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Concept and Evaluation of Heating Demand Prediction Based on 3D City Models and the CityGML Energy ADE—Case Study Helsinki

Maxim Rossknecht [1,*] and Enni Airaksinen [2]

1 Department of Informatics, Stuttgart University of Applied Sciences, 70174 Stuttgart, Germany
2 Forum Virium Helsinki Ltd., FI-00130 Helsinki, Finland; enni.airaksinen@hel.fi
* Correspondence: maxim.rossknecht@gmail.com

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Abstract: The heating of buildings causes the greatest portion of greenhouse gas emissions in Helsinki, more energy-efficient buildings may be a key to achieving carbon-neutrality by 2035 [1]. This work presents a concept for heating demand and resulting CO2 emissions prediction based on a 3D city model in CityGML format in various scenarios under the consideration of a changing climate. Therefore, the Helsinki Energy and Climate Atlas, that provides detailed information for individual buildings conducting the heating demand, is integrated using the CityGML Energy Application Domain Extension (Energy ADE) to provide energy-relevant information together with the 3D city model based on a standardized data model stored in a CityGML database, called 3DCityDB. The simulation environment SimStadt is extended to retrieve the information stored within the Energy ADE schema, use it during simulations, and write simulation results back to the 3DCityDB. Due to 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, heating CO2 emissions are predicted to be reduced by up to 82% by 2035 compared to 1990. The City of Helsinki's assumed heating demand reduction through the modernization of 2.0 TWh/a by 2035 is not achieved with a 3% refurbishment rate. Furthermore, the reduction of CO2 emissions is mainly achieved through lower CO2 emission factors of the district heating network in Helsinki.

Keywords: 3D city model; CityGML; 3DCityDB; EnergyADE; SimStadt; CO2 emission; energy demand prediction

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, the City of Helsinki developed a strategy plan containing more than 100 actions. The target has been set for an 80% reduction in CO2 emissions in Helsinki by 2035 as compared with emissions in 1990. The remaining 20% should be compensated by emission reductions outside the city. The share of greenhouse gas emissions in Helsinki is dominated by heating and energy renovations provide here the greatest potential in reducing CO2 emissions [1]. According to the action plan, 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 owners of buildings with greater reduction potential than others.

On the way towards the carbon-neutral city goal, it is even more important for the city to create a common understanding of what the city's situation is in terms of sustainable development now and in the future. To get an overview of the city, there is a need for a framework and various tools to keep up to date what is happening in the city and where. The availability and clever usage of consistent, accurate, and valid spatial data on buildings and their energy demands is one of the key factors in sustainable urban development. Well-organized urban development and decision-making are responsible activities that provide a sustainable and healthy environment for citizens who work, live, and enjoy the city. Urban development can rely heavily on tools and services implemented with 3D city models. In particular, CityGML city model is very versatile because its data storage and semantics allow knowledge to be integrated into a 3D city model, which is well suited to support application development on a city scale. There are many benefits to utilizing CityGML model and its energy extension, and especially opening up information and services to everyone makes it possible to use the information in business and companies, as well as in the daily lives of any citizen. For an individual, this means that online services display various building information and energy consumption estimations, which can then be compared to actual consumption, and all available information can really encourage to make refurbishment and modernization to the city residents' own homes. Open data and public services can attract the business sector to develop new types of products and services that support sustainable development for the benefit of city and its citizens. The results of the energy demand assessment of buildings can be used to answer the challenge of carbon-neutral city, although achieving the goal is a systematic challenge that no city or authority alone can solve.

The City of Helsinki seeks to provide all available data related to the energy of buildings within the Helsinki Energy and Climate Atlas (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 energy-related information for each building. The Atlas is implemented in the semantic 3D city model, and it is part of the city's toolkit to support the energy efficiency of the building stock, the use of renewable energy and, in the future, also for climate action and climate change adaptation. Because the Atlas is implemented only with the basic properties of the CityGML data model, energy-related features are stored in generic attributes, which can lead to data interoperability problems and data processing difficulties. Researching the CityGML's energy extension takes the development of the Atlas tool tremendously forward, and organizes the energy features of the data model correctly both ontologically and semantically. The Atlas contains a wide variety of energy-related building information in a visual and informative form, and the information is freely available to property owners, city planners, and the housing market, which provide information on building performance, and energy efficiency companies. Open data would also benefit the property management industry, which could develop its work and act as a responsible actor. The Atlas contains measured heating energy consumption data, which is available only for Helsinki-owned residential buildings (fin.: Helsingin kaupungin asunnot Oy, HEKA buildings). The Atlas also provides the estimated energy consumption of other buildings, which is categorized by the year of construction and the usage class of the building, allowing only a rough assessment of the energy demand of a building. In any case, the data contained in the Atlas can be utilized by developing new applications and performing new, more detailed analyzes that utilize all building data, as well as additional information entered. The development of any practical and accurate tool for assessing the energy performance of buildings would make it possible to obtain a preliminary assessment of what kind of energy efficiency and renewable energy studies are worth investing in a property.

This research utilizes the CityGML standard and the Helsinki city information model more extensively than ever before. Originally, the CityGML city information model standard was developed to meet the requirements of many different industries for the uses of 3D city models. Helsinki has also recognized the need for a city information model, which is why there is a very usable and up-to-date city model based on the CityGML standard for the entire Helsinki. The CityGML standard contains definitions of the most important objects and their definitions for the city model, and describes the urban environment geometrically, graphically, ontologically, and semantically. The CityGML model consists of two different thematic parts: the core module and extension modules. The core module contains the basic concepts and components of the CityGML model. Extension modules can be used to add new thematic features to the data model. The most important objects for the city model are divided into different thematic modules according to their characteristics. Different thematic objects include, for example, terrain models, buildings, bridges, water and traffic areas, vegetation, and street furniture. In addition, the CityGML-based city model provides a ready-to-use platform for adding new city objects to the city model using the extension modules. One extension module used in this research is called Energy Application Domain Extension (Energy ADE) which can be used seamlessly to add new energy-related features to the city model.

