A simplified urban building energy model to support early-stage energy plans

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Abstract

The latest attempts in determining the spatiotemporal patterns of energy use in the building sector have led to the development of a new set of tools referred to as "urban building energy models" (UBEMs). Due to the high level of complexity, the computation cost of UBEMs risks becoming impractically large. As a substitution for complex models, in this study, using a simplified steady-state method for calculating the energy performance of buildings, a more computationally efficient UBEM is proposed. The developed model uses the available information of buildings from open datasets, translates them into simplified physical models, and, finally, estimates the energy performance of buildings for desired spatial and temporal resolutions. A comparison of the simplified UBEM with an advanced UBEM, developed around the building energy simulation software EnergyPlus, proves that the suggested simplified model performs within an acceptable range of accuracy. Furthermore, using the simplified model, the computation cost of the model can improve considerably, from hours to only a few seconds. By validating the results of the simplified UBEM against the measured energy performance of buildings from the Swedish energy performance certificate (EPC) database, it can be also seen that the MAPE does not go higher than 31%.

Introduction

Worldwide, the urban building sector is responsible for more than 40% of the energy use as well as greenhouse gas emissions ("European Commission," n.d.). Considering the projected urbanization rate and the new urban agendas on structural transformation of urban energy systems towards energy efficiency and carbon neutrality, the need for urban integrated energy plans becomes more evident (Torabi Moghadam et al., 2017). According to these new plans, the future development of urban energy systems is characterized by reliable energy transition pathways which underline the optimized energy efficiency strategies, increased locally harnessed renewables and decentralized energy systems.

Given the importance of integrated urban energy plans, the ongoing research is focused on the development of a set of analytical tools for mapping out the flows of energy throughout the urban energy systems. With a focus on the building sector, so-called urban building energy models (UBEMs) have been introduced for further analysis of spatiotemporal patterns of energy use in the built environment. According to Reinhart and Cerezo Davila (Reinhart and Cerezo Davila, 2016), an UBEM is a bottom-up engineering-based approach to modeling energy use in large sets of buildings. As in building energy modeling (BEM), in urban building energy modeling (UBEM) the modeling procedure starts with the development of thermal energy models of buildings using established building energy simulation tools or tailor-made algorithms (Johari et al., 2020). However, unlike the conventional BEM methods for extrapolation of urban energy use from a collection of buildings, the UBEM is an integrated framework for modeling and simulation of individual buildings and accumulating the aggregated energy over the urban areas (Johari et al., 2020).

The ongoing research in the field of UBEM has led to the development of various tools differing in handling input data, constructing thermal models, and conducting simulations. Examples of some of the existing UBEMs are found in Ref (Cerezo Davila et al., 2016; Fonseca et al., 2016; Hong et al., 2016a new; Nageler et al., 2018; Nouvel et al., 2015; Robinson et al., 2009).

Urban building energy modeling framework

In the context of urban energy planning, the UBEMs not only illustrate the current status of the energy systems but also make it possible to foresee the results of any changes in the system. These qualities of an UBEM make it an appealing decision-making tool for planning for energy and carbon mitigation scenarios, and extensions to the systems, particularly in new city districts (Ang et al., 2020).

The process of the development of an UBEM can be divided into 5 main steps starting from data collection to model development, simulation, validation, and analysis and outreach (Johari et al., 2020). For the development of an UBEM, both geometrical and non-geometrical characteristics of individual buildings spread over a geographical area are required. A simplified description of the geometry of individual buildings, e.g., building footprints and heights, can be found in 3-dimensional representations of urban structure, known as 3D city models (Biljecki et al., 2015). For non-geometrical characteristics of buildings, including construction assemblies, systems and schedules, individual or collective characteristics of buildings are required. Although there is no custom-made solution for defining these data, most existing UBEMs benefit from the approaches to finding representative building archetypes and extending their characteristics over similar buildings (Monteiro et al., 2017).

