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Development of a citywide UBEM to support heat planning in Kiel

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Abstract

This paper presents the development of a citywide Urban Building Energy Model (UBEM) tailored for communal heat planning in the city of Kiel. We followed the common UBEM development approach, starting from building local building archetypes. Then the building stock is classified into these types. Energy demand of the resulting building models was simulated using EnergyPlus. Despite using just one set of simulation input parameters for building archetypes so far and despite relying on average parameter values from existing standards and scientific literature, the resulting heat demand closely aligns with reported values and actual energy consumption data in the city. The dataset now acts as an important reference for the city's ongoing communal heat planning. However, running the citywide UBEM simulation requires extensive computational resources, time and storage, highlighting the need for more efficient simulation and data management methods. Our future efforts aim to improve these aspects to better support ongoing heat planning in Kiel and other communities in the region.

Introduction

In Germany's energy transition, the proportion of renewable energy used for heating will further increase. Heating systems using fuel oil and natural gas will phase out. Buildings that are not energy efficient require further retrofitting measures. Municipal or communal heat planning (Braunger 2023) provides a pathway to achieve climate-neutral heating in urban and rural areas. It guides local actors and homeowners in choosing cost-effective and climate-neutral heating solutions, while also examining the technical and legal requirements for different options. One of the basic data requirements of heat planning is to understand the city's status quo energy demand and estimate how heat demand will develop in future scenarios.

Urban building energy modelling (UBEM) is a relatively new research field that aims to evaluate the energy performance of building clusters at community- or city-scales (Reinhart & Cerezo Davila 2016). More and more cities are leveraging this tool to strategise their energy saving and emissions reduction targets and evaluate their measures of energy transition (switch from fossil fuels to renewable energies) and building efficiency retrofitting (Cerezo Davila et al. 2016, Chen et al. 2017, Buckley et al. 2021, Ang et al. 2023). UBEM stems from the field of building energy simulation (BES). According to Swan and Ugursal's widely acknowledged review, most UBEMs employ 'bottom-up' approaches that result in physically sound engineering models for building energy simulation (Swan & Ugursal 2009). In, recent years, hybrid models have seen rapid advancement, offering a more comprehensive understanding of building energy modelling (Kong et al. 2023).

UBEM requires the combination of multiple datasets (Wang et al. 2022). Capturing detailed information on all studied buildings, as required by Building Energy Modelling (BEM), would be labour-intensive, time-consuming, and thus prohibitively expensive. Therefore, UBEM often uses 'building archetypes', which are building definitions that represent a group of buildings with similar properties, to assign non-geometric modelling parameters to individual buildings within the group. The European research project TABULA was a notable effort to generate nationwide residential building prototypes for 20 European countries (Loga et al. 2016, Ballarini et al. 2014). In Germany, some states and regions have also developed their own residential building archetypes based on local residential building stocks (ARGEe.V. 2012). The German Institut Wohnen und Umwelt (IWU) developed nationwide building archetypes for non-residential buildings (Hörner 2022*a*,*b*).

Geographic information systems (GIS) and geodata are increasingly linked to UBEM (Wang et al. 2022). This is because geodata often contains rich information about buildings, including not only building footprints, usage, age of buildings, etc., provided by official cadastral maps or open source geodata such as OpenStreetMap, but also information about building heights, window-to-wall ratios, etc., obtained through modern remote sensing (Chen et al. 2019, Dochev et al. 2020). In Germany, 3D building models are usually provided in the format CityGML LoD2 by the surveying and mapping agency (*3D-Gebäudemodelle LoD2 Deutschland (LoD2-DE)* n.d.). Although data used in this study is also partly available through open data, support from the city of Kiel enabled access to officially managed geodata sets.

This paper describes a UBEM for Kiel, following a common workflow implemented via Python. Kiel's UBEM simulates the space heating, hot water and cooling demand of the entire urban building stock for residential and non-residential buildings with a typical meteorological year under predefined space conditioning requirements. The modelled data fills a gap in data demand for developing municipal heat plans for the city of Kiel, pointing out the potential application of UBEM. We also share insights from our experience creating a citywide UBEM.