The aim of this research 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, that can be achieved through renovations, 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, additional information of the Helsinki city register and long-term predicted weather data. Information that conducts the energy demand of a building is integrated into the 3D city model using the Energy ADE. For the heating demand simulation, an accuracy of up to 20% deviation from measured values is expected. Furthermore, the yearly refurbishment rate for achieving the needed reduction of heating demand and CO2 emissions will be calculated.

The paper is organized as follows. Section 2 provides an overview of the related research. In Section 3, the overall research concept is presented. The implementation process of the proposed concept is afterwards described in Section 4. In Section 5, the simulation and prediction results are presented and evaluated. Followed by the conclusions and recommendations for future work, presented in Section 6.

2. Related Research

Heating demand prediction can be achieved using various approaches on different scales. Chalal et al. [3] differentiate possible approaches on urban and building scales. As illustrated in Figure 1, 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.

Artificial intelligence and machine learning are considerable evaluation methods for optimizing the energy consumption of buildings and for intelligent energy management. Artificial neural network (ANN) model and support vector machine (SVM) can respond with their simplicity to complex processes of setting parameters, generating models and defining boundary conditions. In addition, even if the information is not comprehensively available, machine learning technology can still be used, and results obtained quickly and agilely. Overall, novel methods based on single or hybrid machine learning are still under development, but it has potential, especially when a preliminary assessment is needed quickly, and data are not fully available. The main issues with machine learning methods that need to be considered before using such a method are the type and number of inputs available for training, and it should also be possible to make some suggestions to the model to improve the accuracy of the prediction [4,5].

Engineering approaches predict energy consumptions 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's, the Level of Detail (LoD), the heated area, and the behavior of its occupants [6].

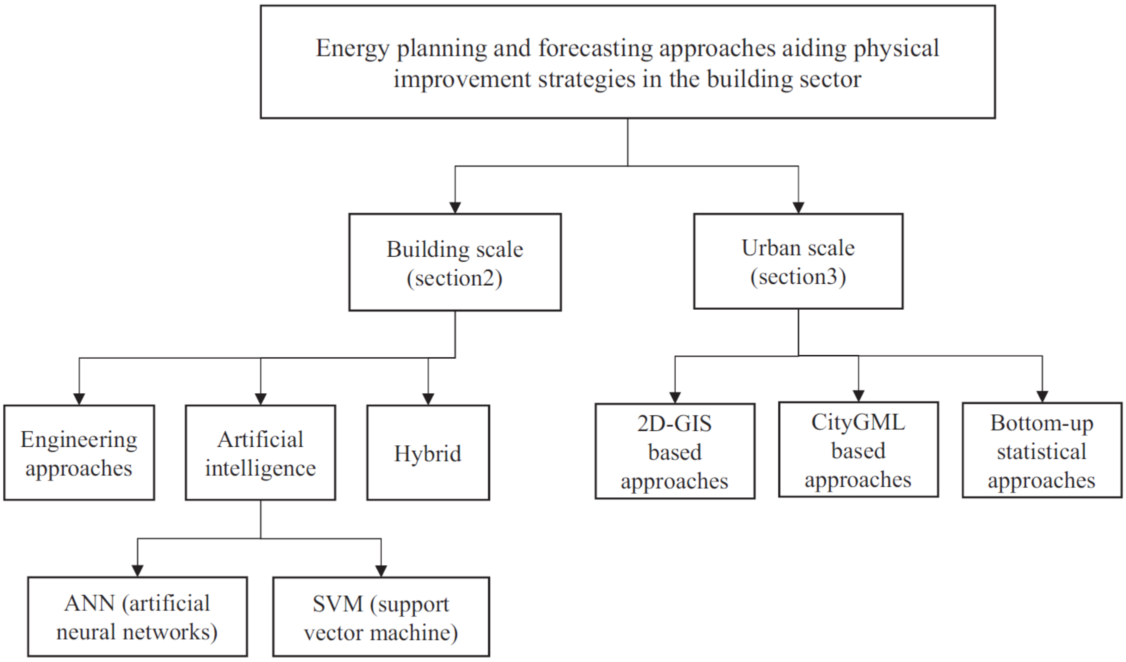

Figure 1. Building energy predictions approach classification [3].

The energy consumption of the Finnish building stock has already been studied using a variety of energy models. An overview of the existing models is provided by Lounasheimo et al. [7]. The POLIREM energy model was developed by the Tampere University of Technology. The researchers developed this model after the EKOREM model, which is frequently used in published works [8]. Both models aim to assess energy consumption and greenhouse gas emissions, primarily based on the building and energy statistics of Finland [9].

Tuominen et al. [10] developed the so-called REMA energy model. Based on representative building types and the IDA Indoor Climate and Energy (IDA ICE) simulation tool, 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 [10].

The same approach was used by Jylhä et al. [11] 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 the year 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 [11].

In 2009, the Laboratory for Solar Energy and Building Physics of the Swiss Federal Institute of Technology Lausanne 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 [12].

The software used in this work, called SimStadt, is a simulation environment that includes physical building and usage models to perform energy simulations based on 3D city models [6]. Several case studies reveal an accuracy in heating demand simulation of 5–21% when compared with measured values. Furthermore, refurbishment scenarios can be applied to calculate the energy saving potential for each building on 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 was 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 by 2050 [13].