After collecting the data, and following the guidelines for BEM, all buildings are translated into models with a sufficient number of thermal zones and simulated for the desired period of time (Johari et al., 2022). This step is an automated procedure where either a BEM tool or a tailor-made BEM model is working in the background. It is generally recognized that no mathematical model is complete without validation. Although not all UBEMs are validated against measurement data, it is still considered as an important step in the development of a reliable UBEM (Oraiopoulos and Howard, 2022). Visualization of the results and application of the model is also an important part of the UBEMs without which there seems to be no benefit in investing time and effort in the development of such a model.

Research gaps and aims

Regardless of the time and effort that is put into the development of an UBEM, it is also commonly stated that the implementation of the model is associated with complexities (Johari et al., 2020; Reinhart and Cerezo Davila, 2016). UBEMs are computationally heavy and each simulation run through the urban building stock can take hours to days (Cerezo Davila et al., 2016). This means that the evaluation of the urban energy systems and the varieties of energy transition scenarios could be an impractically long procedure. In an attempt to reduce the simulation cost of the UBEMs, one of the common methods is to reconsider using customary BES tools such as EnergyPlus and instead of making use of custom-made resistance-capacitance network models. An example of such a method is found in Ref (Robinson et al., 2009). Using this method, the simulation time is reported to be roughly 12 s for each building (Perez et al., 2011). In some other studies such as in Ref (Fonseca and Schlueter, 2015), following the ISO/FDIS 13790:2007 standards, a simple 5R1C network calculates the hourly heat demand of a building. There are also examples of even more simplified models in which the heating degree day (HDD) method is the basis for hourly heat demand calculations ("SimStadt2," n.d.).

Despite the latest developments in proposing simplified yet accurate UBEMs, there is still no model that can handle large sets of buildings in adequate time spans. To cope with this issue, this paper aims to develop a simplified UBEM by which the modeling procedure and the computation cost of implementing the model improve considerably. In the suggested model, the complex physical models of buildings are replaced with simplified equations for steady-state heat transfer through the building envelope. In this respect, it is expected to enhance the investigation of the early-stage urban energy plans to a large extent.

Outline of the paper

This paper is structured into four main sections. In Section 1, the background of the work, research gaps and the aims of this paper are introduced in brief. Section 2 elaborates on the data and the methodology to develop a simplified UBEM to be used for future urban energy plans. In Section 3, the results from the analysis of the energy performance of an area using the simplified suggested model are presented. In this section, in order to validate the model, it is also aimed to compare the results from the simplified model to an advanced UBEM developed around the building energy simulation tool, EnergyPlus and the programming environment, Python. Finally, not only the model but also the future outlook to applications of such a model in the development of urban energy plans are discussed in Section 4. Section 5 summarizes the concluding discussions and the important results.

Data and method

This section elaborates on the data and the method for the development of a simplified UBEM to be applied to early-stage urban energy plans.

Data

- Geodata

This dataset provides information on the geometry, geolocation, and address of the buildings. It also contains information about the type of buildings, i.e., single-family or multifamily, the year of construction or renovation (if any) as well as the estimated height of the buildings. This information was mainly extracted from the national dataset for real property in Sweden. This real property registry, handled by the Swedish Mapping, Cadastral and Land Registration Authority, Lantmäteriet ("Lantmäteriet," n.d.), contains information about property boundaries, addresses, buildings, etc.

- Non-geodata

In connection with the developed function for distinguishing between different building archetypes, this dataset includes some of the main characteristics of buildings such as heat transmission coefficient (U-value), solar transmittance for transparent surfaces (g-value), window to wall ratio (WWR) and room set temperatures. These data were retrieved from the available literature and building codes for the Swedish buildings.

- Weather data

While the model is independent of the type of weather data, for the purpose of model validation and with respect to the available measured data presented based on a normal year weather data, in this study, the hourly typical meteorological year (TMY) weather data for a chosen location is used.

- Validation data

For validation of the model, measured energy performance of buildings found in their energy performance certificates (EPCs) is used. In Sweden, the National Board of Housing and Planning, Boverket ("Boverket," n.d.) compiles the information from the

EPCs in an open dataset. The EPC dataset includes detailed information on buildings and their systems as well as their energy use, and energy class. More information on the Swedish EPC system is found in ("Boverket," n.d.).

