Urban building energy modeling

A systematic evaluation of modeling and simulation approaches

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Abstract

Urban energy system planning can play a pivotal role in the transition of urban areas towards energy efficiency and carbon neutrality. With the building sector being one of the main components of the urban energy system, there is a great opportunity for improving energy efficiency in cities if the spatio-temporal patterns of energy use in the building sector are accurately identified.

A bottom-up engineering energy model of buildings, known as urban building energy model (UBEM), is an analytical tool for modeling buildings on city-levels and evaluating scenarios for an energy-efficient built environment, not only on the building-level but also on the district and city-level. Methods for developing an UBEM vary, yet, the majority of existing models use the same approach to incorporating already established building energy simulation software into the main core of the model. Due to difficulties in accessing building-specific information on the one hand, and the computational cost of UBEMs on the other hand, simplified building modeling is the most common method to make the modeling procedure more efficient.

This thesis contributes to the state-of-the-art and advancement of the field of urban building energy modeling by analyzing the capabilities of conventional building simulation tools to handle an UBEM and suggesting modeling guidelines on the zoning configuration and levels of detail of the building models.

According to the results from this thesis, it is concluded that with 16% relative difference from the annual measurements, EnergyPlus is the most suitable software that can handle large-scale building energy models efficiently. The results also show that on the individual building-level, a simplified single-zone model results in 6% mean absolute percentage deviation (MAPD) from a detailed multi-zone model. This thesis proposes that on the aggregated levels, simplified building models could contribute to the development of a fast but still accurate UBEM.

If not us, who? If not now, when?
John F. Kennedy

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I **Johari, F.**, Peronato, G., Sadeghian, P., Zhao, X., Widén, J. (2020). "Urban building energy modeling: State of the art and future prospects", *Renewable and Sustainable Energy Reviews*, Vol. 128, article id 109902.

II **Johari, F.**, Nilsson, A., Åberg, M., Widén, J. (2019). "Towards urban building energy modelling: a comparison of available tools". In Proceedings of eceee 2019 Summer Study on energy efficiency: Is efficient sufficient?, 3-8 June, Presqu'île de Giens, Hyéres, France, 1515-1524.

III **Johari, F.**, Munkhammar, J., Widén, J. "Validation of simplified building energy models for urban-scale energy analysis of buildings", Manuscript.

Publications not included in the thesis

V Psimopoulos, E., **Johari, F.** , Bales, C., Widén, J.(2020). "Impact of boundary conditions on the performance enhancement of advanced control strategies for a residential building with a heat pump and PV system with energy storage.", *Energies* , Vol. 13, no 6, article id 1413.

Notes on my contribution

I contributed the following to the appended papers:

Paper I, I did the literature survey and wrote all the paper except Sections: 2.1.1, 2.2.1.2, 2.3, 3.3.

Paper II, I developed the building models in IDA ICE, TRNSYS and EnergyPlus, analysed the results and wrote the paper.

Paper III, I developed all the building models and wrote the paper.

Contents

List of abbreviations

BEM	Building energy modeling
CEA	City Energy Analyst
CTF	Conduction transfer function
EPC	Energy performance certificate
GHG	Greenhouse gas
GUI	Graphical user interface
HVAC	Heating ventilation and air conditioning
LiDAR	Light detection and ranging
LoD	Level of detail
MAPD	Mean absolute percentage deviation
R-C	Resistance-capacitance
RMSE	Root mean squared error
UBEM	Urban building energy model
WWR	Window to wall ratio

1. Introduction

Undoubtedly, cities are one of the main contributors to climate change problems. More than 75% of greenhouse gas emissions in the world originate from urban activities and their associated energy use. With globally increased urbanization at an unprecedented rate, from 56% in 2020 to 68% in 2050 [1], there is less chances of reducing global emissions to a safe level unless new and expanding cities are based on low-carbon urban development paradigms [2, 3]. Indeed, cities are a key part of the solution for climate mitigation and adoption.

