web browser together with the simulation results.

4.4.1 Digital globes

Meanwhile, several so-called digital globes are available. A comparison of the existing solutions in 2015 is published by Keysers [22]. In addition to commercial products such as Google Earth, Bing Maps 3D, or ArcGlobe, a variety of open-source solutions exists. A study that focuses on open-source frameworks for 3D web visualizations is done by Krämer and Gutbell [23]. They compared the WebGL frameworks X3DOM, three.js, and Cesium.js for geospatial applications. CesiumJS has the best support for spatial reference systems, as it is directly supported and does not require an extension, like needed for three.js. [23] Furthermore, imagery can be visualized through the OGC's WMS standard, and terrain in a streamable quantized mesh format is supported.

4.4.2 3D Tiles

The common format for visualizing 3D city models on a Cesium globe is the so-called "3D Tiles" format. This is an open specification optimized for streaming and rendering large spatial data sets in 3D web applications. Furthermore, it is possible to store attributive information for each feature. [24] This can be used in this work to specify styles based on the simulated heat demand of a building.

5 Concept

An overview of the proposed concept is provided in Figure 8. The included steps are described in this chapter.

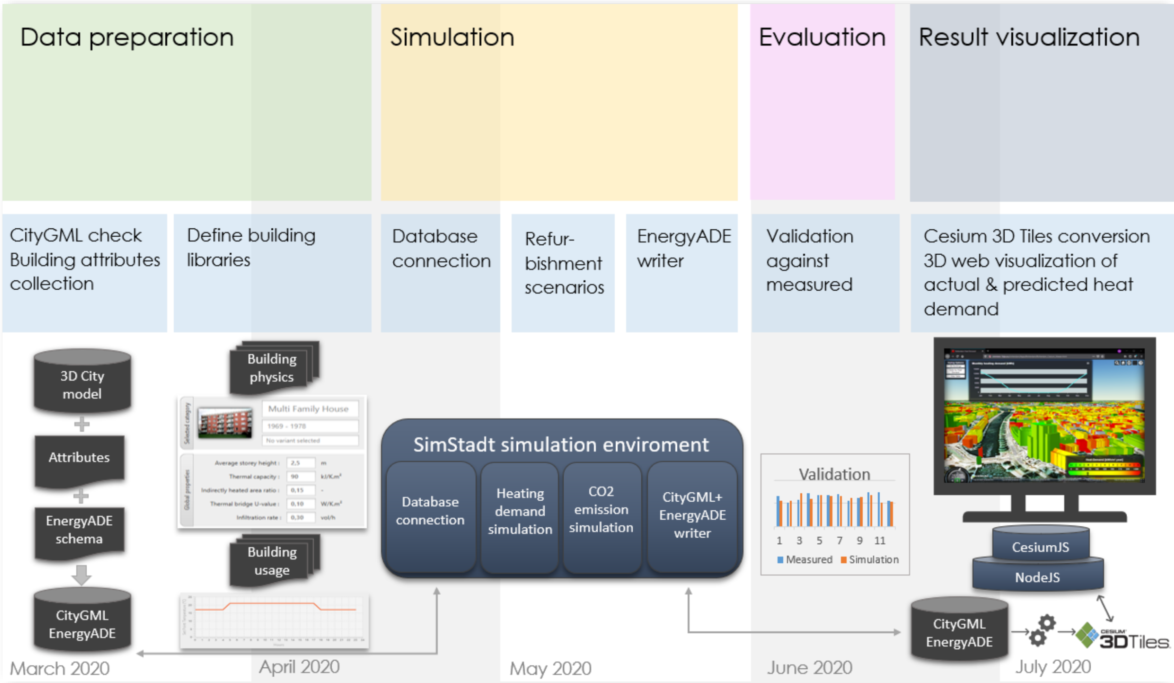


Figure 8: Methodology overview

5.1 Data preparation

In the first step, the 3D city model is enriched with additional attributes for each building. As the heat demand can be calculated only by using solid geometries of the CityGML buildings, the CityGML file must be checked for faulty geometries, such as unclosed solids, duplicated points, or intersecting polygons. Additionally, the CityGML file is validated against the XML schema definition. Errors that may occur must be fixed prior to the simulation.

5.2 Energy ADE integration

Attributes that conduct the energy demand of a building are stored using Energy ADE objects. Therefore, two different approaches are examined: a file-based and database-based approach. These approaches are described in Section 7.3. For both, the target is to store the city model in a database for 3D city models with Energy ADE information.

5.3 Heat demand and CO2 emission simulation

The simulation environment SimStadt allows to calculate the heating demand and the resulting CO2 emissions of a building. In addition to the CityGML 3D city model, building topologies are needed that define the physical behavior of the construction parts, the usage information, and the heating system of a building. These topologies are implemented with the use of so-called libraries. A building library is an XML-encoded file that can be created or edited for a city or country, as is already defined for Germany and New York City. This work investigates the building stock in Helsinki, for which no library has yet been defined. Therefore, the following libraries are created for the Finnish building stock.

Building physics library

The building physics library contains information regarding the physical behavior of the construction material, categorized by the building type and construction year ranges. These include, for example, the heat losses through walls and roofs, window-to-wall ratios, average storey heights, and so on. Furthermore, for each construction year range, refurbishment variants can be defined. A refurbishment variant represents the way in which the building structures are changed when a renovation is performed. These are used in this work to simulate the changes in heating demand following a renovation. The structure of the building physics library is visualized in Appendix C.

Building usage library

In addition to the building physics library, the usage library further categorizes the buildings for various uses. For each usage type, such as residential, office, or retail, different characteristics are assigned to a building (e.g. usage hours, heating profiles, hot water, electricity consumptions, and so on).

SimStadt uses the German ALKIS codes to access the information of the building function from the library. As these are different from the Helsinki usage codes, a mapping file is created to suit the Finnish usage codes.

Energy systems and fuel library

The CO2 emissions of a building, which are caused by heating and domestic hot water (DHW) preparation, are dependent on the system used to generate the heat. Such systems are defined in the energy system and fuel library, which contains information regarding the efficiency of a system and its CO2 emission factors. The heating system most used in Helsinki is the district heating system, which must be defined in this library.

Weather data

As the energy demand for heating is always influenced by the climate condition of the investigated region, weather information in at least a monthly resolution is needed. Existing databases are available that provide such information based on long-term observations. Those weather data sets are referred to as typical meteorological years (TMY) or test reference years (TRY). SimStadt can access the weather databases provided by the INSEL simulation software or an online accessible database called PVGIS. Both databases provide TMYs with weather and climate information, such as the temperature, humidity, windspeed, and irradiation in monthly resolution. Furthermore, if no information for a region is available or if weather data in hourly resolution is needed, it is possible to import TMYs or measured weather data for a specific year in a format called TMY3. To compare the simulation results with the measured energy consumption data from a particular year, weather data for the representative year is used.

It is expected that the climate will change in the future, consequently causing the energy demand for heating to change, as well. This is considered using predicted weather data sets for the future, which are imported to SimStadt.

5.4 Usage of the Energy ADE for heat demand simulations

Until now, SimStadt is not able to use Energy ADE information stored in the CityGML files. To utilize the Energy ADE information in SimStadt, a workflow step is defined that queries the database for additional information stored in the Energy ADE tables. If additional information is present (i.e. the number of occupants that can be stored for the Energy ADE *UsageZone*), it is directly assigned to a building and not taken from the building topologies or estimated calculations during the simulation.

SimStadt provides the opportunity to write simulation results, such as the monthly heating demand, back to a CityGML file using the Energy ADE *EnergyDemand* object. Another approach directly inserts or updates the simulation results to the database using the Energy ADE schema integration. This reduces the intermediate step of importing the CityGML files into the database after each simulation.

With the use of the defined refurbishment variants and energy systems in addition to the long-term predicted weather data, the heating demand can be predicted in various scenarios. The following investigations are performed.

5.5 Heating demand and CO2 emission prediction scenarios

Climate change impact

The impact of a changing climate is investigated by using long-term predicted weather data for the calculation of heating demand, which in turn influences the CO2 emissions caused by heating.

Refurbishment scenarios

The defined refurbishment variants are used to apply refurbishment scenarios to the 3D city model. By specifying a refurbishment rate to the building stock, the heating demand can be calculated in a scenario. It is further possible to investigate the impact of several refurbishment types to the heating demand of a building.

Energy system change

The CO2 emission caused by space heating and DHW preparation depend on the system that is used to produce the heating energy (e.g. oil boilers, electric radiators, or district heat). More than 90% of the buildings in Helsinki are connected to the district heat system. Helsinki aims to improve the district heat system in terms of its CO2 efficiency. This will be achieved by using more renewable energy sources and stopping the use of coal to thereby produce energy with less CO2 emissions. [25]

The expected change of CO2 emissions from the district heat system is expected to significantly reduce the CO2 emissions caused by heating. The changes in CO2 efficiency of the district heat network are implemented in the simulation, and the CO2 emission reduction impact is analyzed.

5.6 Visualization

For the visualization of the simulated results, a 3D web application is created. Therefore, the 3D city model in CityGML format is enriched by the simulated results and converted into 3D Tiles format. A NodeJS server is set up that runs the CesiumJS 3D web application. As a result, the buildings are styled based on attributive information (e.g. the energy demand for heating and the resulting CO2 emissions). Furthermore, each building can be inspected for possible energy performance improvement through renovations.

5.7 Evaluation

The simulated heat demand is validated against the measured consumption data for several years. As a result, a 20% deviation with the measured consumption data is expected. At first, this might sound high, but considering that the impact of the occupants' behavior can influence heating energy consumption by approximately 20%, this can be viewed as a good result. [26] and [27]

6 Used datasets

6.1 Helsinki 3D city model

The Helsinki 3D model consists of approximately 82,000 buildings in LoD2, with textures that can be visualized in a 3D web application. [28] In addition, it is open source and available in CityGML format with respect to the coordinate system ETRS89-GK25FIN. [29] In addition to the geometry of the buildings, further attributes such as the usage class, number of floors, building materials, and year of construction are available, but information related to the energy demand is missing.

6.2 Helsinki Energy and Climate Atlas

Parallel to the 3D city model, the Helsinki Energy and Climate Atlas consists of energy-related attributes for each building. There is also a 3D web application for inspection of the attributes, presented in Figure 9. Additionally, it is available as an Excel file. [2] and [29]

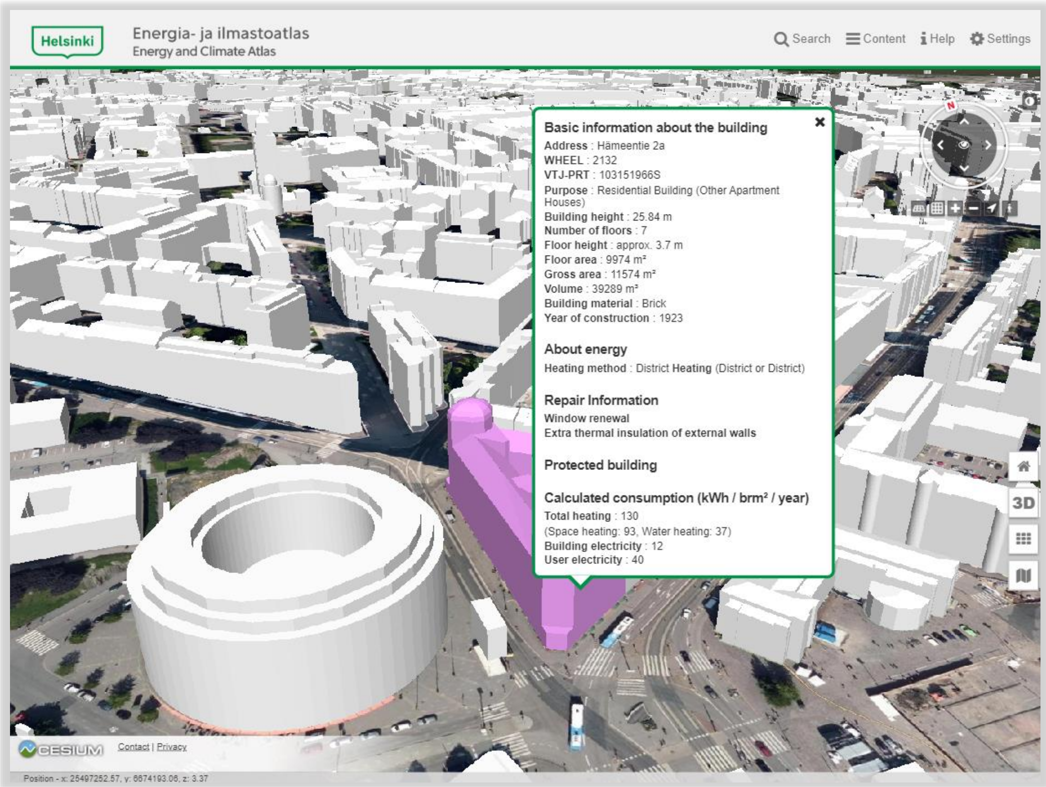


Figure 9: Energy and Climate Atlas 3D web application [translated screenshot: 2]

In total, more than 100 attribute entries are possible for each building. The most important ones are structured as follows:

1. Basic information
   - Year of construction
   - Usage class
   - Number of floors
   - Building material
2. Energy information
   - Heating method
   - Heating source
   - Energy certificate information
3. Repair and renovations (eight entries per building possible)
   - Type of renovation (windows, thermal isolation, technical,...)
   - Date of renovation

Additional energy consumption data for HEKA buildings for 2015–2018 are available:

4. Energy and water consumption data per year for 2015 and 2016. In addition, consumption data for 2017 and 2018 were available in this work, which have not yet been publicly published.
   - District heat consumption [MWh] (including space heating and DHW)
   - Cold water consumption [m3]
   - Electricity consumption [kWh] (for building electricity, not consumer electricity)

The Helsinki Climate and Energy Atlas web application also contains the heating demand values for buildings that are not owned by the city, see Figure 9. These values are categorized based on the year of construction and the usage class of the building. For example, a terraced house constructed before 1939 has a total heat demand of 130 kWh/brm2/a (kilowatt-hours/gross area/year). [30]

6.3 Helsinki city register

The Helsinki city register contains information influencing the energy demand for the heating of buildings. Such information includes the number of apartments per building, the calculated number of occupants, and different usage areas. Furthermore, the building renovation permits are available. Due to privacy reasons, the Helsinki Energy and Climate Atlas does not include renovations for single-family houses and buildings with fewer than 6 apartments. This information is used in this work for the simulation but is not further published.

6.4 Helsinki weather data

The Finnish Meteorological Institute provides weather data sets, especially for energy demand simulations of buildings. [31]

The TRY2012 is the actual test reference year data set in Finland generated based on observations between 1980 and 2009. Furthermore, predicted weather data sets TRY2030, TRY2050, and TRY2100 are available. All of these provide hourly values for temperature, relative humidity, wind direction, and speed, in addition to the direct, global, and diffuse solar irradiation. [32] The data sets are available in PDF and PRN format; in this work, the PRN text files are used.

For the comparison of simulation results against the measured energy consumption from a particular year, the real observations of the corresponding year are used. These observations can be downloaded at the Finnish Meteorological Institute website as CSV or Excel files.

7 Implementation

7.1 Used software

3DCityDB Importer/Exporter-Tool

The Helsinki 3D city model is stored in a database for CityGML called 3DCityDB. It is a database solution based on a PostgreSQL DBMS with a PostGIS extension, and it provides the needed schema definitions to store the 3D model based on CityGML. Additionally, ADE functionality is provided, which extends the database schema for ADEs (i.e. the Energy ADE). The 3DCityDB Importer/Exporter tool is an open-source Java front-end for the 3DCityDB. It is used to manage, store, and export the 3D city model in CityGML format. [14]

This work used the 3DCityDB in version 4.0.1 and the Importer/Exporter-Tool provided from virtualcitySYSTEMS in version 4.0.2, called virtualcityDATABASE. [33] Additionally, an Energy ADE extension is used, which enables the use of the Energy ADE KIT-Profile in the Importer/Exporter-Tool.

CityDoctor

The software CityDoctor is used for the checking and validation of faulty 3D geometries in CityGML and is co-developed by HFT Stuttgart. [34] For this work, an extended version of CityDoctor in version 3.7 is used. The extension provides a healing functionality for faulty geometry in CityGML.

SimStadt

The software SimStadt is a Java-based simulation environment that includes the physical building and usage models to perform energy simulations based on 3D city models. The actual version of SimStadt provides different workflow definitions, such as solar photovoltaic potential analysis, environmental analysis, or heating and cooling demand analysis. A workflow is defined with different workflow steps that can be combined on a modular basis. [35]

This work focuses on heating demand prediction and the calculation of the CO2 emissions caused by heating. For this purpose, the SimStadt workflow is called “Environmental Analysis with Refurbishment Strategy” and is described in this chapter.

The minimum requirement for the workflow is a 3D city model in CityGML format. All buildings require at least the attributes "year of construction" and "function" to be processed through the workflow. This information is used to access the building topologies, so-called building libraries, to enrich the building with additional information for the simulation. The libraries are described in Section 5.3. Having the libraries prepared, the workflow for the simulation and prediction of the heat demand and CO2 emissions is ready to be started. The workflow is structured in several workflow steps, described as follows:

1. Import CityGML

In the first step, the CityGML file is imported into the simulation environment. The used LoDs can be selected, and optionally, the CityGML file can be validated against the schema definition.

2. Create SimStadt model

The subsequent step generates a SimStadt model out of the CityGML information. This includes the use of additional attributes that can be used in further processing (e.g. information concerning the refurbishment status of a building).

3. Preprocessing

The preprocessing workflow step prepares the buildings for the final simulation. The following steps are preprocessed for each building:

a. Geometric preprocessing

The geometrical properties of a building, which are needed for the simulation, are calculated. These include the areas of the building's outer surfaces, their orientation, the building volume, and the building height.

b. Physics preprocessing

During the physical preprocessing, the selected building physics library is used to assign the information concerning the physical behavior of the building's components. Therefore, a classification in the construction year ranges, building types, and refurbishment status is performed. Based on this classification, the physical information is assigned to a building (e.g. the U-values of the outer surfaces, the ratio of walls and windows, or the average storey height). A more detailed overview of the library is given in Appendix C.

c. Usage preprocessing

With the information regarding the building function, the buildings are further categorized into different usages. Based on the usage of a building, the usage models are assigned to a building. This includes the information about the occupancy, the heating temperatures, the DHW usage, and the internal gains. An overview of the library is provided in Appendix B.

d. Systems preprocessing

The previously described preprocessing steps are needed to calculate the monthly energy demand for a building. This step is additionally needed to calculate the resulting primary energy and the CO2 emissions. Therefore, the energy systems of the energy systems and fuel library are assigned to the building. A more detailed description is provided in Section 7.4.3.

4. Refurbishment scenario maker

The refurbishment scenario maker is used to apply prediction scenarios to the city model. It is possible to specify the refurbishment rate for a refurbishment variant defined in the building physics library. Furthermore, the specific buildings that will be first renovated are defined (e.g. the oldest or the less efficient first).

5. Weather processor

The weather processor step imports the specified weather data set into the simulation environment. This prepares the data set for further use during the irradiance processing and the final energy demand calculation.

6. Irradiance processor

During the irradiation processing, the building’s surfaces are evaluated for tilt, area, and azimuth. This information is used to include the energy emitted from the sun on each surface. Furthermore, shadows and reflections from other objects are considered.

7. Monthly energy balance

With the information gathered during the previous workflow steps, the monthly energy demand for each building is calculated according to the DIN-V 18599. The results are written into a CSV file that contains the most important calculations and the calculated energy demand for space heating and DHW.

8. Primary energy and CO2 processor

In the final step, the needed primary energy and CO2 emissions caused by heating are calculated. This is achieved by combining the energy demand with the information concerning the energy system used for heat generation. The resulting calculation is explained in Section 7.4.3.

Eclipse IDE for Java

The previously described SimStadt workflow is extended through new workflow steps to include further information of a building from the 3DCityDB with the Energy ADE extension and store the calculated results in the database. Therefore, the Eclipse IDE version 4.14.0 for Java developers is used.

Liquid Studio

Liquid Studio 2020 is an advanced XML editor used to validate CityGML files against their schema definition. In addition, it is possible to open and edit large XML files. This is useful in this work, as other editors such as notepad++ are not capable of opening CityGML files larger than 3 GB. In this work, the Liquid Studio Community Edition version 18.0.05.8599 is used.

FME

Feature Manipulation Engine (FME) version 2020.0 is used to enrich the 3D city model in CityGML format with the Energy and Climate Atlas Excel file attributes and map the energy-related attributes to Energy ADE features and properties. [36]

HTML, NodeJS, and CesiumJS

To present the simulated and predicted results of the heating demand of buildings, a 3D web application is created. For server-side development, NodeJS is used. The buildings are visualized in a web browser using a Cesium 3D globe. Cesium is a JavaScript library suited for visualizing city models and styling them based on their attributes in 3D Tiles format. [37]

7.2 Data preparation

Before the city model can be used for the simulation, some data preparation must be completed. This is described in the following chapter.

7.2.1 CityGML validation

First, the CityGML files are validated against the schema definition to ensure that the file structure does not contain any errors. This is achieved using the Liquid Studio XML editor.

Another validation is done for the modelled geometry of the buildings. Therefore, the validation and healing tool CityDoctor is used. During the geometrical validation of 1,915 CityGML buildings, a total of 132 errors are detected. Figure 10 presents the overall distribution of geometrical errors in the CityGML file. Approximately half of the errors are caused by not-closed surfaces, and more than 50 errors are caused by self-intersections of polygons.

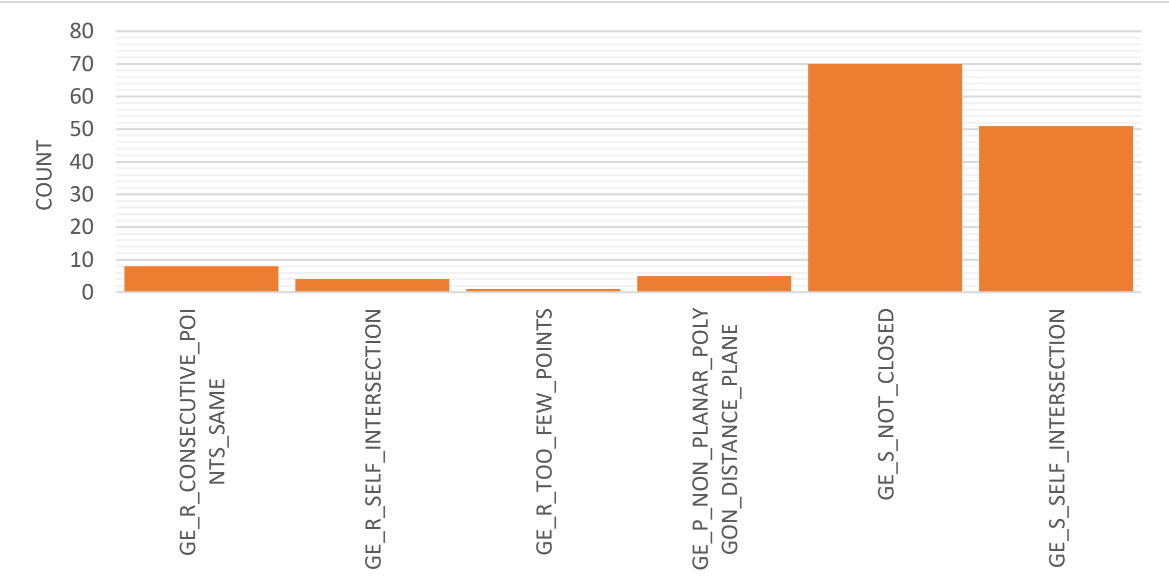


Figure 10: CityDoctor's validation statistics

A visual inspection of the faulty geometries reveals that the errors are rather small modelling problems. Figure 11 illustrates one example of a not-closed surface error of a CityGML building. The modelling error is not visible in the first view; only while more closely examining the polygon edges does the faulty geometry become visible. As seen in Figure 11 on the right, a small offset is located between the two roof surfaces. Furthermore, a wall polygon is pointing inside the building. This might not be necessary and could be deleted.