Simplified model

The proposed model is based on basic heat transfer principles and simplified physical descriptions of buildings in urban areas. An illustration of the model framework is presented in Figure 1. The model includes a set of functions for preprocessing the input data, calculating the components of the heat balance, and finally storing and aggregating the results from individual building level analysis to a district or city. In the model, first, the geometry of buildings, i.e., buildings' footprint and height, is imported to the "Geometry Processor" where it is decomposed and translated into several heat transfer surfaces with known geometry, orientation and tilt. This information is then used to calculate the total solar irradiation on tilted surfaces (at "Irradiation Processor") and the heat losses and gains through heat transfer surfaces (at "Transmission Losses", "Ventilation Losses", "Solar Gain", and "InternalGain"). Finally, by forming the heat and energy balance equations and aggregating the results (at "Heat Balance"), it is possible to estimate the total energy use of buildings at different spatial and temporal resolutions. The underlying method for the development of different components of the model is presented in the following sections.

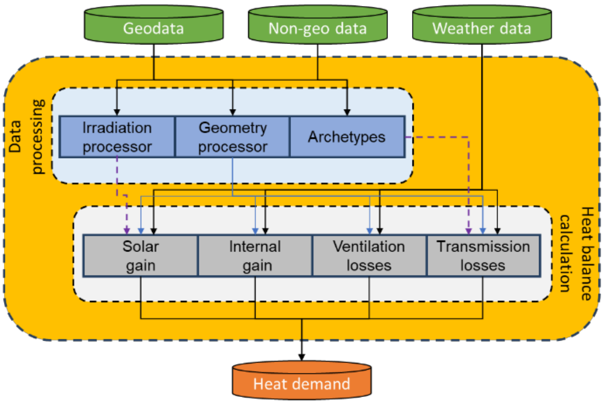


Figure 1: Overview of the structure of the developed UBEM.

- Heat balance

In general, the calculation of the heat balance is the main principle that underlies the simulations for most building energy models. Using the definitions for the single-zone thermal models, the heat balance of a building can be summarized as,

$$\dot{Q}_{trans} + \dot{Q}_{vent} + \dot{Q}_{sol} + \dot{Q}_{intgain} + \dot{Q}_{H} = 0. \quad (1)$$

In this equation, $\dot{Q}_{trans}$ represents the heat conduction losses through the building envelope, $\dot{Q}_{vent}$ summarizes the heat losses from ventilation and infiltration of the building air. $\dot{Q}_{sol}$ is the solar energy gain in the building resulting from the transmittance of solar radiation through windows and absorptance of solar radiation on the external walls. $\dot{Q}_{intgain}$ includes the internal energy gained from occupants' related activities and use of appliances and lighting. Finally, the amount of energy used for space heating is determined by $\dot{Q}_{H}$.

- Transmission losses

In this model, it is assumed that the heat transfer through the building envelope is a steady-state one-dimensional conduction mechanism. With this assumption, there is no storage or conversion of energy through the building envelope and therefore, the rate of heat conduction is constant. It is possible to capture the heat conduction using the Fourier's law,

$$\dot{q}(x) = -k\left(\frac{dT}{dx}\right)_x, \quad (2)$$

where $\dot{q}(x)$ is the heat transfer rate, k is the conductivity and $\left(\frac{dT}{dx}\right)_x$ is the temperature gradient. For a plane surface, for example a wall, Equation (2) can be written as,

$$\dot{q}_{trans} = k\frac{(T_{in}-T_{amb})}{L}, \quad (3)$$

with L being the thickness of the surface, and T_{in} and T_{amb} being the room temperature and the ambient temperature, respectively. For calculating the overall heat transmission through a multi-layer surface, e.g., wall, it is suggested to make use of the thermal resistance network and rewrite Equation (3) as,

$$\dot{q}_{trans} = \frac{(T_{in}-T_{amb})}{R}, \quad (4)$$

with $R = \sum R_i$, where $R_i = \frac{L_i}{k_i}$.