Worldwide, cities adopt different approaches to the style and structure of their climate actions [2]. Many cities and municipalities undertake these actions even in the absence of national policies [4]. Interestingly, these ambitious city-level climate-conscious policies can considerably reduce carbon emissions globally while delivering enormous benefits to the cities [2, 5]. From another perspective, cities can serve as policy laboratories for actions on climate change that help national governments understand the opportunities while designing effective policies [6]. In summary, urban or local policies can contribute to the global climate agenda to a large extent.

Addressing the complexity of climate change, local governments and municipalities require a systematic approach that identifies problems, formulates possible strategies, and evaluates resulting benefits [7]. In this context, urban planning and, in particular, urban energy planning typically seems as a pivotal approach that can be moved to the forefront of the transition to sustainability and carbon neutrality [8, 9]. Urban energy planning is an inclusive concept that targets many individual components of urban energy systems contributing to the interactive process of using and supplying energy [10]. Thus, in managing the transition of urban energy systems, it is required to target these different components, from generation to transmission and consumption, individually or in unison with each other [11].

With buildings being one of the most energy intensive components of the urban energy system, opportunities for accelerated transformation towards sustainability are enormous and can be realized if best practices in energy efficiency and integrated renewable energy technologies in buildings are efficiently used [12]. Statistics show that by construction of more energy efficient buildings and renovation of existing dwellings up to 35% increase in energy efficiency of the European household sector could be achieved during 1991-2016 [13]. However, in order to plan for a more resource efficient built environment, understanding of flows of energy in buildings and synergies between buildings and the other components of the urban energy system is crucial. Historically, translation of physical systems into mathematical equations, i.e., mathematical models, has paved the way for an improved understanding of systems and have given precision to formulating ideas and identifying solutions [14]. In other words, mathematical models, if properly calibrated, are key tools in understanding and explaining the function and dynamics of energy systems and predicting their behaviour in response to internal and external changes.

An Urban building energy model (UBEM) is a bottom-up engineering-based (or physic-based) model of energy use in large sets of buildings within a specific geographic area such as an urban district or a whole city [15]. This is a new concept that has been developing during the last two decades [16]. An UBEM is an analytical tool that simulates and visualizes patterns of energy use in buildings and gives insight into urban energy system behavior related to buildings [17]. Using a broader definition, the UBEM includes not only the use but also the supply of energy and provides an estimation of spatio-temporal patterns of energy flows, both demand and supply, over the whole city. In particular, UBEMs can be applied when designing and investigating both new and existing urban areas and systems which makes them an attractive tool for city planners and policy makers [18]. Overall, the extent and applicability of UBEMs motivate the need and the growing trend for development of such models to aid in improving sustainability and energy efficiency in cities.

It is generally recognized that the development of an UBEM is a challenging task that requires handling big data, automated procedures for modeling, simulation and calibration of many buildings as well as high computational power [16, 19, 20]. To overcome these challenges, choosing the right simulation engine, and deciding on a suitable level of thermal model complexity, are key points in UBEM development that have not been systematically addressed and scrutinized previously, but will be so in this thesis.

1.1 Aim of this thesis

The principal aim of this thesis is to shed new light on the field of urban building energy modeling and contribute to its advancements. More precisely, the intention is to provide a foundation for the development of an accurate UBEM, systematically considering the choice of simulation engine, and complexity of the model. The following precise goals of the thesis were formulated in order to reach this aim:

i Undertake an extensive survey of the existing scientific literature on UBEMs in order to identify the state-of-the-art and best practices in the field.

ii Evaluate the applicability and accuracy of existing building energy modeling (BEM) software for potential use as a simulation engine in the UBEM.

iii Determine a suitable level of complexity for the thermal building models in the UBEM.

