Building and Environment 211 (2022) 108684

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Evaluation of simplified building energy models for urban-scale energy analysis of buildings

F. Johari *, J. Munkhammar, F. Shadram, J. Widén

Division of Civil Engineering and Built Environment, Department of Civil and Industrial Engineering, Uppsala University, 75237, Uppsala, Sweden

ARTICLE INFO

Keywords:
Urban building energy modeling
Building energy simulation
Zoning configuration
Level of detail

ABSTRACT

Simplification of building energy models is one of the most common approaches for efficiently estimating the energy performance of buildings over a whole city. In city-scale models, the abstraction of a building into an information model and the division of the model into representative thermal zones cannot be building-specific but must be generic and applicable to many buildings. Considering the limited research on the performance of such methods, in this study, a comprehensive evaluation of the most relevant assumptions on zoning configurations and levels of detail is conducted in three building energy simulation tools IDA ICE, TRNSYS, and EnergyPlus. The findings from the evaluation of zoning configuration on building level and its comparison with the measured energy performance of buildings suggest that a single-zone model of a residential building gives a very similar result to a multi-zone model with one core zone and perimeter zones for every floor of the building. For the single-zone model, IDA ICE overestimates and EnergyPlus underestimates the energy demand compared to the more complex models by approximately the same amount, but EnergyPlus is preferred due to the shorter simulation time. It is also proven that higher levels of detail in building models can increase the accuracy of the results by approximately 6% annually. When extending the scope of the study from building level to district level analysis where a somewhat lesser degree of accuracy can be allowed on the individual building, the simplified models give acceptable results.

1. Introduction

With a growing interest in urban and regional energy planning [1–3], during the last decade the field of building energy modeling (BEM) has been shifting focus from individual buildings to urban-scale studies [4]. Among the various methods available for developing urban-scale energy models of buildings, bottom-up engineering (physics-based) models, referred to as "urban building energy models" (UBEMs) [4], follow the same approach as in BEM [5]. Using well-established BEM methods, in most UBEMs the aim is to extend the scale of the study from one building to hundreds or thousands of buildings [6]. However, considering technical and methodological barriers [7], e.g., lack of comprehensive data and high computing power, modeling a large number of buildings with the same level of complexity as in individual building energy modeling seems unattainable. To deal with this issue, simplification of the building models and narrowing down the range of included details have been considered as suitable solutions for the development of most existing UBEMs [8,9].

When an UBEM is developed based on tailor-made algorithms, the simplification methods target the algorithms and their solvers. For instance, Kämpf and Robinson [8] and Perez et al. [10] suggested simplified resistance–capacitance (R–C) network models with fewer resistance and capacitance nodes. The model is suggested for single-zone buildings, however, it can also be used for multi-zone models. Kim et al. [11] and Lauster et al. [12] adapted R–C network models which underwent additional physical simplifications and model order reductions. Frayssinet et al. [13] focused on a set of so-called adaptive solutions, i.e., simplification methods for conductive heat transfer functions, zoning, allocation of transmitted solar flux, etc., which could benefit the UBEMs with higher temporal resolutions.

Although such simplification methods based on tailoring the algorithms can improve the performance of UBEMs, they are not applicable for a wide range of UBEMs in which the model is developed around a BEM software. The efficiency and accuracy of the algorithms of commercialized BEM software have already been proven. Therefore, when a BEM software is used as the main simulation core of an UBEM, the focus is not on adjusting the algorithms. Instead, model developers typically focus on translating the building blocks into models which include the main components of a building but limit the details.

In urban building energy modeling (UBEM), one of the most common simplification methods for modeling a building is to decrease

* Corresponding author.
E-mail address: fatemeh.johari@angstrom.uu.se (F. Johari).

https://doi.org/10.1016/j.buildenv.2021.108684
Received 21 October 2021; Received in revised form 7 December 2021; Accepted 12 December 2021
Available online 4 January 2022

the number of thermal zones and define a building in one or a few zones. According to the definitions found in the literature [14,15], a thermal zone is a portion of a building in which the demand for heating, ventilation, and air conditioning (HVAC) is sufficiently similar and can be maintained by a single controlling unit or sensor, e.g., a thermostat. In most BEM studies, following the ASHRAE guidelines for envelope settings and zoning configurations [15], each building is divided into a sufficient number of thermal zones, e.g., one zone for every separated space. However, this detailed thermal zoning requires building-specific information which is most likely unavailable when an urban-scale study is carried out. On the other hand, assigning many thermal zones to one building leads to high modeling complexity and increases the computational power and time which may not be advantageous for UBEMs. Therefore, unlike in BEM, generalized thermal zoning methods with a predefined number of zones are commonly used in UBEMs [6,16,17].

Single-zone building modeling, i.e., assigning one thermal zone to the whole building, is the most straightforward approach in existing UBEMs and can be found in many studies [18–20]. On the other hand, multi-zone modeling, with all of its variations, is another widespread method for defining adequate numbers of thermal zones for urban-scale energy modeling of buildings. In multi-zone models, a building is divided into more than one thermal zone. In an UBEM developed by Nageler et al. [16], thermal zoning is dependent on how the energy demand varies within the building. In this approach, multi-use buildings are divided into up to three vertical zones where the ground, middle, or upper floors can be represented by different thermal zones. Furthermore, Wang et al. [21] and Cerezo Davila et al. [6] applied one thermal zone per each floor of the buildings while Chen et al. [17,22] and Dogan et al. [23] proposed novel auto-zoning algorithms that set multiple perimeter zones and one core zone to each floor of the buildings as specified by ASHRAE 90.1 Appendix G [15].

In addition to thermal zoning, level of detail (LoD) is another important concept in the development of UBEMs. LoD is the definition that is given to the degree of abstraction of real-world objects, in particular buildings, in 3D city modeling [24]. According to the CityGML standards [25], five LoDs can be used to represent a building. With respect to the level of information and availability of detailed floor plans on the individual building level, for conceptualizing the building a higher LoD is used in most BEMs. However, the approach to UBEMs is different, since gathering the same amount of information as in BEM for all buildings of a city would be impractical in most cases [4,26]. Thus, simplified shoe-box models of buildings, corresponding to LoD1, have been used in many UBEMs [6,27], and only a few models have used LoDs higher than one (LoD1+) [20,28].

1.1. Research gaps and scientific contributions

To a large extent, multi-zone models with higher LoDs can better handle the variable boundary conditions in a building, such as differences in the exposure to the ambient, energy use profile, and occupancy, as well as changes in the HVAC system and schedule [14]. However, as has been discussed by Shin and Haberl [29], there is no evidence proving that the prevalent zoning configurations, in particular multi-zone core and perimeter method, lead to higher accuracy or reliability of the results. Moreover, a survey of the existing UBEMs shows that in most of the models, the choice of zoning configuration is done arbitrarily. Except for the study done by Chen and Hong [22] and Dogan et al. [23], there is no analytical justification or proper motivation behind the chosen zoning configurations in existing UBEMs. Thus, to decide on the proper thermal zoning configuration, it is necessary to analyze the impact of the number of thermal zones not only on the accuracy of the simulation results but also on the reliability of the modeling and simulation procedure.

Regarding the LoD, according to Nouvel et al. [30], on aggregated levels, impacts of the roof shape and deviations of the results of LoD1 from the LoD2 building models can be neglected. With a shoe-box model, i.e., a LoD1 building model, in addition to the roof shape, many details on the external elements of a building, including balconies, overhangs, or vertical fins, are excluded from the model. Although these elements of a building do not directly contribute to the heat performance of a building, they can considerably obstruct the incoming solar radiation and, therefore, influence the heating or cooling demand of a building indirectly. This means that focusing on the roof shape is not sufficient to determine the impact of the LoD of a building model. This highlights the need for a more comprehensive analysis of different LoDs and their impact on the accuracy of the building models intended for UBEMs.

In addition, an urban-scale energy model developed around BEM simulation tools is considered a large-scale problem which requires a great extent of computational resources. With more detailed zoning configuration and higher LoD, the scale of the problem increases, which can exhaust memory space and computational power and, thus, significantly increase the computational time [31]. The computational time and its efficiency have become more significant with the recent development and application of optimization and machine learning techniques in building and urban-scale energy modeling where an algorithm automatically performs hundreds of thousands of simulation runs to identify an optimal solution [32,33].

With an increasing need for more time-efficient and yet accurate urban-scale energy models, this study aims to explore the acceptable levels of simplification in terms of zoning configuration and LoD of the building models in UBEM. For this aim, the study quantifies the impact of successive simplification of building models (in terms of zoning configuration and LoD) on the computational time and simulated energy use and compares their outcome with the measured energy performance of buildings. Due to the significance of measured energy performance data for validating the acceptable levels of model simplification and lack of such data for the majority of single-family residential buildings as well as new buildings in Sweden, the study is mainly focused on the performance of existing multifamily residential buildings built in 1970s. Hence, different types of multifamily residential buildings have been modeled and analyzed in the most popular and widespread BEM simulation tools, i.e., IDA ICE, TRNSYS, and EnergyPlus. Finally, to justify the findings from the building level analysis, the spatial scale of the study has been extended from the building level to the district level and an UBEM of a district consisting of 30 multifamily residential buildings in Uppsala, Sweden, has been developed and analyzed comprehensively.

1.2. Overview

The paper is structured as follows. In Section 2, the methodology for comparison of zoning complexity and level of detail in building models is introduced, including which building models, zoning configurations and LoDs are studied. As a basis for analyzing variations in simulated energy use between the three simulation tools (IDA ICE, TRNSYS, and EnergyPlus) this section also outlines how their approaches to building heat balance calculation differ. In Section 3, the results of the study are presented. Section 4 further elaborates on the results and discusses them in more detail. Finally, Section 5 presents the overall conclusions on a suitable level of complexity of building models for future UBEMs.

2. Methodology

A district area with 30 multifamily residential buildings in Uppsala, Sweden, was initially selected for analysis (see Fig. 1). The residential buildings were then divided into different types based on their properties, e.g. type, year of construction and systems. Fig. 1 presents a 3D overview of the area, with buildings color-coded based on their types (A, B and C). For the building-level analysis, energy models of three example buildings were developed based on pre-defined zoning configurations commonly used in existing UBEMs and were compared.

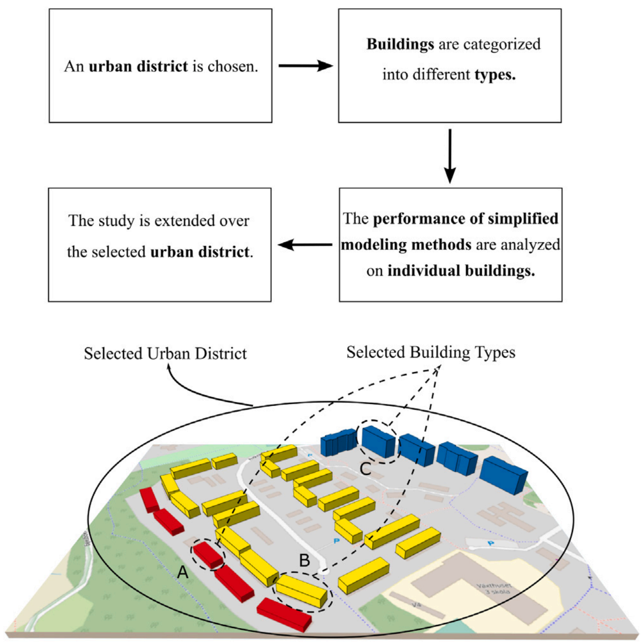

Fig. 1. Overview of the methodology.

The simulated results were then compared with the measured energy performance of each building. In addition to the zoning methods, the LoD and its impact on the reliability of individual building energy models were also evaluated. To extend the findings of the building-level analysis to the whole district and to elaborate on the accuracy and efficiency of the suggested levels of simplifications on larger scales than a single building, an automated UBEM of the district was also developed and evaluated. Fig. 1 shows a simplified flowchart of the analysis process.