By replacing the overall resistivity of the layer with the heat transfer coefficient, U-value, that is commonly known as one of the main characteristics of buildings, it is possible to reach a simplified equation for calculating the heat conduction losses through the building envelope,

$$\dot{q}_{trans} = \sum U_i A_i (T_{in} - T_{amb}). \quad (5)$$

Here, U_i and A_i are the overall heat transfer coefficient and area of the heat transfer surfaces including the walls, windows, roof and the floor. In this equation, T_{in} is the hourly room temperature and T_{amb} is the hourly ambient temperature when the heat conduction through the roof and walls are calculated. However, for the calculation of the heat losses from the floor to the ground, T_{amb} is considered to be the surface on ground temperature.

- Ventilation losses

The rate of heat losses from ventilation of the air is calculated to be equivalent to the losses of heat in the room warm air to the ambient:

$$\dot{Q}_{vent} = \dot{V}\rho_{air}C_{p,air}(T_{in} - T_{amb}). \quad (6)$$

Regardless of the type of the ventilation system, $\dot{V}$ is equivalent to the volumetric flow of air and is the sum of ventilation and infiltration flows. ρ_{air} and $C_{p,air}$ are the density and specific heat capacity of the air, respectively.

- Solar gain

The amount of solar radiation contributing to the energy balance of a building is dependent upon the transmission of the solar radiation through transparent surfaces, e.g., windows, and can be written as

$$\dot{Q}_{sol} = gA_wI_t, \quad (7)$$

where g is the solar energy transmittance of a window, A_w is the area of the window, and I_t is the total irradiance on a tilted surface,

$$I_t = I_bR_b + I_d\left[\begin{matrix}(1-A_i)\left(\frac{1+cos\beta}{2}\right)+\\ A_iR_b + (I_b + I_d)\rho_g\left(\frac{1-cos\beta}{2}\right)\end{matrix}\right]. \quad (8)$$

I_b and I_d are the beam and diffuse components of solar radiation, R_b is the geometric factor, which is the ratio of the beam radiation on the tilted plane to beam radiation on the horizontal plane, A_i is the ratio of the incident beam radiation and the extraterrestrial radiation on the horizontal plane, and ρ_g is the ground reflectance. In this equation, $\left(\frac{1+cos\beta}{2}\right)$ and $\left(\frac{1-cos\beta}{2}\right)$ are the sky and ground view factors of the surface, respectively.

- Internal gain

The internal energy gain corresponding to occupancy and electrical load is calculated as,

$$\dot{q}_{gain} = \dot{q}_{occ} + \dot{q}_{el}\ , \quad (9)$$

where $\dot{q}_{occ}$ represents the contribution of occupants' metabolic heat to the energy balance of a building. According to the Swedish standards for the calculation of energy performance of Swedish buildings (Sveby) (SVEBY, 2012), $\dot{q}_{occ}$ is determined as,

$$\dot{q}_{occ} = N\ \times q_p, \quad (10)$$

where N is the number of occupants and q_p is the daily energy gain from occupants equals $1.12\ \mathrm{kWh/p.day}$.

In Equation (9), $\dot{q}_{el}$ also represents the share of electricity load (used in electrical appliances and lighting) that is converted to heat and added to the energy balance of the building. Refer to Ref (SVEBY, 2012), it can be stated as,

$$\dot{q}_{el} = A_h\ \times q_e. \quad (11)$$

Here, A_h is the heated area of a building and q_e is the share of electric power that is converted to heat and is equal $21\ \mathrm{kWh/m^2}$ y.

EnergyPlus model

Following the methodology that is suggested by the authors, found in Ref (Johari et al., 2022), an automated UBEM of the district was developed using Python and EnergyPlus. Unlike the simplified model, in EnergyPlus, the heat transfer simulations are conducted dynamically. In dynamic (transient) heat transfer calculations, the heat conduction through the building envelope is characterized by the thermal capacity of the building envelope as well as the total heat on the internal and external surfaces of the envelope,

$$\dot{q}_i - \dot{q}_o = \frac{dE_{env}}{dt}, \quad (12)$$

where $\frac{dE_{env}}{dt}$ is the changes in the energy content of the building envelope over time and $\dot{q}_o$ and $\dot{q}_i$ are the heat on the external and internal surfaces. The total heat on internal and external surfaces of the building envelope is a component of the radiation and convention transfers on the surfaces. This can be written as,