1.2 Overview of thesis and appended papers

This licentiate thesis is structured as follows: In Chapter 2, a theoretical background and an overview of important aspects of the field of urban building energy modeling are provided. A review of existing research and identified research gaps are also presented in this chapter. Chapter 3 is a summary of the methods used in the appended papers, including simulation tools, developed models, data and case studies. This is followed by Chapter 4, in which the results of the thesis are presented. Chapter 5 includes further discussion on the findings and an outlook towards further work. Finally, Chapter 6 draws the final conclusions. Overall, this thesis summarizes the work that has been done in the following appended papers:

I *Paper I* provides a comprehensive and up-to-date state-of-the-art literature review of multi-scale bottom-up engineering-based UBEMs. This paper aims to highlight the main approaches, persistent challenges and possible opportunities for the current research. Besides, it suggests a new perspective on integrated modeling that includes different elements of urban energy systems, more specifically buildings and their energy systems, urban microclimate, district energy systems and, most importantly, urban human mobility, in one interactive model. This paper fulfills the first aim (Aim i) of this thesis.

II *Paper II* is a systematic comparison of four simulation tools that could potentially work as UBEM simulation engines, namely, the indoor and climate energy simulation software IDA ICE, the transient system simulation software TRNSYS, and the two building energy simulation tools EnergyPlus and VIP-Energy. This paper compares modeling procedures, inputs, outputs and accuracy of these tools. The main focus of this paper is to investigate the accuracy and suitability of these tools for large-scale application in UBEM simulation. According to the obtained results from this paper, it is possible to reach the second aim (Aim ii) in this thesis.

III *Paper III* investigates the trade-off between complexity and accuracy of the intended building models for the urban building energy modeling. By evaluating the most common zoning configurations and levels of detail in the building envelope components, this paper aims at finding a suitable level of complexity for the building models, which should be simplified but still accurate enough for the scope of the urban building energy modeling. The last aim (Aim iii) of this thesis is pursued with this paper.

2. Background

In this chapter, the background of this thesis and the state-of-the-art of the field of urban building energy modeling are presented as follows. In Section 2.1, urban energy systems and the necessity of their transition towards sustainability are discussed. The aim of this section is mainly to shed light on urban building energy models as a decision-making tool for sustainable urban development of our future cities. Section 2.2 presents an introduction to the field of urban building energy modeling and discusses possible opportunities, and persistent challenges during the development of a reliable model. Section 2.3 reviews the latest advances of the field and introduces some of the notable models that have been developed so far. Finally, in Section 2.4 a number of research gaps are identified and it is explained how these gaps are intended to be filled by the thesis and its appended papers.

2.1 Urban energy systems in transition to sustainability

Considering the unique position of local governments to address causes and effects of climate change, examples of effective local or municipal climate actions are abundant [21]. However, there is no clear action plan for urban energy transition towards sustainability that can be delivered for city-specific conditions [22]. Urban energy system is a broad concept that includes many components interactively contribute to the process of supplying and using energy [10]. Understanding urban energy systems may provide a useful perspective for informed and inclusive policies for urban energy transition with respect to city-specific conditions.

2.1.1 Urban energy systems

There is no doubt that the future of sustainable urban development is tied up with urban energy systems and their characterizations [22, 23]. In the literature, the urban energy system is given different definitions. Grubler et al. [24], define it as a *"composition of all components related to the use and provision of energy services associated with a functional urban system, irrespective where the associated energy use and conversion are located in space"* [24]. Unlike this, Castán Broto [22] emphasises the spatial organization of urban energy systems and describes them as *"spatial organisation of multiple energy* *services depending on how people use energy (for lighting, thermal comfort, communications, cooking, transportation), and how energy services are provided (whether this is for the generation of electricity, gas provision or for the direct use of fuels for heat or mechanical power)"* [22]. However, the most inclusive definition of urban energy systems are provided by Keirstead et al. [10, 25] who define the urban energy system as *"a formal system that represents the combined processes of acquiring and using energy to satisfy the energy service demands of a given urban area"*.