The building models in this part of the study were developed in three established BEM tools, IDA ICE 4.8, TRNSYS 18, and EnergyPlus 9.1. The choice of software was made primarily based on their capabilities in generating accurate models and reliable results. In order to make a relevant comparison between the models developed in each tool, the fundamental differences in terms of simulated energy demand, the equations that form the basis for building heat balance calculation, and how they differ between the tools, were reviewed and outlined in this study.

All the computations in this study were performed on a Windows machine with a Core-i7-8650U CPU @ 1.90 GHz 2.11 GHz processor and 16 GB RAM.

2.1. Data

2.1.1. Case study buildings

Three buildings representing typical district-heated Swedish residential buildings constructed during the 1970s were chosen for the study. The choice of case study buildings was made based on two main reasons. Firstly, these buildings represent a major share of the building stock in Sweden. Secondly, the extent of available information about buildings' system, construction and material is considerable, both from the literature and the housing association company, Uppsalahem [34]. Illustrations of these building types are presented in Fig. 2.

- Building A: Multifamily building with 2 floors.
  Building type A is a residential multifamily building with 2 floors and a 699 m^2 heated floor area. According to the latest energy performance certificate (EPC), total energy performance (including the energy used for space heating, domestic hot water, and operational electricity) in this building is 109 780 kWh/y or 157 kWh/m^{2}y.

Table 1
Overall properties of the case study buildings.

Building specifications	Building A	Building B	Building C
Heated floor area	699 m^2	1498 m^2	5197 m^2
Total floor area	884 m^2	1584 m^2	6072 m^2
Window to wall ratio	25%[a]	29%[a]	25%
Number of floors	2	3	8[b]
Number of apartments	6	18	70
Energy performance	157 kWh/m^{2}y	157 kWh/m^{2}y	173 kWh/m^{2}y
Thermal properties (W/m^{2}K)	**Building A**	**Building B**	**Building C**
External wall	0.54	0.54	2.42
External roof	0.22	0.22	0.22
External floor	1.54	1.54	1.73
Internal wall	3.78	3.78	3.87
Internal floor/ceiling	2.91	2.91	0.75
Window	1.96	1.96	1.96

[a] On long walls only.
[b] 8 heated floors and an unheated basement.

- Building B: Multifamily building with 3 floors.
  As previously mentioned, building type B is also a district-heated multifamily building constructed in 1972. This building has 3 heated floors and a 1498 m^2 heated floor area. Similarly, the overall energy performance of the building is calculated to be 235 209 kWh/y or 157 kWh/m^{2}y.

- Building C: Multifamily building with 8 floors.
  In addition to low-rise multifamily buildings, in this study, a high-rise building with 8 heated floors and an unheated basement is also analyzed. The energy performance for this building is reported to be 896 738 kWh/y which equals 173 kWh/m^{2}y. The total heated floor area is 5197 m^2.

According to the EPC, each building has 5%–15% non-heated areas. However, for this study it was assumed that the whole building area is heated up by the heating system. Detailed characteristics, assumptions, and thermal properties of these buildings are given in Table 1.

2.1.2. Occupancy and schedule

In order to determine the occupants' related energy use and their respective contribution to the heat performance of a building, the given values and conversion factors from the Swedish standards for the calculation of energy performance of Swedish buildings (Sveby) [35] are used. Accordingly, for residential multifamily buildings, the contribution of building occupants to the energy performance of a building through metabolic rate, household and operational electricity, lighting, and domestic hot water can be generalized as follows, all based on Ref. [35].

- The average heat gain from occupants with different activity levels is equal to 80 W per person for 14 h a day.
- The use of electricity for household appliances and lighting is 30 kWh/m^{2}y of heated floor area, 70% of which is converted to heat.
- The electricity use for running auxiliary equipment such as pumps, fans, etc., referred to as operational electricity, is 15 kWh/m^{2}y of heated floor area. Similarly, 70% of this can be converted to heat and added to the heat balance of a building.
- The amount of energy for domestic hot water use in a building is 25 kWh/m^{2}y of heated floor area.

To encompass the effects of occupancy and schedule in the energy performance of a building, the given values are distributed over a year

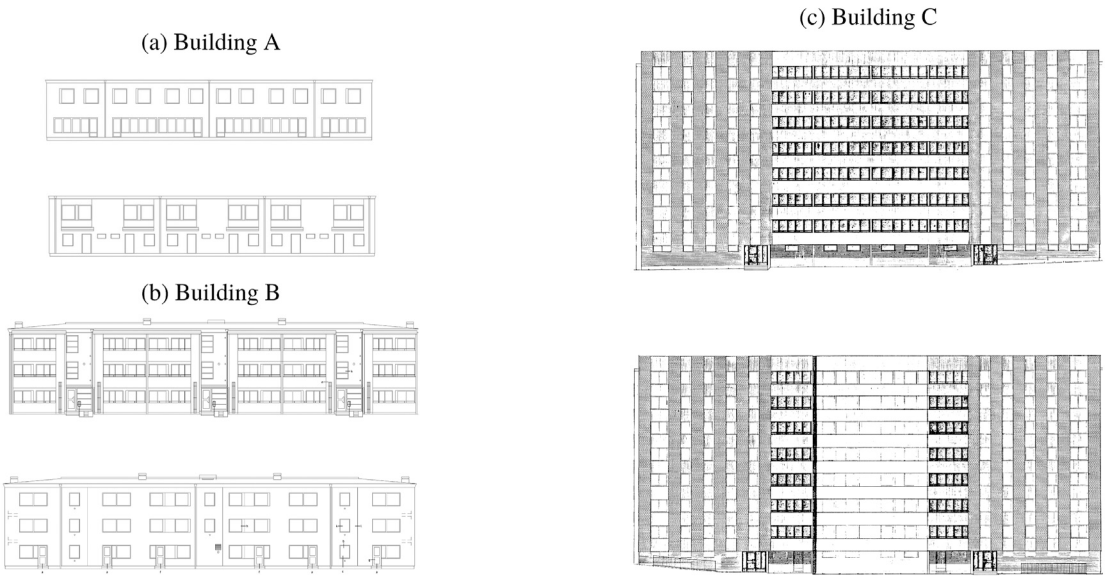

Fig. 2. Overview of the case study buildings from blueprints.

using deterministic user profiles. The obtained profiles are later added or subtracted from the simulated heat demand in buildings as in

$$EP = Q_{sim} + Q_{DHW} + E_{el,h} + E_{el,op} - Q_{occ} - Q_{el,h} - Q_{el,op}, \quad (1)$$

where EP is the calculated energy performance of the building, Q_{sim} is the simulated heat demand, Q_{DHW} is the use of domestic hot water, $E_{el,h}$ and $Q_{el,h}$ are the household electricity use and its respective heat gain, $E_{el,op}$ and $Q_{el,op}$ are the operational electricity use and its related heat gain.

The main reasons behind this method of calculation of the occupancy is to limit the number of input variables to the model and keep the focus on the building model itself.

2.1.3. Weather data

With respect to the requirements for normalization of the climate-dependent energy performance of buildings in Sweden [36], the energy simulation of buildings has to be conducted for a normal year for the given place and time period. The weather data used in this study is typical meteorological weather year (TMY), i.e., ASHRAE's International Weather for Energy Calculations (IWEC), that is available from EnergyPlus weather (EPW) data directory [37]. This dataset covers different locations worldwide and includes at least 12 and up to 25 years of observations.

2.2. Comparative analysis of thermal models

2.2.1. Zoning configuration

Choosing a suitable zoning configuration is an important part of UBEM development. The complexity of the model and computation time differ considerably between a single-zone and a multi-zone thermal model [10]. In BEM, the division of a building into many thermal zones may not be as problematic as in UBEM and large-scale studies. In the latter, a consequence of unnecessary thermal zoning is that the computation cost and modeling effort become larger and in some cases challenging to handle.

Overall, three main zoning configurations were identified through a survey of existing UBEMs. The most straightforward approach is to assign only one thermal zone per each building block (1 zone per building) (Figs. 3(a), (d) and (g)). Although a single-zone model is a simple representation of a building, it improves the computation cost to a large extent. It is also possible to assume one thermal zone per each floor (1 zone per floor) to slightly capture the contribution of internal building elements, e.g., internal floors, but still run the simulation in an acceptable time (Figs. 3(b), (e) and (h)). The other very common method follows the ASHRAE guidelines for envelope setting and zoning configuration, stated in ASHRAE 90.1, Appendix G [15]. Accordingly, different thermal zones are assumed for perimeter and interior spaces that stand at least 4.6 m away from the exterior or semi-exterior walls. If the exterior wall glazing has different orientations, then one thermal zone for each orientation is specified, unless the angle is less than 45°. It is also suggested to consider separated thermal zones for the spaces that are adjacent to the ground or have an exposed roof surface. In multifamily buildings, it is also recommended to have one zone per each dwelling. However, for the scope of UBEM, this assumption is generalized through having separate zones for every floor instead of every apartment, as illustrated in Figs. 3(c), (f), and (i). In this study, this is referred to as a "5 zones per floor" model.

This study also includes other zoning methods that have been used specifically for high-rise buildings to reduce the complexity of the model as well as simulation time even more. As illustrated in Fig. 4, a high-rise building, i.e., building type C with 8 heated floors, can be described through a three-zone model (3 zones per building), consisting of the top and bottom floors as one zone each, and all other intermediate floors as one big zone in between, as shown in Fig. 4(a). Another option is to model only one of the similar intermediate floors, and then extrapolate the results for this floor to the other intermediate floors. This is referred to as a "1 zone per floor (abstract)" model, due to the abstract nature of the intermediate floors. This zoning configuration is shown in Fig. 4(b).

2.2.2. Level of detail in building models

In the absence of comprehensive knowledge on building construction components, UBEM developers make their assumptions based on limited building information. Hence, in most UBEM studies, the description of the building geometry is relatively simplified and the building construction is defined through shoe-box models corresponding to Level of Detail 1 (LoD1), according to CityGML standards [25]. This level of simplification, however, may lead to less accurate results and, therefore, further need for calibration methods to compensate for the deviations from measured data.