$$\dot{q}_o = \dot{q}_{conv,o} + \dot{q}_{abs,o} + \dot{q}_{lw,o}, \quad (13)$$

$$\dot{q}_i = \dot{q}_{conv,i} + \dot{q}_{abs,i} + \dot{q}_{lw,i}. \quad (14)$$

In these equations, $\dot{q}_{conv}$, $\dot{q}_{abs}$ and $\dot{q}_{lw}$ are the convection, absorption of short-wave radiation and exchange of long-wave radiation on both internal and external sides of the surfaces. Detailed analysis of the methods for calculation of the latter parameters is found in the EnergyPlus Engineering Reference Document ("EnergyPlus Documentation- Engineering Reference," 2019) as well as in (Johari et al., 2022).

Model validation

In order to validate the performance of the developed UBEM, the model was applied to a case study area located in Uppsala, Sweden. The choice of location is done arbitrarily. This area includes a combination of both single and multi-family residential buildings of different types and construction years. An overview of the area is presented in Figure 2. With respect to the available information on type and year of construction, these buildings were deterministically classified under five categories, i.e., building archetypes. Table 1 presents a summary of the classification of the buildings in the area. Using available information on thermal characteristics of typical building constructions in Sweden, main properties of the building archetypes, e.g., U-value, were estimated and fed to the model. After extracting the building geometries from the Swedish datasets, and determining the height of the buildings from LiDAR point clouds, they were added to the input of the model. Therefore, with a knowledge of the geometrical and non-geometrical information of buildings and using the developed UBEM, it is possible to conduct a district level hourly simulation of the thermal energy performance of buildings over the whole area and for the period of one year.

Figure 2: Overview of the chosen area with buildings divided into 5 archetypes.

Table 1: Classification and characterization of the building archetypes.

Arche type	**Building properties**		**Number of buildings in the class**
	Type	**Year of construction**	
1	Multifamily	1969-1972	199
2	Single-family	≤1945	17
3	Single-family	1945-1965	11
4	Single-family	1965-1985	512
5	Single-family	1985-2016	13

Results

In this section, the result from the analysis of the developed simplified UBEM and its validation against an EneryPlus-based UBEM as well as EPC measured data are presented in detail.

Building-level analysis

The results from the simulation of thermal energy demand over the case study city district with 752 buildings of different types show that at the building level the mean absolute percentage error (MAPE) of the simplified UBEM from the EnergyPlus UBEM can reach 36% annually. Figure 3 presents the correlation of the simulated annual thermal energy demand of buildings between the two models. As can be seen, for the buildings classified as archetype 1, i.e., multifamily buildings, the simplified model underestimates the demand while for the other archetypes, i.e., single-family buildings, it overestimates the results. The distribution of the absolute percentage error (APE) of the simulation results of the simplified model from the EnergyPlus model (see Figure 4) also proves that the multifamily buildings result in the lowest APE. For single-family buildings, the APE varies from 2% to 60%.

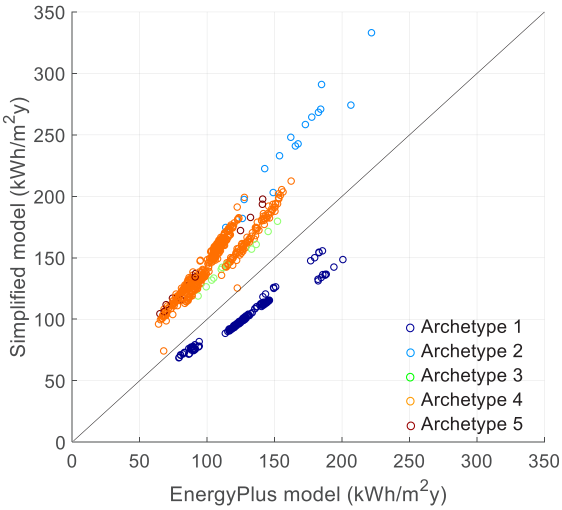
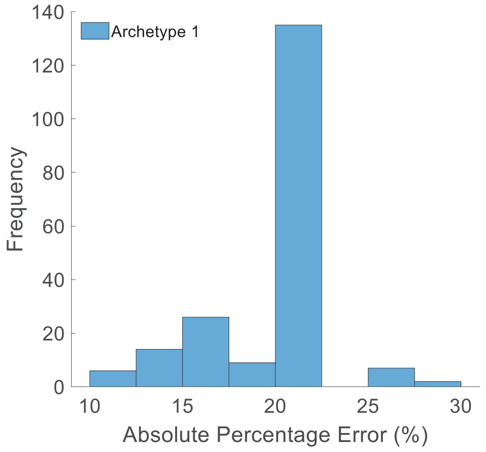