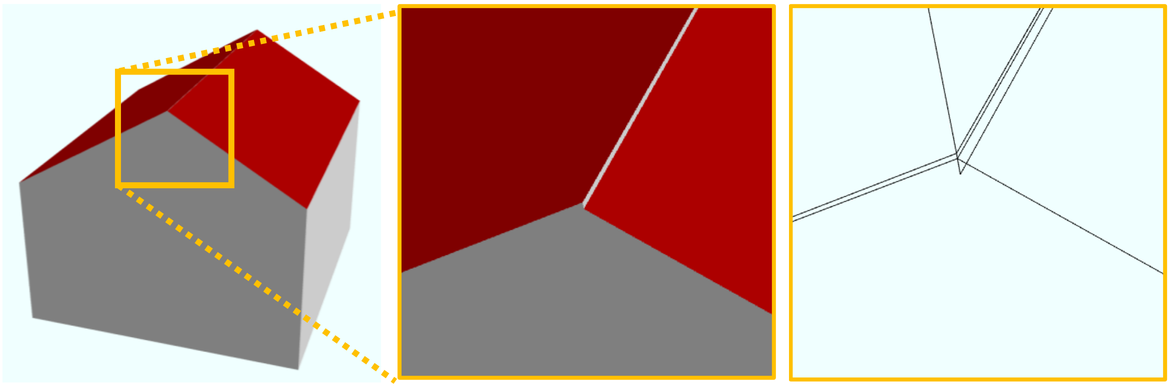


Figure 11: Faulty geometry of a CityGML building

For a subset of buildings with geometrical errors the building geometries are healed to investigate its impact for the simulation. This is done using a CityDoctor version which includes a functionality to fix faulty geometries. As an example, for 34 randomly picked buildings, the volume calculation before and after healing differ up to 0.06% and an averaged difference of -0.02 m³ is calculated.

For a subset of buildings with geometrical errors, the building geometries are healed to investigate their impact on the simulation. This is done using a CityDoctor version that allows for fixing faulty geometry. For example, for 34 randomly selected buildings, the volume calculations before and after healing differ by up to 0.06%, and an averaged difference of -0.02 m³ is calculated.

7.2.1 Weather data preparation

The measured weather observations provided by the Finnish Meteorological Institute described in Section 6.4 must be preprocessed to be used in SimStadt. The downloaded Excel files for temperature and radiation are restructured based on the TMY3 specification to meet the data format that can be imported in SimStadt. The provided hourly TMY3-file for Stuttgart is therefore used as a template, and the observations from the Helsinki weather measurement stations are arranged in the same manner. Another possibility is to use the Metenorm software for this purpose, which provides TMYs and real observation weather data that can be exported in several formats used in simulation environments. [38]

7.2.2 3DCityDB set-up and Energy ADE schema integration

In the first step, the vcDatabase, including the Importer/Exporter-Tool, is installed. Afterwards, a new PostgreSQL database with a PostGIS extension called "HelsinkiDB" is created. Prior to using the provided “CREATE_DB” script to initialize the 3DCityDB, the connection settings are specified in the “CONNECTION_DETAILS” script. With the completion of the configurations, the 3DCityDB is ready for use in the Importer/Exporter-Tool.

The ADE Manager Plugin of the Importer/Exporter-Tool can now be used to automatically derive the needed relational table structures based on the Energy ADE XML schema definition (XSD) file and register the ADE in the 3DCityDB. The ADE is now supported in the 3DCityDB, and the database schema citydb is extended by 33 tables prefixed with ng_ for Energy ADE features and relations.

However, the importer/exporter tool does not process ADE content in the CityGML files, since an additional Java library must be implemented. The Java library that extends the Importer/Exporter-Tool to handle Energy ADE content is provided for this work by virtualcitySYSTEMS. The ADE extension implements the Energy ADE KIT-profile version 1.0 used in this work. The characteristics of the Energy ADE KIT-profile compared with the general Energy ADE are provided in Appendix A.

After copying the Java library into the “ade-extensions” folder of the Importer/Exporter installation directory, a software restart is required. Additionally, the Energy ADE is now supported in the Importer/Exporter tool. Figure 12 presents the information concerning the registered ADE with the table prefix “ng_”, the used object class ids, and the Namespace specification. The number of object classes differs from the number of prefixed Energy ADE tables in the database, as some object classes use the same tables (e.g. “DHWFacilities” and “LightningFacilities” are both stored in the “ng_facilities” table).

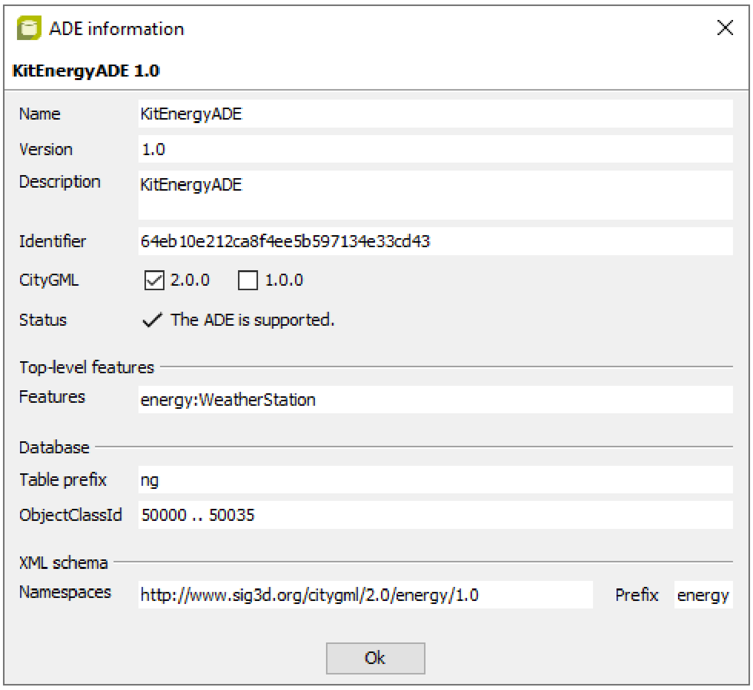


Figure 12: Energy ADE registration information in the 3DCityDB Importer/Exporter tool

7.3 Energy ADE integration

The enrichment of energy-relevant information in CityGML using the Energy ADE can be achieved in different ways. This work differentiates two possible approaches: a file-based approach and a database-based approach. Both are implemented using FME and end up in the same result. The CityGML buildings are enriched by energy-related information using the Energy ADE features and properties presented in Figure 13.

A building may have a *ThermalZone* with information regarding the heating and cooling status and the *floorArea* and *volume*. A *ThermalZone* may contain several *UsageZones*. For a *UsageZone*, the *usageZoneType* and *floorArea* are specified. Furthermore, a *UsageZone* may be occupied; therefore, the *numberOfOccupants* is stored for the *Occupants*. In addition, a building could also have information about the measured *EnergyDemand* for a specific *endUse* (e.g. for space heating, DHW, or both). The consumed energy is stored as *energyAmount* in a *TimeSeries*. The *floorArea* is an additional building property for which it is possible to specify the *net-* and *grossFloorArea* and the *energyReferenceArea*.

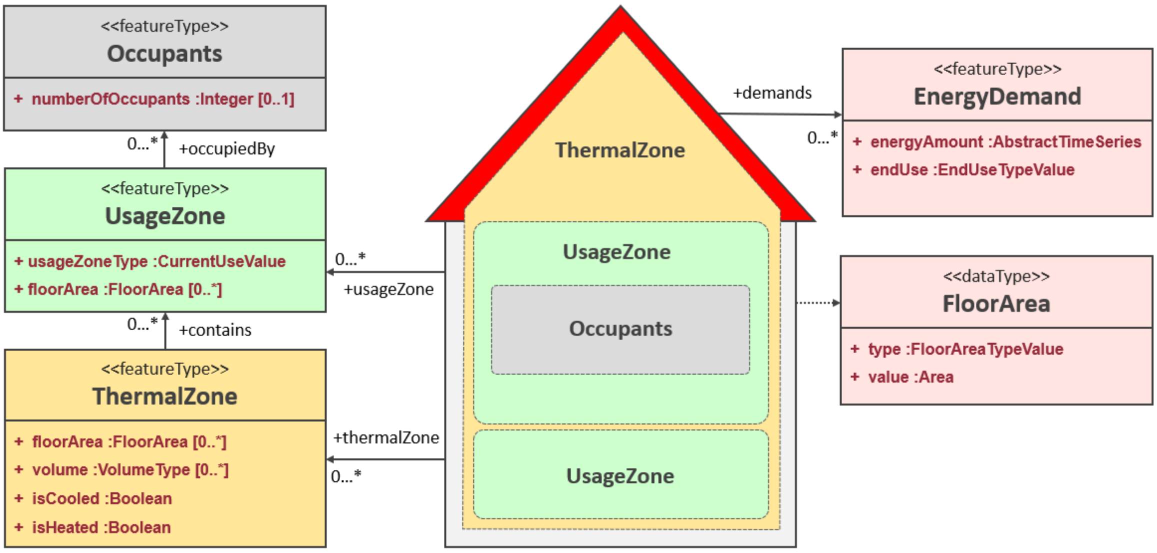


Figure 13: Simplified CityGML building with used Energy ADE information

7.3.1 File-based Energy ADE integration

The main concept of the file-based approach is to read a CityGML file and additional attribute information provided as Excel or CSV files, map the energy-related attributes to the Energy ADE features, and write the enriched 3D city model back to the CityGML file with additional Energy ADE information.

First, the 3D city model and the attribute information are imported into a new FME Workbench; therefore, a CityGML and an Excel reader are defined. The different data sets are joined by an identical identifier called "VTJ_PRT", which is the identification code for buildings. This is done using the *FeatureMerger* transformer. To access the needed Energy ADE feature types in the workbench, a new CityGML writer is created. Figure 14 presents the parameter setting while creating the CityGML writer. The Energy ADE schema file and the "*xsi:schemaLocation*" must be specified. The FME feature types are defined by selecting the "Import from Dataset" functionality. FME displays all available features if the data set specification is left empty.

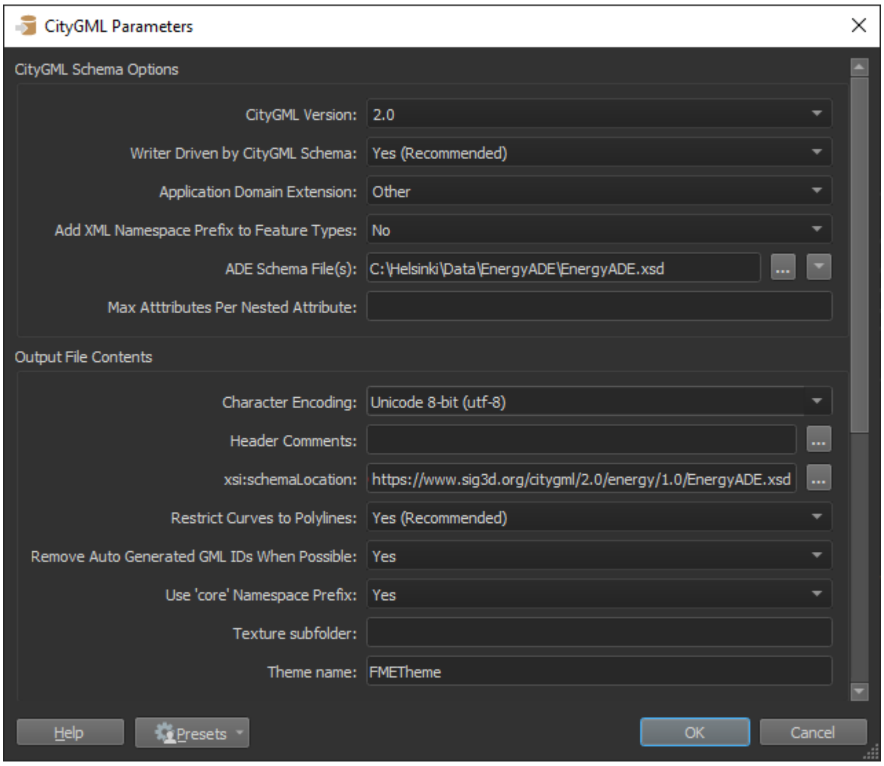


Figure 14: FME CityGML with Energy ADE Writer definition

As the Energy ADE features are now supported in the FME workbench, the CityGML and the additional information from the Excel files can be mapped to Energy ADE features or properties. This is explained for the examples *floorArea* and *EnergyDemand*.

Energy:FloorArea

For the mapping of the floor area attribute, the Energy ADE *floorArea* property of a building is used. Therefore, the AttributeManager transformer is used to create three new attributes. As presented in Table 1, the *floorArea* is defined in a list. In this example, the first list element with the information regarding the type, unit, and value itself is created.

Table 1: Definition of ab Energy ADE floorArea property in FME

Attribute	Value
energy_floor_area{0}.energy_floor_area_energy_value	@Value(total_floor_area_brm2)
energy_floor_area{0}.energy_floor_area_energy_type	grossFloorArea
energy_floor_area{0}.energy_floor_area_energy_value_units	m2

Energy:EnergyDemand

The creation of an *EnergyDemand* feature is more elaborate, as it is a separate city object linked to another city object. This process is visualized in Figure 15.

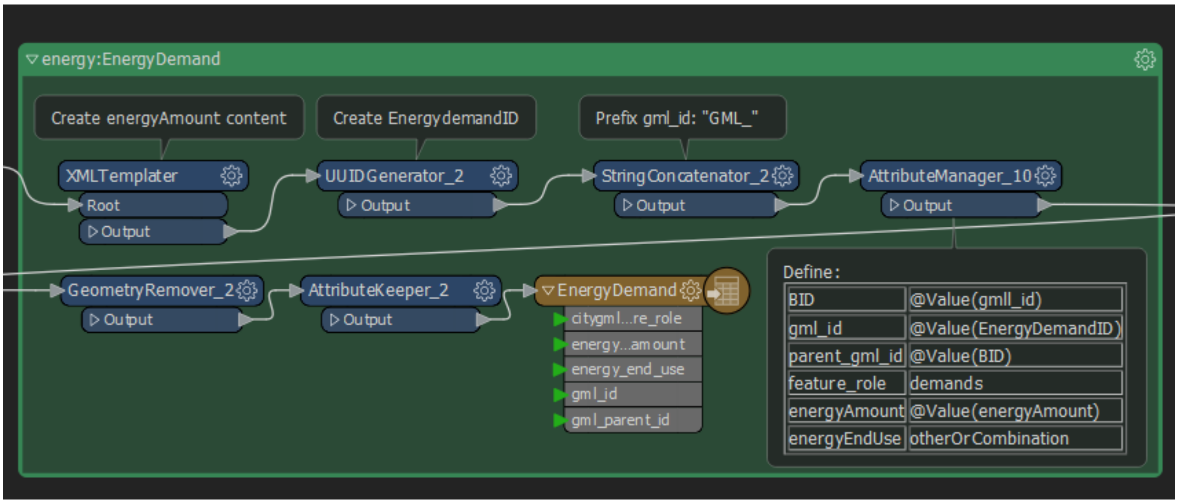


Figure 15: FME workflow for creating an EnergyDemand feature

In the first step, the XMLTemplater transformer is used to create the *EnergyAmount* content presented in Figure 16. This workaround is used as the *RegularTimeSeries* is no feature type in the FME workbench. Since a city object such as the *EnergyDemand* always requires a unique ID, the UUIDGenerator transformer is used to create this gml id, followed by the StringConcatenator transformer, which prefixes the created gml id with 'GML_'. With the use of the AttributeManager transformer, the gml id of *EnergyDemand* is set to be a newly defined id, the parent gml id is set to the building's gml id, and the CityGML feature role is set to "demands". Furthermore, the end use and the created *EnergyAmount* is specified. As a result, it is known that this *EnergyDemand object* relates to a building that consumes the specified energy for space heating and DHW preparation.

```
declare namespace gml="http://www.opengis.net/gml";
declare namespace energy="http://www.sig3d.org/citygml/2.0/energy/1.0";

<energy:RegularTimeSeries>
  <energy:variableProperties>
   <energy:TimeValuesProperties>
    <energy:acquisitionMethod>measurement</energy:acquisitionMethod>
    <energy:interpolationType>averageInSucceedingInterval</energy:interpolationType>
    <energy:source>Helsinki Energy and Climate Atlas</energy:source>
    <energy:thematicDescription>Space heating + DHW</energy:thematicDescription>
   </energy:TimeValuesProperties>
  </energy:variableProperties>
  <energy:temporalExtent>
   <gml:TimePeriod>
    <gml:beginPosition>2015-01-01T00:00:00</gml:beginPosition>
    <gml:endPosition>2018-12-31T23:00:00</gml:endPosition>
```

```
     </gml:TimePeriod>
    </energy:temporalExtent>
    <energy:timeInterval unit="year">1</energy:timeInterval>
    <energy:values uom="MWh">{fme:get-attribute("DH_2015")} {fme:get-attribute("DH_201
6")} {fme:get-attribute("DH_2017")} {fme:get-attribute("DH_2018")}</energy:values>
</energy:RegularTimeSeries>
```

Figure 16: EnergyAmount content of an EnergyDemand CityObject

The procedure for creating the *ThermalZone, UsageZone,* and *Occupants* objects for a building is the same as for the *EnergyDemand object.* A new gml id is created, the parent gml id is set to the upper level feature's gml id, and the feature role is defined. Furthermore, the properties of the object are specified.

The written CityGML file containing Energy ADE features and properties can now be imported into a 3DCityDB with the Energy ADE extension.

7.3.2 Database-based Energy ADE integration

The database-based approach aims to insert or update attribute information from Excel or CSV files directly into Energy ADE database tables in an existing 3DCityDB. Therefore, the city model must already be stored in a 3DCityDB with the Energy ADE extension.

In the first step, the FeatureReader transformer is used to import the existing city objects from the database to the FME workbench. In the "WHERE" condition of the reader, it is specified that only building or building part features are used. This is done by restricting the object class id to be 25, which is the object class id of a "BuildingPart", and 26, which represents the "Building" class.

Figure 17 illustrates the workflow of joining the city objects in a 3DCityDB with additional data in the FME workbench. The SQLExecutor is used to retrieve the building identification code "VTJ_PRT" from the generic attributes of a city object. The SQL statement presented in Figure 18 is executed, and the "VTJ_PRT" attribute is exposed in the SQLExecutor. The building code is now used to merge the city objects with additional attributes from Excel files.

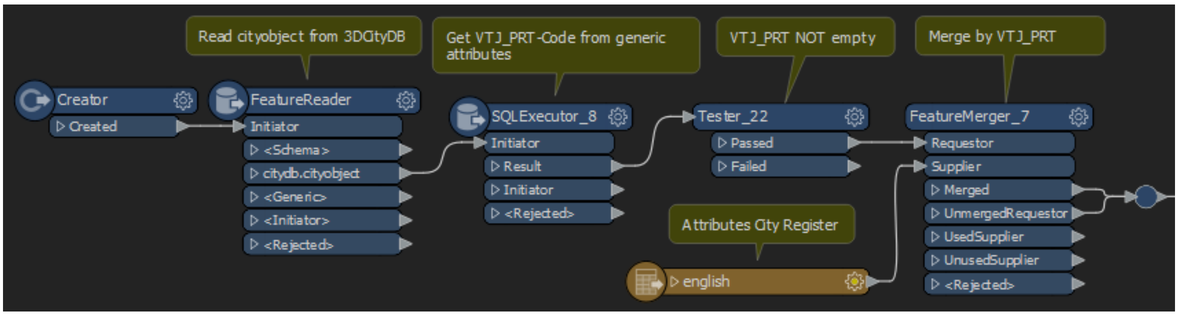


Figure 17: FME workflow for reading city objects from a 3DCityDB and join them by generic attribute

```sql
SELECT
    cityobject_genericattrib.strval AS "VTJ_PRT"
FROM
    citydb.cityobject_genericattrib
WHERE
    cityobject_genericattrib.cityobject_id = '@Value(id)' AND
    cityobject_genericattrib.attrname LIKE 'Rakennustunnus_(VTJ-PRT)';
```

Figure 18: SQL statement to retrieve the building code from the 3DCityDB

The workbench is now prepared for the mapping of attributes to Energy ADE properties or feature types. This is illustrated for the examples *floorArea* and *EnergyDemand*.

Energy:FloorArea

The process of creating the Energy ADE property *floorArea* for a building in FME is presented in Figure 19. First, the building is registered to the Energy ADE by inserting the city object id to the *ng_building* table. If the attribute regarding the floor area of a building is present, the information is inserted into the ng_floorarea table using the SQLExecutor transformer. The used SQL statement is provided in Figure 20.

The *floorArea*'s type and unit are defined, and for the id of the *floorArea*, the floorArea sequence is used. This ensures that each entry has a unique id. A *floorArea* can be linked to a *Building*, a *ThermalZone*, or a *UsageZone*. In this case, the *floorArea* relates to the in the first step registered ng_building, which represents the building feature.

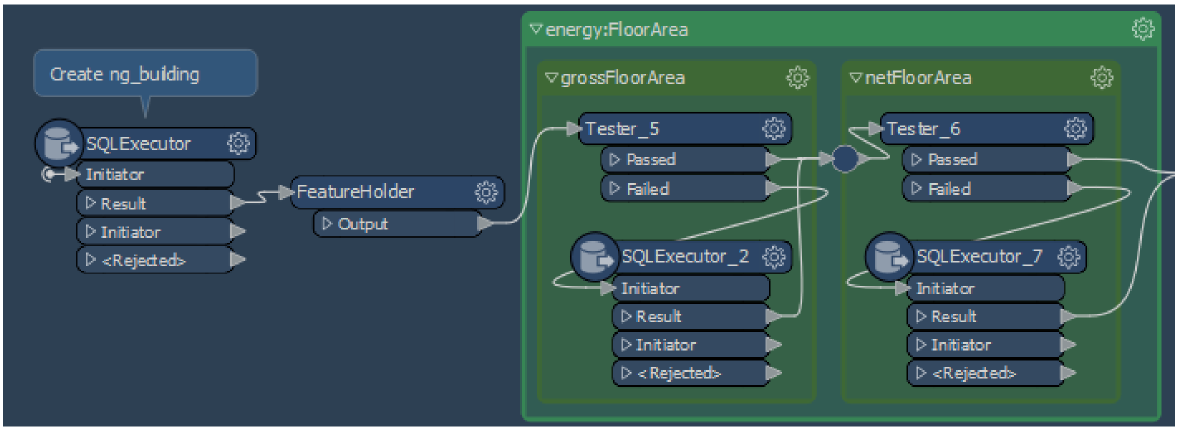


Figure 19: FME workflow to insert the Energy ADE floorArea property for a building

```
INSERT INTO
    citydb.ng_floorarea (id, building_floorarea_id, type, value, value_uom)
    SELECT
        (SELECT nextval('citydb.ng_floorarea_seq')),
        '@Value(ng_building_id)',
        'grossFloorArea',
        '@Value(total_floor_area_brm2_m2)',
        'm2'
    WHERE NOT EXISTS (SELECT 1 FROM citydb.ng_floorarea
        WHERE
            building_floorarea_id = '@Value(building_id)' AND
            type = 'grossFloorArea');
```

Figure 20: SQL statement to insert the floor area to the ng_floorarea table in a 3DCityDB with Energy ADE extension

Energy:EnergyDemand

To store the energy consumption of a building using the Energy ADE *EnergyDemand* object, multiple tables are conducted. As previously described, the *EnergyDemand* is not only a property of a feature type, such as the *floorArea*; rather, it is a separate class of the Energy ADE core module, which can be linked to a city object (e.g. a building). The UML notation for the *EnergyDemand* in relation to a city object is provided in Figure 21.