3. Concept

The following section presents the aim and conceptual method of the presented research work. An overview is presented in Figure 2. First, the data needed for the heating demand prediction is prepared. Building attributes conducting the heating demand are integrated into the 3D city model using the Energy ADE schema and stored in a database. Additionally, building typologies representing the investigated building stock need to be defined. To utilize information stored with the Energy ADE schema, modifications and extensions of the simulation software SimStadt are done, i.e., a connection between the simulation environment and database to request additional information for individual buildings. Defined refurbishment strategies are applied to the city model, and the heating demand, as well as the resulting CO2 emissions, are simulated. Another software extension is created, which enables a database connection for inserting or updating simulation results directly into the original database using Energy ADE objects and properties. The results are evaluated against measured consummation data before the city model is converted into 3D Tiles format, to be visualized in a 3D web application based on a virtual CesiumJS globe.

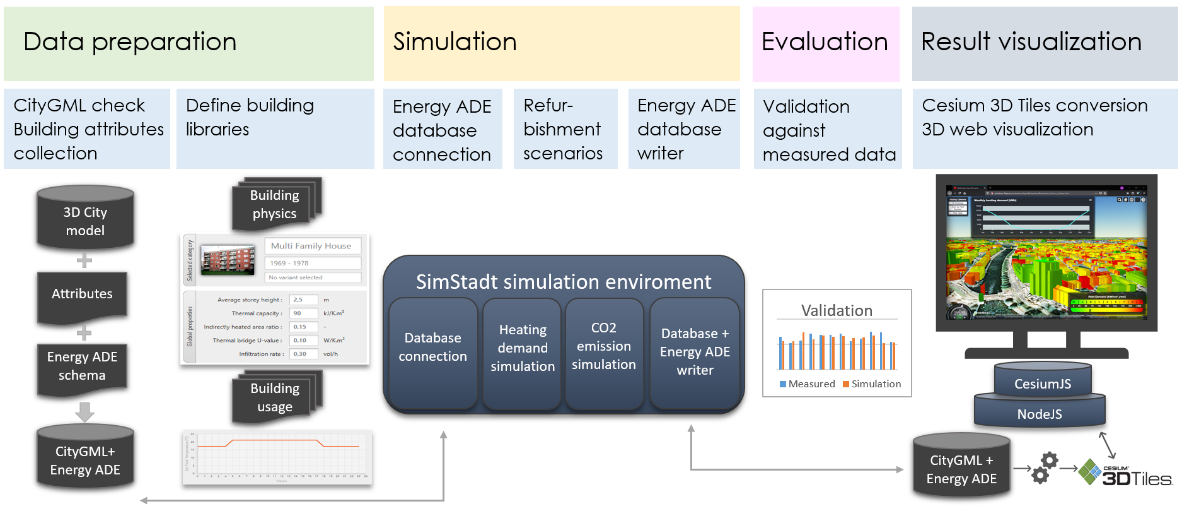

Figure 2. Overview of the proposed concept.

3.1. Data Preparation

Before the 3D city model is used for heating demand simulations, it is checked if the geometries of the CityGML buildings are correctly modeled. Faulty geometries, such as unclosed solids, duplicated points, or intersecting polygons, result in incorrect geometry calculations, that are needed for heating demand calculations. [14]

Furthermore, the 3D city model is enriched with attribute information for each building (e.g., the year of construction and building function). This enables to access so-called building libraries, that model the building stock in needed detail.

3.1.1. Energy ADE Data Integration

Information about the year of construction and building function can already be stored in the standardized CityGML version 2.0 data model using the "bldg:yearofconstruction" and "bldg:function" child elements of a CityGML building. Other building specific information conducting the heating demand of a building, such as the total floor area, different usage areas, or the number of occupants, is stored in the city model using Energy ADE properties and objects. Therefore, two different approaches are examined: a file-based and a database-based approach. As presented in Figure 3, for both, the target is to store the city model in a database for 3D city models with Energy ADE extension, called 3DCityDB. The 3DCityDB is a database solution based on a PostgreSQL DBMS with a PostGIS extension, and it provides the needed schema definitions to store 3D models in CityGML format [15]. Additionally, ADE functionality is provided, which extends the database schema for ADEs (i.e., the Energy ADE). Additionaly, the 3DCityDB Importer/Exporter tool, an open-source Java front-end for the 3DCityDB, is used to manage, store, and export the 3D city model in CityGML format.

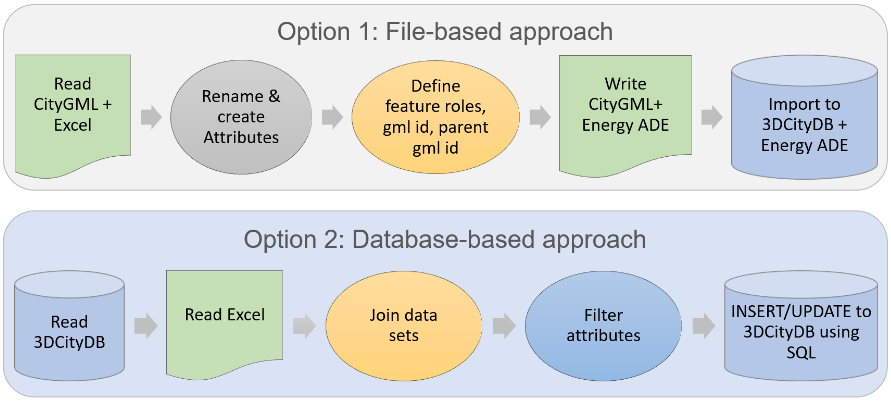

Figure 3. Principles of the Energy Application Domain Extension (ADE) integration approaches.

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. The resulting CityGML file is then imported into a 3DCityDB.

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 extended by the Energy ADE.

3.1.2. Building Typologies

Building typologies, here called building libraries, are used to define the physical behavior of the construction parts, the usage information, and the heating system of a building.

The simulation environment SimStadt already provides these libraries for Germany and New York, but Helsinki is not yet supported. As it is expected that the Finnish building stock differs from the German one, building libraries for Helsinki need to be defined first.