To compare the performance of the most common assumptions on the LoD of building construction and their impacts on building energy modeling, three building models with distinct levels of detail were defined and analyzed for the case study building type B. In

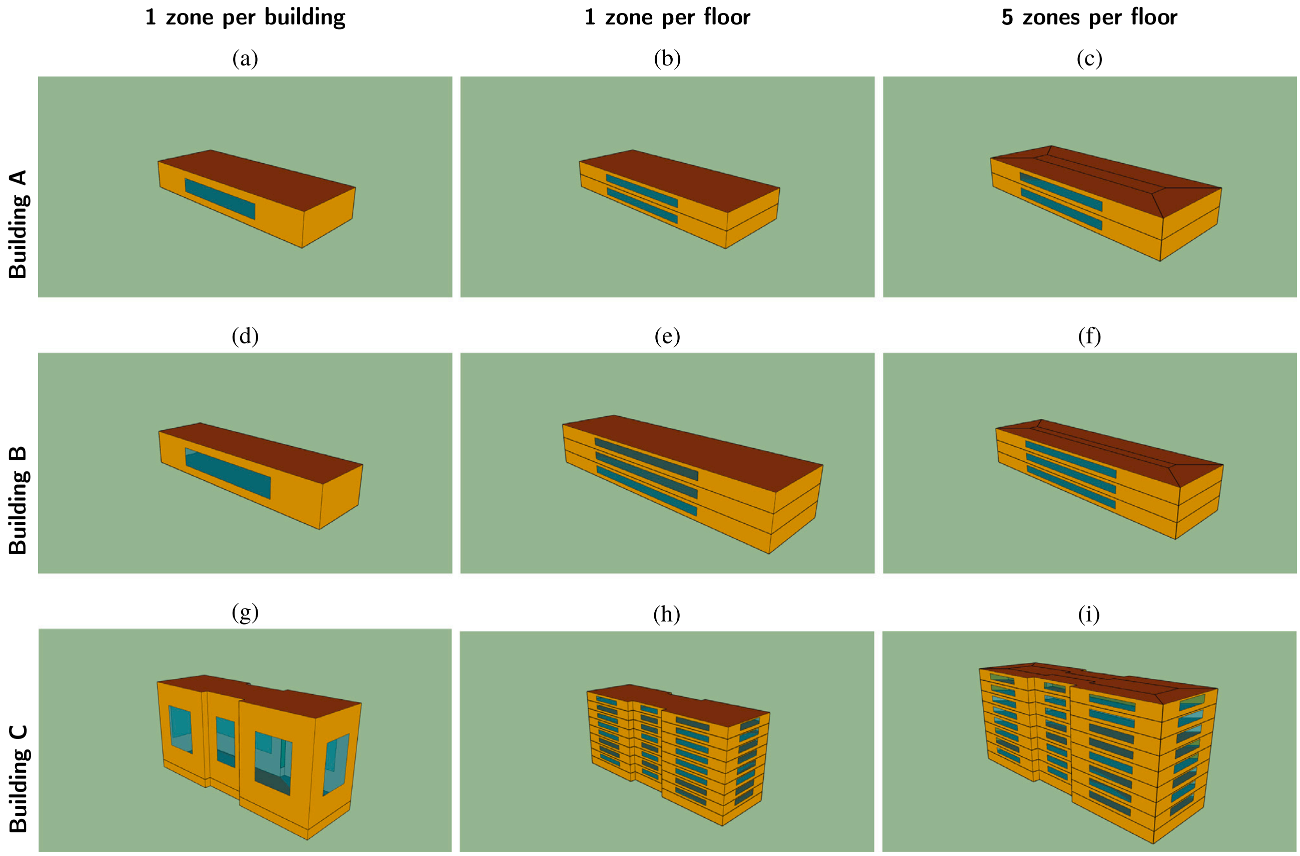

Fig. 3. Zoning configuration in the three case study building models. Subfigures (a), (d), and (g) show models with one zone per building, subfigures (b), (e), and (h) show models with one zone per floor, and subfigures (c), (f), and (i) show models with 5 zones per floor.

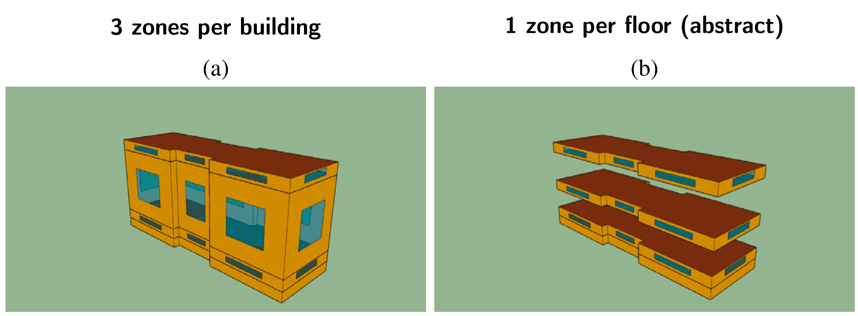

Fig. 4. Zoning configuration and simplification in high-rise building models (building C). Subfigure (a) shows a model with 3 zones per building while subfigure (b) shows a model with 3 selected zones out of 8, where the middle floor is representative of the other 5 intermediate floors (simplification from one zone per floor model).

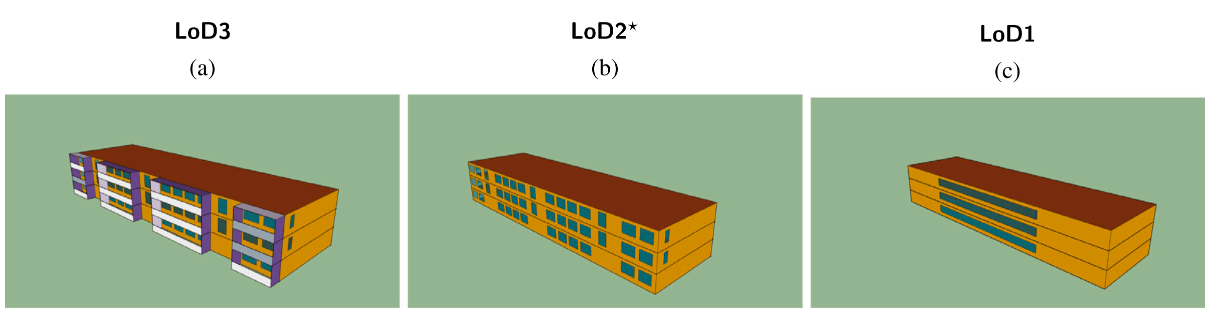

Fig. 5. Illustration of the analyzed levels of detail (LoD) for building type B. Subfigures (a), (b) and (c) show LoD3, LoD2* and LoD1, respectively.

this study, the defined LoDs, however, are slightly different from the defined LoDs from the CityGML standards, in particular for LoD2. According to CityGML standards, a building with LoD2, as compared to LoD1, is a simplified model with information on the shape of the roof. As the impact of the roof shape on the performance of an UBEM has already been discussed in [30], it has been excluded from this study. Instead of a CityGML LoD2, a customized LoD, referred to as "LoD2⋆" has been defined. Accordingly, regardless of roof construction, LoD2⋆ is a shoe-box model with a window fenestration that is clearly differentiated in the building model, as shown in Fig. 5. On the other hand, the other two LoDs include almost the same information as in the CityGML standards. The model with LoD1, as mentioned, is a shoe-box model of the building block with a 25% window to wall ratio (WWR), and the building model LoD3 includes building components with detailed features and adjacent shading elements, e.g., windows, shading balconies, and vertical fins. Building type B was chosen for this analysis due to the availability of detailed data, i.e., complete construction blueprints and plans.

2.2.3. District level analysis

To generalize the findings from the analysis of the effects of the model complexity in UBEM, the analysis was extended over a district with 30 multifamily buildings of types A, B and C. Fig. 1 presents a 3D overview of the area. To systematically handle the subsequent energy modeling and simulation of buildings, an UBEM operating around EnergyPlus V9-1-0 and Python 3 was established. This UBEM reads the input information from tabular data, automatically generates individual thermal energy models of all the buildings, runs consecutive dynamic energy simulations and reports the simulated results on different spatiotemporal resolutions.

As suggested in [7], an UBEM of this type requires comprehensive information on geometrical and non-geometrical properties of all the buildings of the district. For the non-geometrical data, e.g., construction material and assemblies, HVAC systems, schedule and occupancy, the information from the representative building types A, B and C (presented in Section 2.1) was used. To determine the geometry and geo-location of the buildings in the district, the building footprints obtained from the national geodata collected by the Swedish Mapping, Cadastral and Land Registration Authority (Lantmäteriet) [38] were used.

To determine the effects of the three zoning configurations on the accuracy of the results of the UBEM, the annual thermal energy needs of the buildings were compared against the values reported in the EPC database for each of these buildings.

2.3. Building thermal modeling in the different simulation tools

Finding the most suitable zoning configuration and LoD depends not only on the scale of the study but also on the simulation tool that is used as the main core in the UBEM simulation engine. In this study, to validate the already mentioned configurations, the three different case study buildings were modeled and analyzed in three simulation tools, IDA ICE, TRNSYS, and EnergyPlus.

The intention has been to make the building models as similar as possible between the analyzed simulation tools. However, in addition to systematic differences between the three tools, the underlying methods of calculating the equations for heat balance and the solvers differ, causing differences in simulation results. For this reason, an overview of how the heat balance is calculated in each tool is given in this section.

2.3.1. Heat transfer between external surfaces and surroundings

The thermal behavior of a building can be described through equations for heat and mass transfer inside the building, through the building envelope, and between the building envelope and the surroundings. For the heat transfer, most thermal models rely on the heat balance on outside and inside surfaces of the building as well as the heat flux through the building envelope.

Generally, and in all the simulation tools, the net heat transfer between an exterior surface such as a wall and the ambient at each instance of time is modeled as

$$Q_{wall,o} = Q_{conv,o} + Q_{abs,o} + Q_{lw,o}, \tag{2}$$

where $Q_{conv,o}$ is the convective heat transfer, $Q_{abs,o}$ is the absorbed solar radiation, and $Q_{lw,o}$ is the long-wave radiation exchange with the surroundings. These heat flows are treated differently in the different tools, as outlined below.

First, the convective heat flow is calculated in all tools as

$$Q_{conv,o} = h_c A(T_{air} - T_{wall,o}), \tag{3}$$

where h_c is the convective heat transfer coefficient, A is wall area, T_{air} is the ambient air temperature and $T_{wall,o}$ is the wall outside surface temperature. However, each software uses a different approach for calculating the heat transfer coefficient h_c, which influences the simulation results to some extent. In IDA ICE, the convective heat transfer coefficient for external surfaces is calculated based on the heat transfer coefficient as a factor of local wind velocity:

$$h_c = 5.678\left[a + b\left(\frac{V}{0.3048}\right)^n\right], \tag{4}$$

where V is the local wind velocity, and the parameters a, b and n are 1.09, 0.23 and 1, respectively, when the wind velocity is less than 4.88 m/s. For wind velocity of greater than 4.88, a, b and n are defined as 0, 0.53 and 0.78. EnergyPlus, however, has a very different approach, offering a choice between various options for modeling the convective heat flow. In this study this was kept at its default. As default, EnergyPlus applies the TARP algorithms [39], in which the total convective heat transfer coefficient is the sum of coefficients for forced and natural convection:

$$h_c = h_f + h_n. \tag{5}$$

The heat transfer coefficient for forced convection is defined as

$$h_f = 2.537 W_f R_f \left(\frac{P V_z}{A}\right)^{1/2}, \tag{6}$$

with W_f being related to wind direction and equal to 1 or 0 for windward or leeward surfaces, i.e., the hypothetical wind directions from a reference point, R_f is the roughness of the surface, P is the perimeter of the surface, V_z is the local wind speed calculated above the ground, and A is the area of the surface. The heat transfer coefficient for natural convection is calculated in relation to the temperature difference between the air and the surface, and the tilt of the surface, as

$$h_n = \frac{9.482|\Delta T^{\frac{1}{3}}|}{7.283 - |\cos \Sigma|}, \tag{7}$$

where ΔT is the temperature gradient between the external surface of the building and the air and Σ is the surface tilt angle. TRNSYS, on the other hand, offers the possibility of having user-defined values for both internal and external coefficients or making use of internal calculations for convection heat transfer. In this study, the external convective heat transfer coefficient, h_c is kept as its default value, suggested by TRNSYS. The default values for external and internal convective heat coefficients are 64 kJ/hm^{2}K and 11 kJ/hm^{2}K.

The second component of the heat balance, Eq. (2), absorbed solar radiation $Q_{abs,o}$ is in general calculated as

$$Q_{abs,o} = \alpha A(I_b + I_d), \tag{8}$$

where α is the solar absorptance of the surface, A is the wall area, and I_b and I_d are beam and diffuse solar radiation components, respectively, on the wall surface. By default, EnergyPlus relies mainly on the Perez model [40] for estimating beam and diffuse solar radiation (I_b and I_d) from the global radiation. IDA ICE also takes full advantage of the ASHRAE guidelines [15] in calculating beam and diffuse radiation on building surfaces. It offers the Perez model [40] for calculating the diffuse solar radiation on building surfaces. Components of solar radiation in TRNSYS are estimated using the standard component library and the weather data processor, Type 15-3, in which among 5 options the Hay and Davies Model [41] was chosen in the input.