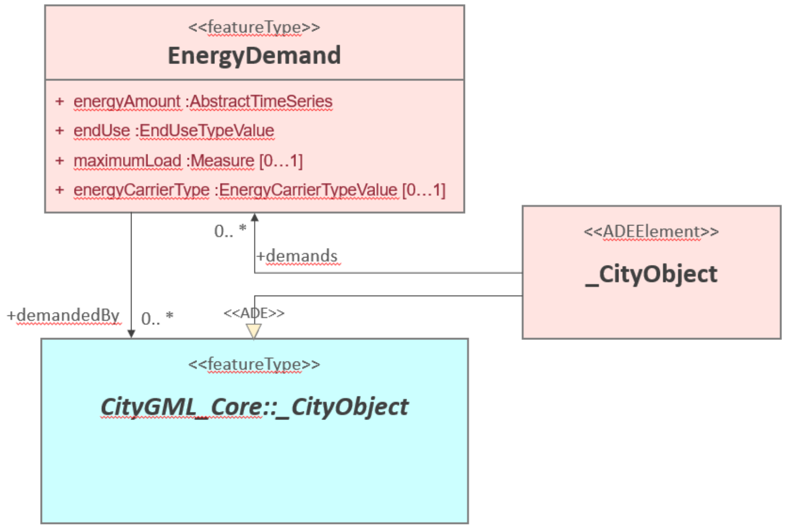


Figure 21: UML diagram of the EnergyDemand and its relations to a city object

The FME workflow for storing the measured energy consumption as Energy ADE *EnergyDemand* in the 3DCityDB is presented in Figure 22. The first step is to create an Energy ADE city object, which represents the feature that demands the energy. Therefore, the city object id of the building is inserted into the ng_cityobject table. Afterwards, a gml id is created for the *EnergyDemand*, and a new *EnergyDemand* is inserted into the "cityobject" table; the same is done for the *RegularTimeSeries*. The properties of the regular time series are then inserted into the ng_timeseries table, and the values of the energy demand are inserted into the ng_regulartimeseries table. At the end, the energy demand is linked by inserting the *EnergyDemand* city object id, the city object id of the building that demands the energy, and the id of the time series to the ng_energydemand table.

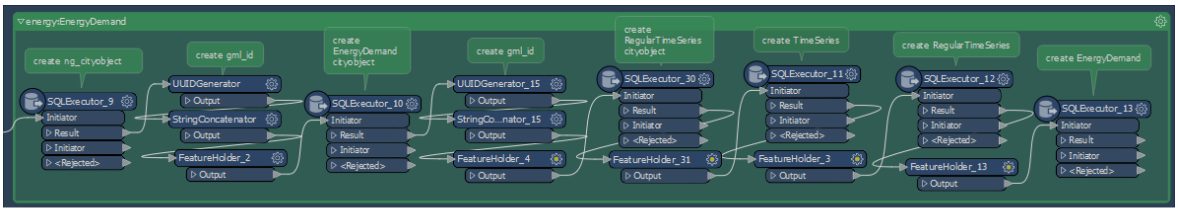


Figure 22: FME workflow to insert energy consumption information of a building to a 3DCityDB using the Energy ADE EnergyDemand object

As presented in Figure 23, the resulting *EnergyDemand* is now a feature type of a building in CityGML.

```
<energy:demands>
  <energy:EnergyDemand gml:id="GML_8298ce3d-5949-40d1-b60a-509c3e61fa0f">
    <gml:name>HeatDemand</gml:name>
    <energy:energyAmount>
      <energy:RegularTimeSeries gml:id="GML_c1f3f5a7-afdc-4619-8e0f-6d11802659ed">
```

```xml
        <gml:name>RegularTimeSeries</gml:name>
        <energy:variableProperties>
          <energy:TimeValuesProperties>
            <energy:acquisitionMethod>measurement</energy:acquisitionMethod>
            <energy:interpolationType>averageInSucceedingInterval</energy:interpolationType>
            <energy:source>Helsinki Energy and Climate Atlas</energy:source>
            <energy:thematicDescription>Space Heating and DHW</energy:thematicDescription>
          </energy:TimeValuesProperties>
        </energy:variableProperties>
        <energy:temporalExtent>
          <gml:TimePeriod>
            <gml:beginPosition>2015-01-01T00:00:00Z</gml:beginPosition>
            <gml:endPosition>2018-12-31T22:59:59Z</gml:endPosition>
          </gml:TimePeriod>
        </energy:temporalExtent>
        <energy:timeInterval unit="year">1.0</energy:timeInterval>
        <energy:values uom="MWh">117 114 120 108</energy:values>
      </energy:RegularTimeSeries>
    </energy:energyAmount>
    <energy:endUse>otherOrCombination</energy:endUse>
  </energy:EnergyDemand>
</energy:demands>
```

Figure 23: Resulting EnergyDemand object for the measured consumption data of a building

7.4 Definition of Finnish building libraries

In addition to the 3D city model itself, the building topologies for Helsinki are needed for the simulation of the heating demand and its CO2 emissions. Therefore, three SimStadt libraries are defined.

7.4.1 Building physics library

It is expected that the Finnish building stock differs from the German building stock in terms of the building constructions and their physical behavior. Therefore, a building library for Finland is created. Most European countries are participating in the EPISCOPE Tabula project. The aim of the project is to provide building topologies in a structured and comparable manner for different countries in the TABULA webtool. Based on the building topologies, the energy performance and the impact of refurbishments can be investigated. [39] As Finland is not part of the project, the information regarding the building topology in Finland must be obtained from other sources.

Here, the decree of the Ministry of the Environment on the energy certificate of a building provides the most detailed information available. [40]

Table 2 displays the classification of the Finnish building stock by the year of the building permit application. Based on this classification, the U-values for the construction parts of a building are available. The years used in the classification are shifted by about one year to assume the year of construction that is needed in the building physics library.

Table 2: U-values for different building parts for the Finnish building stock [translated: 40]

Building Part	**The year submitted of the building permit application**								
	-1969	**1969-**	**1976-**	**1978-**	**1985-**	**10/2003-**	**2008-**	**2010-**	**2012- 2018-**
Warm spaces									
Outer wall	0.81	0.81	0.7	0.35	0.28	0.25	0.24	0.17*	0.17*
Ground-bearing slab	0.47	0.47	0.40	0.40	0.36	0.25	0.24	0.16	0.16
Ground floor of crawl space	0.47	0.47	0.40	0.40	0.40	0.20	0.20	0.17	0.17
Ground floor adjoining the open air	0.35	0.35	0.35	0.29	0.22	0.16	0.16	0.09	0.09
Attic floor	0.47	0.47	0.35	0.29	0.22	0.16	0.15	0.09	0.09
Door	2.2	2.2	1.4	1.4	1.4	1.4	1.4	1.0	1.0
Window	2.8	2.8	2.1	2.1	2.1	1.4	1.4	1.0	1.0

In addition to the U-values of the building parts, the air leakage rate for the Finnish building stock is given in the same classification. Here, the air leakage rate is specified with the n50 number, which describes the airtightness of the building envelope at a reference pressure of 50 Pascal. The n50 value cannot be directly used in the building physics library. The natural air exchange is modelled in SimStadt using the annual infiltration rate in vol/h. Jokisalo et al. [41] analyzed the relationship between the air leakage rate and the infiltration rate for energy simulation in the Finnish building stock and concluded that the infiltration rate can be estimated by dividing n50 by 25. The resulting infiltration rates for the classification of the building stock in Finland are presented in Table 3.

Table 3: Calculated infiltration rate for the Finnish building stock

Building permit	**-1969**	**1969-**	**1976-**	**1978-**	**1985-**	**10/2003-**	**2008-**	**2010-**	**2012- 2018-**
Infiltration [vol/h]	0.24	0.24	0.24	0.24	0.24	0.16	0.16	0.16	0.08

A further classification of different building types is done using the average storey height of a building. This information is used to calculate the heated area of a building according to the DIN 4108-6 standard, which is achieved by relating the average floor height to the heated volume of a building. This, in turn is estimated by the volume of the geometry, the footprint area, and the height of a building.

SimStadt classifies a building depending on its geometrical properties. The German building types are adopted for the classification of the Finnish building stock. These are single-family houses, terraced houses, multi-family houses, big multi-family houses, and high towers.

For single-family and terraced houses, the average storey height is assumed to be 2.6 m. For the other types, the average storey height is assumed to be 2.8 m when the building was built before 1985; beyond this year, an average storey height of 3 m is assumed. [42, 43]

The Finnish building library is created based on the described information. An example of the resulting construction year range classification and the defined properties is provided in Appendix D.

Definition of refurbishment variants

A refurbishment variant aims to model the physical behavior of a renovated building, which can be used for two purposes. First, it allows for including already-executed renovations in the building stock; thus, the energy demand of a renovated building can also be calculated. Furthermore, renovation variants can be used to predict the energy demand of a building when a renovation is done.

This work differentiates two types of renovations:

1. Typical refurbishments of building parts

The needed U-values for refurbished buildings are not available in the Finnish building code. Under the assumption that the Finnish building stock does not significantly differ from the Swedish one in terms of U-values, the values for the Swedish building topology are adopted to represent refurbished buildings in Finland. To verify the assumption, the U-values of the Finnish building regulations are compared against the Swedish and German building topology provided by the EPISCOPE Tabula project. [39] The comparison for two construction year ranges is given in Appendix E.

The assumption makes it possible to use the information of how far the U-value of a building part is reduced when a renovation has been performed. Therefore, the medium refurbished category of the Swedish building topology is used to create a refurbishment variant for each building part and a combination of them. The created refurbishment variants are listed in Figure 24.

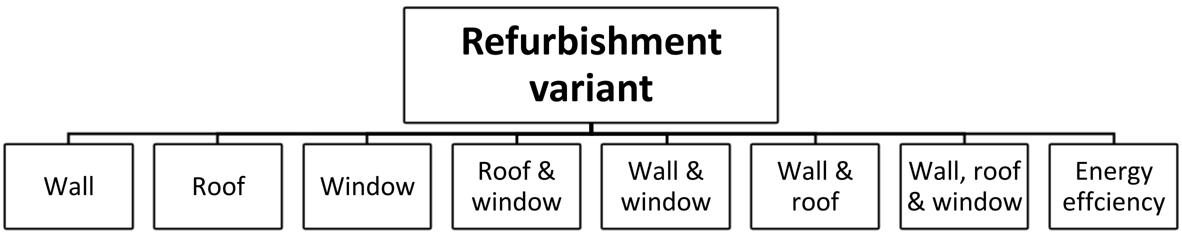


Figure 24: Overview of the defined refurbishment variants in the building physics library

1. Energy efficiency refurbishments according to the Finnish building code.

The energy efficiency refurbishment variant represents the implementation of the EU directive on the energy performance of buildings, which forces members of the European Union to improve the energy efficiency of buildings during renovations. [18]

The implementation of this in Finland is done through the "Ministry of the Environment decree on improving the energy performance of buildings undergoing renovation and alternation". [44] The following requirements are established for renovations of buildings that aim to improve the energy performance:

"1) External walls: The original U-value x 0.5, but not higher than 0.17 W/(m2 K). [...]

2) Roofs: The original U-value x 0.5, but not higher than 0.09 W/(m2 K). [...]

3) Floors: The energy performance is improved as far as possible.

4) The U-value of new windows and external doors must be 1.0 W/(m2 K) or better. [...]" [44, section 4]

The regulation is used to create the energy efficiency refurbishment variant. Therefore, the original defined U-vales are modified accordingly. As no values are specified for the ground of the building, the U-values for the advanced refurbishment type of the Swedish building topology are adopted. [39] The resulting U-values are presented in Table 4.

Table 4: U-values of the energy efficiency refurbishment variant

From	To	Wall	Roof	Ground	Window
-	-	W/K.m²	W/K.m²	W/K.m²	W/K.m²
-	1969	0.17	0.09	0.21	t
1970	1976	0.17	0.09	0.23	1
1977	1978	0.17	0.09	0.2	1
1979	1985	0.17	0.09	0.2	1
1986	2003	0.14	0.09	0.18	1
2004	2008	0.125	0.08	0.18	1
2009	2010	0.12	0.075	0.18	1
2011	2012	0.085	0.045	0.18	1
2013	-	0.085	0.045	0.18	1
Source		[40, 44]	[40, 44]	[39]	[44]

7.4.2 Building usage library

The building usage library further categorizes a building by its function (e.g. residential, office, hotel, or healthcare). For each usage type, the parameters needed for the energy demand calculation are specified; these include the occupancy, heating temperatures and schedules, DHW usages, or ventilation. An overview of the different usage types and the parameters is provided in Appendix B.

The created building physics library is based on the German usage library, which in turn is based on the DIN-18599 standard. Therefore, only numerical values available for Finland are modified according to the "Decree of the Ministry of the Environment on the energy efficiency of buildings". [45]

Occupancy

The occupancy module describes how many persons per square meter are typically in a building or usage zone when it is occupied. The usage days and hours per day are adopted from the German usage library. The personal density per usage type is listed in Table 5.

Table 5: Occupancy density in the Finnish building usage library

Usage type	Occupancy density [pers./m²]
Single-family house	1/43
Multi-family house	1/28
Office and administration	1/17
Education	1/5
Event location	1/10*
Hall	1/3*
Health care	1/11
Hotel	1/21
Industry	1/20*
Restaurant	1/1.2*
Retail	1/5*
Sport location	1/17
Non-heated	0*

* adopted from German usage library

Set point temperature

The set point temperature is used to define the heating schedules of a building or usage zone and represents the typical desired air temperature. According to the DIN-18599-10, German residential buildings are heated between 6 a.m. and 11 p.m. to 20 °C, whereas Finnish residences are heated to 21 °C. [19, 45] The set point temperatures for the different usage types are listed in Table 6.

Table 6: Set point temperatures and DHW consumption in the Finnish usage library

Usage type	Set point temperature [°C]	DHW consumption [l/person/day]
Residential	21	50
Office and administration	21	4.7
Education	21	2.6
Event location	21*	-*
Hall	21*	-*
Health care	22	15.7
Hotel	21	37.8
Industry	18	44.3
Restaurant	21*	27.7*
Retail	21*	24.6*
Sport location	18	15.7
Non-heated	-	-

* adopted from German usage library

DHW consumption

The cold-water temperature in Finland is defined to be 5 °C colder compared with Germany, namely 5 °C. The desired preparation temperature is defined to be 55 °C. Furthermore, the consumption of DHW per usage type is specified in Table 6. Based on the consumption, the occupancy of a usage zone, and its area, the energy demand for the DHW preparation of a building can be calculated.

Usage code mapping

The simulation environment SimStadt uses the function attribute of a CityGML building to access the building usage library and its information. The usage library function ID of a usage type is specified by the German "ALKIS"-code, which is commonly used to represent building usage. As Finland uses a different code space for its building usage, a mapping must be defined.

In the Helsinki Energy and Climate Atlas, more than 70 so-called "wide usage class" codes are available. For each, the most likely ALKIS code is defined. Some examples for commonly used building functions are presented in Table 7. The actual mapping is achieved by creating an XML file which specifies the related ALKIS code for each code. The file is then used in the simulation environment SimStadt to access the parameters of the usage library by the Finnish wide usage class code.

Table 7: Examples of the ALKIS function code mapping

Finnish description translated	Wide-usage-class	ALKIS code	German description translated
One-dwelling houses	11	1010	Dwelling house
Two-dwelling houses	12	1010	Dwelling house
Other detached houses	13	1010	Dwelling house
Other apartment houses	39	1010	Dwelling house
Shop halls	111	2050	Retail building
Hotels, motels, guest houses, spa hotels	121	2071	Hotel, motel, and guest house
Restaurants, canteens, and bars	141	2081	Restaurant
Office buildings	151	2020	Office building
Railway and bus stations, airport, and port terminals	161	2412	Waiting hall
Vehicle protection and maintenance buildings	162	2463	Garage
...	...	...	...

Especially in urban areas, a building may have a mixed usage (e.g. a shop in the basement floor and apartments in the storeys above). Such mixed usages are considered by ALKIS codes that represent multi-usages. In this example, the ALKIS code 1123 describes a residential building that also includes one or more retail facilities. Since the Finnish wide usage codes represent only a single usage, the information regarding the floor area per usage type is used for mapping double usages. The information about the usage areas is obtained from the Helsinki city register data. For the example stated above, if the business premises area exists for a residential building, the function code is defined to be 39111, which is mapped to the ALKIS code 1123. In this case, SimStadt assumes that the ground floor is used for retail purposes, while the other floors are used for residential purposes.

Another possibility of including multi-usages for buildings is to use the Energy ADE *UsageZones* created in Section 7.3. As described in Section 7.5, the created *UsageZones* are then imported into SimStadt and assigned to a SimStadt building.

7.4.3 Energy systems and fuel library

The predefined energy systems and fuel library provide a list of systems that are used for space heating, space cooling, or DHW preparation. For each of these operation modes, the yearly global efficiency is specified. Furthermore, a system always requires fuel to generate energy. Fuel is defined with its primary energy factor and CO2 emission factor. Two examples for an energy system in SimStadt are provided in Table 8.

Table 8: Energy systems and fuel library examples for electric radiators and oil boiler

System	Electric radiators		Oil boiler	
ID	7		2	
Name	Electric radiators		Oil boiler	
Description	Direct electric resistance heating		Fuel oil fired boiler	
Nominal efficiency	1		0.85	
Efficiency unit	Efficiency		Efficiency low heating value	
Fuel	**ID**	5	**ID**	2
	description	electricity	**description**	oil
	Primary energy factor	2.5	**Primary energy factor**	1.1
	CO2eq emission factor	0.521	**CO2eq emission factor**	0.318
Operation modes	**End use**	Space heating	**End use**	Space heating
	Yearly global efficiency	1	**Yearly global efficiency**	0.75
Operation modes	**End use**	DHW	**End use**	DHW
	Yearly global efficiency	-	**Yearly global efficiency**	0.75

SimStadt uses this information to calculate the CO2 emissions and primary energy required for each end use. For example, the CO2 emissions for space heating are calculated in SimStadt using the following formula:

$$\text{CO2 emission}_{\text{SH}} = \frac{\text{Energy demand}_{\text{SH}}\ [\text{kWh}]}{\text{yearly global efficiency}\ [-]} \cdot \text{CO2 emission factor}\ [\frac{\text{kgCO2}}{\text{kWh}}]$$

One possibility of assigning an energy system to a building in SimStadt is to use the information about the energy source of a building directly. The Helsinki Energy and Climate Atlas contains such information regarding the energy source of a building. Figure 25 displays the distribution of the energy sources. Unfortunately, the energy source specified in the Helsinki Energy and Climate Atlas represents the first-used energy source when the building was constructed. Updates for the energy source information are in progress but are not yet available.

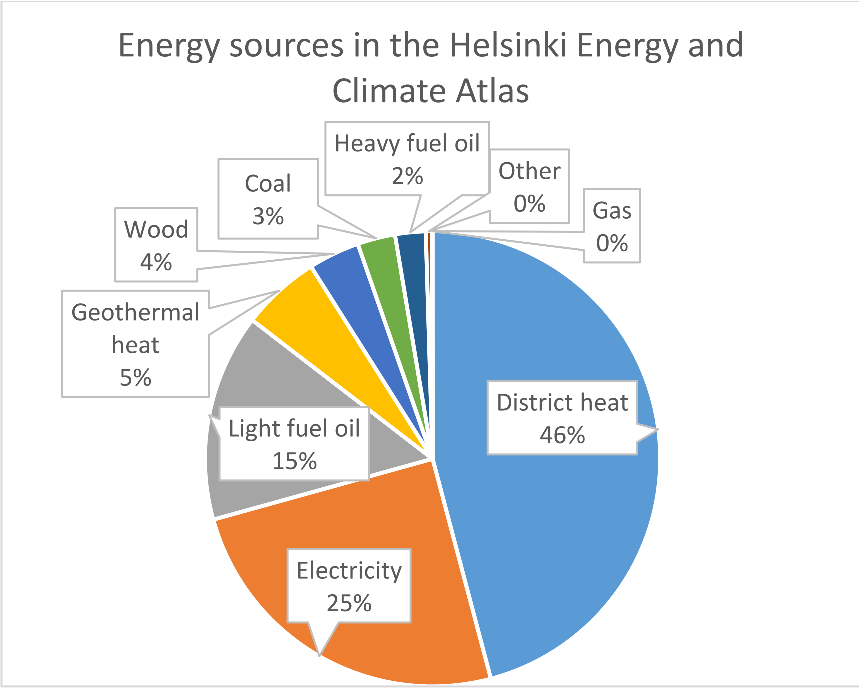


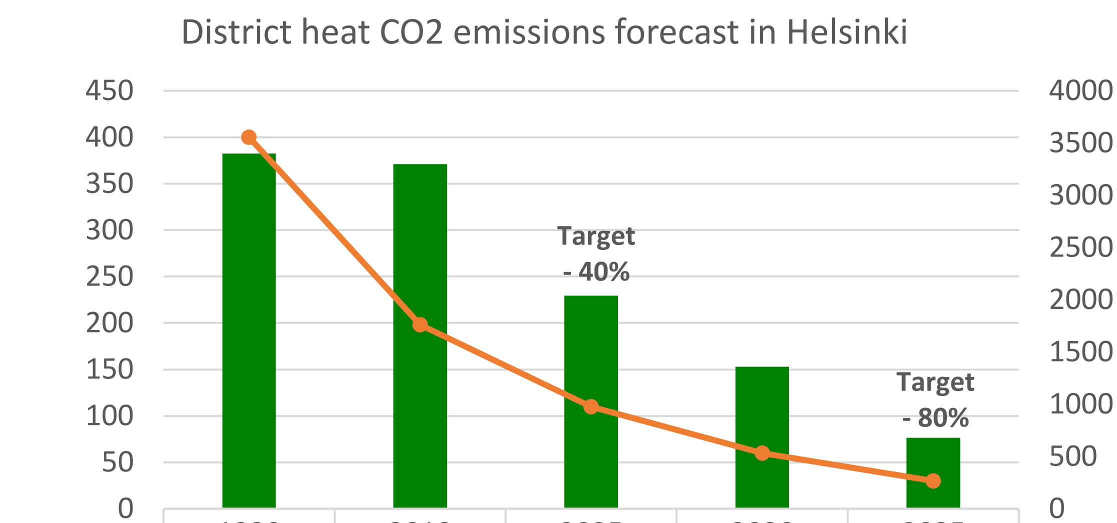
Figure 25: Distribution of energy sources in the Helsinki Energy and Climate Atlas [2]

Another possibility is to assign the energy system to a building in SimStadt via an assessment scenario. An assessment scenario uses the global distribution of energy systems in the city and assigns it to a building by chance.

Overall, 92% of the buildings in Helsinki are connected to the district heat system, while the remaining 8% of the heating energy is shared between electric and oil heating (4% for both). [46] Assigning this distribution to a building by chance may cause a minor error, which is accepted in this work.

As the Helsinki district heat system is a unique energy system that uses serveral types of energy sources, it must be defined first.

The yearly global efficiency for space heating and DHW preparation of the Helsinki district heat system is defined to be 0.9. [47] and [48] Each year, the provider Helen publishes the calculated CO2 emission factors for the production of district heat, electricity, and district cooling. Additionally, Helen published the expected CO2 emission factors for up to 2035. [49] As illustrated in Figure 26, the CO2 emission factor of the Helen district heating network is expected to decrease significantly over the next 15 years. This will be achieved by shifting to more renewable energy sources and significantly reducing the use of coal. [25]



	1990	2019	2025	2030	2035
kt	3400	3300	2040	1360	680
g/kWh	400	198	110	60	30

Figure 26: Expected development of the Helen district heat network CO2 emissions [adapted from: 49]

To use the Helen district heat network as an energy system in SimStadt for the prediction of CO2 emissions caused by heating, four new energy systems are defined in the Energy System and Fuel library. One of the energy systems represents the state of the art in 2019 with a CO2 emission factor of 0.198 kgCO2/kWh, while the three others are for the years 2025, 2030, and 2035 (0.11, 0.06, and 0.03 kgCO2/kWh). Even though Helen aims to be CO2 neutral by 2050, the CO2 emission prediction in this work uses the CO2 emission factors expected for 2035 for simulations later than 2035.

7.5 SimStadt 3DCityDB with Energy ADE connection

To use the energy-relevant information of the 3D city model that is stored in generic attributes or Energy ADE features and properties, a new SimStadt workflow with additional workflow steps is created. First, the possible information that can be retrieved from the database is presented. For the sake of clarity, the implementation process is then described with one example.