According to the definition given by Keirstead et al. [10], it can be concluded that the transition towards more sustainable urban energy systems requires coordinated energy planning including the whole chain from primary energy extraction, through energy conversion, transmission, distribution and use [26].

Given the existing urban and regional energy planning, Asarpota and Nadin [27] highlight the components (or the areas) of urban energy systems that can be instrumental in urban energy transitions into sustainability and carbon neutrality. Transport and accessibility is one of the main components of the urban energy systems that show a potential role in spatial planning and low emission energy strategies, as can be found in the studies from [28]. Energy infrastructure is the other key component of the urban energy systems which includes the technologies on district energy systems such as district heating and cooling networks, multi-energy systems and energy hubs, and renewable energy generation at district scale [19] as well as electricity network and smart grids [29]. The other energy related component which plays an important role both on supply and use of energy is the building stock [27]. From design to systems, buildings suggest a wide range of opportunities for energy efficiency and integrated renewable energy strategies [10].

2.1.2 Building energy policies

Among the different elements of the urban energy systems, the building stock has the greatest contribution to energy use and thus, greenhouse gas (GHG) emissions. It is estimated that buildings account for 40% of energy use and 36% of GHG emissions in the EU [30]. At the same time, the building stock provides a great opportunity in renewable energy resource integration, e.g., building integrated solar [31]. In this respect, to cope with future impacts of climate change and to move towards a more sustainable future, national, regional, and local authorities deploy a wide range of building oriented policies and building codes which mainly aim at follows:

- Improved energy efficiency in buildings through design, construction, and renovation of buildings and their heating ventilation and air conditioning (HVAC) systems.

- Increase the share of renewable energy resources through building integrated and decentralized energy systems, such as building-integrated or building-applied solar technologies.

National building codes and regulations are primarily means for increasing energy efficiency in buildings [32], yet their effectiveness is often constrained in several ways, among them difficulties and differences in compliance and enforcement of the regulations [33]. Nonetheless, a combination of these regulations with local policies, and improvement of the same based on city planning and development strategies, can be one of the most effective ways of achieving the target goals for climate mitigation and sustainable development [34]. In many cities, building standards and installations of energy-efficient technologies have become widely adopted into local energy and climate action plans [35]. As an example, in the U.S., Massachusetts municipalities have introduced an above-code appendix to the "base" building energy codes, so called "stretch-code" [36]. The stretch code emphasises the adoption and enforcement of energy efficient technologies in buildings, is designed to make the new constructions more energy-efficient than the base energy codes. Therefore, the building code in Massachusetts is required to become updated every few years according to the new stretch-code. This eventually leads to incorporation of stretch-code to the base code [36]. However, although the concept of localization of building standards seems to be successful, it requires substantial funding and a structured local government with sufficient means [37].

2.1.3 The need for a decision-making tool

Local governments require proper tools and knowledge on how and where the building policies should be implemented. Traditionally, benchmarking and certification systems have been common frameworks for identification and implementation of the energy efficiency improvements, and energy use reduction practices in buildings [38]. LEED (Leadership in Energy and Environmental Design) [39] and BREEAM (Building Research Establishment Environmental Assessment Method) [40] are the two recognized examples of a such green certification systems that have been commonly used by decision-makers, and stakeholders internationally. When benchmarking is applied to buildings energy use, it serves as a mechanism to measure the energy performance of a single building over time, relative to other similar buildings or to simulations of a reference building [41]. For years, dynamic energy modeling and simulation of individual buildings have been widely used in benchmarking of buildings for planning, demonstration, and evaluation of energy conservation measures and thermal comfort improvement in individual buildings [42]. However, considering interactions between buildings and the urban environment, their role in renewable resource envelope solution and dynamic influences of buildings energy use on district energy systems, the focus has begun to shift from benchmarking and individual building energy studies to district and city-level solutions. For instance, in the latest action plans towards a carbon free Boston, the urban building energy modeling is the only measure for examination of energy efficiency improvement in buildings [43].