The third heat flow component in Eq. (2), the long-wave radiation exchange between a wall's external surface and the surroundings, can be generally defined as a sum of heat flows between the surface and the sky, ground and ambient air, respectively:

$$Q_{lw,o} = Q_{lw,sky} + Q_{lw,ground} + Q_{lw,air}, \tag{9}$$

where each individual heat flow can be expressed as

$$Q_{lw,x} = \epsilon\sigma F_x A(T_x^4 - T_{wall,o}^4), \tag{10}$$

with ϵ being the long-wave emittance of the surface, σ the Stefan–Boltzmann constant, F_x the view factor between the surface and the sky, air or ground, A the surface area, T_x the temperature of the sky, air or ground, and $T_{wall,o}$ the surface temperature of the wall. The simulation tools differ in which components are included and how they are calculated. In IDA ICE, only $Q_{lw,sky}$ and $Q_{lw,ground}$ are considered, while EnergyPlus includes all three components. In TRNSYS, only radiative exchange with sky and ground are included, and with a somewhat different expression:

$$Q_{lw,o} = \epsilon\sigma A(T_{f,sky}^4 - T_{wall,o}^4), \tag{11}$$

where $T_{f,sky}$ is the fictive sky temperature, defined as

$$T_{f,sky} = (1 - F_{sky})T_{ground} - F_{sky}T_{sky}. \tag{12}$$

2.3.2. Heat transfer between internal surfaces, internal air and internal sources

For calculating the internal heat balance on the building's internal surfaces, the overall heat balance can be written as

$$Q_{wall,i} = Q_{conv,i} + Q_{abs,i} + Q_{lw,i}, \tag{13}$$

where $Q_{conv,i}$ is the convective heat transfer to the zone air, $Q_{abs,i}$ is the transmitted solar radiation through windows that is absorbed by the internal surfaces of the walls as well as the short-wave radiation from internal sources of energy such as lighting. $Q_{lw,i}$, is the long-wave radiation exchange between the internal surfaces of the building, and between surfaces and the internal sources of energy such as lighting, household appliances, heating surfaces, and building occupants.

In Eq. (13), the convective heat transfer to the building (zone) air is calculated using the same terminology as in Eq. (3), in which the heat transfer is a factor of the internal building surface temperature, the zone air temperature and the convective heat transfer coefficient inside the building. Similarly, EnergyPlus offers a wide range of optional equations in calculating the convective heat transfer while TRNSYS, as default, relies on uniform user-defined values. In IDA ICE, the heat convection, however, is a function of the slope of the surface, and the temperature gradient between the zone air and the internal surfaces.

The absorbed solar radiation transmitted through windows, $Q_{abs,i}$, is estimated differently in each tool. In IDA ICE, it is assumed that the building enclosure is a diffuse gray enclosure, with material properties, view factors, and surface areas summarized into an absorption factor,

$$Q_{abs,i} = \psi_{sw} I_{d,i}, \tag{14}$$

where ψ_{sw} is the net absorption matrix and $I_{d,i}$ is diffuse solar radiation transmitted through windows. In TRNSYS, the absorbed radiation is calculated from the distribution of both direct and diffuse solar radiation. For description of the direct solar radiation entering a zone, TRNSYS uses its auxiliary tool TRNSHD in order to calculate the solar sunlit and distribution factors on external windows. The diffuse solar radiation in an enclosure is estimated from

$$Q_{abs,i} = -AG_d^T I_{d,i}, \tag{15}$$

where A is the diagonal matrix describing the surface areas, G_d^T is the transposed Gebhart matrix for diffuse solar radiation [42] that is calculated as a function of view factors and reflectance of the surface. In EnergyPlus, solar radiation absorption involves the interior solar radiation absorbed by opaque surfaces as well as windows. In summary, the absorbed solar radiation can be written as

$$Q_{abs,i} = \frac{\alpha_j A_j}{\Sigma \alpha_j A_j} I_{d,i}, \tag{16}$$

with $I_{d,i}$ being the total diffuse short-wave radiation entering the zone, A_j and α_j the area and absorption coefficients of the jth internal surfaces.

The long-wave radiation exchange in EnergyPlus is calculated based on the radiation exchange coefficients and the general equation

$$Q_{lw,i} = A_j F_{j,k}(T_j^4 - T_k^4), \tag{17}$$

with A_j being the surface area, $F_{j,k}$ a matrix of radiation exchange coefficient between pairs of surfaces (known as ScriptF) and T_j and T_k the temperature of the surfaces. In IDA ICE, the long-wave radiation is determined as a function of the long-wave absorption matrix as in

$$Q_{lw,i} = \psi_{lw}\sigma A T^4, \tag{18}$$

where ψ_{lw} represents the long-wave absorption matrix and A and T are the area and temperature of the surface. In TRNSYS, using the detailed Gebhart model [42], the calculations of long-wave radiation exchange are conducted accurately.

The calculations of internal short- and long-wave radiation exchange from internal sources of energy are excluded from further analysis in this study, mainly due to the fact that the occupancy profiles and associated energy use are calculated externally.

2.3.3. Heat transfer through the building envelope

Calculation of the heat flux through the opaque surfaces, e.g., walls, is dominated by the conduction transfer function (CTF) method [43]. Without knowledge of the internal temperatures of the wall, this method is able to perform the calculations of the heat flux based on the coefficients of the wall's thermal transfer functions and hourly temperatures of the wall surfaces [44]. Examples of the transfer coefficients for different walls are given in ASHRAE Handbook of Fundamentals [15].

The CTF method is the basis for the calculations in both EnergyPlus and TRNSYS, however the equations are solved differently. TRNSYS makes use of a time series response factor method for estimation of the heat transfer through a multi-layer surface, e.g., a wall, developed by Mitalas and Arseneault [45]. With this method, the wall is considered as a black-box and the heat transfer is modeled using the Laplace transform of surface heat flux and surface temperature. In the literature this method is commonly known as the "Direct Root Finding" method for solving the CTF models [43].

In EnergyPlus, on the other hand, the basis for calculation of the CTF is a "State Space" method in which the heat flux is a linear function of surface temperatures [37]. However, unlike in the previous method, the surface is no longer treated as a black box, but rather discretized into temperature nodes that are represented by the state variables [46].

Overall, the CTF method is based on the evaluation of the CTF series, which are time dependent. These time series equations are evaluated at equal time intervals (that can be a portion of or equal to the simulation time step). Besides, these time intervals implicitly define the thermal mass of the walls both in TRNSYS and EnergyPlus. In TRNSYS, the time interval is referred to as the "time-base" and can be defined by the user. In EnergyPlus, on the other hand, the time intervals are equal to the time steps of the simulation. However, by choosing a resolution of 6 time steps per hour, i.e., 10-min time intervals, EnergyPlus gives a more realistic estimation of the heat transfer through the building envelope.

Considering the CTF method as the main method, IDA ICE makes use of an optimized resistance–capacitance (R–C) wall model [47] to represent parts of the building envelope, for example a wall, by fewer resistances and capacitances, mainly according to the layers of the surface material, which if calculated accurately can result in accurate estimations of the heat flux through the wall [48]. The basis of this method is presented in a study by Akander [48], which allows the values for resistance and capacitance to be approximated first and optimized later.

3. Results

In this section, the results from a comparative analysis of the simplified building energy models are presented. First, in Section 3.1, the final results from the evaluation of the zoning configuration on the energy performance of the three case study buildings are presented. In this section, justification of the results with respect to the underlying methods of calculating building energy use in each simulation tool is also presented. Then, in Section 3.2, a detailed analysis of the impact of the LoD of a building model and its effects on the accuracy is given. Finally, in Section 3.3, the results from the UBEM of a district with different levels of complexity are presented.

3.1. Zoning configuration

3.1.1. Case study building A

This section presents the obtained results from energy modeling and simulation of the case study building A. First, the results from analysis of thermal zones in the three simulation tools are given in brief. Then, the observed differences in the results of the three simulation tools in relation to their different thermal modeling methods (presented in Section 2.3) are analyzed. Finally, validation of the simulation results against annual measurements from the energy performance of the building is presented.

Fig. 6 illustrates the results from energy modeling of the low-rise residential building, i.e., building type A, with different zoning configurations in IDA ICE, TRNSYS and EnergyPlus. Figs. 6(a), (c), and (e) show the daily average and Figs. 6(b), (d) and (f) show duration plots of the hourly heat demand, in this building. Finally, Fig. 6(g), shows the total annual heat demand for all simulation tools and zoning configurations.

As can be seen in Figs. 6(a), and 6(b), in IDA ICE, simulation of the building models with 1 zone per building and 1 zone per floor (i.e., two zones in total), result in very similar instantaneous heat demand, with an absolute percentage error (APE) of less than 2% for annual results. However, with the increase in the number of thermal zones to 5 zones per each floor (and a total of 10 zones in the building), the daily average heat demand is considerably reduced, particularly during the cold months when more energy is needed. Investigation of the hourly results leads to similar conclusions. However, it is also proven that the degree of variability of the hourly heat demand profile has been smoothed out to a large extent.

In TRNSYS, Figs. 6(c), and (d), the results for the 1 zone per floor and 5 zones per floor models follow each other closely. However, as in IDA ICE, for the building model with 5 zones per floor, the hourly heat profile is more uniform as compared to the 1 zone per floor and 1 zone per building models. The results from the 1 zone per building model tend to diverge more from the other two, particularly during the colder periods of the year. The mean absolute percentage error (MAPE) of the results from the model with 5 zones per floor reaches 15% and 41% for 1 zone per floor and 1 zone per building model, respectively.

Evaluation of the simulation results in EnergyPlus (Figs. 6(e) and (f)) shows that with assigning fewer thermal zones to the building, the heat demand slightly decreases. This is the trend that has been observed in TRNSYS as well. The MAPE from the 5 zones per floor model is less than 6% for the 1 zone per floor model and 10% for the 1 zone per building model.

The differences observed in the simulated results of each software is related to their fundamental differences in implementation of the building models. Some of these differences are recognized to have a higher impacts on the deviation of the results. Calculation of the thermal mass of a building and its contribution to regulating the heat performance of the building is one the parameters that are treated differently in each software. IDA ICE does not assign any thermal mass to external surfaces of a simple building model [49]. However, it includes the contribution of thermal masses of the internal walls and floors when a building with more than one thermal zone is modeled. The increased inertia of the building model in multi-zone models works against the temperature fluctuations in the building. The stability of the room temperature results in lower heat use, especially when more thermal zones are added to the model. TRNSYS uses the thermal response factor model for multi-layer walls [45] by which the heat transfer wall is considered as a black box. In the calculation of the transfer function coefficients, the thermal mass of the external surfaces is not explicitly included in the calculations. However, choosing the right time-base for the building model (cf. Section 2.3), particularly for heavy constructions, has an impact on the calculations. Unlike IDA ICE and similar to TRNSYS, in EnergyPlus, incorporation of the heat storage rate of the building envelope in the heat demand of a building is embodied in the conduction transfer function equations. The changes in the thermal performance of a building in EnergyPlus are therefore unrelated to the thermal mass of the building envelope and its capacity to regulate the heat demand.

In addition to the thermal inertia of the building, it has been observed that in the 5 zones per floor model, contribution of solar gain can influence the results to a large extent, particularly in the case of IDA ICE where the sensitivity of the building model to solar radiation is higher [50]. Investigation of the results in IDA ICE proves that the internal walls facing external windows have a higher sensitivity to solar radiation and, thus, higher solar gain. This energy is stored in the internal walls and discharged into the zone later when it is needed. By comparing the results in EnergyPlus, an increase in absorption of solar radiation in the more complicated zoning configurations can be also seen. However, the increased convection coefficient and therefore increased convective heat gain on the internal surfaces leads to higher conduction losses from the building envelope, i.e., higher heat losses from windows and opaque surfaces. This outweighs the effects of higher solar gains and raises the need for higher thermal energy demand in the building.