As presented in Figure 27, the new workflow step allows for requesting the following information from the database and assigning it to a building.

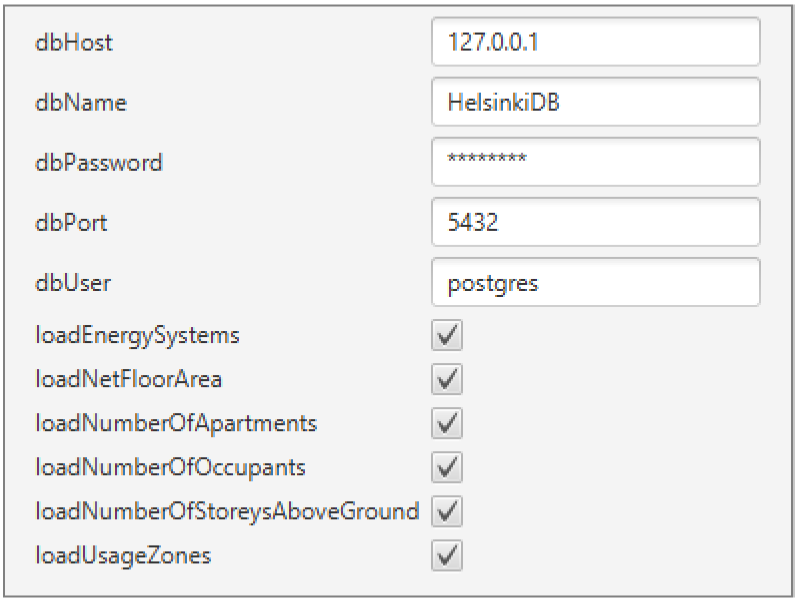


Figure 27: GUI parameters of the “3DCityDB with Energy ADE connection” workflow step

Energy systems

Allows for using the energy source attribute to assign the energy system type to a building. The Energy ADE Energy Systems module is not included in the Energy ADE Kit-profile; thus, the energy systems have been not modelled in the 3DCityDB. Nevertheless, the generic attribute energy source can be used to map the energy system from the energy systems and fuel library to a building.

Net floor area

Uses the Energy ADE *floorArea* of type “netFloorArea” to set the heated area for the simulation. If not present, the heated area is calculated by the average storey height and the heated volume during the building physics preprocessing. The heated volume is calculated by the height of the building, the footprint area, and the calculated volume of the geometry.

Number of apartments

The number of apartments is typically estimated during the usage preprocessing. For the calculation, the heated area, building type, and function are used. This method loads the information from the 3DCityDB, so SimStadt does not need to estimate it.

Number of occupants

As with the number of apartments, the number of occupants is typically estimated during the usage preprocessing. This method uses the information regarding the number of occupants stored in the Energy ADE Occupants object from the 3DCityDB with Energy ADE. The number of occupants is a property of the Energy ADE *Occupants* feature related to a *UsageZone*. The *UsageZone* is related to a *ThermalZone*, which in turn relates to a CityGML *_AbstractBuilding*.

Number of storeys above ground

The number of storeys is a property of a CityGML *_AbstractBuilding* and is divided into the number of storeys above ground and the number of storeys below ground. If the property of the number of storeys above ground is present for a building, it is used for the energy demand calculations; otherwise, it is assessed during the physics preprocessing by the average storey height and the geometrical height of a building.

As the CityGML buildings in Helsinki are not geometrically modelled with the storeys below ground, the information is omitted from the simulation. Otherwise, it causes incorrect calculations during the building physics preprocessing, which in turn influence the energy demand calculations.

Usage zones

As described in Section 7.4.2, SimStadt supports only two usage types per building. These can be assigned to a building by the representative ALKIS codes. For example, if the ALKIS function code 1152 is specified, it is assumed that the basement floor represents a commercial usage zone, while the other floors represent a residential usage zone.

The new functionality enables the use of multiple usage types for a building. Therefore, the in Section 7.3 created Energy ADE *UsageZones* of a *_AbstractBuilding*'s *ThermalZone* are retrieved from the database and are set to be the usage zones of a "SimStadtBuilding".

7.5.1 Creation of a new SimStadt workflow

To ensure that the already existing workflows are not influenced by the additional workflow step, a new workflow must first be created. In this case, the "Environmental Analysis with Refurbishment Strategy" is used as a template. A description of the workflow and its workflow steps is provided in Section 7.1.

To develop a new SimStadt workflow, a new Java class is created. This class is extended by the SimStadt "WorkflowProvider" class, which adds the required methods to the newly created SimStadt workflow. First, the workflow name displayed to the user is defined in the "workflowName" method. In this case, the name is set to 'Environmental Analysis with Refurbishment Strategy and 3DCityDB Connection'. Furthermore, the "workflowDescription" and "workflowVendor" methods are defined. Additionally, the "isExperimental" method specifies whether the workflow should be considered experimental. The actual workflow with its workflow steps is then created in the "buildWorkflow" method. To keep the main functionalities of the original "Environmental Analysis with Refurbishment Strategy" workflow, its workflow steps are copied. The workflow is then prepared for modifications. The later-created workflow step is added to the "Preprocessing" workflow step, as presented in Figure 28.

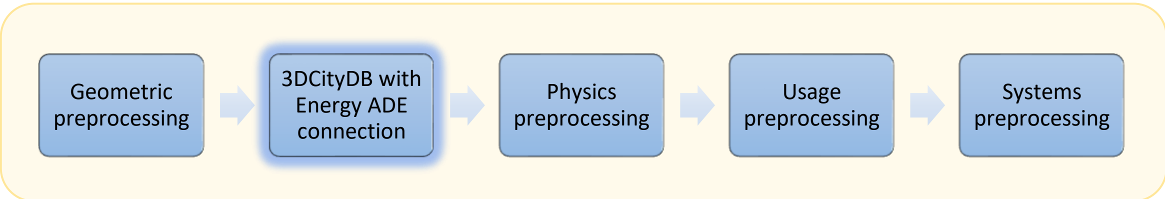


Figure 28: SimStadt Preprocessing workflow step with the new created workflow step

7.5.2 Creating the workflow step for the new workflow

The actual workflow step is built by creating another class, "CityDBEnergyADEConnection", which extends the class "WorkflowStep". While extending the abstract class "WorkflowStep", three object types must be specified: "SimStadtBuilding" for input and output and "SimStadtModel" for the context type.

Additionally, the extended class requires that three methods be implemented, namely “stream”, “displayResult”, and “resetResult”. The “displayResult” and “resetResult” methods can be used for graphical user interface (GUI) changes, which are not needed in this case. Most important for this work is the “stream” method: In this function, the 3DCityDB is queried for additional information about buildings, and the information for a “SimStadtBuilding” is set. The procedure is now described for the example of the Energy ADE *UsageZones*.

To access the database with SimStadt, the PostgreSQL JDBC driver is needed. Therefore, the PostgreSQL JAR file in version 42.2.12 is added to the referenced libraries. To specify the database connection credentials in the GUI, the connection parameters are represented as private String variables. The possible user parameters are presented in Figure 27. Through the addition of getters and setters for the user variables, SimStadt automatically adds the input fields to the GUI. Additionally, for each created loading functionality, a Boolean variable is specified. This is used to check whether a property should be retrieved from the database.

The connection to the database itself is achieved by putting the GUI-specified connection parameters together to a connection URL. As presented Figure 29 line 2, it consists of the path to the database, the username, and the password. Afterwards, the connection to the database is established.

```
1.  // Prepare DB connection url
2.  String url = "jdbc:postgresql://" + dbHost + ":" + dbPort+ "/" + dbName + "?user=" +
                 dbUser + "&password=" + dbPassword + "&ssl=false";
3.
4.  // connect to DB
5.  conn = DriverManager.getConnection(url);
6.
7.  // GUI checkbox checked?
8.  if (isLoadUsageZones()) {
9.      //load energy:UsageZones from 3DCityDB
10.     loadUsageZones();
11. }
```

Figure 29: Database connection specifications in Java

When the corresponding checkbox in the GUI is checked, the Energy ADE *UsageZones* is requested from the 3DCityDB. The SQL statement displayed in Figure 30 lines 2–12 is used to retrieve the building’s gml id, usage zone type, and floor area for all *UsageZone*s in the database. After the definition of the SQL string, the statement is prepared and executed.

```java
// Build the SQL statement
String SQL = "SELECT cityobject.gmlid,ng_usagezone.usagezonetype,ng_floorarea.value"
            + " FROM"
                + " citydb.building, citydb.cityobject, citydb.ng_building,"
                + " citydb.ng_usagezone, citydb.ng_floorarea"
            + " WHERE"
                + " building.id = cityobject.id"
                + " AND building.id = ng_building.id"
                + " AND ng_usagezone.building_usagezone_id = ng_building.id"
                + " AND ng_floorarea.usagezone_floorarea_id = ng_usagezone.id"
            + " ORDER BY"
                + " cityobject.gmlid ASC, ng_floorarea.value DESC";

// Prepare the SQL statement and execute
PreparedStatement pstmt = conn.prepareStatement(SQL);
ResultSet rs = pstmt.executeQuery();
```

Figure 30: SQL statement to retrieve the usage zones of all buildings from the database

To utilize the *UsageZones* of a building in SimStadt, the result set of the SQL query is looped. As presented in Figure 31, at first, the gml id of the previous result is set to the old gml id. This is done to check whether the result is still relating to the same building. In both cases, a new Energy ADE *UsageZone* is created, and its type and area are set. Then, it is checked whether the *UsageZone* is still relating to the same building as the previous. If not, the *UsageZone* is added to a new list of *UsageZones*. If the result relates to same building as the previous entry, the zone is added to the last list of *UsageZones*. At the end, the gml id with its *UsageZoneList* is added to a HashMap.

```java
// Loop over the results
while (rs.next()) {
    oldgmlid = gmlid;
    gmlid = rs.getString(1);
    // Create a Energy ADE UsageZone, set type and area
    uz = new UsageZone();
    uz.setUsageType(rs.getString(2));
    uz.setZoneArea(rs.getDouble(3));

    // Store all usageZones for a single building in a UsageZoneList
    // Check if building gml id changed
    if (!oldgmlid.equals(gmlid)) {
        // Create a new UsageZoneList
        uzList = new UsageZoneList();
        // Add the UsageZone to the UsageZoneList
        uzList.getUsageZone().add(uz);
    } else {
        // Same building, but new UsageZone
        uzList.getUsageZone().add(uz);
    }
    // Store the usageZoneList for a building in the UsageZoneList HashMap
    // will be overwritten if duplicate gml id
    // This ensures only one UsageZone List with all UsageZones for a building
    uzLists.put(gmlid, uzList);
}
```

Figure 31: Processing the SQL result and putting the usage zones of all buildings into a HashMap

To execute the SQL statement only once per CityGML model, all *UsageZones* are retrieved at the same time and temporarily stored in the HashMap. The buildings are then looped at the end of the workflow step's stream function. If the building's gml id is present in the HashMap, the list of *UsageZones* is assigned to the "SimStadtBuilding". This is presented in Figure 32.

```
// set UsageZones if present
if (uzLists.containsKey(simStadtBuilding.getGmlId())) {
    simStadtBuilding.setUsageZoneList(uzLists.get(gmlid));
}
```

Figure 32: Set the usage zone list for a SimStadtBuilding

7.6 SimStadt 3DCityDB with Energy ADE writer

As with the reading of Energy ADE information, the results of the simulations are written back to the 3DCityDB using Energy ADE features and properties. Additionally, for this purpose, a new workflow step is created. The connection to the database is established as was done for the reading workflow step described above.

As visualized in Figure 33, in addition to the database credentials, the simulation year can be specified; it is set to the current year by default. If a prediction scenario is simulated, the year can be specified to the target year. This allows for storing more than one Energy ADE *EnergyDemand* feature for a building.

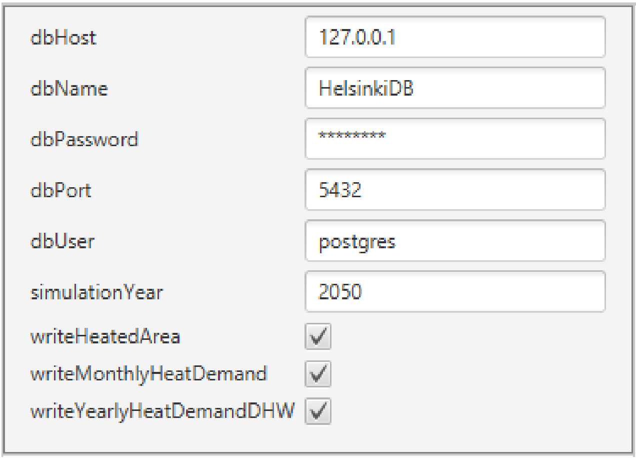


Figure 33: GUI parameters for writing simulations results to the 3DCityDB

Additionally, it is possible to select which results should be written to the database: in this case, the heated area as Energy ADE *floorArea* property of type "energyReferenceArea", the monthly energy demand for space heating, and the yearly energy demand for space heating and DHW. For both, a new Energy ADE *EnergyDemand* feature is created. The used Energy ADE features and properties are presented in Figure 34, and the used properties are highlighted in bold. For the sake of clarity, the data types and enumerations are not displayed.

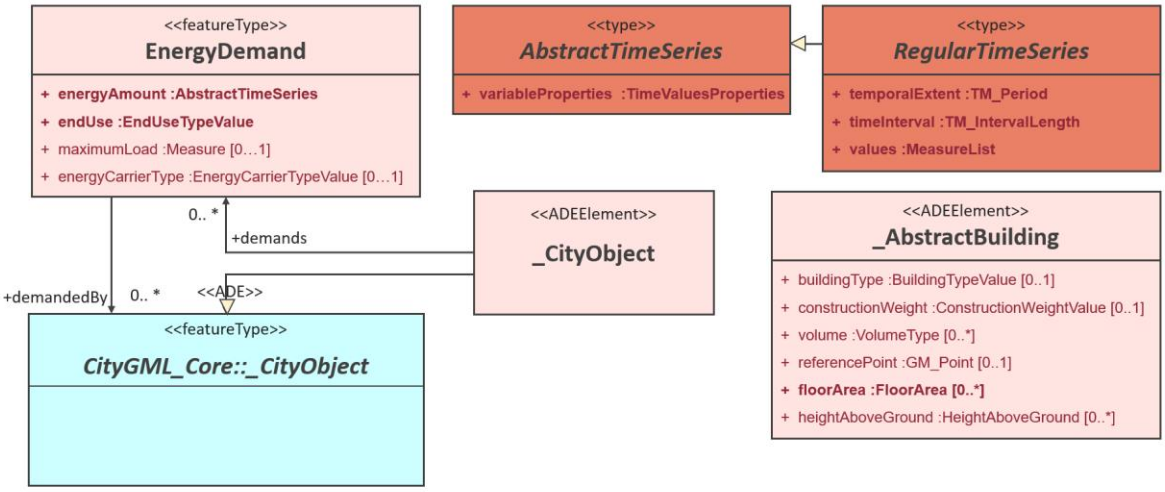


Figure 34: UML notation for the used Energy ADE features and properties [adapted from: 16]

Before a new *EnergyDemand* feature is created, it is checked whether simulation results are already present for a particular year. In this case, the results are updated rather than newly created. The process of inserting simulation results into the database is described in the example of the monthly space heating demand, presented in Figure 35.

```java
private void insertMonEnergyDemand(String gmlid, double[] SH) throws SQLException {
    // Initialize
    Integer bldgCObjID = null;
    Integer EDcObjID = null;
    Integer rtsCObjID = null;
    Integer timeSeriesID = null;
    Integer regTimeSeriesID = null;

    // STEP 1: Create Energy ADE ng_CityObject for the building
    bldgCObjID = createADECityObj(gmlid);

    // STEP 2:  Create EnergyDemand CityObject
    EDcObjID = createEDCObj();

    // STEP 3:  Create RegularTimeSeries CityObject
    rtsCObjID = createRTSCObj();

    // STEP 4: Create TimeSeries for EnergyDemand
    timeSeriesID = createMonthlyTimeSeries(rtsCObjID, bldgCObjID);

    // STEP 5: Create RegularTimeSeries for EnergyDemand
    regTimeSeriesID = createMonthlyRegTimeSeries(timeSeriesID, SH);

    // STEP 6: Create EnergyDemands entry
    createMonthlyEnergyDemand(EDcObjID, bldgCObjID, timeSeriesID);
}
```

Figure 35: Java function for inserting the monthly heating demand to the database

To store the simulated monthly space heating demand in the 3DCityDB with the Energy ADE extension, an object of the *EnergyDemand* class is created. Therefore, multiple database tables are conducted. The process can be structured into six steps, as follows:

1. First, the building is registered to the ADE by inserting the id of the city object into the "ng_CityObject" table.
2. An *EnergyDemand* city object with a new unique gml id is created.
3. The *RegularTimeSeries* city object with a new unique gml id is created.
4. Afterwards, a new entry in the "ng_timeseries" table is done. The acquisition method is set to "simulation", and the interpolation type, a thematic description, and a source are specified.
5. The heating demand values are written to the "ng_regulartimeseries" table (see Figure 36 lines 13–16). Here, the time-period properties are specified, as well. Therefore, the year from the GUI parameters is used (see Figure 36 lines 10 and 11).
6. In the final step, a new entry in "ng_energydemand" table is written. Therefore, the *EnergyDemand* city object id, the city object id of the building, and the time series id are specified. The end use property is set to "spaceHeating".

```
1. private Integer createMonthlyRegTimeSeries(Integer timeSeriesID, double[] SH) throws SQLException {
2.     // Initialize
3.     Integer regTimeSeriesID = null;
4.     // Create SQL string
5.     String SQL = "INSERT INTO citydb.ng_regulartimeseries (id, timeinterval, timeinterval_unit, timeperiodprop_beginposition, timeperiodproper_endposition, values_, values_uom) "
6.                     + " VALUES ("
7.                     + timeSeriesID + " ,"
8.                     + " 1,"
9.                     + " 'other:month',"
10.                    + " '" + simulationYear + "-01-01 01:00:00',"
11.                    + " '" + simulationYear + "-12-31 23:59:59',"
12.                    + " '";
13.    for (int i = 0; i < SH.length; i++) {
14.        double d = SH[i];
15.        SQL = SQL + Math.round(d) + " ";
16.    }
17.    SQL = SQL + "', 'KWh') RETURNING id;";
18.    PreparedStatement pstmt = conn.prepareStatement(SQL);
19.    ResultSet rs = pstmt.executeQuery();
20.    while (rs.next()) {
21.        regTimeSeriesID = rs.getInt(1);
22.    }
23.    return regTimeSeriesID;
24. }
```

Figure 36: Java code for inserting heating demand values to the regular time series table

7.7 Heating demand and CO2 emission prediction

Based on the defined refurbishment variants in Section 7.4.1, the expected change of CO2 emissions from the Helen district heat network, and the predicted climate change, possible scenarios are simulated. All scenarios are based on the simulation results for the current building stock in Helsinki and are calculated in five-year intervals up to 2050.

7.7.1 Climate change impact

The first scenario focuses on the impact of the changing climate for the heating demand of buildings in Helsinki. Therefore, long-term predicted weather data for 2020 to 2050 is used. The data sets are described in Section 6.4.

Figure 37 presents the predicted change in ambient temperature for the region of Helsinki. In general, the monthly average temperatures are expected to be warmer. Furthermore, winter seasons are more affected than summer seasons, which also influences the demand for heating and cooling in Helsinki.

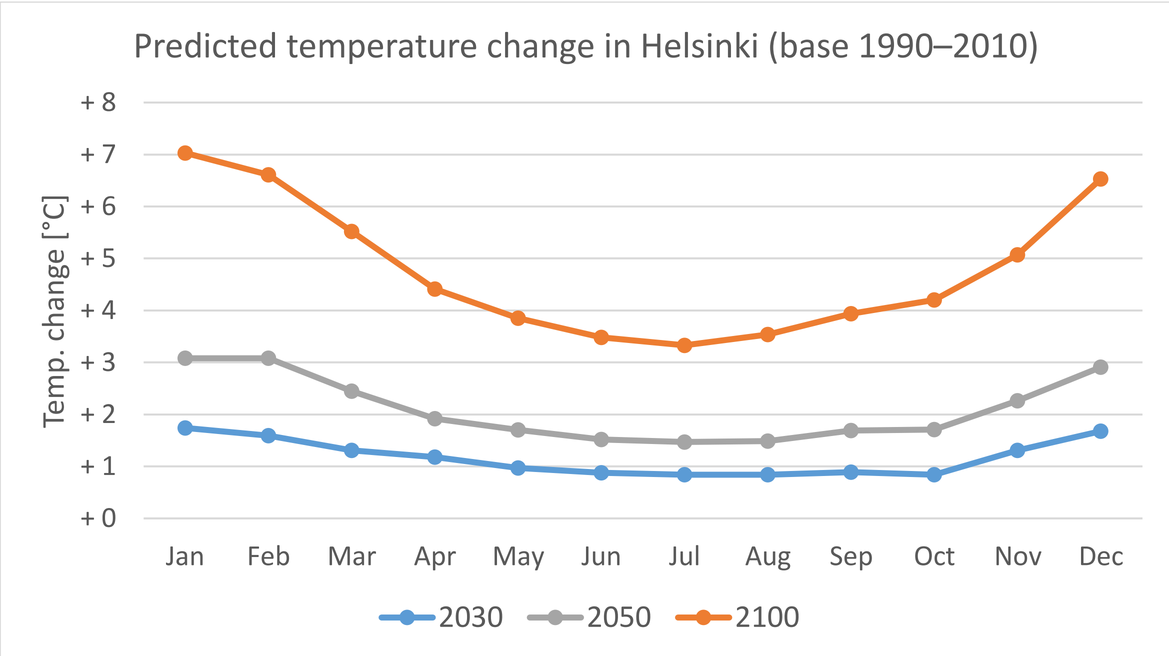


Figure 37: Predicted temperature change in Helsinki compared to base years 1990-2010

How much the heating demand and its CO2 emissions are influenced by the expected climate change is investigated in this scenario. It is calculated for the actual building stock in Helsinki without further assumptions made for refurbishments or other changes. To utilize the predicted weather data sets (described in Section 6.4), a SimStadt

"WeatherProcessor" for PRN files is developed. The weather processor parses the PRN files and generates a new SimStadt "WeatherDataSet". This allows for using the downloaded files directly without any preparation, such as a conversion to TMY3 format.

To ensure that SimStadt uses the correct weather data during the simulation, it is recommended to disable caching in SimStadt or delete the latest cached irradiance tables from the cache folder. Otherwise, SimStadt uses the latest generated irradiance tables that are available for the location for the irradiance processing.

7.7.1 Business as usual scenario

The business as usual (BAU) scenario aims to represent the actual developments in Helsinki without further actions. The typical refurbishment rate in Helsinki is investigated using the information concerning building renovations permits from the Helsinki city register. The renovations type and year of completion are mapped to the CityGML buildings by the permanent building code "VTJ_PRT". If the year of completion is missing for a building renovation permit, it is estimated using the date of arrival plus one year.

Figure 38 displays the renovation types per year with respect to the number of buildings, namely 46,643 buildings.