2.2 What is urban building energy modeling?

In this section an overview of city-scale energy modeling of buildings and, more specifically, bottom-up engineering energy models of building, referred to as urban building energy models (UBEMs), is presented. This section is a short summary of the most important findings from the review of the field in Paper I.

2.2.1 City-scale energy modeling of buildings

City-scale dynamic energy modeling of buildings is highly dependant on the availability and granularity of input data and can vary from top-down to bottom-up models [42, 44]. Top-down models approach the aggregated energy use data and tend to find its interconnections with end-use related variables. Based on this terminology, top-down models determine the long-term transitions in urban energy data and do not focus on individual end-users [45]. As regards the emphasis on socio-econometric and socio-technical factors, most top-down models are primarily based on the correlations between energy and variables such as income, employment rate, energy price, population, household size, and appliance ownership [44]. However, despite being a straightforward method for analyzing the overall urban energy use, top-down models are inherently unable to capture the dynamics in individual-level data. They also lack any technological and physical details. Thus, they are less suitable for the identification of improvement areas in existing buildings and scenario planning of future buildings [44, 46].

Bottom-up models, on the other hand, are developed based on disaggregated data which are then used for aggregation or extrapolation to the district or city level. In bottom-up models, the description of the individual building is based on type of input data, i.e., dwelling properties, building physics and energy use [42]. Accordingly, bottom-up models can be categorized into three distinct methods: statistical, engineering (or physical) and hybrid models [20]. Statistical or data-driven bottom-up models rely on the analysis of time-series or cross-sectional actual energy use data with respect to end-use information, and give an estimation of energy demand. This means that similar to top-down models, statistical models are also capable of capturing the consumption patterns based on the end-use related variables. However, the dependency of statistical models on historical measurement data makes them less useful for studying technological changes and future developments [47, 48].

In engineering (or physical) models, however, the approach is to establish a close to reality description of a building and its HVAC system using mathematical modeling. This means that in engineering techniques, individual building-level energy use is solely estimated from physical and technological characteristics of buildings and, thus, no previous knowledge on consumption patterns or demographic factors is necessary. However, the required level of detail in the data on physical properties of the building and its systems is quite extensive [16, 46].

Although these engineering models are practical representations of buildings, they cannot be reflective of the uncertain variables of the building models, such as occupants' behavior. In addition, they are unable to handle the systematic uncertainty of the simplified modeling techniques. Thus, the third type of models, so-called hybrid models, has gained increasing popularity among model developers. A hybrid model is a collection of both statistical and engineering models with all their respective advantages. In the hybrid models, while the building is modeled according to the engineering methods, the uncertainty of the input variables as well as the simplified model is approached by statistics and statistical models [16]. In the existing literature, bottom-up models that benefit from engineering models of buildings, is commonly refer to as "urban building energy models" [16]. Table 2.1 summarizes the strengths and weaknesses of these three modeling techniques in brief.

Table 2.1. *Comparison of bottom-up city-scale energy models of buildings: statistical, engineering and hybrid models.*

Models	Strengths	Weaknesses	References
Statistical models	• End-user information and variability in occupant behaviour is covered. • No detailed technological information is needed. • Demographic factors can be considered.	• Extensive data and a large number of samples are required. • Highly dependant on historical data. • Not applicable for development studies.	Torabi Moghadam et al. [12], Nutkiewicz et al. [49], Yang et al. [50], Lo et al. [51]
Engineering models	• Estimation of energy use for different spatio-temporal resolutions is possible. • Detailed technical information and systems are considered. • Development studies, e.g., efficiency measure and urban development, are possible.	• Detailed technical information on buildings and systems is required. • Extensive computational effort is required. • No information on end-user as well as demographic information is included.	Nageler et al. [52], Cerezo Davila et al. [53]
Hybrid models	• Estimation of energy use for different spatio-temporal resolutions is possible. • End-user information and variability in occupant behaviour is covered. • Detailed technical information and systems are considered. • Results in the most accurate urban energy development tool.	• Detailed technical information on buildings and systems is required. • Extensive data is required. • Extensive computational effort is required.	Nouvel et al. [54], Ghiassi et al. [55]