Figure 3: The simulated annual thermal energy demand of buildings using the simplified model vs EnergyPlus model.



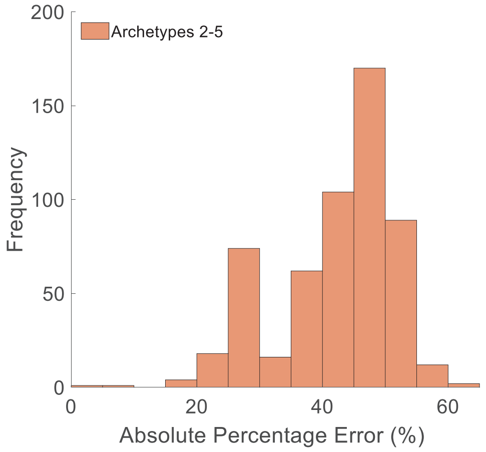


Figure 4: Distribution of APE for different building types.

To understand the behavior of the simplified model as compared to the EnergyPlus model, calculated hourly energy performance of buildings were meticulously investigated. The hourly thermal energy performance of an example building for a short period of time in winter as well as summer is given in Figure 5. Due to the direct relation between the weather conditions, in particular ambient temperature and solar radiation, they are also illustrated in this figure.

Clearly, during the heating season, the calculated heat demand from the simplified model follows almost exactly the results from the EnergyPlus model. However, the simplified model experiences more fluctuations in response to the weather conditions. During the low or no heating seasons, the two models show the greatest deviations from each other, particularly when the solar radiation and therefore solar energy gain through windows have higher contribution to the energy balance of the building.

After an investigation of the underlying methods in both models, it is possible to pinpoint two sources of discrepancies between the two models. First, in EnergyPlus the heat losses from windows are proportional to absorbed solar radiation on windows ("EnergyPlus Documentation- Engineering Reference," 2019). The higher the solar gain on windows the lower the losses.

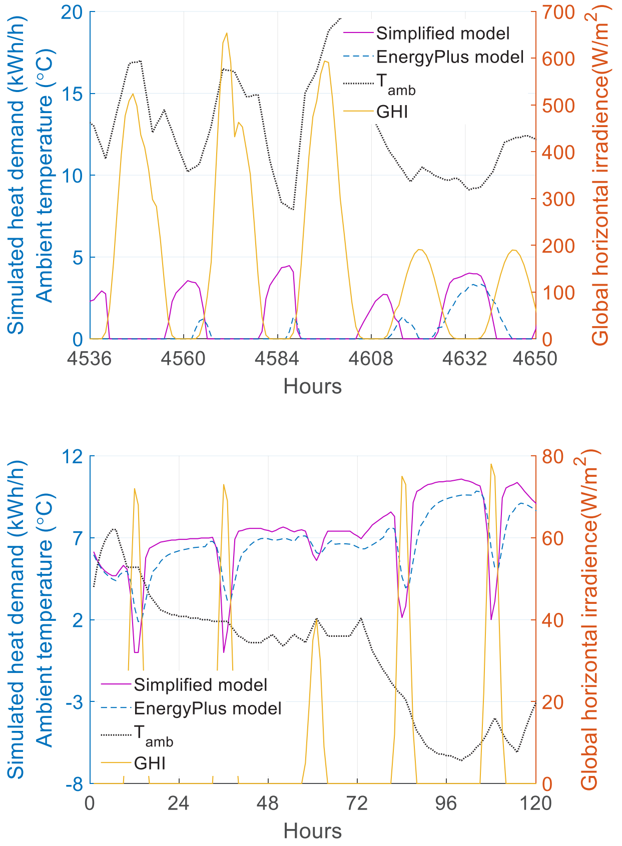


Figure 5: Comparison of the results in relation to ambient temperature and solar radiation.