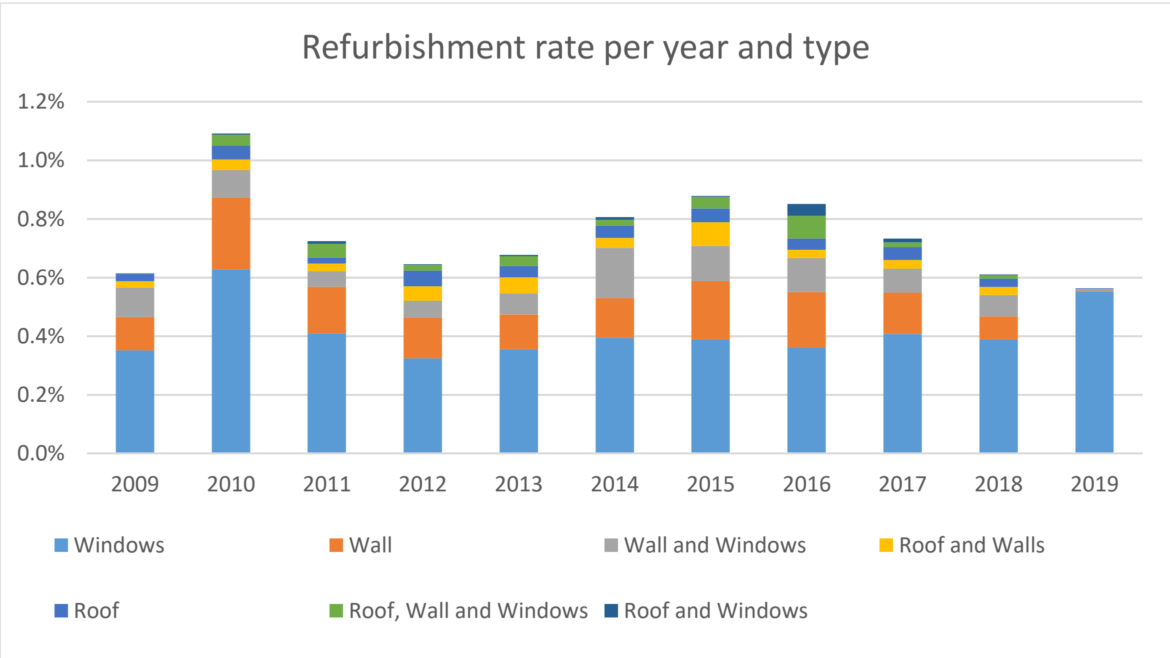


Figure 38: Refurbishment rate in Helsinki by year and type of renovation

In this work, only energy-relevant renovations of the building structures are investigated; these are additional thermal insulations of the exterior walls, additional thermal insulations of the attic floor, and window renewals. It is likely that some types of renovations are missing for 2019. This may be explained by changes in the building renovation permit procedures.

The averaged renovation rate between 2009 and 2018 is calculated to be 0.75% per year. Some types of renovations may be missing that affect the energy efficiency, such as roof construction changes. The renovation rate for the BAU scenario is consequently set to 1% per year. Furthermore, the refurbishment priority criterion is set to “Less efficient first”; thus, buildings with a greater mean U-value are refurbished before buildings that already have a smaller mean U-value.

In summary, the BAU scenario assumes that 1% of the building stock is renovated according to energy efficiency refurbishment variant described in Section 7.4.1.

7.7.1 Business as usual plus scenario

The business as usual plus (BAU+) scenario adopts the characteristics of the BAU scenario and also includes the expected CO2 emissions reduction of the Helen district heat network described in Section 7.4.3. The defined district heat energy systems for the years between 2020 and 2035 are used in a five-year stepwise prediction of CO2 emissions. Therefore, for every prediction step, a different district heat energy system is used. The district heat system defined for 2035 is also used for predictions after 2035.

7.7.2 Rapid development scenario

The final scenario represents a rapid development (RD) in terms of energy performance improvements during renovations in Helsinki. According to Tuominen [6], the renovation rate in Finland is assumed to be 3.5%. The scenario assumes that each year, 3% of the buildings in Helsinki are renovated according to the energy efficiency improvement during renovations regulation. [44] Additionally, the expected change in Helsinki’s district heat network’s CO2 emissions are considered.

7.8 Visualization

For the visualization of the final energy demand simulation results in addition to the CO2 emissions and heating demand savings that can be achieved through energy renovations, a 3D web application is created. Therefore, a NodeJS server is set up that runs a CesiumJS application.

Before the city model is converted into a streamable 3D Tiles format, the CityGML attributes concerning refurbishments are deleted for all buildings with six or fewer apartments to meet the data privacy agreements.

Afterwards, the simulated results needed for the visualization are imported into the 3DCityDB as generic attributes. Therefore, an FME workflow is created that reads the simulation results from Excel files and inserts the attributes into the 3DCityDB with the SQLExecutor transformer. As a result, the CityGML city model is prepared to be converted into 3D Tiles format. Therefore, the virtualcitySYSTEMS Publisher is used, a software that runs on the university server and allows for converting CityGML files or city models stored in a 3DCityDB directly into 3D Tiles format.

It is noticeable that attributes are stored as an "attributes" JSON object inside the b3dm batch table JSON object rather than being directly stored as separate entries in the batch table. This is displayed in Figure 39 and must be considered while accessing the feature attributes in the CesiumJS web application.

```
{
    header: { magic: 'b3dm', version: 1 },
    featureTable: { json: { BATCH_LENGTH: 10 }, binary: <Buffer > },
    batchTable: {
        json: {
            "gml_id" : ["BID_6032XXX","BID_06a0XXX", ... ],
            "olcs_geometryType" : [1,1,...],
            "parentPosition" : [-1,-1,...],
            "classId" : [26,26,...],
            "attributes" : [{"VTJ_PRT":"10XXX","Height":5.25,...},
                            {"VTJ_PRT":"11XXX","Height":4.75,...},...]
        },
        binary: <Buffer 00>
    },
    glb: <Buffer 77 6c 86 36 ...>
}
```

Figure 39: Simplified b3dm file created with VCS Publisher [modified from: 50, p. 12]

As a base map, the Helsinki aerial imagery from 2017 in an 8 cm resolution is used. It can be accessed as an OGC Web Map Service (WMS). To display the imagery on the globe, a Cesium WMS imagery provider is defined.

To explore the heating demand, CO2 emissions, and possible heating demand savings, several colorization styles are defined. Furthermore, by clicking on a building, a chart with more detailed information about the building's heating demand is displayed. These charts are created using the JavaScript library ApexCharts.js. [51] The developed visualization is presented in Section 9.6.

8 Evaluation

The evaluation of the proposed concept is structured as follows. First, the Energy ADE integration approaches are validated against the Energy ADE schema definitions. Afterwards, the usage of the developed 3DCityDB with an Energy ADE extension connection is evaluated. Therefore, the newly integrated information is compared with the calculations that would be used rather than given values. Furthermore, the simulation results are compared with the measured consumption data on building scale and on city scale with statistical data provided from the statistics of Helsinki. The results of the prediction scenarios are presented in the following chapter.

8.1 Energy ADE schema validation

The software Liquid Studio is used to validate the CityGML files that are enriched by the Energy ADE features and properties. Therefore, the 3D city model stored in the 3DCityDB with the Energy ADE extension is exported using the 3DCityDB Importer/Exporter tool. Afterwards, the files are loaded in Liquid Studio and validated against the schema definition files.

Liquid Studio uses the XSD files for the validation; these files are specified in the "xsi:schemaLocation" attribute of the "CityModel" tag, see Figure 40, lines 10–15. During the validation, it was noticed that the Energy ADE namespace is defined (Figure 40 line 5), but the schema file location specification in the "xsi:schemaLocation" for the Energy ADE is missing (Figure 40 lines 14–15).

```
1.  <CityModel
2.      xmlns="http://www.opengis.net/citygml/2.0"
3.      xmlns:xAL="urn:oasis:names:tc:ciq:xsdschema:xAL:2.0"
4.      xmlns:gml="http://www.opengis.net/gml"
5.      xmlns:energy="http://www.sig3d.org/citygml/2.0/energy/1.0"
6.      xmlns:bldg="http://www.opengis.net/citygml/building/2.0"
7.      xmlns:gen="http://www.opengis.net/citygml/generics/2.0"
8.      xmlns:xlink="http://www.w3.org/1999/xlink"
9.      xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance"
10.     xsi:schemaLocation="http://www.opengis.net/citygml/building/2.0
11.     http://schemas.opengis.net/citygml/building/2.0/building.xsd
12.     http://www.opengis.net/citygml/generics/2.0
13.     http://schemas.opengis.net/citygml/generics/2.0/generics.xsd
14.     http://www.sig3d.org/citygml/2.0/energy/1.0
15.     http://www.sig3d.org/citygml/2.0/energy/1.0/EnergyADE.xsd">
```

Figure 40: CityGML namespace declarations and schema location definitions

This problem does not occur for the CityGML files created using the file-based approach described in Section 7.3.1. For this approach, the Energy ADE schema location is specified in the FME CityGML writer “xsi:schemaLocation” parameter.

Thus, the missing schema location specification in the database-based approach is caused by the 3DCityDB Importer/Exporter tool. In this case, the schema location is inserted by hand Figure 40, line 14–15), and the schema validation of the Energy ADE integration approach is successfully completed without further errors.

The validation of the 3DCityDB with the Energy ADE writer SimStadt workflow is validated against the Energy ADE schema, as well. Therefore, the city model is exported after the simulation to a CityGML file, the schema location is added by hand, and the file is validated with Liquid Studio.

It was noticed that the time interval unit “month” for the monthly energy demand is not supported. The data type of this unit is defined by the “gml:TimeUnitType”. The implementation of CityGML is done as an application schema of GML in version 3.1.1. The unit month is not listed as an enumeration value for the “TimeUnitType” in the GML version 3.1.1. Therefore, the pattern “other:\w{2,}” is used (i.e. “other:month”). The missing month unit is already fixed in GML version 3.2.1.

8.2 Energy ADE integration approaches

Both presented methods for storing energy-relevant information in CityGML using the Energy ADE are valid against the schema definition and provide their own advantages and disadvantages, as identified in Table 9.

Table 9: Comparison of the Energy ADE integration approaches

File-based approach	Database-based approach
+ Works without database	+ Simple updating possibilities
- Not all ADE features on the fly definable	+ Can be used in other techniques like Java
- Large file sizes	+ No limitation in database size
- CityGML knowledge needed	- SQL knowledge needed
	- Usually multiple tables conducted

As the CityGML 3D city model is already stored in a 3DCityDB and the results will be used again in a 3DCityDB, the database-based approach is selected as the most fitting approach.

The procedure can be extended for other Energy ADE features, and the update for new input data can be done directly in the database.

8.3 3DCityDB with Energy ADE connection in SimStadt

Once the Energy ADE features and properties are defined in the 3DCityDB, it is possible to access the information through a database connection in Java. The ADE features can be requested from the database for the entire city model. This reduces the processing time, as only one database query is executed for all buildings instead of querying the database for each building separately. Establishing a connection to the database took 0.03 seconds, and retrieving the heated area from the Energy ADE *floorArea* property took 0.7 seconds for 47,371 rows.

8.4 SimStadt 3DCityDB with Energy ADE writer

The implemented workflow step to write the simulation results directly to the database as Energy ADE *EnergyDemand* features is valid against the ADE schema definition.

The workflow step offers the benefit that the simulation results directly in the source data set are available. Additionally, the performance for writing to the database is tested for 1,915 buildings. Updating the heated area as an Energy ADE *floorArea* property took 2.1 seconds, whereas updating the simulated monthly heat demand as Energy ADE *EnergyDemand* features took 4.5 seconds.

8.5 Validation of simulation results

The validation of the simulation results is achieved using the measured consumption data from 2018. In particular, this information is available for 1,915 HEKA buildings. As the heating demand refers to 2018, for the simulation, the observed weather data for that particular year is used.

8.5.1 Finnish building physics and usage library

Figure 41 presents the total measured and simulated heating demand using the German and Finnish building libraries for the simulation. Using the German libraries for the simulation results in an 8% greater heat demand compared with the measured consumption data. For the Finnish building libraries, the deviation is 10% lower than measured. The mean absolute percentage error (MAPE) is calculated as 27.2% using the German libraries, whereas a MAPE of 18.5% is calculated using the Finnish libraries.

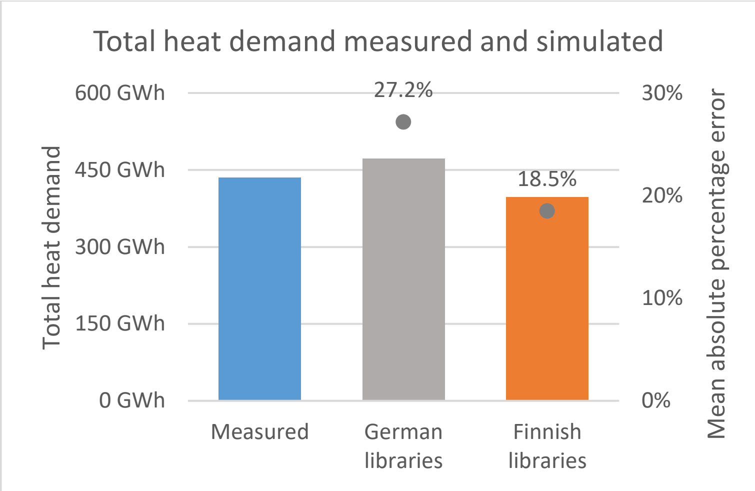


Figure 41: Comparison of simulation results for the Finnish and German building libraries

Based on the distributions of the deviations in the histograms presented in Figure 42, the Finnish libraries better suit the simulation, as the number of deviations with less than +/- 10% is greater compared with that of the German libraries. For both simulations, it is noticeable that there are also deviations with more than 100% compared with the measured data. Upon investigating the possible reasons for the deviations with more than 100%, it is most assumed that there are errors in data mapping of the consumption data to a CityGML building.

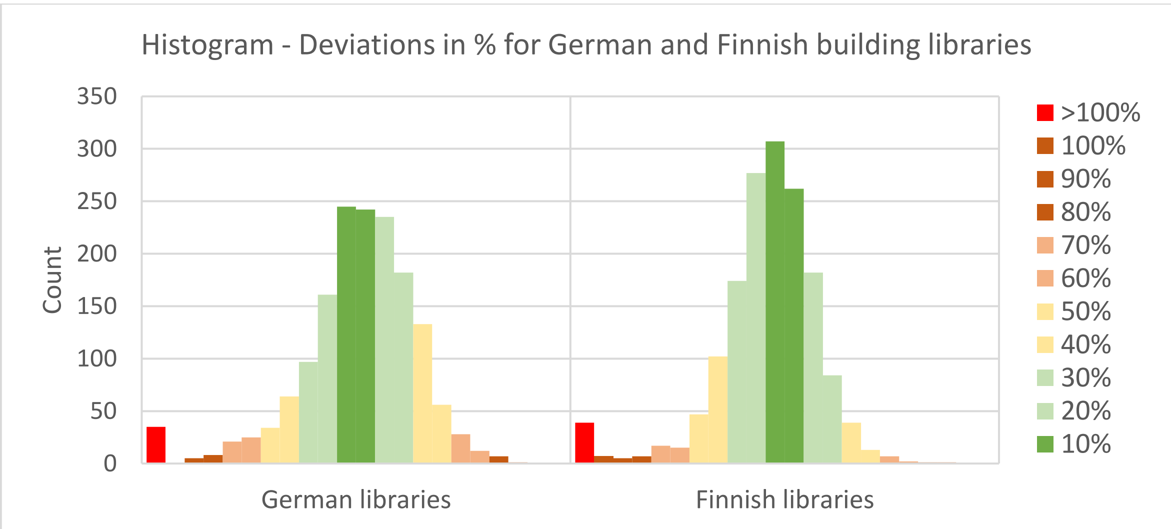


Figure 42: Histogram showing the deviations of the simulations results for the German and Finnish building libraries

Figure 43 presents a building complex for which the heat demand was simulated to be more than 3 times lower compared with the provided consumption data. The CityGML building used in the simulation analysis is highlighted in orange. Based on the imagery base map, the building is connected to the surrounding buildings, which are modelled separately in the 3D city model. It is most likely that the provided energy consumption data refers to all three buildings rather than the single building in the middle. During the investigation of other buildings with deviations greater than 100%, similar behavior was found.

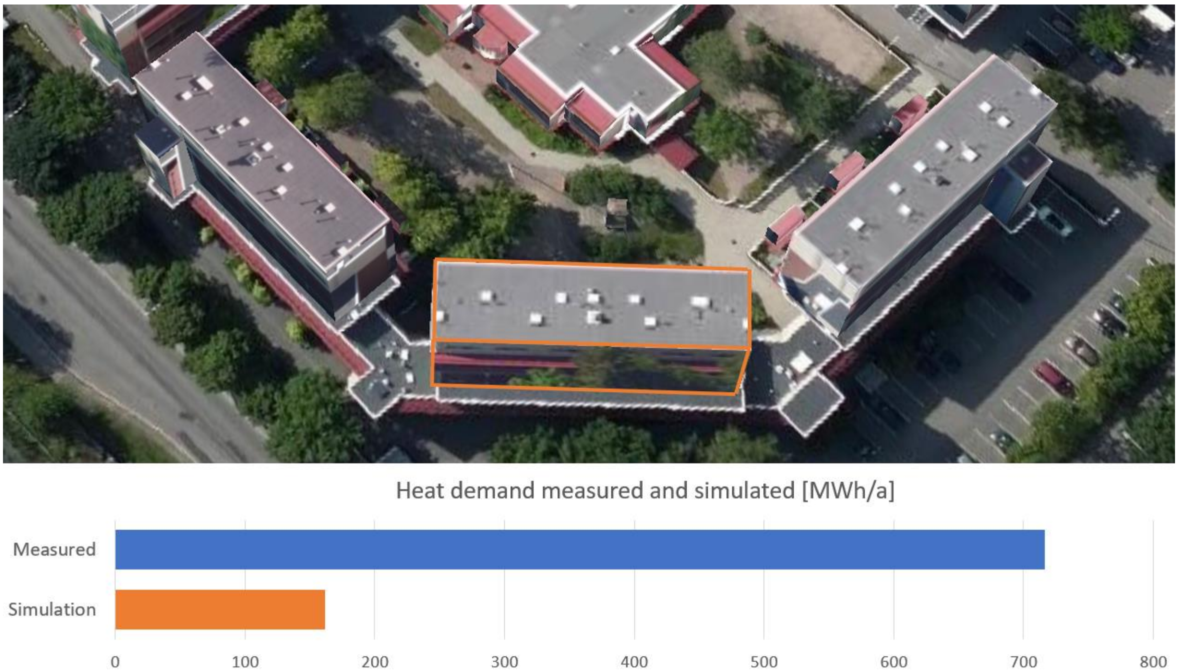


Figure 43: Possibly incorrect mapped heat demand of a building

8.5.1 Workflow step functionalities

The developed workflow step functionalities for using additional information from the 3DCityDB are analyzed in the following section.

Number of apartments and occupants

Using the information concerning the number of occupants and apartments from the city register, the MAPE changed from 19.53% to 19.59%, about a + 0.06% difference, focusing on the buildings for which the information is present. The total heat demand including DHW changed by about + 0.03%. Thus, the influence of using the provided information rather than an estimation during the simulation is minor.

Heated area and usage zones

Figure 44 presents the simulated heat demand using the defined usage zones and the heated area. While using the usage zones for the simulation, the MAPE was calculated as 25.6% and as 19.6% if the net floor area from the city register is used instead. The total heat demand using the heated area deviates from the expected values by -3% and for the usage zones by -32%.

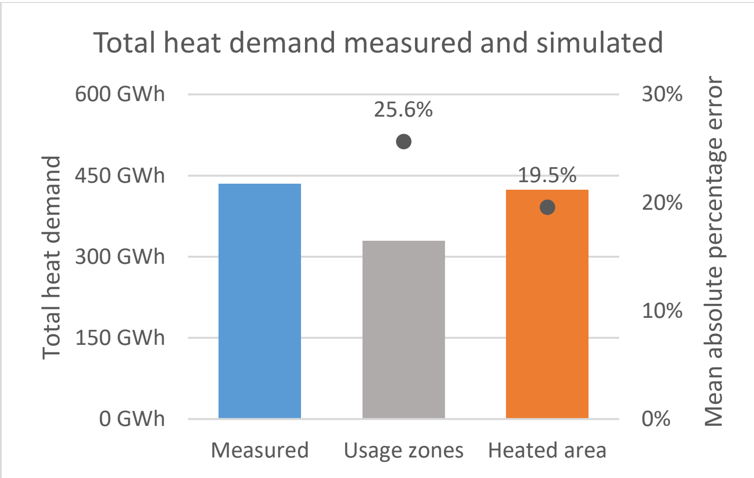


Figure 44: Total heat demand simulated with usage zone and heated area information

One explanation for the high deviations can be obtained by considering Figure 45. In general, the heat demand using the usage zone information is simulated to be low. Additionally, for 96 buildings, deviations of more than 100% are calculated. These are most likely caused by faulty usage zone floor area information in the city register. Thus, the decision is made to exclude the information on usage zones in further simulations.

For using the heated area information, deviations of up to 20% are simulated for 61% of the buildings. The highest deviations are calculated to be -332% for a residential building (displayed in Figure 43) and +67% for a building in the retail usage class.

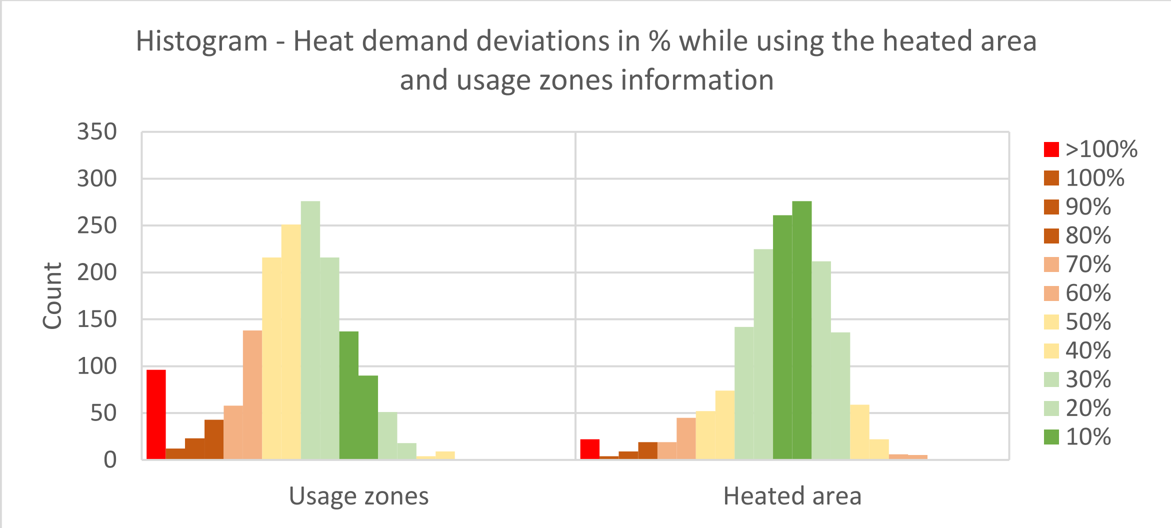


Figure 45: Distribution of deviations using the usage zone and heated area information for the simulation

8.5.2 City scale

For the validation of the simulation results on urban scale, statistical data provided by the Helsinki region environmental services (HSY) is used. [52, 53] A comparison between the heating energy demand and the CO2 emission caused by heating is provided in Figure 46. The total energy demand for heating is simulated to be 6.28 TWh/a. Additionally, the statistical energy demand is 0.74 TWh/a higher, namely 7.02 TWh/a. The resulting CO2 emissions are simulated to be 1,519 kt CO2/a, whereas the statistical CO2 emissions are given to be 1,439 kt CO2/a, which differs by approximately -5% with respect to the simulation. Furthermore, the statistical information does not represent a true value, so the deviations between the simulated and expected values are accepted.