Overall, with a more complex zoning configuration, i.e., 5 zones per floor, all three tools tend to produce very similar results, in particular on the annual basis where the deviation between the tools is less than 1%. However, on higher temporal resolutions, daily and hourly, depending on the time of the simulation year, the results can vary up to 5 kWh/h, especially in very cold hours during the early stages of the simulation or on warm days when no or low heating is required. When reducing the number of thermal zones to 1 zone per floor and 1 zone per building, the heat demand profiles start diverging from each other to the extent that in the simplest model, i.e., 1 zone per floor, IDA ICE gives 9% higher values compared to EnergyPlus and TRNSYS. In IDA ICE there is a systematic tendency to overestimate the results by 5% while EnergyPlus and TRNSYS underestimate the results by 4% when the simpler zoning configurations are applied.

To validate the results, the estimated annual heat demand was compared with the energy performance of the building as obtained from the energy performance certification (EPC) database in Sweden [51]. Table 2 shows a comparison of the results from the simulations with the reported energy performance (EP) of the building.

Table 2 also shows and compares the simulation time of building A in various energy simulation tools and with respect to different zoning configurations. As shown in Table 2, in terms of computational time, EnergyPlus outperforms the other building energy simulation tools, whereas TRNSYS provides the highest computational expense (i.e., more than 239 times longer simulation time than EnergyPlus). Table 2 also shows that the more detailed the zone modeling, the longer it takes for the building energy simulation tools to perform a simulation run.

3.1.2. Case study building B

Fig. 7 illustrates the results from modeling and simulation of building type B, Multifamily with three floors. As seen, IDA ICE still estimates the heat use for the 1 zone per building model 6% higher than

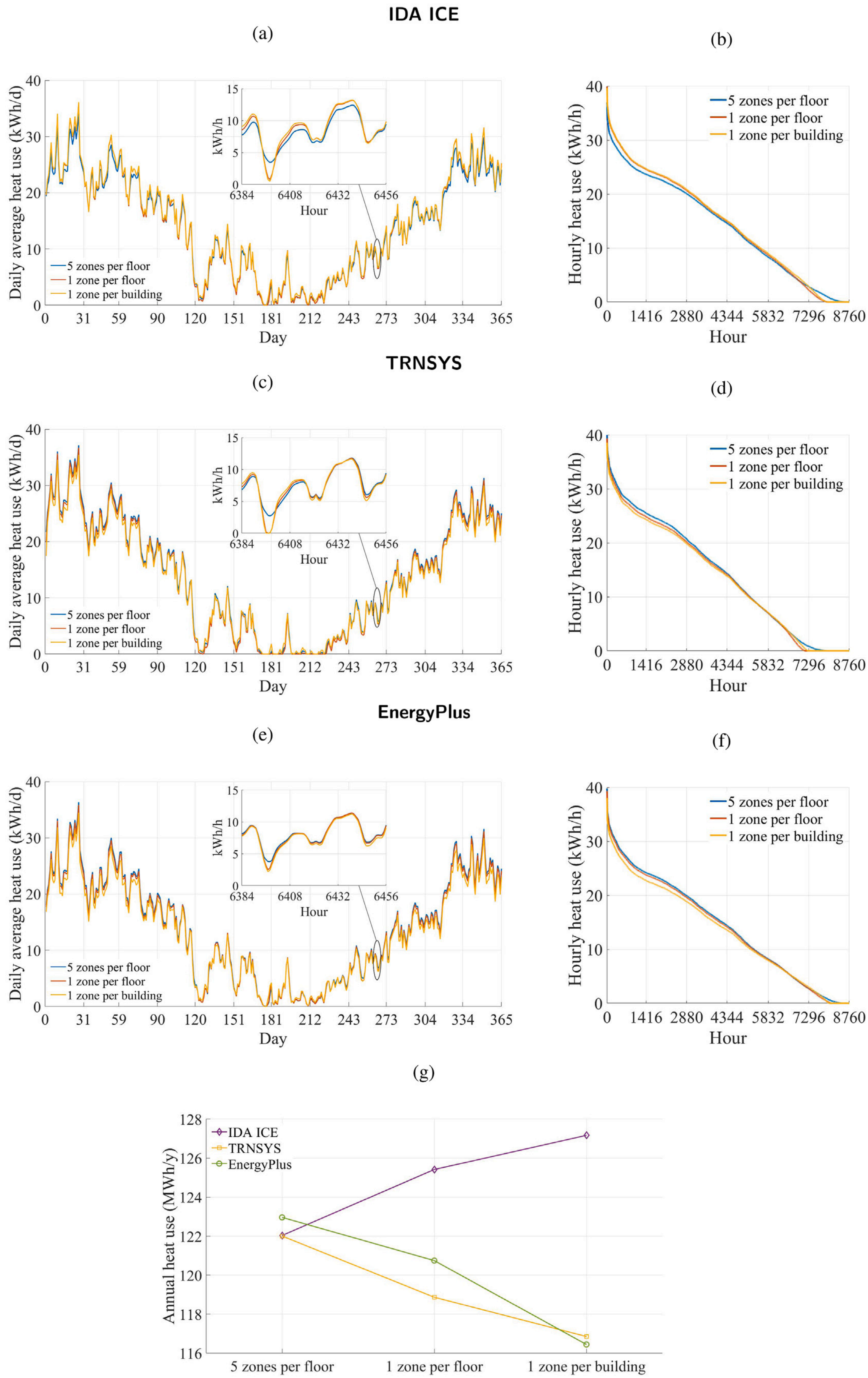

Fig. 6. Comparison of simulated heat demand with different zoning configurations in each simulation tool for building model type A. Subplots (a) and (b) show results for IDA ICE, subplots (c) and (d) for TRNSYS, and subplots (e) and (f) for EnergyPlus. Subplots to the left show daily values, and subplots to the right show the duration plots for the hourly heat demand. Finally, subplot (g) shows the annual heat demand for all different zoning configurations and all three simulation tools.

Table 2
The simulated energy performance (SEP) and simulation time for building A.

Zoning	IDA ICE		TRNSYS		EnergyPlus		EPC
	SEP (kWh/m^2y)	Time (s)	SEP (kWh/m^2y)	Time (s)	SEP (kWh/m^2y)	Time (s)	EP (kWh/m^2y)
5 zones per floor	138.2	44	138.2	2146	139.3	9	
1 zone per floor	142.0	17	134.6	1902	136.7	4	157
1 zone per building	144.0	12	132.4	1708	131.9	3	

Table 3
The simulated energy performance (SEP) and simulation time for building B.

Zoning	IDA ICE		TRNSYS		EnergyPlus		EPC
	SEP (kWh/m^2y)	Time (s)	SEP (kWh/m^2y)	Time (s)	SEP (kWh/m^2y)	Time (s)	EP (kWh/m^2y)
5 zones per floor	131.9	97	126.7	2156	132.9	9	
1 zone per floor	131.6	18	123.6	1925	132.1	5	157
1 zone per building	139.3	13	121.8	1753	127.1	3	

the 5 zones per floor model. However, as a result of the higher number of floors and the added thermal mass to the building in building B, which has three floors, the MAPE between the 1 zone and 5 zones per floor models reduces to 8%. This can be compared to building A, which had two floors and 19% MAPE. TRNSYS and EnergyPlus show a similar trend as in the results from building A.

The simulation results for building type B are compared to the reported EP of the building in Table 3. Overall, there is a general trend for all three tools to underestimate the annual heat demand for building B. It is difficult to further analyze the reason for the deviations without having access to hourly measurement data. In terms of computational time, building type B yielded quite similar outcomes to building A (see Table 3), where EnergyPlus outperformed the other energy simulation tools and the simulation expense was increased as the zone modeling became more detailed.

3.1.3. Case study building C

As above, this section includes main findings on the energy simulation of building type C using pre-defined zoning configurations, the reasoning on the impacts of the modeling strategies with different tools, and the validation of the results with measured data.

In Fig. 8, the results from modeling and simulation of a multi-family with 8 floors, building C, are presented using the same zoning configurations as for the previous two building types. As shown in Fig. 8(a) and 8(b), in IDA ICE the number of thermal zones plays a significant role in estimating the thermal energy performance of the building during warmer seasons. Representing the building with a larger number of zones results in higher thermal capacities and thus less fluctuation in the heat use profile. In TRNSYS and EnergyPlus, using different configurations of thermal zones bring no major discrepancies in the results of the 5 zones and 1 zone per floor models. However, a comparison of the annual results, in Fig. 8(g), shows that EnergyPlus estimates a 7% lower heat demand as compared to TRNSYS and IDA ICE. This gap between the results is due to the ground coupling and the calculation of heat transfer from the building to the ground. As mentioned, in EnergyPlus, using detailed calculations on conduction heat transfer to the ground from its auxiliary Basement tool, makes the results for building C with an unheated basement different from the other two tools.

In addition, considering the complexity of this building model and the computation time associated with a large number of thermal zones in high-rise buildings, the two types of 3-zone models (3 zones per building) are also examined. When assigning three thermal zones to the building, i.e., 2 zones representing the top, bottom floor and one zone including all the intermediate floors, it can be seen that the results are almost similar to the results for the 1 zone per building model. However, in mixed-use buildings where the lower floors are more likely to have use profiles different from those of the upper floors, this method can be more suitable than a 1 zone per building model. As mentioned in Section 2.2.1, an alternative to modeling each floor individually is modeling the top and bottom floors as well as one of the intermediate floors which is thought to be representative of the rest, i.e., the 1 zone per floor (abstract) model. The result show that the deviation of the simplified model (1 zone per floor (abstract)) from the complete model (1 zone per floor) including all the floors is less than 1%, which can be ignored completely. Thus, it is concluded that this simplification strategy is deemed to be accurate enough to be used in further UBEM studies.

The simulated energy performance of building C with all of the previously mentioned zoning configurations are presented in Table 4.

As mentioned, the results from EnergyPlus are considerably lower than TRNSYS and IDA ICE. This overall difference in the results is mainly related to the calculations of the heat flux through the ground-coupled floor (external floor). To model the heat transfer from the building to the ground below the slab or the basement in IDA ICE, it is sufficient to determine the average annual ground temperature as well as slab and soil properties. According to ISO 13370 [52], IDA ICE calculates the heat resistance of layers below the building construction and, accordingly, the heat transfer through them. In TRNSYS the procedure is not as effortless as in IDA ICE. For this purpose, the external slab components from the TRNSYS library should be connected to the building model. In this study, the slab component (Type 49) is used to model the case study buildings A and B. However, for modeling building type C, with an unheated basement, no proper ground coupling component is available in the TRNSYS standard library, and, thus, Type 49 is still used for calculating the heat flux through the basement envelope. In contrast, in EnergyPlus, the two associated auxiliary tools for Basement and Slab modeling give an accurate estimation of the heat exchange with the ground and make the modeling as accurate as possible. In terms of simulation time, the results for building type C were similar to those of the other building types, with EnergyPlus having the fastest simulations and the simulation time increasing as zoning became more detailed (see Table 4).

3.2. Level of detail in building models

Fig. 9 shows monthly as well as hourly variations in the simulated heat demand for the case study building B with three different levels of detail, namely, LoD3, LoD2⋆, and LoD1, in IDA ICE, TRNSYS and EnergyPlus.