A building physics library is defined to classify the building stock in different construction year ranges, building types, and refurbishment statuses. For each type, general properties, such as thermal capacity, average storey height, or infiltration rate are specified. Additionally, for the building's construction elements (ground, walls, roofs, and windows), the thermal transmittance (U-value) is defined.

Furthermore, a building usage library is created for a further classification of buildings by its function (e.g. residential, office and administration, or retail). Per usage type, usage properties such as occupancy, ventilation, heating profiles and temperatures, or hot water and electricity consumption are defined.

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 heat. Those systems are defined in the energy system and fuel library, which contains information regarding the efficiency of a system and its CO2 emission factors.

3.1.3. Weather and Climate Data

As energy demand for heating is influenced by the climate of the investigated region, weather and climate information in at least a monthly resolution is needed for the monthly energy balance calculations according to the DIN V 18599. For comparing simulation results with the measured energy consumption data from a particular year, observed weather data for the representative year in hourly resolution is used during simulations. 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 long-term predicted hourly weather data sets for the heating demand simulation.

3.2. Simulation Environment

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 several 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 [16].

The minimum requirement for the heating demand simulation in SimStadt is a 3D city model in CityGML format and a building typology representing the investigated building stock. This information is used enrich the buildings with the information from the defined libraries to calculate the monthly energy balance according to the DIN V 18599 standard for building's energy calculations.

The general concept of the monthly energy balance 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). The final heating demand of a building's zone is then calculated by combining the sum of heat sinks and sources with a degree of utilization [17]. 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 [6].

In the first step, the system is validated using measured consumption data from the year 2018. Therefore, observed weather data from the representative year are used. It is investigated if the defined libraries suits for the Finnish building stock and if specific building information from the Helsinki Energy and Climate Atlas is usable for the heating demand simulation on an urban and building scale.

Afterwards, refurbishment scenarios are applied for a prediction of heating demand in several scenarios. Previous refurbishment information from the Helsinki City Register is investigated to apply a business as usual (BAU) scenario. Therefore, refurbishments are assigned to individual buildings of the building stock by chance, but less efficient buildings are used first. A repaid development scenario with enhanced refurbishment rate is selected to predict heating demand and CO2 emissions if more refurbishments are carried out in the future.

To show the heating demand reduction potential that can be achieved through refurbishments for an individual building, the heating demand after a refurbishment is simulated for all buildings and compared against the actual simulated heating demand.

3.3. Energy ADE Extension

To utilize the information stored using the Energy ADE schema 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 (e.g., the number of occupants that can be stored for a UsageZone as a property of an Occupants object), it is directly assigned to a building and not taken from the building typologies or estimated 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 is developed, that directly inserts or updates the simulation results into the database using the integrated Energy ADE schema. This reduces the intermediate step of importing the CityGML files into the database after each simulation.

3.4. 3D Web 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 a CesiumJS 3D web application. Cesium is a JavaScript library suited for visualizing large city models and styling them based on their attributes in 3D Tiles format [18]. As a result, the buildings are styled based on attribute 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.

4. Implementation

The following section presents the implementation of the proposed concept described above.

4.1. Energy ADE Integration

This work differentiates between two approaches for the Energy ADE integration: a file-based approach and a database-based approach. Both are implemented using the Feature Manipulation Engine (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 4. Using the attributes from the Helsinki Energy and Climate Atlas, the following information is defined for the buildings.

A building may have a thermal zone with information regarding the heating and cooling status, the floor area, and volume. A thermal zone may contain several Usage zones. For each usage zone, its type and floor area are specified. Furthermore, a usage zone may be occupied; therefore, the number of occupants is stored. In addition, a building could also have information about the measured energy demand for a specific end use (e.g., for space heating, DHW, or both). The consumed energy is stored as energy amount in a time series. The floor area is an additional ADE building property for which it is possible to specify the net- and gross-, and energy reference area.

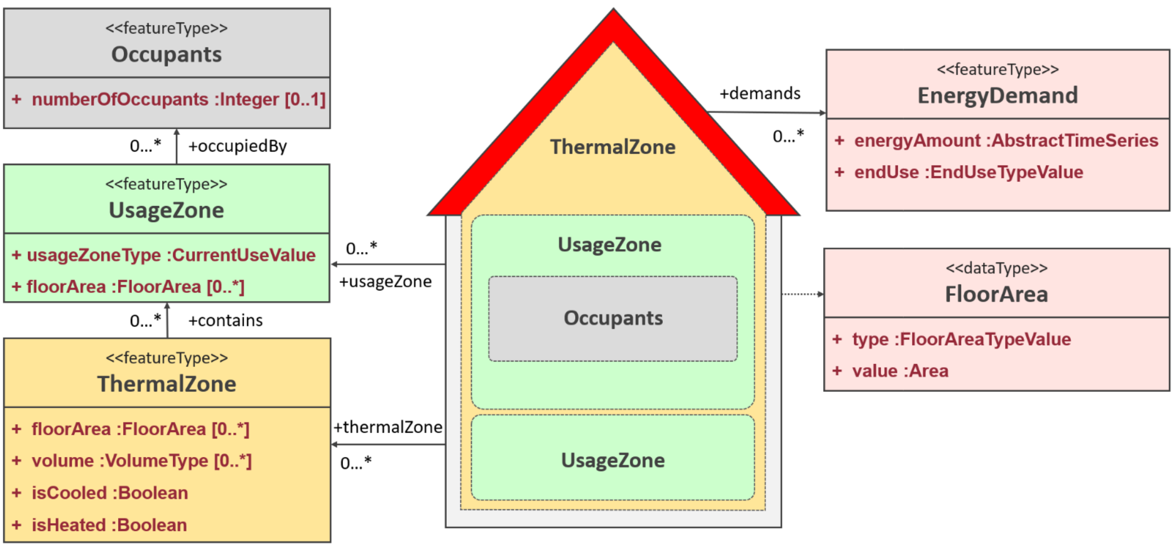

Figure 4. Simplified CityGML building with used Energy ADE information.