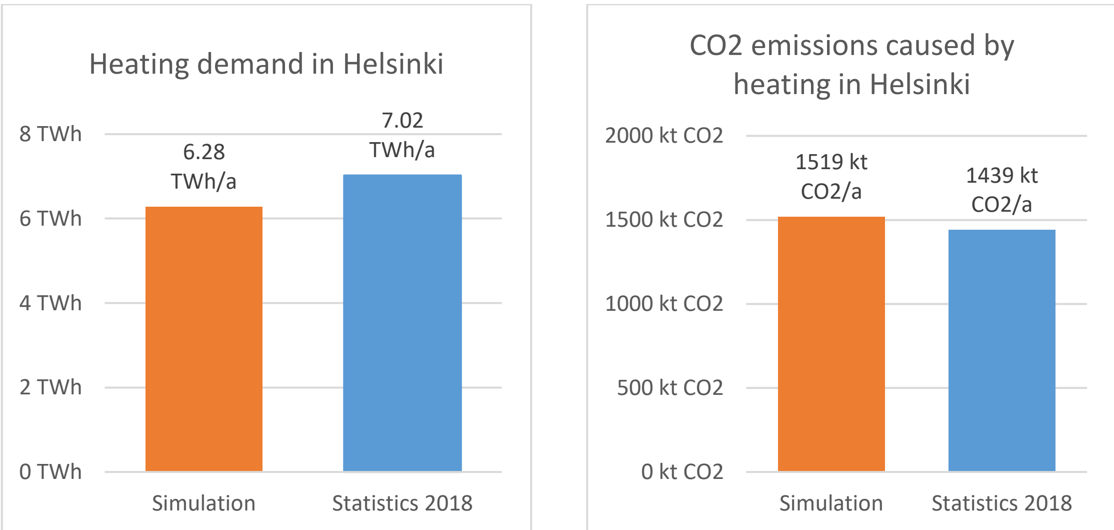


Figure 46: Simulated heating energy demand and CO2 emissions compared to statistics

9 Results

The following chapter presents the predicted heating demand and resulting CO2 emissions for the scenarios presented in Section 7.7. All the scenarios are based on the simulated energy demand for space heating and DHW in 2020 for the actual building stock. The reduction of CO2 emissions caused by space heating and DHW is compared with the statistical value from 1990.

9.1 Climate change scenario

The influence of the changing climate on the heating demand of the actual building stock in Helsinki is presented in Figure 47. The heating demand of 6.28 TWh in 2020 will decrease to 5.93 TWh/a by 2035, which results in a reduction of 6%, or 0.36 TWh. By 2050, a reduction of 11% to 5.65 TWh is calculated, meaning a reduction of 4% per decade. It must be considered that the increasing energy demand for cooling is not included in this analysis.

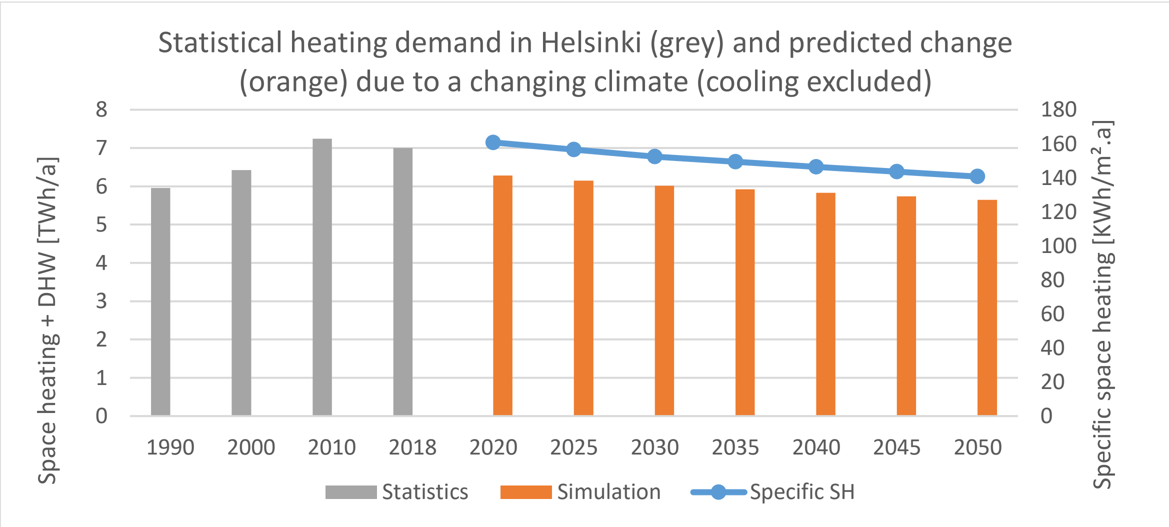


Figure 47: Statistical heating demand in Helsinki (grey) and predicted change (orange) using long-term predicted weather data (cooling demand not considered)

Figure 48 presents the predicted reduction of CO2 emissions for heating in Helsinki under climate change conditions. While the simulated CO2 emissions are already reduced by 18% compared with the statistical data in 1990, climate change causes a further reduction of 5% by 2035 and 8% by 2050.

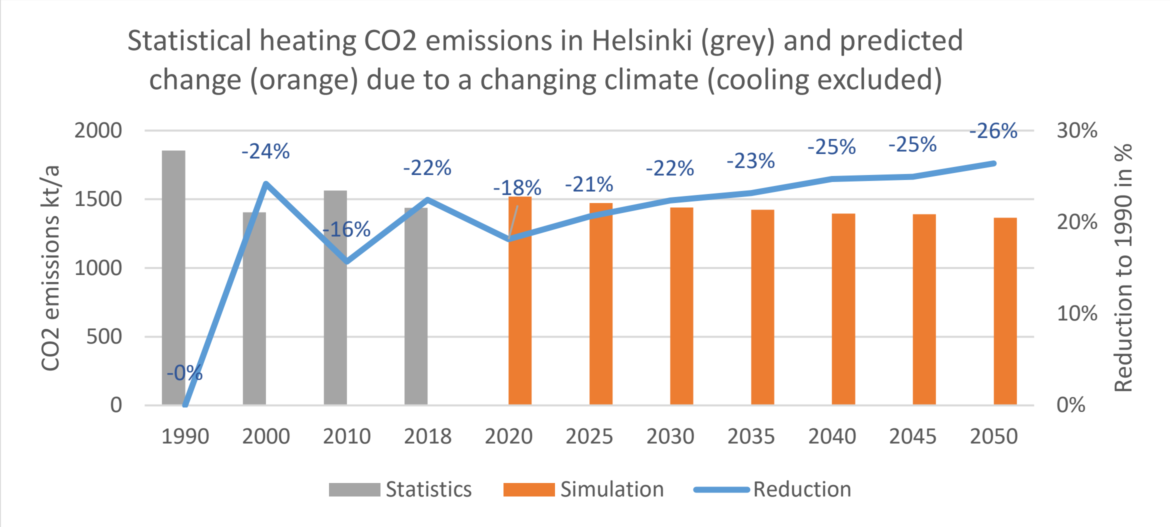


Figure 48: Statistical CO2 emissions caused by heating in Helsinki and predicted change (orange) using long-term predicted weather data (cooling demand not considered)

9.2 BAU scenario

Figure 49 presents the heating demand of the actual building stock in Helsinki with a renovation rate of 1% per year. According to the simulation, the energy demand for heating will decrease by about 0.71 TWh from 2020 to 2035 and about 1.37 TWh by 2050. This leads to reductions of 13% and 28%, respectively. The averaged space heating demand per square meter and year decreases from 161 kWh/(m².a) to 128 kWh/(m².a) in 2035 and to 103 kWh/(m².a) in 2050.

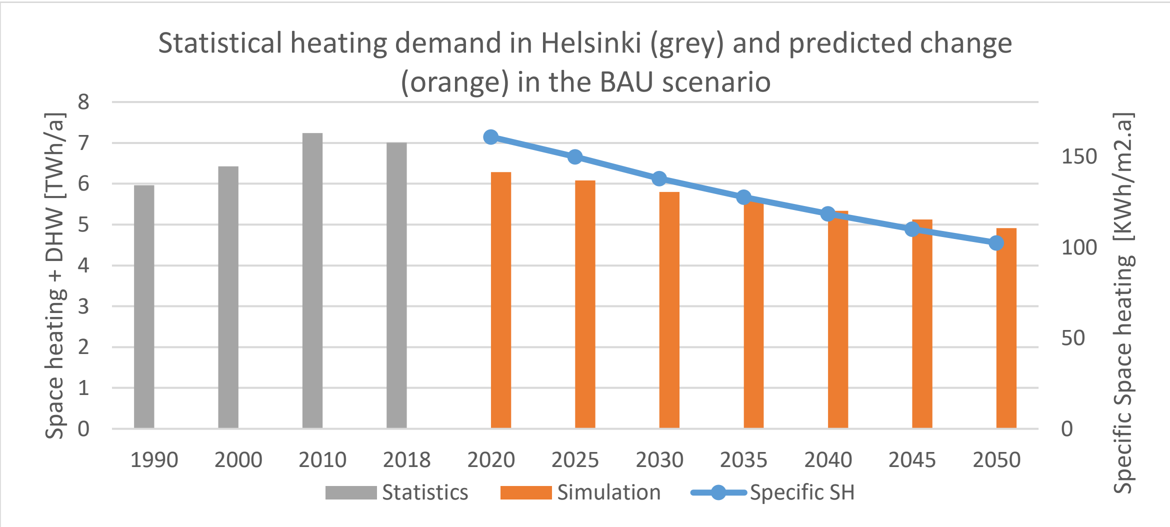


Figure 49: Statistical heating demand in Helsinki (grey) and predicted change (orange) in the BAU scenario

The reduction in CO2 emissions compared with 1990 are illustrated in Figure 50. The reduction is calculated to be 28% in 2035 and 36% in 2050 if the 1% refurbishment rate of the BAU scenario is applied. The reduction between 2020 and 2035 (10%) is 5% higher compared with the climate change scenario.

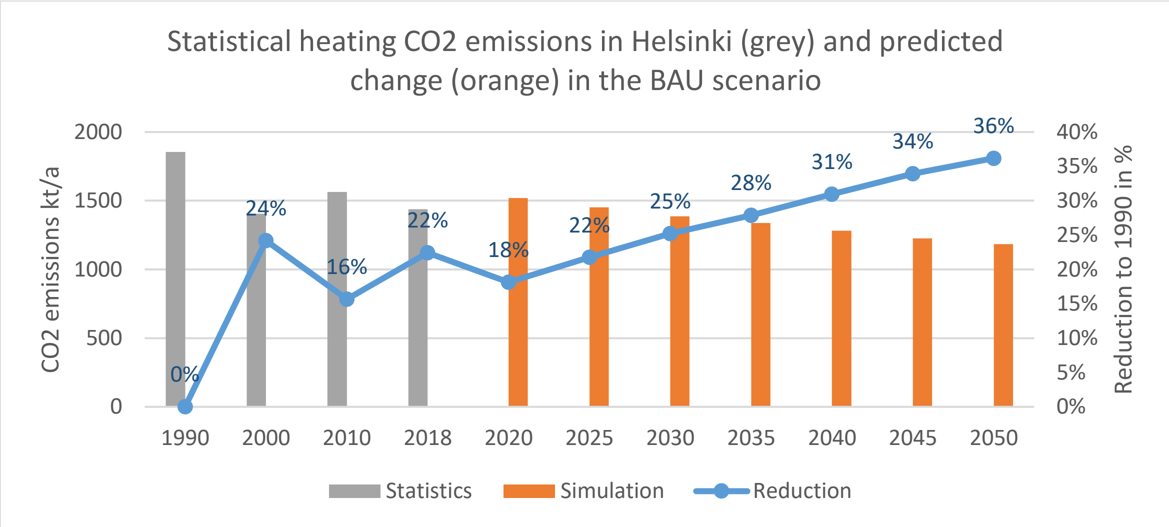


Figure 50: Statistical CO2 emissions caused by heating in Helsinki and predicted change (orange) in the BAU scenario

9.3 BAU+ scenario

Including the proposed improvements of the district heat network in Helsinki from Helen [49] to the 1% refurbishment rate, the CO2 emissions are decreasing significantly, as presented in Figure 51. A reduction of 79% by 2035 compared with 1990 and of 81% by 2050 are predicted. The heat demand itself is the same as in the BAU scenario.

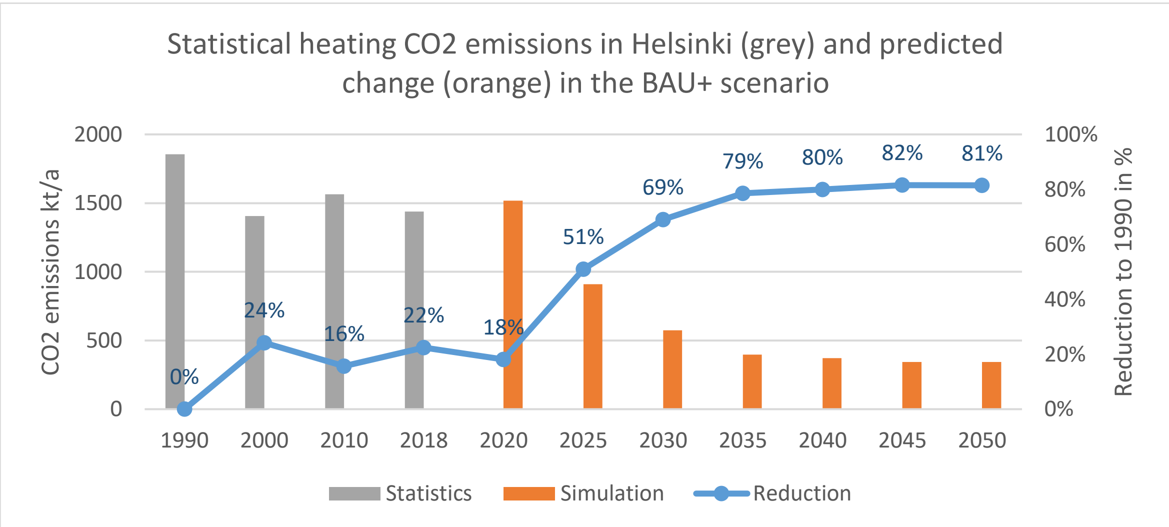


Figure 51: Statistical CO2 emissions caused by heating in Helsinki and predicted change (orange) in the BAU+ scenario

9.4 RD scenario

The final scenario assumes a 3% refurbishment rate, including the improved district heating network in Helsinki. The resulting heating demand predictions are displayed in Figure 52. Based on the simulated heat demand of 6.28 TWh in 2020, a reduction of 1.5 TWh to 4.76 TWh by 2035 is simulated. By 2050, a reduction of 2.4 TWh to 3.89 TWh is calculated. The average heat demand per square meter and year is simulated to be 96 kWh/(m².a) in 2035 and 70 kWh/(m².a) in 2050.

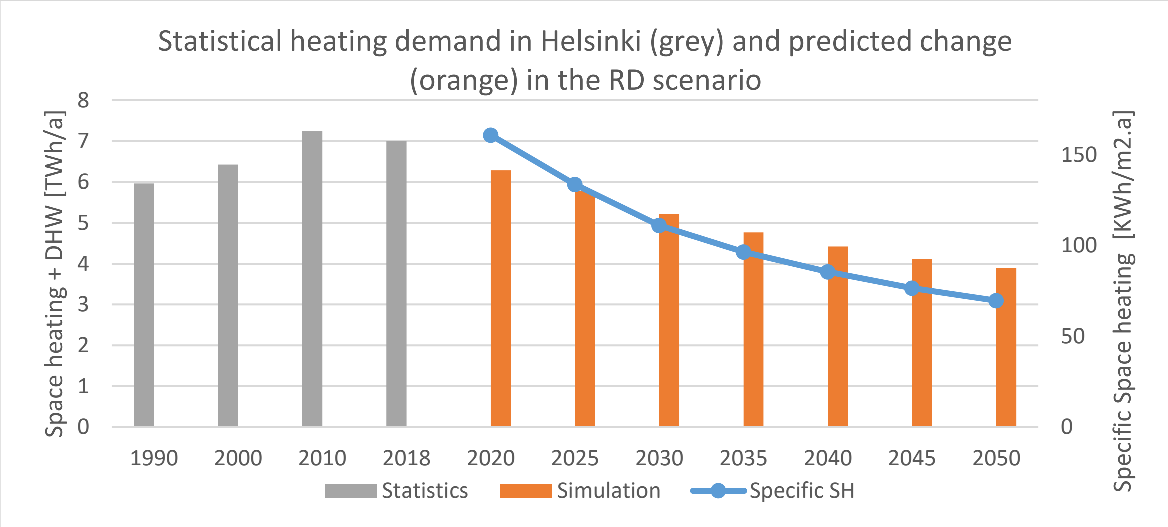


Figure 52: Statistical heating demand in Helsinki (grey) and predicted change (orange) in the RD scenario

In the RD scenario, the CO2 emissions are decreasing by 82% from 1990 to 2035 and by 86% to 2050. The reduction by 2035 is 3% higher (5% by 2050) compared with the BAU+ scenario.

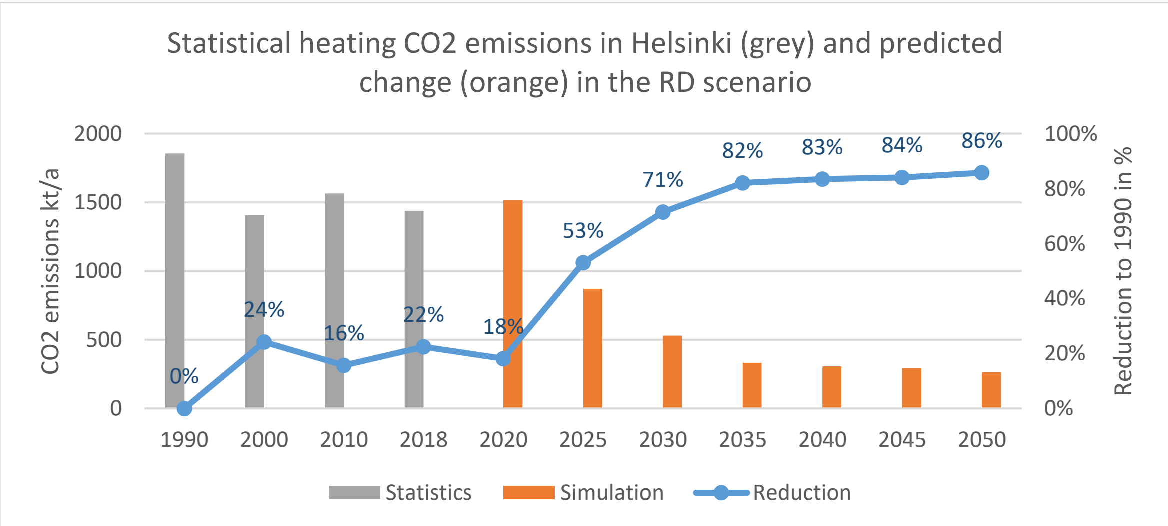


Figure 53: Statistical CO2 emissions caused by heating in Helsinki and predicted change (orange) in the RD scenario

9.5 Refurbishment types analysis

The impact of the defined refurbishments on the space heating demand of a building is visualized in Figure 54. The original category represents the building as originally constructed. The categories wall, roof, and window represent the space heating demand if the corresponding type of refurbishment is applied to the usual extent. The energy efficiency category represents a full energy improvement refurbishment according to the energy efficiency improvement during renovations regulation. [44] This includes the ground structure of a building in addition to its walls, roofs and windows.

For example, for a building constructed between 1960 and 1980, the average space heat demand is reduced by 26% with additional thermal insulation of the exterior walls, by 13% with additional thermal insulation of the roof, by 10% with window renewals, and up to 154% with advanced refurbishment of the entire building structure.

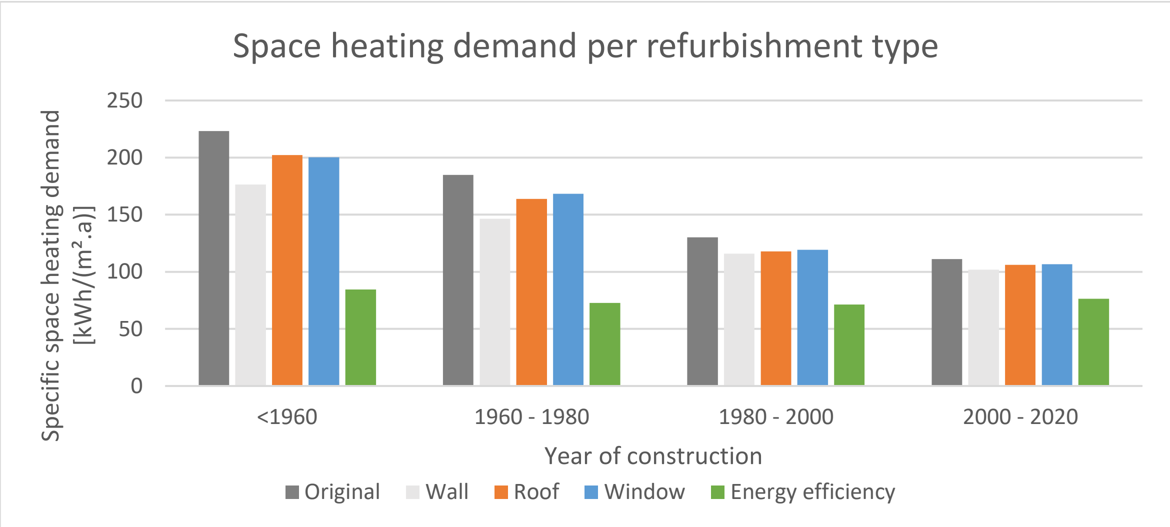


Figure 54: Averaged heating demand per square meter and year in different construction year ranges per refurbishment type

9.6 3D web visualization

Opening the 3D web application, the user faces a popup window containing a general description about the research project, as presented in Figure 55. Additionally, the previously presented results of the prediction scenarios for the entire city are provided as interactive charts.

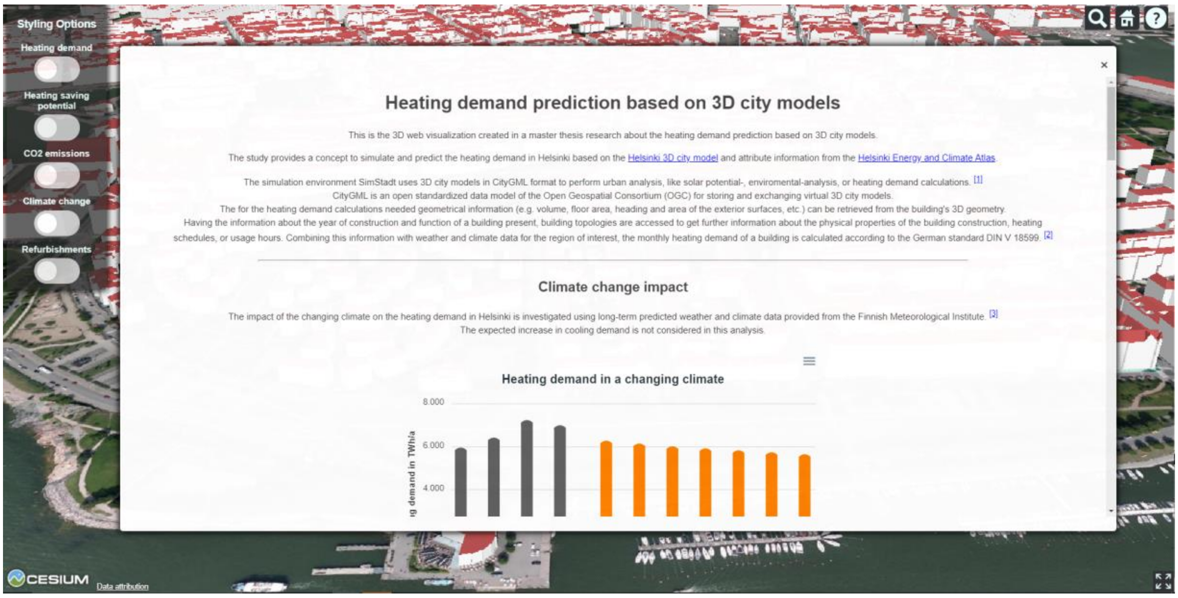


Figure 55: Landing page of the 3D web application

For exploring and comparing of the building's properties, colorization styles based on following information are defined: The space heating demand per square meter and year, CO2 emissions caused by heating per square meter and year, and building's the heating-saving-potential. For each, a corresponding legend is displayed. As an example, the legend of the space heating demand is presented in Figure 56. The categorization of the heating demand is oriented on the latest energy performance certificate in Finland.

Figure 56: Space heating demand legend

Additionally, it is possible to get further information about a specific building by clicking on or hovering over a building feature. By clicking on a building, a table pops up that displays the building's general information, as listed in Figure 57.