Study Area and Background

The city of Kiel has around 250,000 inhabitants. The local building stock consists of 41,141 buildings (37,913 residential and 2,915 non-residential) as stated by local statistics (Stadtamt 2023). According to Kiel's master plan for climate protection (SCS 2017), the city emitted 2,150,000 t CO_2eq in 2014. The final energy demand of the building stock for space heating and hot water, currently covered by gas, district heating, and heating oil, was modelled citywide for the master plan. With a total of 2,517 GWh (1,768 GWh from private households, 721 GWh from commerce, trade and service sector) it represented around 54% of the city's overall final energy demand in 2014. Nevertheless, no mapping of the building heat demand was done for this master plan at that time.

By the end of 2024, a communal heat plan (Braunger 2023) needs to be provided by Kiel and other communities based on the law of the federal state (Landesregierung 2017). These heat plans must include a mapping of heat demand to develop spatial concepts for renewable heating solutions in each community's building stock. Already in 2021, a pilot study was conducted by one of the authors of this paper to model the heat demand of a district in the city in high detail. Together with city representatives from Kiel, the author joined a multinational workshop on 'UBEM.io', a tool developed by MIT Boston's Sustainable Design Lab (Ang et al. 2022). In 2023, Kiel started the official citywide heat planning process. Modelled data on the status quo of heat demand was needed since no complete citywide geodata set on energy consumption was available. The Kompetenzzentrum GeoEnergie (KGE) at Kiel University (CAU) then set up its own UBEM workflow based on EnergyPlus and Python, to automatically simulate the heating and cooling demand of every building (residential and non-residential) in Kiel to support the planning process. This paper describes the efforts to use this newly developed tool to create a citywide UBEM for Kiel.

The UBEM Kiel Workflow

Preprocessing

Merging Available Geodata

Two available geodata sets on the cities' current building stock (3D city model in a level of detail 2 (LoD2) with building geometries and heights; building footprints with usage and year of construction) were provided by the cities' geodata department. Buildings and building parts in LoD2 were merged with building footprints based on their identifiers and spatial relationships. The results retain attributes such as median building height, construction period and usage. Heated buildings were identified based on their usage. All residential buildings were assumed to be heated. For non-residential buildings, it was decided by their usage. For example, offices, schools, stores, repair shops, and warehouses were assumed to be heated, while sheds, stables, garden huts, or underground car parks were assumed not heated. The resulting geodata set consists of 41,155 heated building footprints (35,934 residential and 5,221 non-residential) with associated attributes for further processing and simulation.

Creating Building Type Simulation Templates

A regional building typology for residential buildings (ARGEe.V. 2012) was used to create residential building simulation templates with necessary input parameters. This typology gives typical construction and material used for building parts of single-family houses (SFH) and multi-family houses (MFH) with resulting heat transfer coefficients (U-values) for walls, roofs, windows, and floor slabs in six different construction periods (before 1918, 1918 to 1948, 1949 to 1957, 1958 to 1968, 1969 to 1978, 1979 to 1987). Residential buildings built after 1987 were considered as new buildings. Information on each type is provided in three refurbishment versions (not modernised, slightly modernised, and moderately modernised). All templates were created based on information for the slightly modernised refurbishment status. To assign these residential building types to building footprints in the merged geodata set (see above), residential building stock was classified into SFH and MFH based on footprint area (MFH has more than 250 m²) or number of floors (MFH has more than 3.5 floors, assuming a floor height of 3.5 m).

For non-residential buildings, a nationwide building typology (Bischof 2022) was used to create simulation templates. This typology gives U-values of walls, roofs, floor slabs, and windows for 11 building usage classes (e.g. office, education or commerce and industry) in three construction periods (built until 1978, 1979 to 2010, built after 2010) and one consolidated type per usage. These 44 non-residential types were matched to the more detailed classification in the geodata set. Window-to-wall ratios for non-residential building types were also derived from this typology.

Further simulation parameters including heating and cooling setpoints, schedules of people's presence inside buildings, available square meter per person, the heat emitted by people, lighting and electric devices, or energy demand for hot water preparation were set according to the German standard (DIN 2018) and existing researches (Ahmed et al. 2017, Bischof et al. 2022). Due to the lack of details for each building, we set these parameters for each building archetype separately, and buildings of the same type were simulated using the same settings.