2.2.2 UBEM workflow

As in individual building energy modeling (BEM), in UBEMs every part of the model is shaped around geometrical and non-geometrical information, i.e., construction, materials, systems and occupancy, which are then imported to a simulation engine where the energy performance of buildings under specific weather conditions is calculated and then analyzed. Nonetheless, considering the scope of urban building energy modeling, following the same procedure as for BEM is impractical. Successive modeling of hundreds or thousands of buildings with the same level of detail and model complexity as for BEM requires endless effort and large sources of information that are not available [16, 17]. To overcome these issues, UBEM developers rely on a multi-step procedure, as illustrated in Figure 2.1, with steps that are conducted in sequence or simultaneously.

A description of the geometries of buildings and their surrounding objects is first obtained from a pre-processing step for generating 3D models of buildings in a city, referred to in the following as a 3D city model [56]. In the 3D city model, building footprints (2D polygons) are extruded from buildings' height and elevation information acquired from national geodatasets, photogrammetry or laser scanning, i.e., light detection and ranging (LiDAR) data [57]. This virtual extrusion of buildings based on their height (2.5D massing) results in shoe-box models of buildings corresponding to what is called Level of Detail 1 (LoD1) [17], as seen in Fig 2.2. However, to give an accurate estimation of the thermal energy performance of buildings and to investigate the solar po-

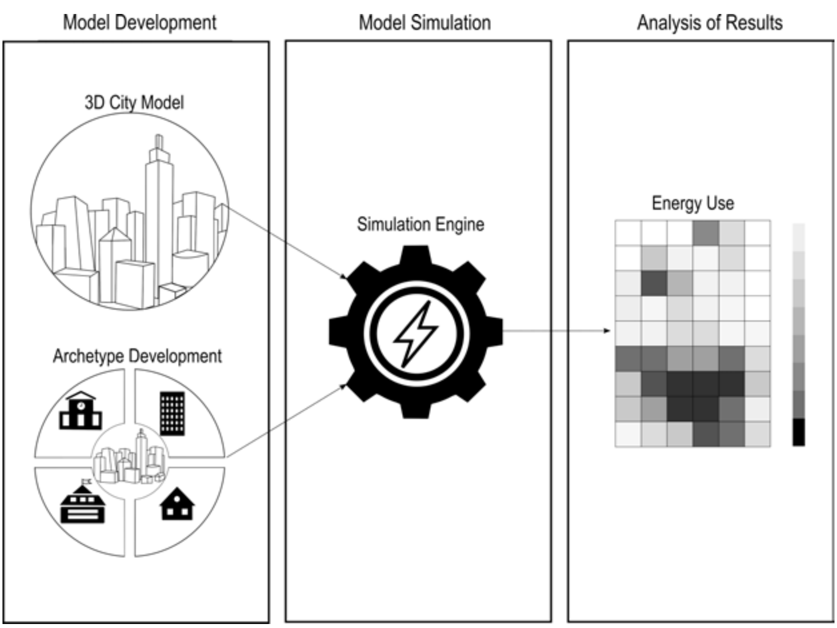


Figure 2.1. Illustration of the overall urban building energy modeling workflow.