This leads to an increase in the window surface temperature and therefore elimination of the heat losses through the windows during the hours when solar energy gain is sufficient. In contrast, in the simplified model the heat gains and heat losses through windows are directly unrelated. Therefore, so long as the ambient temperature is lower than the room temperature and the heat gains are lower than the heat losses, heat has to be added to the building. Unlike in EnergyPlus, in the simplified model no temperature node on the surfaces of the building envelope is considered.

Second, the heat capacity of the building envelope plays an important role in smoothing the results of the EnergyPlus model. As described in (Johari et al., 2022), in the dynamic calculation of the heat conduction function in EnergyPlus, the energy that is stored in the building envelope is automatically taken into consideration. Yet, in the simplified model, no heat capacity is assigned to the buildings.

District-level analysis

Using the simplified model, the aggregated annual thermal energy demand of the district is estimated to be 37.1 GWh/y. This is only 2% lower than the obtained value from the EnergyPlus model. However, the approximations of the hourly thermal energy demand provided by the two models show larger deviations. As mentioned, the major share of this deviation happens during the low- or no-heating hours when the contribution of solar radiation as well as the heat capacity of the building is higher (see Figure 6). With validating the aggregated annual results with the measured energy demand obtained from the EPC dataset, it is also seen that the MAPE of the simplified model is 31%. For the EnergyPlus model, the same MAPE is calculated. This means that both models have the same output performance when it comes to comparing with the measured data.

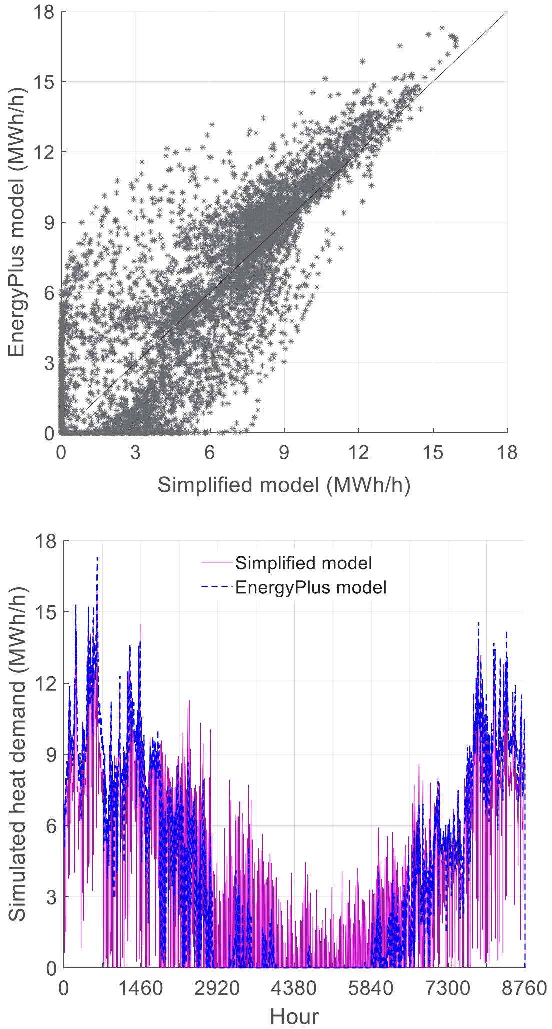


Figure 6: *Comparison of the hourly simulation results of the simplified model vs EnergyPlus model.*

As a result of less computational complexities, the simulation time of the simplified model is considerably lower. While using the EnergyPlus model, it takes 6900 s to complete a simulation for the period of one year; with the simplified model it only takes 36 s. A summary of the outcome of the implementation of the two models on the aggregated district level is presented in Table 2.