The simulation results obtained from IDA ICE show the sensitivity of the model to the levels of detail, in particular during the months when the solar heat gain is higher. During winter, when the solar gain is lower, the LoDs play a negligible role in estimating the heat used in the building. On the contrary, during the warmer months of the year the deviation between the results reaches its maximum, particularly in

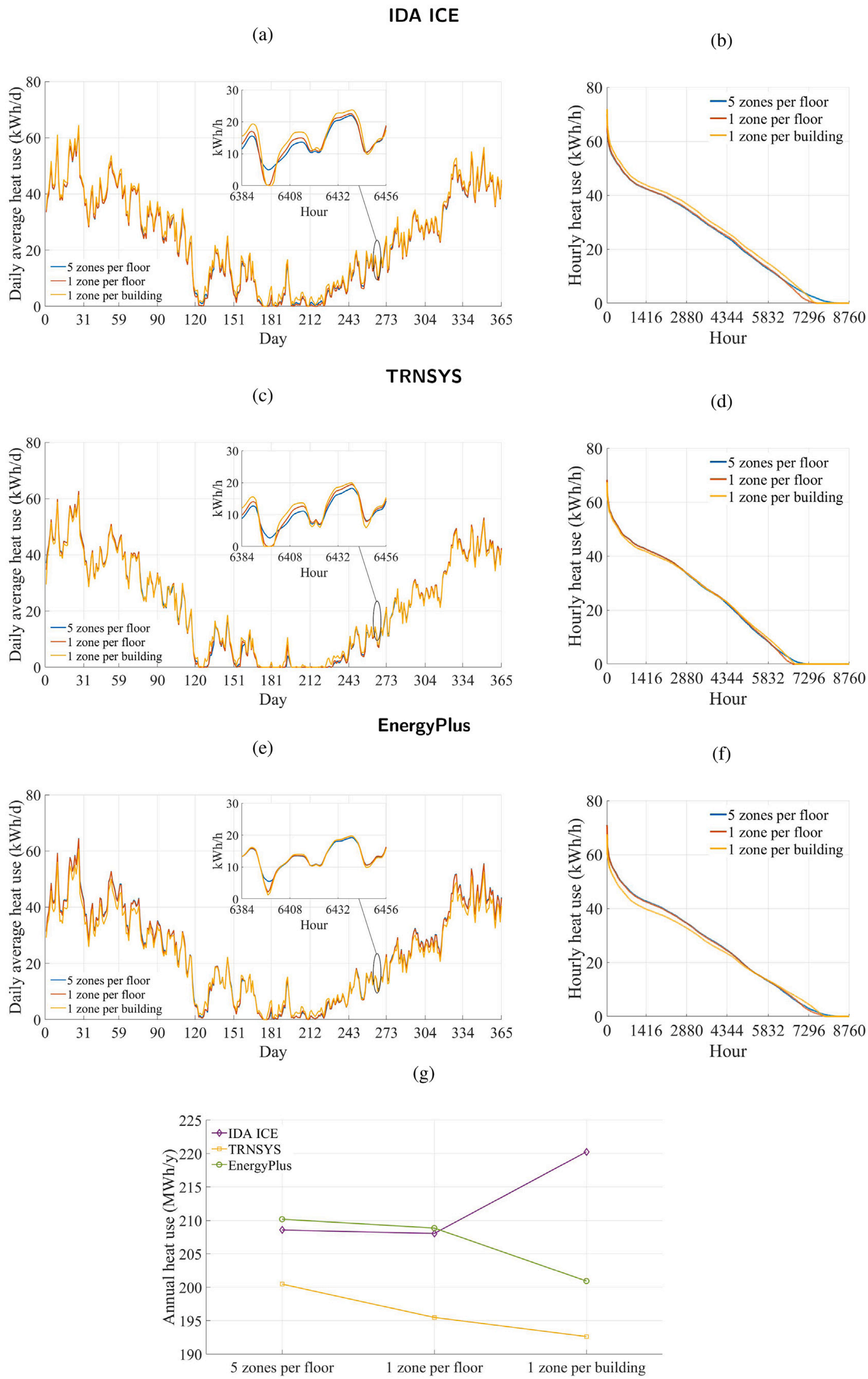

Fig. 7. Comparison of simulated heat demand with different zoning configurations in each simulation tool for building model type B. Subplots (a) and (b) show results for IDA ICE, subplots (c) and (d) for TRNSYS, and subplots (e) and (f) for EnergyPlus. Subplots to the left show daily values, and subplots to the right show the duration plots for the hourly heat demand. Finally, subplot (g) shows the annual heat demand for all different zoning configurations and all three simulation tools.

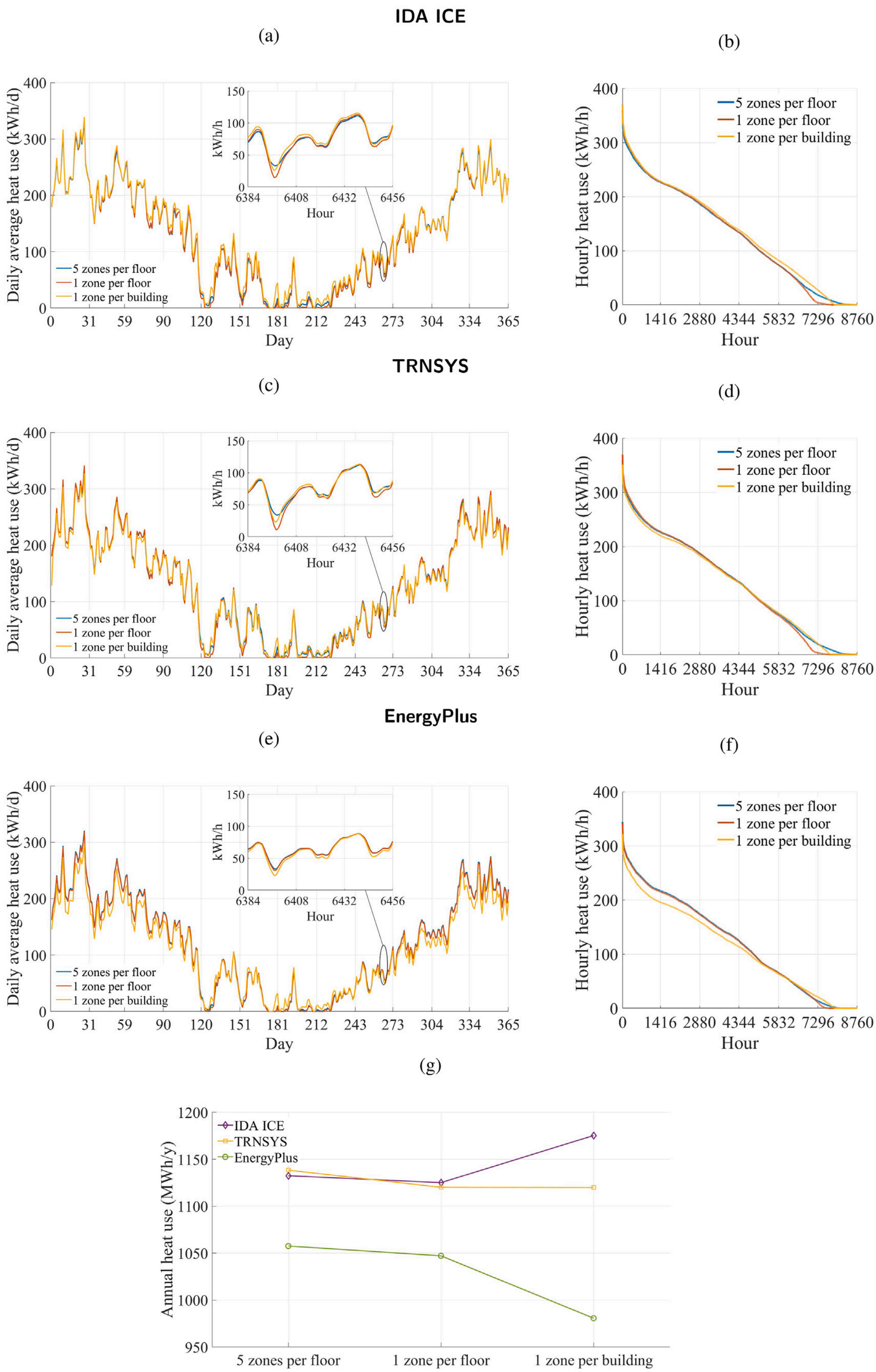

Fig. 8. Comparison of simulated heat demand with different zoning configurations in each simulation tool for building model type C. Subplots (a) and (b) show results for IDA ICE, subplots (c) and (d) for TRNSYS, and subplots (e) and (f) for EnergyPlus. Subplots to the left show daily values, and subplots to the right show the duration plots for the hourly heat demand. Finally, subplot (g) shows the annual heat demand for all different zoning configurations and all three simulation tools.

Table 4
The simulated energy performance (SEP) and simulation time for building C.

Zoning	IDA ICE		TRNSYS		EnergyPlus		EPC
	SEP (kWh/m²y)	Time (s)	SEP (kWh/m²y)	Time (s)	SEP (kWh/m²y)	Time (s)	EP (kWh/m²y)
5 zones per floor	186.8	283	187.8	2182	174.2	61	
1 zone per floor	185.6	94	184.8	2041	172.4	28	173
1 zone per building	194.1	20	180.6	1836	161.5	5	
3 zone per building	193.9	36	182.8	1993	165.3	9	173
1 zone per floor (abstract)	185.3	36	184.4	1956	171.0	8	

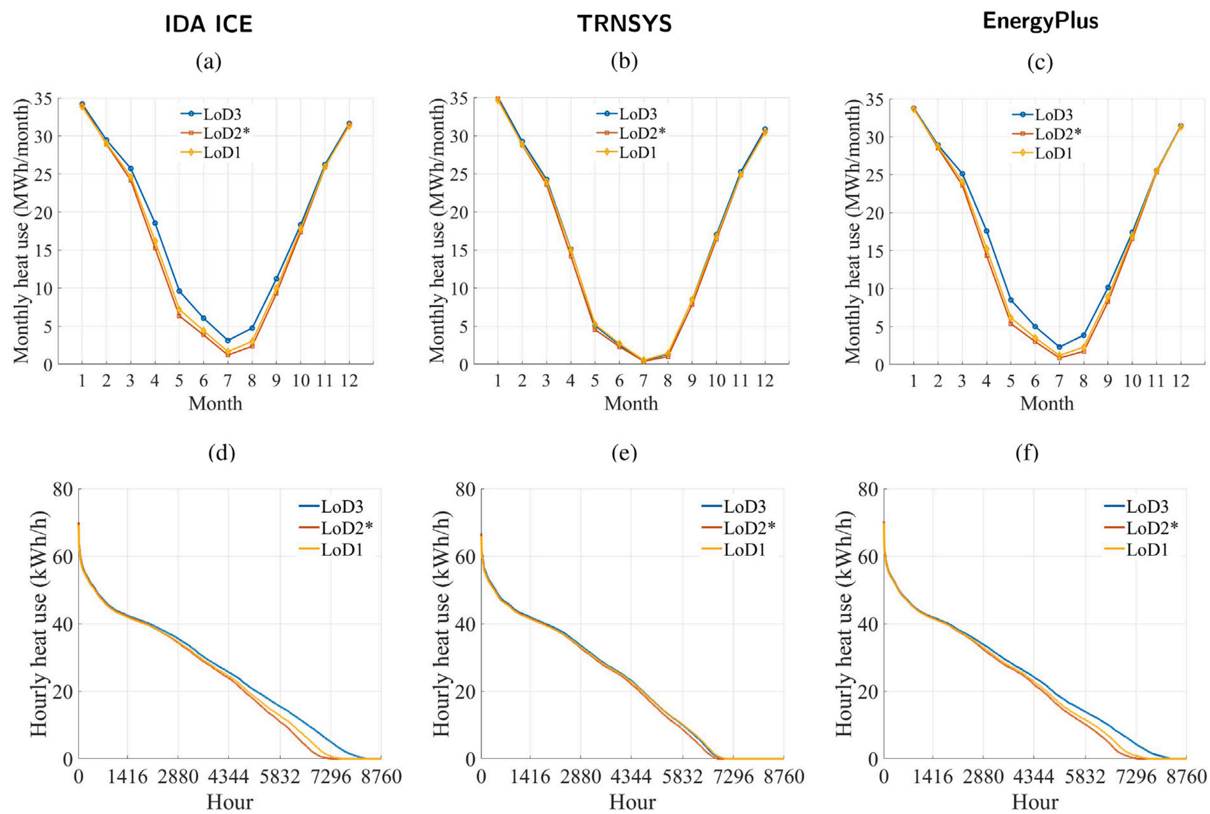

Fig. 9. Comparison of level of detail in building model simulated in different tools. Subplot (a), (b) and (c) represent the monthly heat demand in IDA ICE, TRSNYS, and EnergyPlus. Subplots (d), (e) and (f) show the corresponding duration plots for the hourly results.