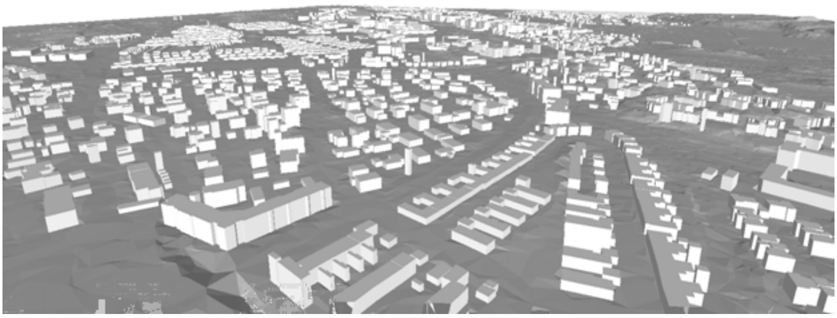


Figure 2.2. 3D city model with LoD1 for a district in Uppsala based on the data obtained from the Swedish mapping, cadastral and land registration authority, Lantmäteriet [59].

tential on rooftops, a higher level of detail, e.g., LoD2, is used in many studies [54, 57, 58]. In addition to building geometries, the other advantage of a 3D city model is that it can be used to identify adjacent buildings, which generally escapes the attention of model developers in the absence of any 3D city model. Adjacencies of buildings can impact the thermal energy balance of buildings to a large extent [60]; adjacent walls of buildings influence the heat transmission and adjacent buildings can be used in shading analysis and calculation of solar irradiance availability on buildings.

Acquisition of non-geometrical information on buildings, e.g., material and construction, HVAC systems, and occupancy profiles, is a challenging task, especially when accessible sources of information are limited. On the other hand, transforming a large amounts of information into distinctive building models involves considerable amount of time and resources that is beyond the scope of UBEMs [61]. As an alternative, model developers commonly focus on reference or representative buildings instead. These representative buildings, known as building archetypes, summarize the building stock into a smaller numbers of buildings while maintaining their diversity. In this respect, they are expected to limit the amount of effort and information put into the models without compromising accuracy. Identification of building archetypes and finding their most important characterization is still one of the most important parts of UBEMs, elaborated upon further in Section 2.2.3.

Once the 3D city model and the building archetypes are available, they, together with the prevalent weather data, are imported into an UBEM simulation engine where the building models are implemented and the energy demand is calculated and output. This simulation engine is capable of executing simple to complex models of buildings and their energy systems. In some cases, it can also handle interconnections of buildings with their urban environment directly, or through co-simulation with other tools [52].

Nevertheless, not every UBEM simulation engine is comprehensive enough to include different models of not just buildings but also energy systems and their components such as district heating and electricity distribution. In this respect, co-simulation [52] and modular [54] approaches seem to open new opportunities for more advanced UBEMs.

To increase the accuracy and reliability of the results, as in BEM, the UBEMs also need to be calibrated and validated against actual energy use data. Depending on the availability of data, the calibration and validation of the results can be done for different temporal and spatial scales. For instance, Cerezo Davilla et al. [53] compared simulation results with annual and hourly energy use data on a district scale, Moreover, using Bayesian calibration techniques, Wang et al. [62] validated the postcode level simulation results with 2 years of measurement data. Methods for calibration and validation of UBEMs are elaborated upon in Section 2.2.5.

2.2.3 Definition of building archetypes

As mentioned, collecting and handling data are some of the main challenges of large-scale energy modeling of buildings and, in particular, UBEMs. However, the introduction of building archetypes, i.e., reference buildings that are representative of a group of buildings with similar characteristics, is expected to moderate modeling complexities to some extent.

To define building archetypes, the building stock is first classified based on common characteristics that are likely to affect the energy performance of buildings. With a deterministic approach, it suffices to classify the buildings based on a collection of features such as buildings' use, type, year of construction, HVAC system, or heated floor area [63, 64]. However, the simplified deterministic approach may lead to a misconceived classification of buildings. More precisely, by systematic classification of buildings based on generalized features and unrelated to energy use values, distinguish between variations or similarities in energy performance of buildings could be hard, specially when the building performance does not follow its characterizations such as type of use and year of construction [53]. This stresses the need for the second method of building classification in which adopting influential features and classifying buildings are conducted with respect to their energy use [65]. Applications of probability classification using probability distribution of a set of building's common features and supervised learning have been proven to be successful [66, 67]. Recently, attention has moved to a third classification method using unsupervised learning and cluster analysis. The advantage of clustering over the other methods is its approach in not only classifying but also finding the most representative buildings, to be the building archetype, from each class or cluster of buildings [55, 68].