Discussion

The suggested methodology for the development of a simplified version of an UBEM can be further used for early- stage urban energy plans where reaching a holistic

Table 2: District-Level analysis of the results from the simplified vs EnergyPlus model.

UBEM	**Aggregated heat demand (GWh/y)**	**Computation time (s)**	**MAPE EPC (%)**
Simplified model	37.1	36 (0.04 s per building)	31
EnergyPlus model	37.6	6900 (9 s per building)	31

view of the energy demand of the area is more important. Using this method, and in a short period of time, not only the base case but also any changes to the system can be investigated easily. An illustration of the output from the simplified UBEM is presented in Figure 7.

There is no doubt that with further improvement of the underlying algorithms of the model it is possible to reach higher accuracies. Yet, the methods have to be kept as simple as possible to not adversely affect the simulation cost of the model.

In this study, the suggested UBEM is more focused on the buildings, as the main component of the urban energy system. However, the urban energy systems are composed of many more components, from supply to distribution and use. Therefore, the outlook to this study is to extend the model to include not only the buildings but also renewable and decentralized energy technologies, distribution systems and transportation.

Conclusion

Using a simplified model for calculation of the heat balance of buildings, an UBEM capable of efficiently calculating the energy performance of urban buildings was developed in this study. Validation of the simplified UBEM with an EnergyPlus-based UBEM showed that the MAPE of the annual heat demand was 36% on the building level, but as low as 2% on the aggregated level. On the aggregated level, it was also seen that the MAPE of the two models from the measured energy performance of the buildings was 31%. Therefore, when it comes to aggregated level studies, with accepting some degrees of deviation for annual values, the simplified UBEM is as good as an EnergyPlus model. On the hourly time scale, the deviation is higher, but the study has indicated possible areas to improve the accuracy.

(a)

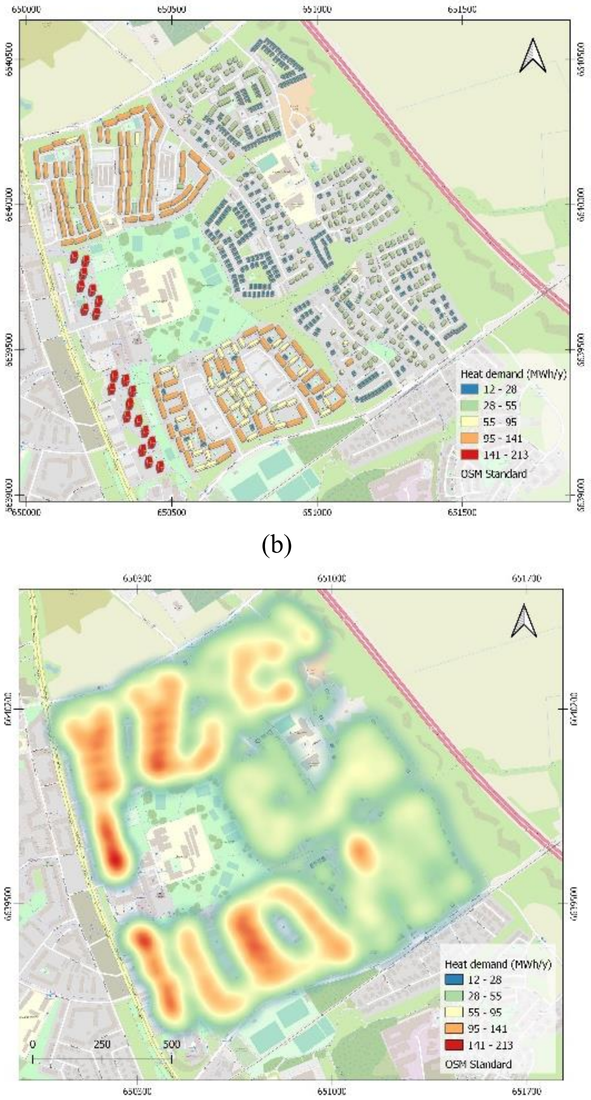


Figure 7: Visualization of the estimated thermal energy demand of the district. (a) Building-level and (b); District-level.

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