4.1.1. File-Based Approach

For the file-based approach, FME is used to merge CityGML and attribute information from Excel files by the unique identification code "VTJ_PRT". Before the attributes are mapped to Energy ADE properties and objects, a new CityGML-writer is defined. Here, the Energy ADE schema file and the "xsi:schemaLocation" are 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.

The mapping of attributes to Energy ADE properties is explained for the example of floor area attribute. Therefore, the Energy ADE *floorArea* property of a building is used. The AttributeManager transformer is used to create three new feature 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 the FME attribute manager.

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

4.1.2. Database-Based Approach

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 existing city objects from the database to the FME workbench. The SQLExecutor transformer is used to retrieve the building identification code "VTJ_PRT" from the city object's generic attributes. The building code is used to merge the city objects with additional attributes from Excel files. The building is now registered to the Energy ADE by inserting its 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 5. 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 an unique id. A floorArea can be linked to a Building, a ThermalZone, or a UsageZone. In this case, the floorArea relates to the building feature.

```sql
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 5. SQL statement to insert the floor area to the ng_floorarea table in a 3DCityDB with Energy ADE extension.

4.2. Building Physics Library and Refurbishment Definition

For defining the building physics library for Helsinki, the decree of the Ministry of the Environment on the energy certificate of a building [19] provides the most detailed information available. A classification of the Finnish building stock is provided by the year of the building permit application. For each year range, the U-values of the construction parts are specified. Furthermore, the air leakage rate is provided in the same classification. The classification years are shifted by about one year to assume the year of construction that is needed in the building physics library.

The needed U-values for already 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, provided from the EPISCOPE Tabula Project [20], are adopted to represent refurbished buildings in Finland. The resulting classification by year of construction ranges for original and refurbished buildings is provided in Table 2.

Table 2. U-Values and infiltration rate by year of construction ranges.

		Original				Refurbished			
From	**To**	**Wall**	**Roof**	**Ground**	**Window**	**Wall**	**Roof**	**Ground**	**Window**
-	-	W/K.m^2				W/K.m^2			
-	1969	0.81	0.47	0.47	2.8	0.33	0.11	0.21	Replaced by original value based on renewal year
1970	1976	0.81	0.47	0.47	2.8	0.22	0.1	0.24	
1977	1978	0.7	0.35	0.4	2.1	0.16	0.08	0.21	
1979	1985	0.35	0.29	0.4	2.1	0.16	0.08	0.21	
1986	2003	0.28	0.22	0.36	2.1	0.14	0.07	0.19	
2004	2008	0.25	0.16	0.25	1.4	0.14	0.07	0.19	
2009	2010	0.24	0.15	0.24	1.4	0.14	0.07	0.19	
2011	2012	0.17	0.09	0.16	1	0.14	0.07	0.19	
2013	-	0.17	0.09	0.16	1	0.14	0.07	0.19	

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 [21]. The implementation in Finland is done through the Ministry of the Environment decree on improving the energy performance of buildings undergoing renovation and alteration [22].

The following U-value reduction 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. [. . .]" [22, Section 4]

The regulation is used to create an energy efficiency refurbishment variant. Therefore, the original defined U-vales are modified accordingly. As no values are specified explicitly for the ground of the building, the U-values for the advanced refurbishment type of the Swedish building topology [20] are adopted.

4.3. Building Usage Library

The created building usage library is based on the German one, which in turn is based on the DIN V 18599. Meaning, only numerical values available for the occupancy, heating temperatures, and DHW consumption are modified according to the decree of the Ministry of the Environment on the energy efficiency of buildings [23].

4.4. Energy Systems and Fuel Library

Overall, 92% of the buildings in Helsinki are connected to the district heating system, while the remaining 8% of heating energy is shared between electric and oil heating (4% for both) [24].