April when the monthly heat demand for LoD2⋆ and LoD1 is calculated to be 18% and 13% lower than for LoD3. This is also seen in the duration plots, where the peak demand is not at all affected. Although LoD2⋆ includes more details than LoD1, the differences from LoD3 are higher. EnergyPlus gives similar results to IDA ICE. Among the three simulation tools, TRNSYS proves to be less influenced by the changes in LoD and shading obstacles adjacent to the building, e.g., overhangs, fins, and shading balconies. The MAPE of the results from a building model with LoD1 and LoD2⋆ from LoD3 in TRNSYS is roughly 3%, while it can reach above 10% and 15%, respectively, in EnergyPlus.

3.3. District level analysis

Analysis of the annual results from urban building energy modeling of the area shows that while on the building-level the mean absolute percentage error (MAPE) and the mean absolute error (MAE) (on average for the three zoning configurations) reach 14.1% and 20.6 kWh/m^{2}y respectively on the district level, these numbers can decrease by roughly 75% and fall below 9% and 13 kWh/m^{2}y. This means that in general, regardless of the zoning method, there is a considerable improvement in the accuracy of the results of an UBEM when evaluated on aggregated levels.

The calculated MAPE and MAE of the three zoning configurations, namely, 5 zones per floor, 1 zone per floor and 1 zone per building, are presented in Table 5. These values indicate that despite having more complexities in the 5 zones per floor model, as compared to the other simpler configurations, it does not bring additional advantages to the results.

Fig. 10 allows a closer look into the deviation of the simulated results from the values given in the EPC of the buildings. As seen in Fig. 10(a), in buildings with 5 zones and 1 zone per floor models, the distribution of absolute percentage error (APE) is wider. The measure of variability, the standard deviation (STD), for these two models over the whole population is equal to 8.5 kWh/m^{2}y and 5.2 kWh/m^{2}y. However, for the 1 zone per building model, the STD is calculated to be 6.5 kWh/m^{2}y.

Furthermore, Fig. 10(b) indicates that for buildings with simpler structural shapes, e.g., building types A and B, the UBEM is more reliable. For complex structures, as building type C, the simulated energy need of the buildings is less correlated to their EPCs. Apparently, for more complex buildings, the 1 zone per building model can generate more accurate results as compared to the 5 zones and 1 zone per floor models. This is particularly pronounced in one of the most complex building constructions (marked in the figure) where the building has a

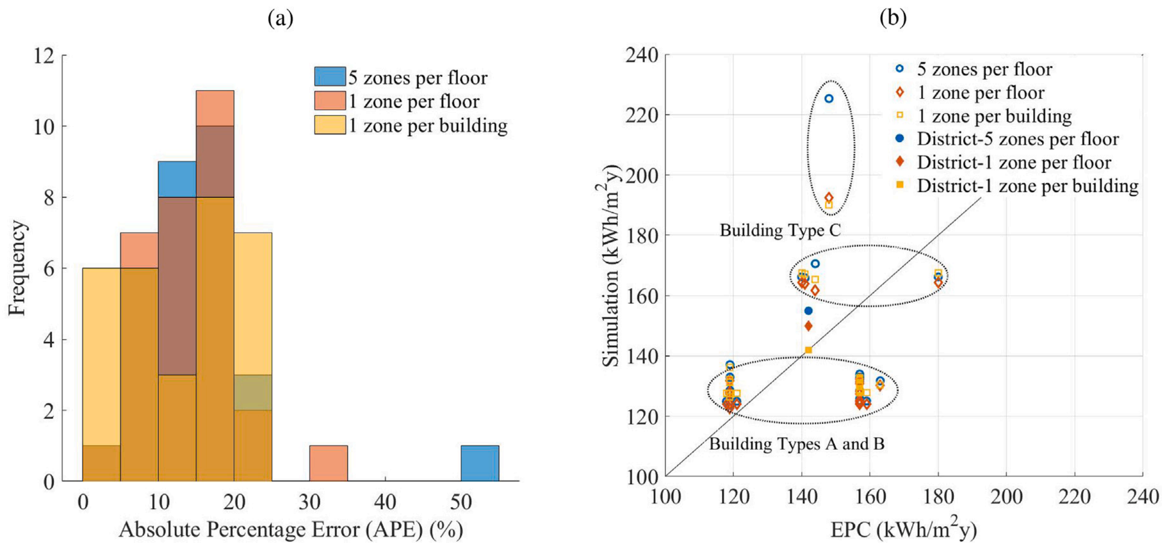

Fig. 10. Analysis of the energy performance of buildings on the district level. (a) Distribution of the APE of the simulated energy use vs EPC, (b) Correlations between simulated energy use vs EPC for the buildings as well as the district.

Table 5
Accuracy of the various zoning configurations on building and aggregated levels.

Zoning configuration	Total energy demand (MWh/y)	Total energy demand (kWh/m^{2}y)	MAPE (%)		MAE (kWh/m^{2}y)		Time (s)
			Building	District	Building	District	
5 zones per floor	10872	155	15.2	9.1	21.8	12.9	866
1 zone per floor	10525	150	14.1	5.6	20.4	8.0	327
1 zone per building	9955	142	13.1	0.1	19.6	0.1	170
EPC	8800	142					

complex shape and many external surfaces exposed to the ambient. This leads to higher heat losses through the building envelope and therefore a higher heat demand. Evaluation of the aggregated energy demand of the district also reveals that the 1 zone per building model results in the highest correlations between the measured and simulated energy use (Fig. 10(b)).

Regarding the computation cost of the UBEM with different levels of complexity, shown in Table 5, it takes 866 s to simulate the 5 zones per building thermal models and complete the simulation over the whole area. However, this process takes only 327 s and 170 s for the 1 zone per floor and 1 zone per building configurations, respectively. Considering the simulation time, choosing the 1 zone per building model can considerably improve the computation time of the UBEMs.

4. Discussion

In UBEM, development of reasonably accurate building models with a sufficient amount of details is one of the main challenges in existing research. Besides abstracting buildings into a limited number of archetypes [7], simplification of building models and reduction of the number of thermal zones are two common methods used in UBEM development.

As found in the building-level analysis, by accepting a ± 5% deviation from the most complex building models studied here, the UBEM could be based on single-zone models (1 zone per building). The simulation tools IDA ICE and EnergyPlus seem to offer different possibilities that make them interesting for UBEMs and large-scale analysis. However, as seen, the major discrepancy in the results for IDA ICE is presumably due to exclusion of the thermal mass of the external surfaces in the model. Including additional internal thermal mass in the single-zone model might slightly improve the results, yet this assumption is lacking proper justification and analysis. In the case of TRNSYS, in addition to computation time, the complicated procedure in modeling and simulation of a building using a detailed building model (Type 56) and its limitation in properly determining the effects of the shading both from building components and neighboring buildings make it less suitable for UBEMs.

In an UBEM, the amount of details of a building model (LoD) is derived from a 3D city model and underlying methods of determining the urban context. In order for a 3D city model to result in higher levels of details (LoD2+), more advanced modeling techniques should be used. However, higher accuracy of the input data, e.g., LiDAR, is equally important. In the absence of, for example, high-resolution LiDAR data or in case of other limitations in generating detailed 3D city models, the results of this study show that LoD1 can still result in an acceptable output from the model. As seen, during the heating seasons, when the heating demand is at its highest, LoD1 does not deviate from LoD3. However, during certain periods of the year when the solar radiation is higher, the differences in the results increase. Using proper correction factors for compensation of the lower LoD, and calibration techniques, the deviation of LoD1 from higher LoDs should be possible to reduce to some extent. It should be noted, though, that these results might not be relevant for warmer climates, particularly where a higher heating demand and a sufficient gain through solar radiation might coincide.

When extending the results from the building-level analysis to the district-level, the single zone model outperforms the other two models, particularly at lower temporal resolutions, i.e., month or year. The simplified models leave a wider margin for uncertainties or discrepancies of the model from reality. The increased levels of uncertainty might escalate the fluctuations of the energy use profile of a building at high temporal resolutions. However, when aggregating the results for individual buildings to the district level, the deviations between aggregated modeled and actual energy demand become even smaller as differences between buildings are averaged out. This means that by accepting some degrees of deviations on the individual building level, the large-scale results based on simplified building models could stay within an acceptable accuracy range. This may open up opportunities for making use of the simplified building models in future UBEMs and improving the computation cost of the UBEM even further.

Concerning the computation cost of the district level analysis using EnergyPlus, while it takes almost 15 min to compute the 5 zones per floor models, it decreases to 3 min for the 1 zone per building models (almost 5 times faster). This means that in urban-scale studies, the computation time can decrease considerably. The computation time is repeatedly reported to be of significant importance where an algorithm automatically performs hundreds or thousands of simulation runs in order to find an optimal solution [6,33].

This study has analyzed model complexity of residential buildings on building- as well as district-level, in a heating dominated climate. However, to generalize the findings of this study to various cases worldwide, the future outlook is to apply the method to temperate or cooling dominated climates as well. Further research should also investigate not only simplified building models but also to what extent the thermal simulation procedures can be simplified in order to reduce the computational complexity and simulation time. Furthermore, although the results confirm the use of single-zone models for residential buildings, in modeling multi-use and non-residential buildings, it is still suggested to divide the model into more thermal zones corresponding to different user profiles in the building.

5. Conclusion

This study has analyzed the impact that successive simplification of the zoning configuration and reduction of the level of detail of building models has on the simulated energy use of different types of residential multifamily buildings. The results show considerable differences between the studied building simulation tools (IDA ICE, TRNSYS, and EnergyPlus) in terms of their response to model simplification. The general pattern is that the simulation results are very similar between the tools for the most complex zoning configurations and the highest levels of detail, but that they diverge with increasing simplification.

In general, although for the simplified single-zone model as compared to the complex multi-zone model, EnergyPlus underestimates while IDA ICE overestimates the heat demand, the relative difference did not go beyond $\pm$ 5%. The analysis of the level of detail showed that in the heating seasons the level of detail plays a negligible role, whereas it has a significant impact over the whole year; the deviation between the shoe-box model (LoD1) and the most detailed model (LoD3) reached up to 9%.

By extending the methodology over a residential district with a few buildings, it can be concluded that regarding model complexity, a zoning configuration of 1 zone per building combined with LoD1 would be sufficient for UBEMs. These simplified models considerably reduce the computation cost of UBEMs of residential buildings while offering equally accurate results as more complex models. The findings of this study prove that the accuracy of UBEMs increases when validation is done for lower spatial and temporal resolutions.

Based on the findings in this study, the building simulation tools that are recommended for UBEM simulations with simplified building models are EnergyPlus or IDA ICE depending on whether the risk for underestimating or overestimating is worse. Yet, in terms of computation time, EnergyPlus is more advantageous. Furthermore, for multi-use buildings, it is suggested to increase the number of thermal zones to be equivalent to the number of distinct energy use patterns in the building. Finally, as this study is limited to residential buildings in a heating-dominated climate, further research should extend the analysis presented here to other climates and building types.