BID_133ce55c-240f-413c-81d2-708abca33de3

VTJ_PRT	1031131023
RATU	1501
Adress	Merikatu 9
Function	Muut kerrostalot
Year of construction	1908
Storeys above ground	6
Total floor area	12192 m²
Volume	44841 m³

Figure 57: Table with the building's general information

As visualized in Figure 58, more detailed information concerning the building's heating demand can be accessed by selecting the "Climate change" or "Refurbishments" buttons. Selecting the "Refurbishments" button, the building's space heating demand in different refurbishments is displayed in a chart.

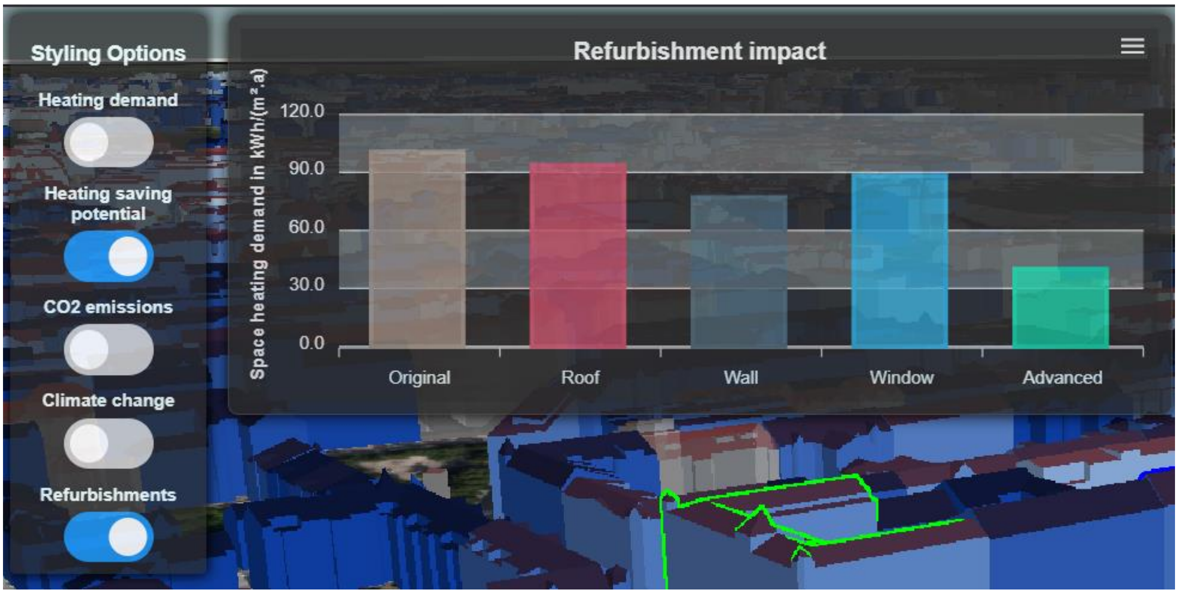


Figure 58: Information selector (left) and refurbishment impact chart (right)

Figure 59 presents the chart displaying the building's monthly space heating demand in 2020 and additionally under consideration of the predicted climate change in the years 2035 and 2050. It is displayed by selecting a building while the "Climate change" button is activated.

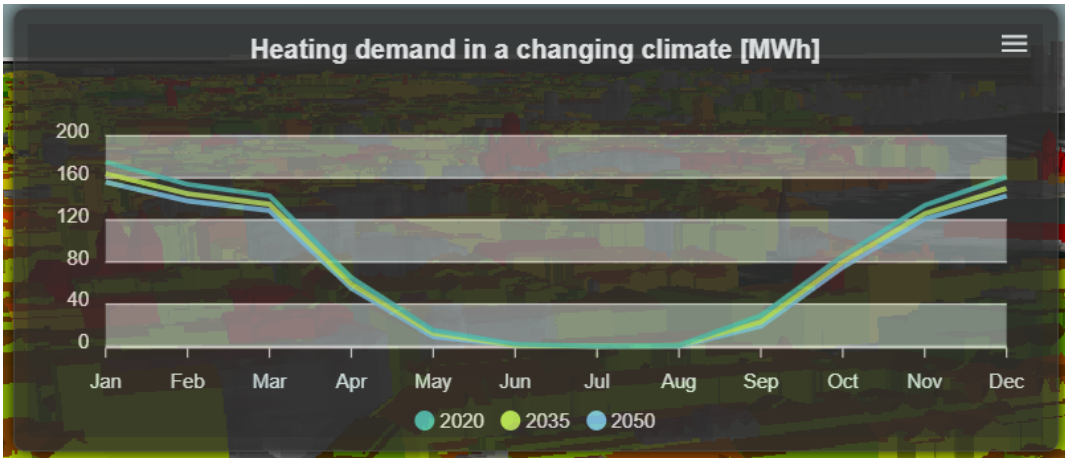


Figure 59: Building's monthly heating demand in different climatic years

9.6.1 Evaluation of the 3D web visualization

The created 3D web application provides the possibility to present the heating demand simulation and prediction results for the entire city, but also to investigate and compare the results for individual buildings. Through the focus on the most important information and presenting data in interactive charts, an intuitive platform is created that enables to explore detailed information in high density.

A visual inspection in the heating demand in the 3D web visualization shows that some buildings are colorized in gray (see Figure 58). This behavior occurs for buildings that are not heated (e.g. bus stops or garages), or the heating demand is not simulated as the at least required information about the year of construction and function is missing.

Furthermore, it is noticed that a duplication of a greenhouse in the botanical garden Kaisaniemi is flying above the ground. The buildings have not identical gml id's, thus it is assumed that the problem is not caused by the 3D Tiles generation. It is more likely that the building is modelled twice in the Helsinki 3D city model.

10 Discussion

First, it must be considered that the heating demand prediction focuses on the actual building stock in Helsinki. Buildings that will be demolished or constructed in the future are not included in this analysis. Since newly constructed buildings will already be energy efficient, the reduction potential of the old building stock is with 81% the major part. [25]

Furthermore, the defined energy efficiency refurbishment variant might be too optimistic to be used in a BAU scenario. The number of refurbishments which conduct the entire building shell provided by the city register is lower than 1% per year, but through changes in the building permit procedures, the analysis of executed refurbishments in Helsinki in Section 7.7.1 might not contain all the executed refurbishments. Additionally, it must be considered that the defined energy efficiency refurbishment variant is also applied to buildings that are landmarked. It might not be possible to apply such an advanced refurbishment to the shell of a landmarked building.

Furthermore, a refurbishment might not be appliable to every building in an identical extend, thus the predicted heating demand and the resulting heating-saving-potential for a refurbished building should be considered as an estimation that can be achieved.

Since the heating demand is not simulated for some buildings due to missing year of construction and function information, the total heating demand in Helsinki may be even higher than calculated in this work. This also explains the deviation of the heating demand on city scale compared to the statistics (see Section 8.5.2).

The climate change heating demand reduction of 0.36 TWh/a by 2035, which is a reduction of 4% per decade, agrees with the 2–4% reduction per decade assessed by Jylhä et al. [9] The Helsinki Carbon-neutral 2035 Action Plan assumes an annual decrease in heating demand of 0.5% due to climate change, [25, p. 29] which is, with 5% per decade, 1% higher per decade than simulated in this work. The expected increase in cooling demand is not included.

Furthermore, according to the Carbon-neutral Helsinki 2035 Action Plan, "The modernisations are estimated to achieve energy conservation of 1.1 TWh/a by 2035 in the basic scenario and 2.0 TWh/a in the enhanced scenario." [25, p. 126] Compared with the simulated reductions with energy efficiency improvements of 0.7 TWh/a by 2035 in the

BAU scenario and 1.5 TWh/a in the RD scenario, the reduction of 2.0 TWh/a by 2035 in the enhanced scenario would be not achieved.

The action plan assumes that the building's CO2 emissions from 1990 can be reduced by more than 80% by 2035. [25, p. 11] The reduction potential with a 1% refurbishment rate of 28% in the BAU scenario does not fulfill this requirement. While including the assumed CO2 efficiency improvements of the district heat network, a reduction of 79% in the BAU+ scenario is achieved. The RD scenario with an enhanced refurbishment rate of 3% confirms the action plan's assumption with a reduction of 82%.

The decrease in CO2 emissions of the district heat network in Helsinki significantly influences the reduction potential of CO2 emissions caused by heating. Without any changes in the district heat network, the CO2 reduction of more than 80% could not be achieved.

11 Conclusion

The simulated heating demand is compared with the measured consumption data to be validated. The target accuracy of deviations up to 20% is achieved for 61% of the buildings. The other buildings show deviations of up to -332% and +67%; here, it can be assumed that the greatest negative deviations are due to a lack of reliable consumption data, while the positive ones are due to a special usage of the building (e.g. healthcare and retail). Summarizing the measured and simulated heating demand of all HEKA building's, a deviation of -3% is achieved.

The yearly refurbishment rate for achieving the needed reduction in CO2 emissions is calculated to be 3%, but it must be considered that the reduction is significant influenced by the expected CO2 emissions reduction of the district heat network in Helsinki. Without the district heat improvements, the CO2 emissions could not be reduced by more than 80%. In the Helsinki Carbon-neutral 2035 Action Plan's enhanced scenario, the assumed heating demand reduction through the modernization of 2.0 TWh/a by 2035 is not achieved with a 3% refurbishment rate.

The impact of the climate change on the heating demand is also investigated using long-term predicted weather data for heating demand simulations; as a result, the energy demand for heating is expected to be reduced by 4% per decade. The expected increase in cooling demand is not investigated in this work.

The Energy ADE is suitable as an extension of the data model for the Helsinki 3D city model in CityGML. The Helsinki Energy and Climate Atlas provides a list of attribute information that can be modelled in Energy ADE schema. The information stored in the Energy ADE data model can then be included as additional information for heating demand simulations. The Energy ADE KIT-profile does not include all features and properties of the original Energy ADE. The Helsinki Energy and Climate Atlas provides information that can be modelled in the Energy ADE, but not in the in this work used KIT-profile of the Energy ADE (e.g. refurbishment measure, energy performance certification, landmarked status, and energy source and system).

The created SimStadt workflow step, which connects the simulation environment with a 3DCiytDB extended by the Energy ADE, allows for retrieving additional energy-related information from the 3DCityDB with the Energy ADE extension. The information can then be used in the heating demand simulation. A limitation exists in the availability of reliable information. Thus, it was decided to exclude the information of the building's different usage floor areas, as the data set was not considered to be sufficiently consistent.

The developed workflow step, which provides the ability to write the results of the simulation directly back to the original database, is considered to be advantageous. The simulation results are directly integrated into the 3D city model using the standardized Energy ADE data model. For the current developments, the simulation of heating demand can be done in an hourly resolution. Storing 8,760 hourly values per year for thousands of buildings in a CityGML file results in large data and file sizes. Even if the Energy ADE provides the ability to link the energy demand values to an additional text file, the storage of the city model together with the simulation results in a database is limitlessly extensible in terms of database size. [54]

12 Future work

The database-based Energy ADE integration approach could be simplified using predefined SQL procedures. Giorgio and Holcik [55] created a collection of SQL scripts for the 3DCityDB with Energy ADE. Unfortunately, the 3DCityDB is supported only in version 3.3.1, and the Energy ADE in version 0.8 is implemented.

Since the Finnish Meteorological Institute provides weather data sets, particularly for simulations of the energy demand of buildings, the weather and climate data could also be integrated into the city model using the Energy ADE feature type "WeatherStation".

The created building topologies might also be integrated into the city model using the Energy ADE. Thus, it might be possible to provide the physics and usage information needed for the simulation in SimStadt within the city model. Furthermore, the in this work created "3DCityDB with Energy ADE writer" could be extended to enrich the city model with the information from the building libraries. For example, the U-values of the building construction parts could be written as Energy ADE "Construction" of its "ThermalBoundary". SimStadt could then be used as a kind of Energy ADE enrichment tool.

Considering the ongoing developments, simulations based on city models can be done as a web service. In this approach, the city model is sent to a server through the OGC's Web Feature Service (WFS). The simulation is performed on the server, which runs the SimStadt simulation environment. As the Energy ADE can also be processed in WFS [17], the results could be sent back with the Energy ADE's "EnergyDemand" features to the original database.

For the final presentation, the 3D city model is enriched by the simulated results, and the attributes are stored in the 3D Tiles batch table. Thus, the 3D Tiles must be newly created after every simulation. Singh [50] investigated the possibility of automatic updates of 3D Tiles by changes. Another possibility to omit the new creation of 3D Tiles is to retrieve the simulation results directly form the database instead of writing the information into the 3D Tiles batch table. [56]

The accuracy of the simulation could be improved by building libraries that represent the Finnish building stock in more detail. For example, the information about U-values of construction parts in the Finish building code are not categorized in building types. A more detailed building stock model will probably result in higher accuracy of simulation results.

For a prediction on city scale, the in future demolished and new constructed buildings could be considered by excluding a percentage of old buildings that are not landmarked and copying a percentage of the simulation results of the latest constructed buildings. Another possibility would be to specify a renewal rate, that sets the year of construction of old buildings to the actual year or a year in the future. In this case, the simulation environment assumes that the building is new constructed, and the physical properties of a new building are used for the heating demand simulation.

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Appendix

Appendix A: Energy ADE KIT-profile

Following UML class diagrams are adopted from the Energy ADE Specification v1.0. [16] The UML diagrams are modified to illustrate the changes of the Energy ADE KIT-profile compared with the original Energy ADE.

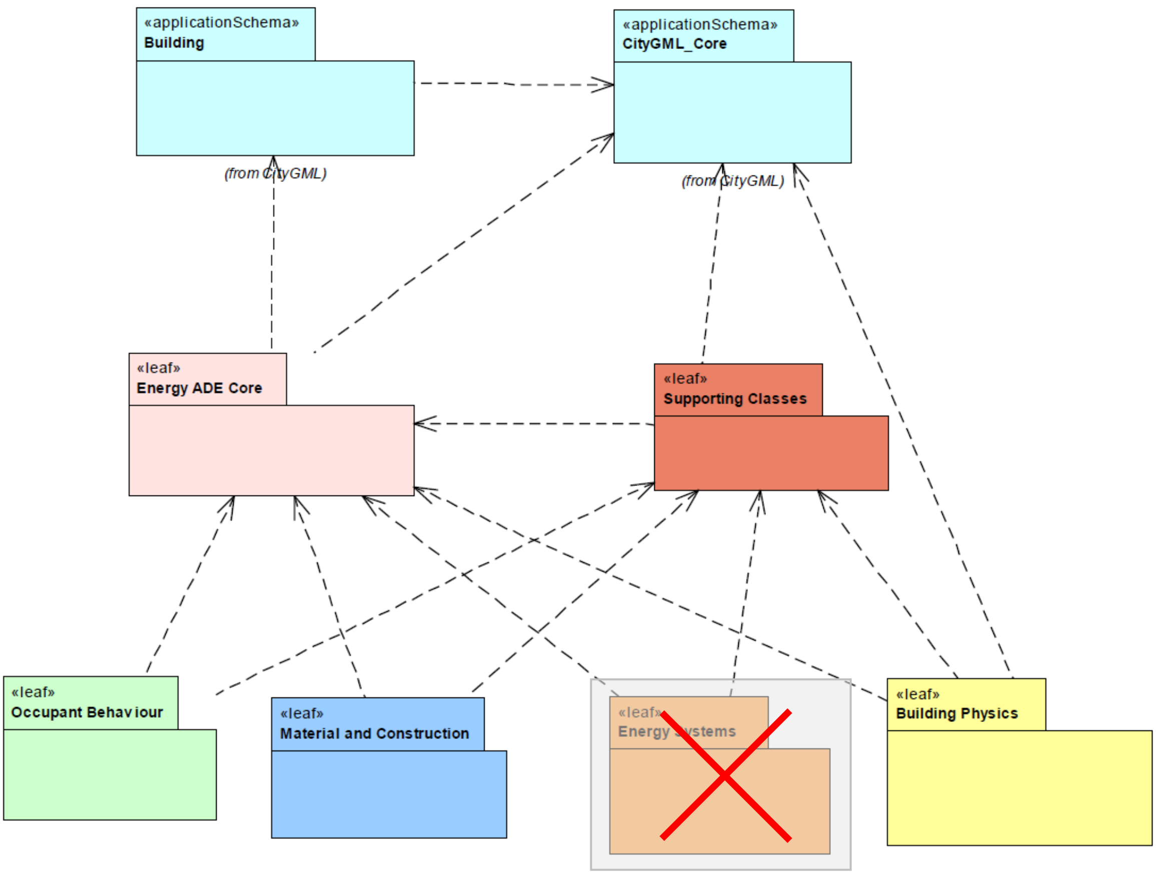


Figure 60: Energy ADE KIT profile: Overview [adapted from: 16]

Energy ADE Core module

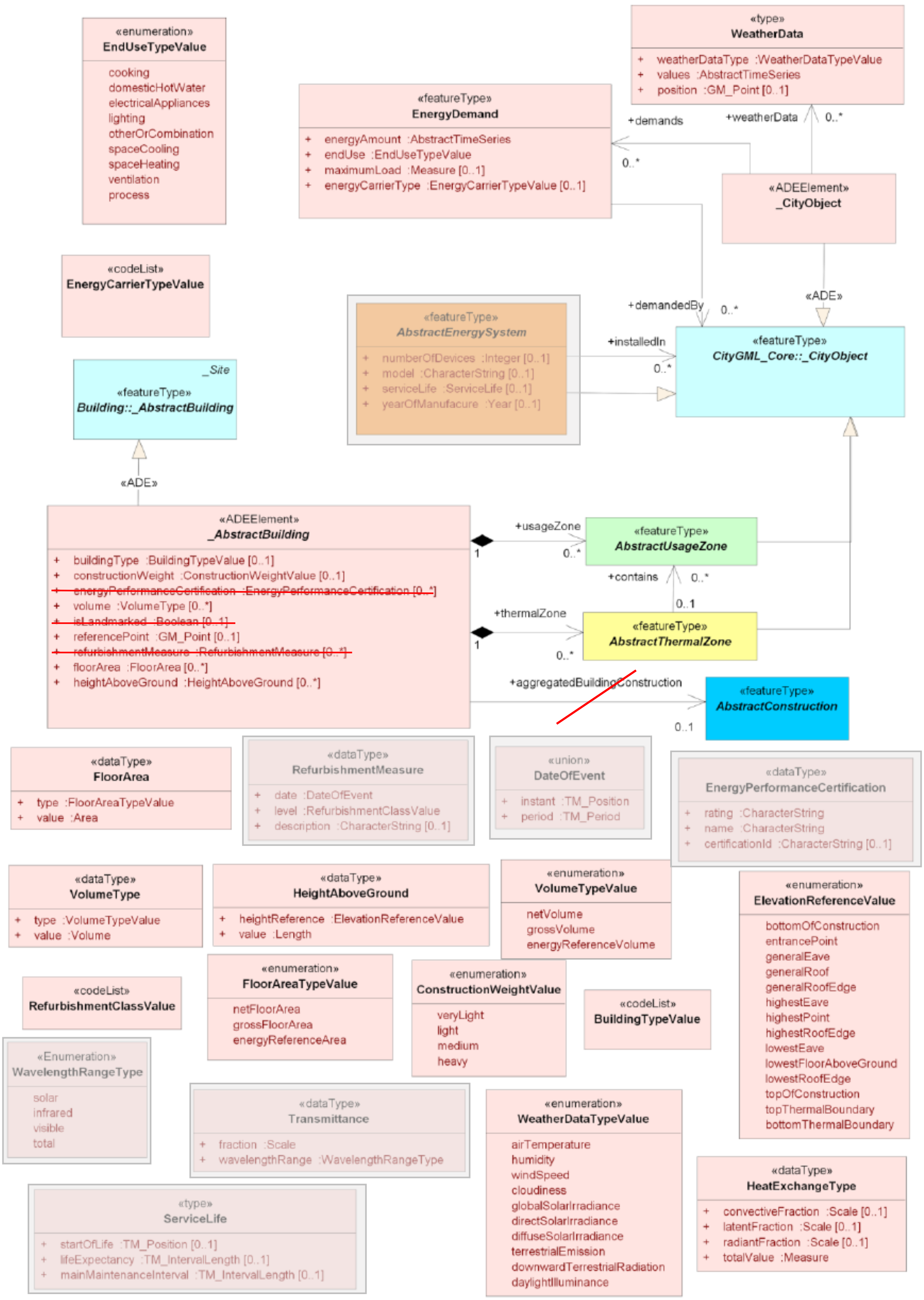


Figure 61: Energy ADE KIT-profile: Core module [adapted from: 16]

Building Physics module

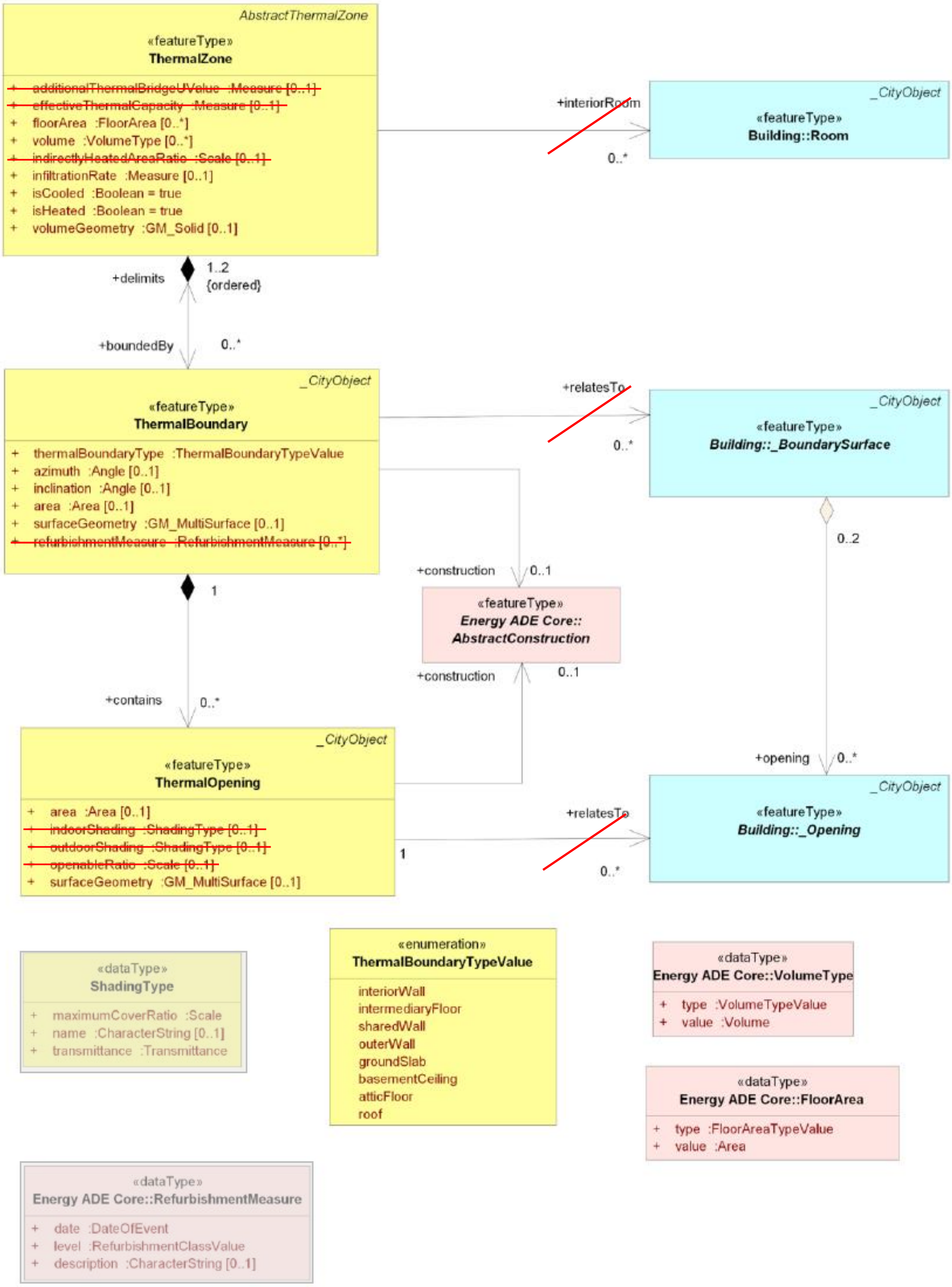


Figure 62: Energy ADE KIT-profile: Building Physics module [adapted from: 16]