As illustrated in Figure 6, 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 reducing the use of coal. In addition to investing in low-emission energy production, Helen also evaluates the opportunities offered by new energy solutions related to energy saving and efficiency, energy storage technologies and the response to heating demand. The demand response for district heating means adapting to heat consumption and the timing of heating production according to demand.

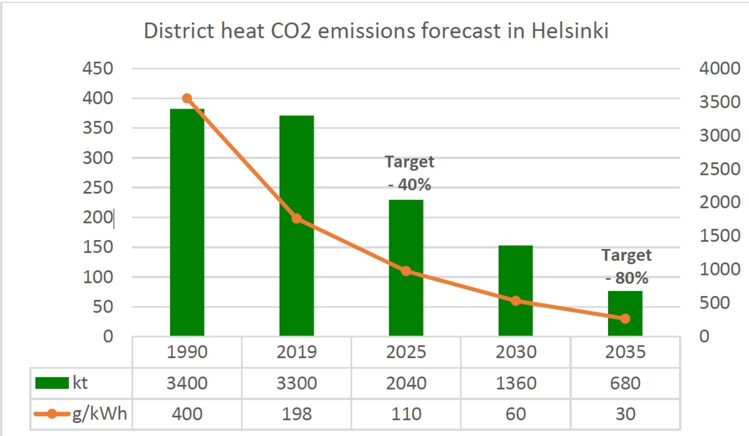

Figure 6. Expected development of the Helen district heating network CO2 emissions [25].

To use the Helen district heating 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.The three others are representative of 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.

Combining the simulated heating energy demand with the yearly global efficiency factor of the district heating network, namely, 0.9 [26], the CO2 emissions for space heating (SH) are calculated in SimStadt using the following formula.

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

4.5. Weather Data Preparation

The Finnish Meteorological Institute provides real observed weather and climate data, as well as long-term predicted test reference year data sets especially developed for building energy simulations [27]. The data sets can be downloaded as CSV files, which are converted to TMY3 format in order to be imported into the SimStadt simulation software. The long-term predicted weather data, provided for the years 2012, 2030, and 2050, are linearly interpolated in five-year steps to enable a stepwise heating demand prediction with consideration of the climate change.

4.6. SimStadt Extension

To use the energy-relevant information that is stored using Energy ADE features and properties, a new SimStadt workflow with additional workflow steps is created. The PostgreSQL JDBC driver is used to access the 3DCityDB with SimStadt. This enables to query the database for the Energy ADE features presented in Section 4.1 for all buildings of the city model at once and assigns the information to a building. As an example, if the Energy ADE property *floorArea* of type *netFloorArea* is present for a building, it is set to be the heated area for the heating demand calculation. This information is otherwise estimated by the average story height and the heated volume, which is in turn calculated by the height of the building, the footprint area, and the calculated volume of the geometry.

As with the reading of Energy ADE information, the results of the simulations are written back to the 3DCityDB using Energy ADE features. 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:

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. Next, 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 then written to the "ng_regulartimeseries" table. Here, the time period properties are specified, including the simulation year.
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".

4.7. Result 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. The CityGML city model is converted into 3D Tiles format using the virtualcitySYSTEMS Publisher, a software that runs on the university server and allows for conversion of CityGML files or city models stored in a 3DCityDB directly into 3D Tiles format. As a base map, the Helsinki aerial imagery from 2017 in an 8 cm resolution is chosen. It is accessed as an OGC Web Map Service (WMS) and through defining a Cesium WMS imagery provider, it displays the imagery on the virtual globe.

An overview of the created 3D web visualization is presented in Figure 7. For exploring the heating demand, CO2 emissions, and possible heating demand savings, several colorization styles are defined. Furthermore, by clicking on a building, interactive charts with more detailed information about the building's heating demand is displayed (see Figure 7, upper left). These charts are created using the JavaScript library ApexCharts.js.

The online service is very useful as it brings together new information about buildings and their energy demands, energy savings and energy demand changes over the years. The heating demand service reveals also quite effectively buildings with good heat consumption and buildings that may consume too much energy for heating. As the heating demand is simulated with an accuracy of 20% deviation from the measured values, some of the results contain errors and these errors stand out in this application. However, completely error-free applications based on building attributes and city model data no one can promise. Because the data is brought together in this study and imported to the city model, small discrepancies in the data become visible very easily. In other words, either an individual property owner may notice a significant deviation in the results from their own consumption, e.g., the energy demand would be exceptionally high based on the simulation, or some buildings do not contain any data at all. However, the fear of the incidence of errors is very small compared to the benefits of integrating data into city model. Errors are part of data management and processing that stems from the data source and cannot be automatically corrected. In any case, most of the results are very useful for looking at both an individual building and a city-wide energy consumption estimate for the present and the future.