Simulation using EnergyPlus

Modelling Input Data Files

Simulation parameters are combined to generate input data files (IDF), for the open-source building simulation software EnergyPlus (e+, version 22.2) (USDOE 2017).

Thermal properties of the building including window-to-wall ratio, U-values of the building envelope, infiltration and ventilation rate, and occupancy behaviour are derived from the corresponding building types.

Thermal zones of a building are automatically generated from the geodata, using building footprint and median height. Several geometry zoning approaches were reported for UBEM (Faure et al. 2022, Chen & Hong 2018). Based on our pilot experiments, the use of the shoe box model tends to overestimate the heating demand compared to the actual consumption data, while the use of the single heat zone model tends to underestimate the heating demand. The single zone per floor model provides a closer approximation to the actual consumption data. The findings are also in alignment with the work by Faure et. al.(Faure et al. 2022). The shape of the roof and the presence or absence of a basement in the building were not taken into consideration, as it is difficult to confirm whether the roof floor and the basement are heated or not, which may result in discrepancies between the modelled and actual results, and the magnitude of the effect needs to be further investigated.

Each thermal zone's heating and cooling system is modelled as an ideal air load system to obtain the heat required to be added or removed from the indoor environment to reach the predetermined indoor temperature (20 to 26°C).

Configurations

Based on these IDFs, heating demand (space heating and domestic hot water) and space cooling demand were simulated on an hourly basis for each building model. A local typical meteorological year (TMY) from the period 2007 to 2021 sourced from the website *climate.onebuilding.org* in EnergyPlus weather file format (EPW) was used for the simulation.

Due to a lack of soil temperature data, we assumed a soil temperature of 18 degrees Celsius, the recommended value for Energy Plus. In addition, we set the simulation's time step to 10 minutes to ensure its accuracy with less computation time.

Postprocessing and Visualisation

Simulation results include hourly indoor air temperature for each thermal zone, hourly energy demand that the heating or cooling system needs to add or remove to each thermal zone to reach the predefined room temperature as well as the energy needed to cover simulated hot water demand. Since the simulation results are stored separately for each building, each item is read separately and merged into a single comma-separated file (CSV). Each line in the CSV file represents simulation results for a building and is indexed by a building identifier (ID). Based on this ID, results can be merged and visualised with geodata like the 3D city model as shown in Figure 1.

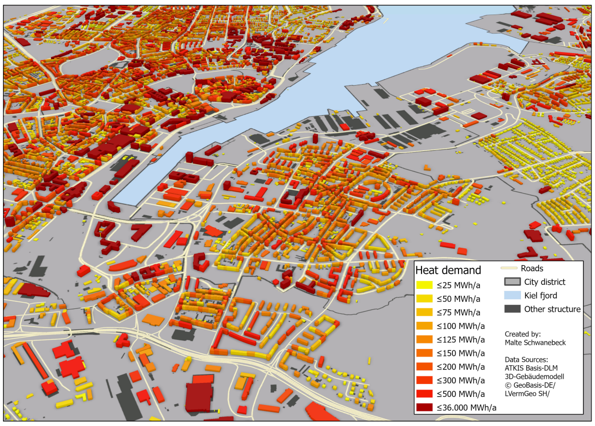

Figure 1: Simulation results mapped on 3D city model showing annual heat demand per building for the city centre of Kiel.

Results Analysis and Discussion

Simulation results with an hourly resolution for total heat demand, space heating and hot water heat demand of heated buildings were aggregated to monthly and annual demand (Tab. 1). To validate the developed UBEM, only a few data sets were openly available for the study area. We first compared simulation results to modelled numbers from the cities' master plan for climate protection. When comparing the simple percentage deviation between validation data and simulation results in Table 1, please note that in the master plan non-residential buildings cover just commerce, trade and service sector buildings and numbers are given in final energy demand for the year 2014.