Occupant Behavior module

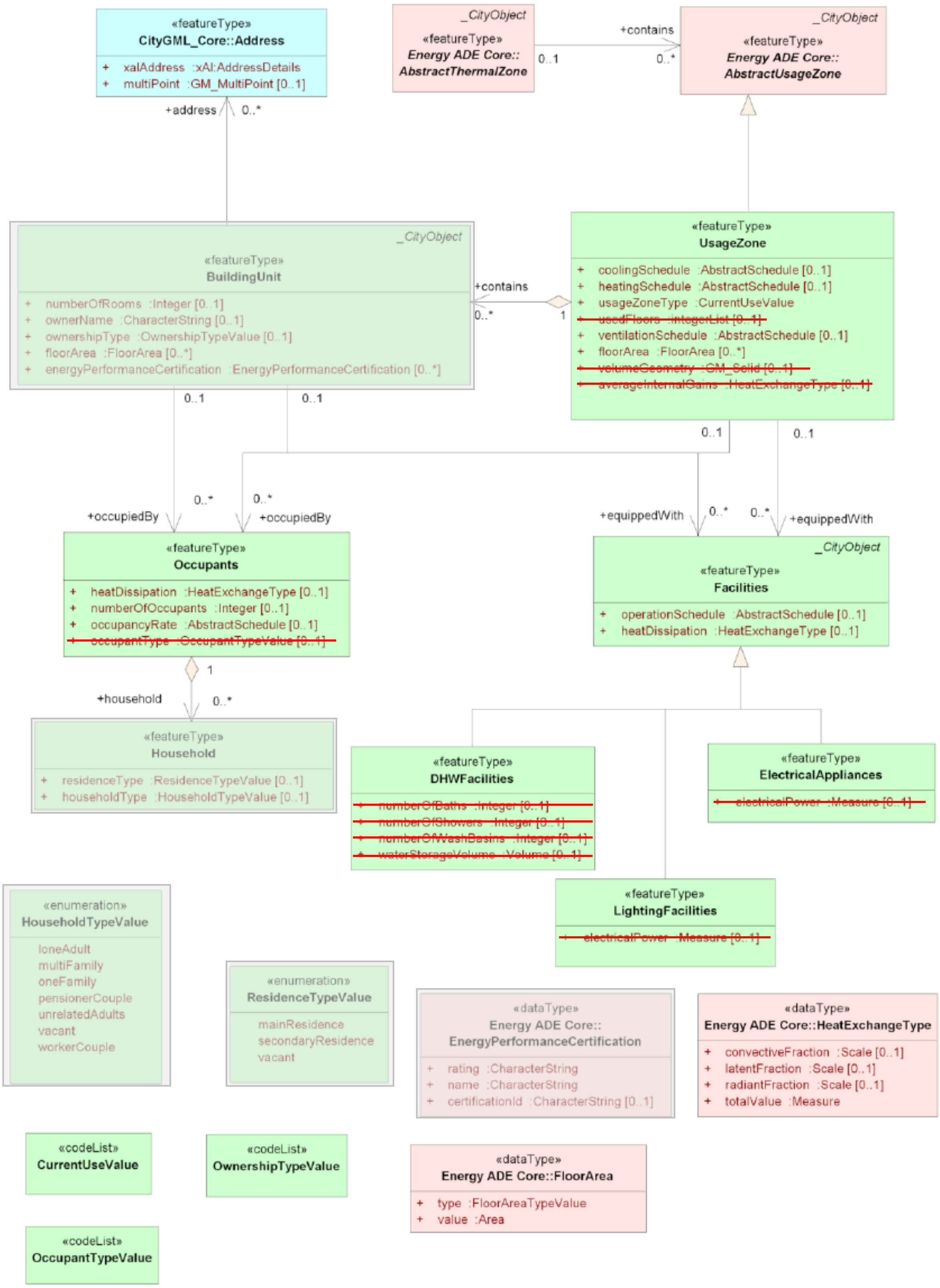


Figure 63: Energy ADE KIT-profile: Occupant Behavior module [adapted from: 16]

Material and Construction module

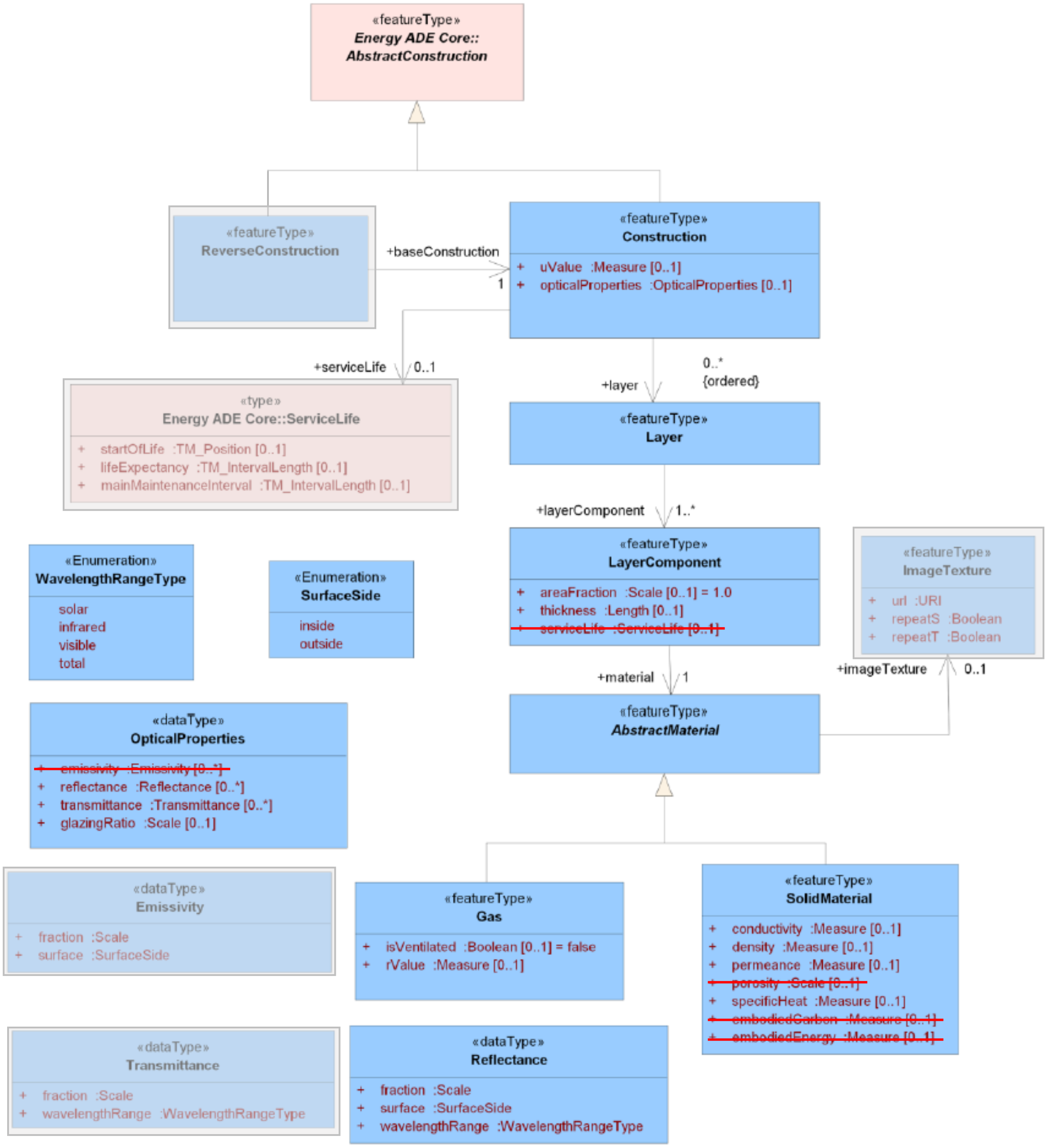


Figure 64: Energy ADE KIT-profile: Material and Construction module [adapted from: 16]

Supporting Classes

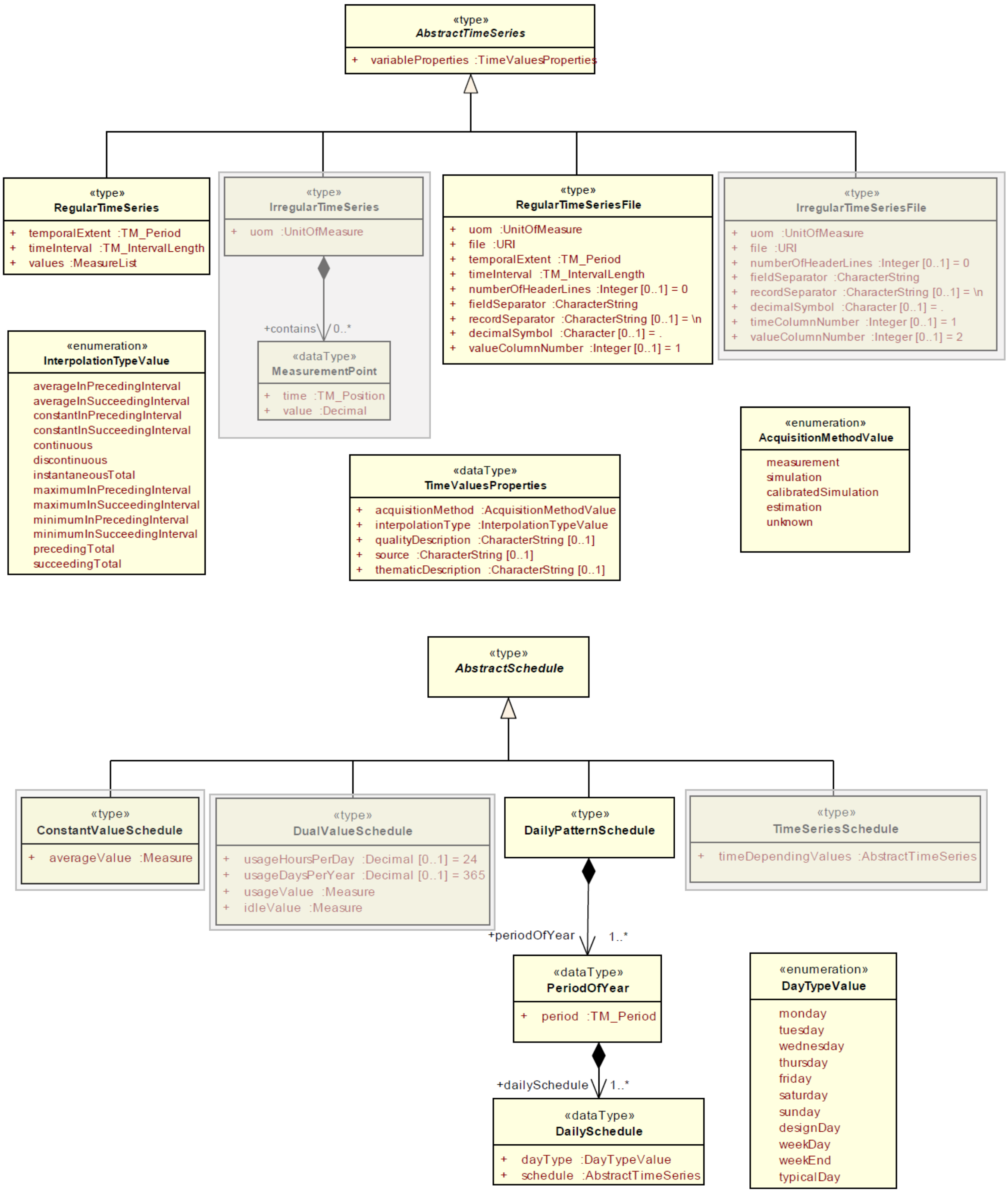


Figure 65: Energy ADE KIT-profile: Supporting Classes [adapted from: 16]

Weather data

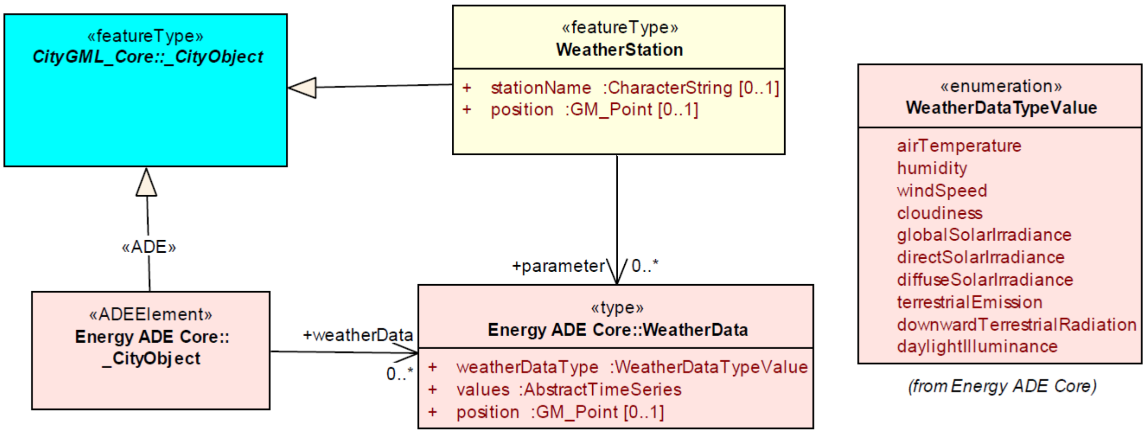
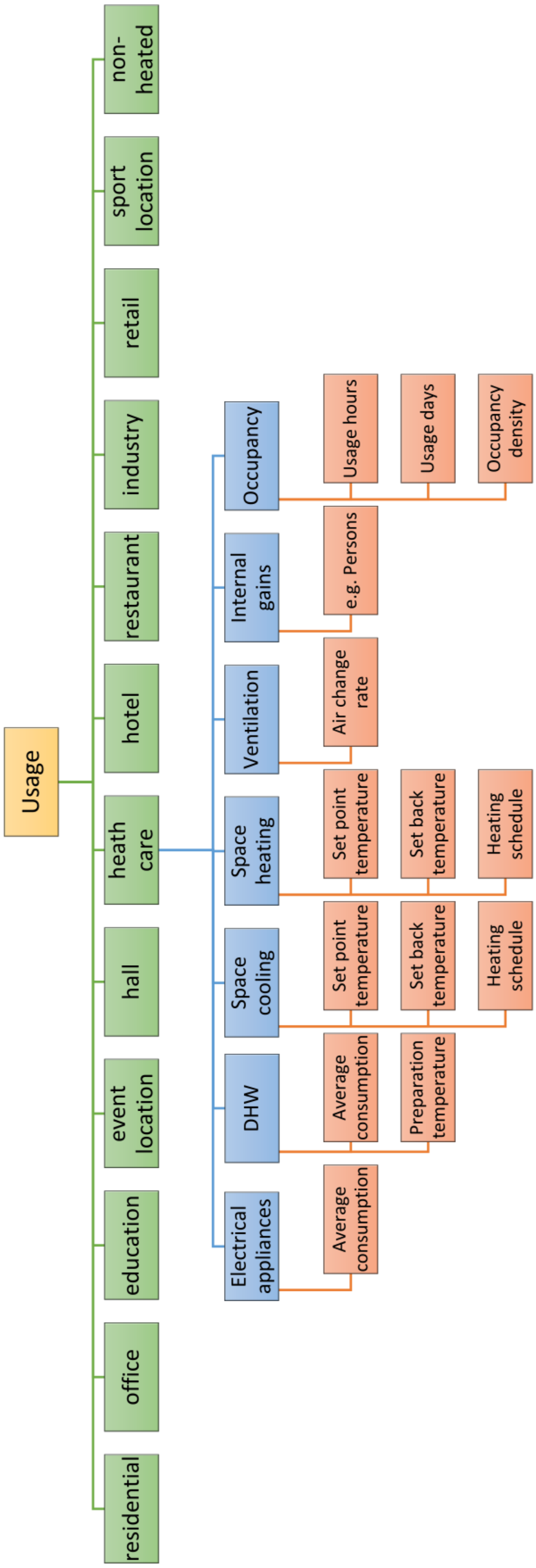
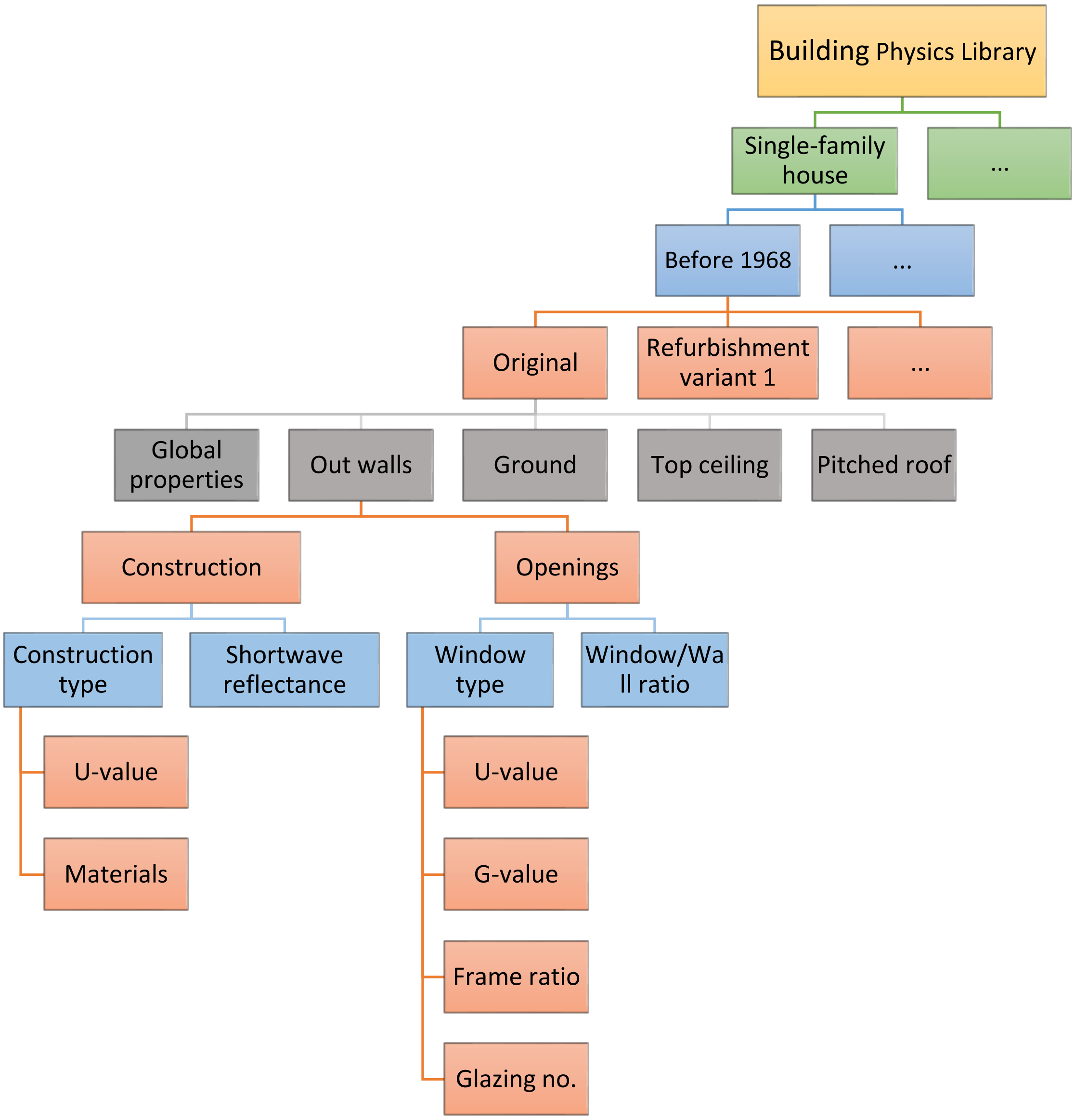


Figure 66: Energy ADE KIT-profile: Weather data [adapted from: 16]

Appendix B: Overview building usage library



Appendix C: Overview building physics library



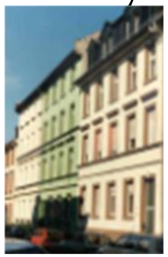
Appendix D: U-values for a single-family house

Table 10: Parameters of the Finnish building physics library for a single-family house

From	To	Average storey height	Thermal capacity	Indirectly heated area ratio	Thermal bridge U-value	Infiltration rate	Wall	Roof	Ground	Window U-value	Window G-value
YYYY	YYYY	m	kJ/K.m²	-	W/K.m²	vol/h	W/K.m²	W/K.m²	W/K.m²	W/K.m²	-
-	1969	2.6	90	0.25	0.1	0.24	0.81	0.47	0.47	2.8	0.76
1970	1976	2.6	90	0.25	0.1	0.24	0.81	0.47	0.47	2.8	0.76
1977	1978	2.6	90	0.25	0.1	0.24	0.7	0.35	0.4	2.1	0.76
1979	1985	2.6	90	0.25	0.1	0.24	0.35	0.29	0.4	2.1	0.76
1986	2003	2.6	90	0.25	0.1	0.24	0.28	0.22	0.36	2.1	0.76
2004	2008	2.6	90	0.25	0.1	0.16	0.25	0.16	0.25	1.4	0.63
2009	2010	2.6	90	0.25	0.1	0.16	0.24	0.15	0.24	1.4	0.63
2011	2012	2.6	90	0.25	0.1	0.16	0.17	0.09	0.16	1	0.5
17	-	2.6	90	0.25	0.1	0.08	0.17	0.09	0.16	1	0.5
Source		[32, 33]	[25]	[25]	[25]	[30, 31]	[30]	[30]	[30]	[30]	[40]

Appendix E: Comparison of German, Finnish and Swedish building topologies

Source	[29]	difference	[29]	difference	[30]	difference
	Germany	**DE-SE**	**Sweden**	SE-FIN	**Finland**	**DE - FIN**
					-	
YOC range	1995 2001		1996 2005		1985 2003	
Building Type	MFH		MFH		Residential	
Wall	0.4	0.2	0.2	-0.08	0.28	0.12
Attic Floor	0.32	0.19	0.13	-0.09	0.22	0.83
Floor / Base	0.4	0.19	0.21	-0.15	0.36	0.41
Door	2	0.5	1.5	0.1	1.4	0.8
Window	1.9	-0.07	1.97	-0.13	2.1	-0.1
Mean		**0.20**		**-0.07**		**0.67**

Source	[29]	difference	[29]	difference	[30]	difference
	Germany	**DE-SE**	**Sweden**	**SE-FIN**	**Finland**	**DE - FIN**
					-	
YOC range	1860 1919		- 1960		- 1969	
Building Type	MFH		MFH		Residential	
Wall	2.2	1.62	0.58	-0.23	0.81	0.12
Attic Floor	1.3	0.94	0.36	-0.11	0.47	0.1
Floor / Base	0.88	0.56	0.32	-0.15	0.47	0.04
Door	3	0	3	0.8	2.2	0.6
Window	2.7	0.5	2.2	-0.6	2.8	-0.2
Mean		**0.72**		**-0.06**		**0.13**

Digital Appendix

The following data produced during this research is provided on the enclosed CD.

1 SimStadt workflow step source code

The source code of the developed SimStadt workflow steps for reading from and writing into a 3DCityDB. The needed SimStadt Java libraries are not included.

2 FME Workspaces

The developed FME workspaces of the file-based and database-based Energy ADE integration approaches.

3 CityGML with Energy ADE files

The CityGML files enriched with attribute information using the Energy ADE. Information about building's renovations is removed.

4 Cesium visualization

The developed Cesium 3D web application runnable on localhost.

5 Building libraries

The defined libraries: building physics library, building usage library, and the energy systems and fuel library, as well as the ALKIS code mapping file.

6 Weather data

The weather and climate data sets used in the simulation.

7 Simulation results

The results of the simulation in the defined scenarios for the entire city model