Figure 7. Screenshot of the 3D web visualization, showing the buildings colorized by simulated space heating demand.

5. Evaluation

5.1. Validation of Simulation Results

For validating the heating demand simulation, the results are compared to measured consumption data available for 1915 HEKA buildings. While using the additional usage zones area information for the simulation, the mean absolute percentage error was calculated as 25.6% and as 19.6% if the net floor area information from the Helsinki Energy and Climate Atlas is used as the heated area. The total heating demand when using the heated area information deviates from expected values by −3%. When using the usage zone information, it deviates by −32%.

Figure 8 presents the histogram of deviations using the additional information about usage zones and heated area of a building. In general, the heating demand using the usage zone information is simulated to be lower than measured. Furthermore, for 96 buildings, deviations of more than 100% are calculated. These are most likely caused by faulty or missing usage zone floor area information in the Helsinki Energy and Climate Atlas. Thus, the decision is made to exclude the information on usage zones in further simulations.

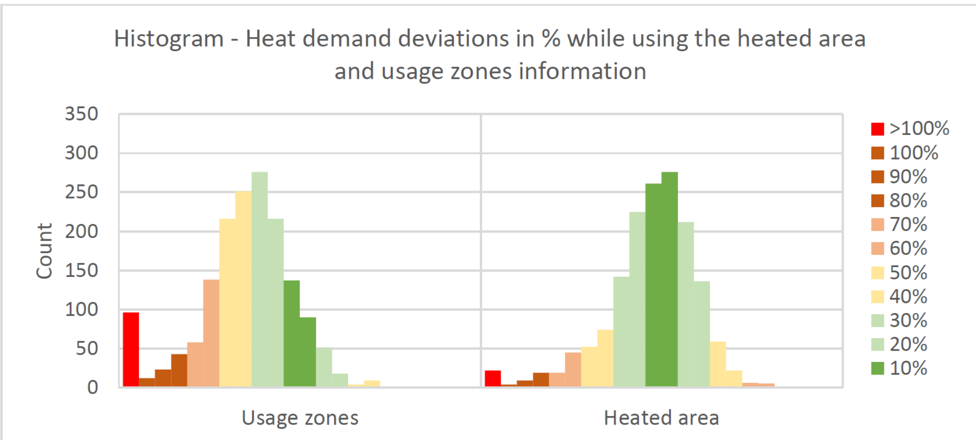

Figure 8. Distribution of deviations using the usage zone and heated area information for the simulation.

While 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 9) and +67% for a building of the retail usage class. 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).

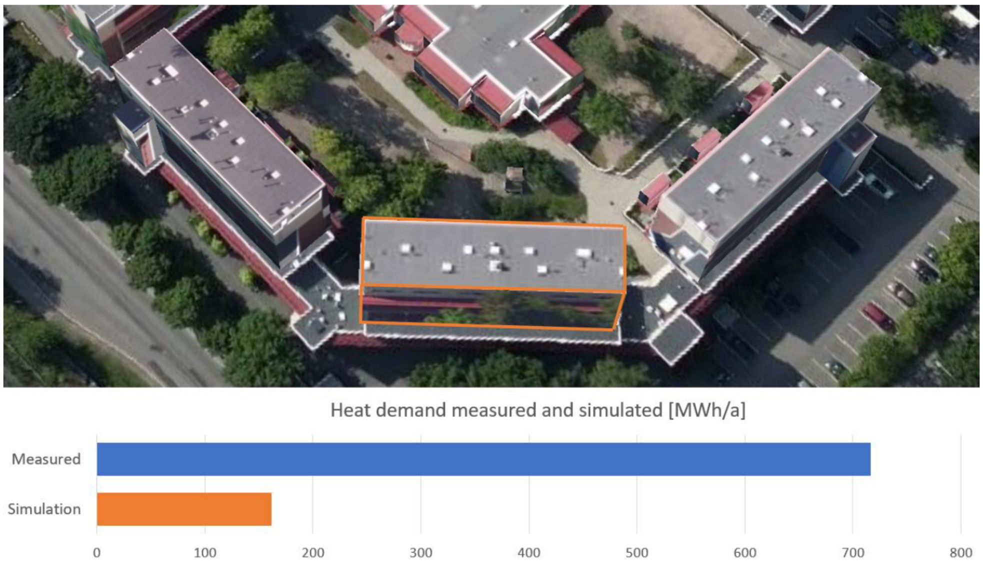

Figure 9. Possible incorrectly mapped heat demand of a building.

Figure 9 presents a building complex for which the heat demand was simulated to be more than three 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 modeled 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.

5.2. Prediction Results

Due to climate change, the heating demand for space heating and DWH of 6.28 TWh in 2020 will decrease to 5.93 TWh/a by 2035, which results in a reduction of 0.36 TWh. By 2050, a reduction to 5.65 TWh is calculated, meaning a reduction of 4% per decade. The calculated reduction agrees with the 2–4% reduction per decade assessed by Jylhä et al. [11]. However, it must be considered that the increasing energy demand for cooling is not included in this analysis.

Figure 10 presents the heating demand of the actual building stock in Helsinki with a renovation rate of 1% per year in the BAU scenario. 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. The reduction in CO2 emissions compared with 1990 are illustrated in Figure 11. The reduction is calculated to be 28% in 2035 and 36% in 2050 if the CO2 emission factors of 2019 are used during the whole period.

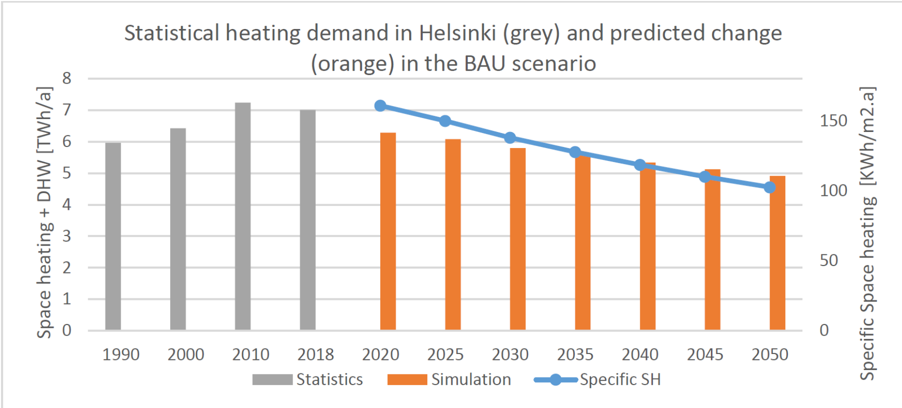

Figure 10. Statistical heating demand (gray) and predicted heating demand (orange) in Helsinki, assuming a 1% refurbishment rate in the BAU scenario.

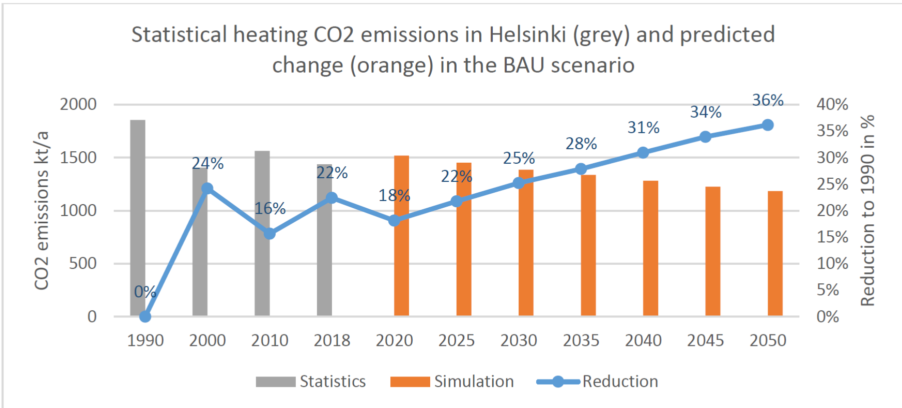

Figure 11. Statistical (gray) and predicted (orange) CO2 emissions in Helsinki with a 1% refurbishment rate, using the 2019 CO2 emission factor for district heating.

The rapid development (RD) scenario assumes a 3% refurbishment rate, including a significant improvement of the district heating network in Helsinki. The resulting heating demand predictions are displayed in Figure 12. Based on the simulated heating 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. As presented in Figure 13, the CO2 emissions are decreasing by 82% from 1990 to 2035 and by 86% from 1990 to 2050.

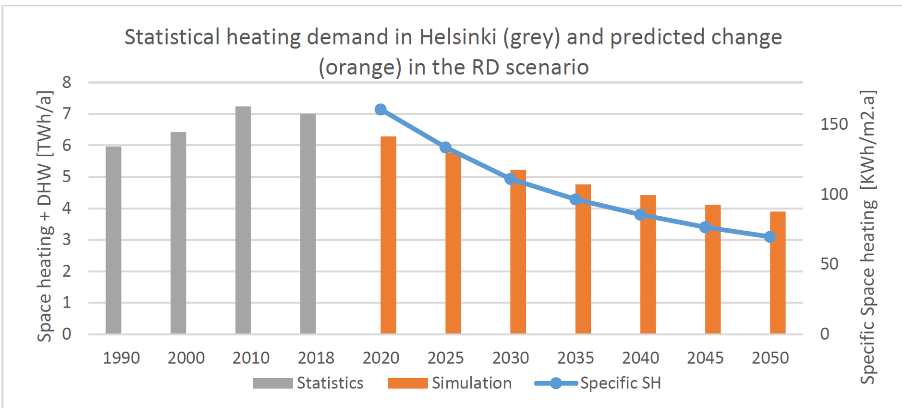

Figure 12. Statistical heating demand (gray) and predicted heating demand (orange) in Helsinki, assuming a 3% refurbishment rate for the actual building stock.

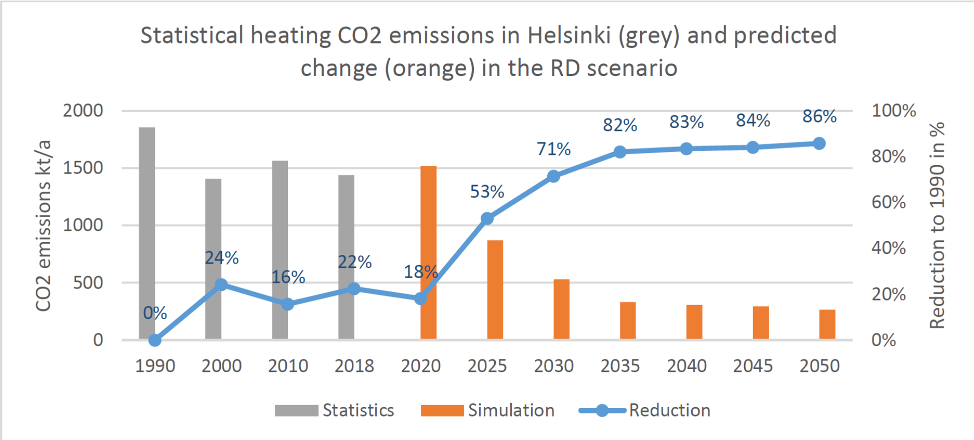

Figure 13. Statistical (gray) and predicted (orange) CO2 emissions in Helsinki with a 3% refurbishment rate and CO2 efficient district heating network.