Furthermore, we compared our results to natural gas consumption data provided by the local energy supplier, but only for one residential district with about 500 buildings. The data set itself represents again just approximately 80% of the annual heat consumption in this district, since not all buildings are connected to the local gas grid and in some buildings water might be heated using electric flow heaters. This data on natural gas consumption was converted from m³/a into MWh/a assuming 12 kWh/m³ as a gross calorific value of the gas. The resulting value stated in Table 1 is an average over three years (2018 to 2020) including weather effects on space heating demand while the developed UBEM uses typical meteorological weather data for the 15 year period 2007 to 2021.

Another available data set was on annual district heating consumption of about 50 non-residential buildings located at one part of Kiel's university main campus area provided by the university building management department for the years 2017 to 2023. Again this consumption data might not reflect the total heat demand in this area, since in some buildings also electric flow heaters might be used to heat water.

UBEM simulation results for space cooling demand are not given in Table 1 since to the knowledge of the authors, there was no local validation data set available. Annual cooling demand adds up to 339,223 MWh, where non-residential buildings have the main share with 262,586 MWh (77.4%) compared to 76,637 MWh for residential buildings. Simulated total annual space cooling demand therefore as a share of 12% on total simulated energy demand for heating and cooling of buildings in the City of Kiel. Currently, devices for space cooling or even district cooling systems are not widely applied in the building stock but this might change if in future this cooling demand increases due to regional effects of ongoing global warming and intensification of urban heat island effects. This should be investigated in scenarios using potential future weather data sets.

In general, the developed UBEM overestimates validation data on heat demand by 6.7% to 33.6%. Considering the above-mentioned aspects and that reported modelled and measured data might represent slightly different numbers of buildings due to different input data or definitions of heated buildings, simulation results are in reasonable agreement with available validation data. So far only one of several possible sets and combinations of simulation input parameter values e.g. for U-values of wall constructions for residential buildings or air infiltration rates in non-residential buildings was chosen to represent the local building stock. The effects of choosing different input parameters on a deviation between simulation results and validation data should be investigated in parameter studies.

Practical considerations

Simulation of 41,155 buildings requires a significant amount of storage space and computational time. The simulation for the city-wide UBEM takes about 27 hours with about 240 GB of intermediate data (output files of EnergyPlus). To further support the

Table 1: Citywide **simulation results (useful energy)** for annual heat demand, space heating, hot water and results for a residential district and for non-residential buildings on a part of university campus compared to available ***validation data (final energy)***.

Simulation results [MWh/a] for ...	**heat demand**	space heating	hot water	***validation data***	deviation
all heated buildings	**2,827,523**	2,013,278	814,245	***2,517,000***	12.3 %*
all residential buildings	**1,887,294**	1,477,947	409.347	***1,768,000***	6.7%*
all non-residential buildings	**940,229**	535,331	404,898	***721,000***	30.4%*
all buildings of a residential district	**11,789**	9,168	2,621	***8,824***	33.6%*
all buildings of a university campus area	**12,333**	8,587	3,747	***10,160***	21.4%*

***Notes:** Validation data modelled for the master plan is given as final energy in GWh/a in master plan document.
Non-residential buildings in master plan cover just commerce trade and service sector buildings.
District average consumption data just represents approximately 80% of heat consumption.

heat planning in Kiel, several scenarios shall be analysed using the developed UBEM. Therefore, the simulation's running speed will be critical. This requires a more compact and efficient solution for storing, managing, and analysing the data in future.

Conclusion

This paper demonstrates the development of a citywide UBEM to support municipal heat planning in the city of Kiel. The development of the model follows a common workflow for UBEM. We extracted geometric information on buildings from available geodata and classified buildings into archetypes based on usage, footprint area, number of floors and construction period. We developed local building simulation templates for Kiel based on regional and national building typologies to assign non-geometric attributes to each building via the Python tool and simulated energy demand for all buildings of the city using EnergyPlus software. Comparison with reported demand and actual consumption data shows that the UBEM results are close to available validation data, despite the fact that no special calibration process was carried out and only average values from standards and the scientific literature were used. It became obvious that running the developed UBEM requires significant computational resources, computational time, and storage space. To continue supporting municipal heat plan development in the region, we are planning to adopt a faster simulation methodology and more compact approaches to data storage and management.

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