CRediT authorship contribution statement

F. Johari: Conceptualization, Investigation, Validation, Visualization, Writing – original draft, Methodology, Writing – review & editing. **J. Munkhammar:** Supervision, Writing – review & editing. **F. Shadram:** Supervision, Writing – review & editing. **J. Widén:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This study was performed within the research project ‘‘Activity-Based Urban Building and Mobility Energy Modeling (UBMEM) for Planning of Future Cities’’, as part of the strategic innovation program Viable Cities, which is financed by the Swedish Energy Agency, VINNOVA and Formas (project number: 46068-1). This work also forms part of the Swedish strategic research program StandUp for Energy. Tomas Nordqvist, the energy manager at the housing company Uppsalahem, is acknowledged for his help in providing the study with the building blueprints.

References

[1] C. Brandoni, F. Polonara, The role of municipal energy planning in the regional energy-planning process, Energy 48 (2012) 323–338, http://dx.doi.org/10.1016/j.energy.2012.06.061.

[2] S. Cajot, M. Peter, J.-M. Bahu, A. Koch, F. Maréchal, Energy planning in the urban context: Challenges and perspectives, Energy Procedia 78 (2015) 3366–3371, http://dx.doi.org/10.1016/j.egypro.2015.11.752.

[3] S. Torabi Moghadam, C. Delmastro, S.P. Corgnati, P. Lombardi, Urban energy planning procedure for sustainable development in the built environment: A review of available spatial approaches, J. Cleaner Prod. 165 (2017) 811–827, http://dx.doi.org/10.1016/j.jclepro.2017.07.142.

[4] C.F. Reinhart, C. Cerezo Davila, Urban building energy modeling – a review of a nascent field, Build. Environ. 97 (2016) 196–202, http://dx.doi.org/10.1016/j.buildenv.2015.12.001.

[5] L.G. Swan, V.I. Ugursal, Modeling of end-use energy consumption in the residential sector: A review of modeling techniques, Renew. Sustain. Energy Rev. 13 (2009) 1819–1835, http://dx.doi.org/10.1016/j.rser.2008.09.033.

[6] C. Cerezo Davila, C.F. Reinhart, J.L. Bemis, Modeling boston: A workflow for the efficient generation and maintenance of urban building energy models from existing geospatial datasets, Energy 117 (2016) 237–250, http://dx.doi.org/10.1016/j.energy.2016.10.057.

[7] F. Johari, G. Peronato, P. Sadeghian, X. Zhao, J. Widén, Urban building energy modeling: State of the art and future prospects, Renew. Sustain. Energy Rev. 128 (2020) 109902, http://dx.doi.org/10.1016/j.rser.2020.109902.

[8] J.H. Kämpf, D. Robinson, A simplified thermal model to support analysis of urban resource flows, Energy Build. 39 (4) (2007) 445–453, http://dx.doi.org/10.1016/j.enbuild.2006.09.002.

[9] T. Dogan, C. Reinhart, Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation, Energy Build. 140 (2017) 140–153, http://dx.doi.org/10.1016/j.enbuild.2017.01.030.

[10] N. Perez, P. Riederer, C. Inard, V. Partenay, Thermal building modelling adapted to district energy simulation, in: Proceedings of BS2015: 14th Conference of International Building Performance Simulation Association, 2015, pp. 8.

[11] E.-J. Kim, G. Plessis, J.-L. Hubert, J.-J. Roux, Urban energy simulation: Simplification and reduction of building envelope models, Energy Build. 84 (2014) 193–202, http://dx.doi.org/10.1016/j.enbuild.2014.07.066.

[12] M. Lauster, J. Teichmann, M. Fuchs, R. Streblow, D. Mueller, Low order thermal network models for dynamic simulations of buildings on city district scale, Build. Environ. 73 (2014) 223–231, http://dx.doi.org/10.1016/j.buildenv.2013.12.016.

[13] L. Frayssinet, F. Kuznik, J.-L. Hubert, M. Milliez, J.-J. Roux, Adaptation of building envelope models for energy simulation at district scale, Energy Procedia 122 (2017) 307–312, http://dx.doi.org/10.1016/j.egypro.2017.07.327.

[14] M. Shin, J.S. Haberl, Thermal zoning for building HVAC design and energy simulation: A literature review, Energy Build. 203 (2019) 109429, http://dx.doi.org/10.1016/j.enbuild.2019.109429.

[15] Ansi/ASHRAE/IES standard 90.1-2019 – energy standard for buildings except low-rise residential buildings, 2019.

[16] P. Nageler, G. Zahrer, R. Heimrath, T. Mach, F. Mauthner, I. Leusbrock, H. Schranzhofer, C. Hochenauer, Novel validated method for GIS based automated dynamic urban building energy simulations, Energy 139 (2017) 142–154, http://dx.doi.org/10.1016/j.energy.2017.07.151.
[17] Y. Chen, T. Hong, M.A. Piette, City-Scale Building Retrofit Analysis: A Case Study using, CityBES, in: Proceeding of Building Simulation 2017, 2017, pp. 8.
[18] R. Nouvel, M. Zirak, H. Dastageeri, V. Coors, U. Eicker, Urban energy analysis based on 3d city model for national scale applicatioNS, in: Proceeding of Fifth German-Austrian IBPSA Conference, BauSIM 2014, 2014, pp. 83–90.
[19] G. Dall'O', A. Galante, M. Torri, A methodology for the energy performance classification of residential building stock on an urban scale, Energy Build. 48 (2012) 211–219, http://dx.doi.org/10.1016/j.enbuild.2012.01.034.
[20] R. Kaden, T.H. Kolbe, CITY-wide total energy demand estimation of buildings using semantic 3d city models and statistical dATA, in: Proceeding of ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences, 2013, pp. 163–171.
[21] D. Wang, J. Landolt, G. Mavromatidis, K. Orehounig, J. Carmeliet, CESAR: A bottom-up building stock modelling tool for Switzerland to address sustainable energy transformation strategies, Energy Build. 169 (2018) 9–26, http://dx.doi.org/10.1016/j.enbuild.2018.03.020.
[22] Y. Chen, T. Hong, Impacts of building geometry modeling methods on the simulation results of urban building energy models, Appl. Energy 215 (2018) 717–735, http://dx.doi.org/10.1016/j.apenergy.2018.02.073.
[23] T. Dogan, C. Reinhart, P. Michalatos, Autozoner: an algorithm for automatic thermal zoning of buildings with unknown interior space definitions, J. Build. Perform. Simul. 9 (2) (2016) 176–189, http://dx.doi.org/10.1080/19401493.2015.1006527.
[24] F. Biljecki, J. Stoter, H. Ledoux, S. Zlatanova, A. Çöltekin, Applications of 3D city models: State of the art review, ISPRS Int. J. Geo-Inf. 4 (4) (2015) 2842–2889, http://dx.doi.org/10.3390/ijgi4042842.
[25] Citygml | OGC, 2020, https://www.ogc.org/standards/citygml. (Accessed on 16 November 2020).
[26] T. Hong, Y. Chen, X. Luo, N. Luo, S. Lee, Ten questions on urban building energy modeling, Build. Environ. 168 (2020) 106508, http://dx.doi.org/10.1016/j.buildenv.2019.106508.
[27] J.A. Fonseca, T.-A. Nguyen, A. Schlueter, F. Marechal, City energy analyst (CEA): Integrated framework for analysis and optimization of building energy systems in neighborhoods and city districts, Energy Build. 113 (2016) 202–226, http://dx.doi.org/10.1016/j.enbuild.2015.11.055.
[28] G. Agugiaro, J. Benner, P. Cipriano, R. Nouvel, The energy application domain extension for citygml: enhancing interoperability for urban energy simulations, Open Geosp. Data Softw. Stand. 3 (1) (2018) 2, http://dx.doi.org/10.1186/s40965-018-0042-y.
[29] M. Shin, J.S. Haberl, Thermal zoning for building HVAC design and energy simulation: A literature review, Energy Build. 203 (2019) 109429, http://dx.doi.org/10.1016/j.enbuild.2019.109429.
[30] R. Nouvel, M. Zirak, V. Coors, U. Eicker, The influence of data quality on urban heating demand modeling using 3D city models, Comput. Environ. Urban Syst. 64 (2017) 68–80, http://dx.doi.org/10.1016/j.compenvurbsys.2016.12.005.
[31] Z. Zheng, J. Chen, X. Luo, Parallel computational building-chain model for rapid urban-scale energy simulation, Energy Build. 201 (2019) 37–52, http://dx.doi.org/10.1016/j.enbuild.2019.07.034.
[32] S. Nagpal, C. Mueller, A. Aijazi, C.F. Reinhart, A methodology for auto-calibrating urban building energy models using surrogate modeling techniques, J. Build. Perform. Simul. 12 (1) (2019) 1–16, http://dx.doi.org/10.1080/19401493.2018.1457722.
[33] F. Shadram, S. Bhattacharjee, S. Lidelöw, J. Mukkavaara, T. Olofsson, Exploring the trade-off in life cycle energy of building retrofit through optimization, Appl. Energy 269 (2020) 115083, http://dx.doi.org/10.1016/j.apenergy.2020.115083.
[34] Uppsalahem, https://www.uppsalahem.se/. (Accessed on 06 December 2020).
[35] Sveby, https://www.sveby.org/. (Accessed on 15 September 2021).
[36] Normalisering av energianvändningen, https://www.boverket.se/sv/. (Accessed on 01 December 2021).
[37] EnergyPlus, https://energyplus.net/. (Accessed on 21 September 2020).
[38] Lantmäteriet, https://www.lantmateriet.se. Accessed on 16 June 2020.
[39] G.N. Walton, Thermal Analysis Research Program reference manua, Washington, DC, 1983, pp. 296.
[40] R. Perez, P. Ineichen, R. Seals, J. Michalsky, R. Stewart, Modeling daylight availability and irradiance components from direct and global irradiance, Sol. Energy 44 (5) (1990) 271–289, http://dx.doi.org/10.1016/0038-092X(90)90055-H.
[41] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, fourth ed., Wiley, 2013.
[42] B. Gebhart, Heat Transfer, McGraw-Hill, 1971.
[43] X.Q. Li, Y. Chen, J.D. Spitler, D. Fisher, Applicability of calculation methods for conduction transfer function of building constructions, Int. J. Therm. Sci. 48 (7) (2009) 1441–1451, http://dx.doi.org/10.1016/j.ijthermalsci.2008.11.006.
[44] G. Pernigotto, A. Gasparella, Extensive comparative analysis of building energy simulation codes: Heating and cooling energy needs, HVAC& R Res. 19 (5) (2013) 481–492, http://dx.doi.org/10.1080/10789669.2013.794088.
[45] G.P. Mitalas, J.G. Arseneault, Fortran IV program to calculate z-transfer functions for the calculation of transient heat transfer through walls and roofs, Ottawa, 1972, pp. 41.
[46] J.E. Seem, Modeling of heat transfer in buildings, (Ph.D. thesis), University of Wisconsin-Madison, 1987, p. 177.
[47] M. Vuolle, A. Bring, P. Sahlin, An nmf based model library for building thermal simulation, in: Proceeding of Building Simulation 1999, 1999, pp. 8.
[48] J. Akander, The ORC Method – Effective Modelling of Thermal Performance of Multilayer Building Components (Ph.D. thesis), KTH Royal Institute of Technology, Stockholm, 2000, p. 177.
[49] M.V. Axel Bring, Models for building indoor climate and energy simulation, 1999, IEA SHC Task 22: Building Energy Analysis Tools.
[50] P. Nageler, G. Schweiger, M. Pichler, D. Brandl, T. Mach, R. Heimrath, H. Schranzhofer, C. Hochenauer, Validation of dynamic building energy simulation tools based on a real test-box with thermally activated building systems (TABS), Energy Build. 168 (2018) http://dx.doi.org/10.1016/j.enbuild.2018.03.025.
[51] Energideklaration, https://www.boverket.se/sv/energideklaration/. (Accessed on 22 November 2020).
[52] ISO 13370:2017, https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/57/65716.html. (Accessed on 03 December 2020).