A visual inspection of the heating demand in the 3D web visualization shows that some buildings are colorized in gray (see Figure 7). This occurs for buildings that are not heated (e.g., bus stops, storage spaces, or garages), or the heating demand is not simulated as the minimum required information about the year of construction and function is missing. Thus, the total heating demand in Helsinki may be even higher than calculated in this work. This also explains the deviation in heating demand on city scale compared to the statistics (see Figures 10 and 12, 2018–2020)

According to the Carbon-neutral Helsinki 2035 Action Plan, "The modernizations 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." [28, 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 not be achieved.

6. Conclusions and Future Work

The simulated heating demand is compared with the measured consumption data, which is validated. The target accuracy of deviations up to 20% is achieved for 61% of the buildings. Summarizing the measured and simulated heating demand of all HEKA buildings, 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 significantly influenced by the expected CO2 emissions reduction of the district heating network in Helsinki. Without district heating improvements, 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. In any case, much remains to be done to be one step closer to the goal of a carbon-neutral city, and especially the developed browser-based application for energy efficiency in buildings can encourage all properties in urban areas to take action to improve energy efficiency and energy use. As the service provides insights into the energy efficiency of buildings and related issues, the service helps city units and urban planners to plan long-term comprehensive and sustainable procurement. The service is intended also for citizens and the private sector. The service serves companies operating in the housing market, as it reveals the energy consumption patterns of buildings and, on the other hand, provides options for refurbishment and improvement measures.

The Energy ADE is suitable as an extension of the data model for the Helsinki 3D city model in CityGML, and for attributes provided by the Helsinki Energy and Climate Atlas. The created SimStadt workflow step, which connects the simulation environment with a 3DCityDB extended by the Energy ADE, allows for retrieving additional energy-related information. 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 advantageous. The simulation results are directly integrated into the 3D city model using the standardized Energy ADE data model. For current developments, the simulation of heating demand can be done in an hourly resolution. Storing 8760 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. The database-based Energy ADE integration approach could be simplified using predefined SQL procedures. Agugiaro and Holcik [29] 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.

Furthermore, 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 Finnish building code are not categorized in different building types. In addition, the air leakage rate, which is estimated by the building's year of construction, may also be a potential cause of deviation.

Even if the number of occupants and households of a building is considered, the behavior of occupants is still an influencing factor in heating demand simulations, which is, like the mechanical and natural ventilation processes, a possible cause of deviations. A more detailed building stock and usage model will probably result in higher accuracy of simulation results.

This work focuses on the actual building stock in Helsinki. In the future, demolished and newly 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 to a year in the future. In this case, the simulation environment assumes that the building is newly constructed, and the physical properties of a new building are used for the heating demand simulation.

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Abbreviations

The following abbreviations are used in this manuscript.

ADE	Application Domain Extension
Atlas	Helsinki Energy and Climate Atlas
BAU	Business as usual
BESTEST	Building Energy Simulation Test
CSV	Comma separated values
DHW	Domestic hot water
FME	Feature Manipulation Engine
HEKA	Helsingin kaupungin asunnot Oy (Engl.: Helsinki owned building)
IDA ICE	IDA Indoor Climate and Energy
LoD	Level of Detail
RD	Rapid development
SH	Space heating
WMS	Web Map Service

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