After the classification of buildings and identification of building archetypes are completed, non-geometrical characteristics are collected either for a real or a virtual building. Using this information, building models can be developed not only for the building archetypes but also for all similar buildings in every class. Nevertheless, due to the diversity of buildings and their characteristics, calibration of the models for building archetypes is often necessary [63, 69]. Methods for calibration and validation of models and archetypes are presented in Section 2.2.5.

2.2.4 UBEM simulation engine

In the BEM, a thermal model of a building based on geometrical and non-geometrical information is simulated under prevailing weather conditions. This results in the thermal energy performance of the building, e.g., energy demand for comfort cooling and heating, and room temperature [70].

In urban building energy modeling, the principal approach is to model and simulate the buildings as in the BEM. However, considering the scale of a city, the simulation needs to be extended over hundreds or thousands of buildings. For this purpose, traditional procedures and step-by-step modeling techniques, as in BEM, seem not to be working efficiently. Yet, many model developers rely on the validity of the BEM and intend to upscale its capability for urban building energy modeling. In this case, a BEM software is placed in the main core of the model in order to conduct the simulation while a set of algorithms handle the automated procedure of simulating the whole city. The approach of making use of BEM-based simulations is found in the majority of studies such as the models developed by Cerezo Davila et al. [53], Chen et al. [71], Nageler et al. [52] and Wang et al. [72]. Although these types of models deploy the resources and capabilities of the BEM simulation software to accurately estimate the energy use in buildings, their use comes with increased complexity and computation cost of the model. For this reason, tailor-made simulation engines might be more appropriate.

Describing buildings through the resistance-capacitance (R-C) analogy was introduces around early 1970s when the very first energy models of buildings came into being. The BEM simulation tools also use this approach in their internal calculations, although the level of complexity might be different. Developing tailor-made algorithms based on the R-C analogy and on simplified heat balance equations helps modelers to considerably reduce the computation time as well as the complexity and level of detail in UBEMs. The models developed by Robinson et al. [73] and Fonseca et al. [74], are some well known examples of this modeling approach.

In addition to the type of simulation core, i.e., BEM software or tailor-made algorithms, the UBEMs may differ in considering single or multi-zone building models. Traditionally, depending on the boundary conditions, e.g., exposure to the ambient condition, and variations in the internal heating, ventilating and air conditioning of a building, the thermal model is designed to have one zone or multiple zones. However, in urban building energy modeling, in the absence of detailed building-level information, it is assumed that all buildings can be defined through similar zoning configurations. Thus, the UBEM simulation engine is also responsible for the implementation of the predefined zoning configuration.

2.2.5 Model calibration and validation

UBEMs heavily rely on physical and operational characteristics of buildings. Yet, accessibility to such data is restricted in many cases and existing methods of generalization from discrete sources of data add to systematic uncertainties of the model [62]. Furthermore, some of the model parameters, such as occupancy profiles, are inherently uncertain and no model is able to fully capture their variations in time [75]. On the other hand, to reduce associated complexities of UBEMs, simplification of the model is a common method that also increases the performance gap between the model and reality. To reduce the input data uncertainty and optimize the performance of simplified models, calibration of the model becomes an important part of the UBEMs [62, 76, 77].

The approach to calibrate and refine the model varies in existing research, but two common methods can be distinguished. An iterative process of adjusting the model parameters and comparing the results with energy use data is commonly used in many studies. Due to the simplicity of the method and its flexibility in adapting data with various spatial and temporal resolutions, it seems a straightforward approach to use. This method can be found in the studies conducted by Heiple and sailor [78], and Leroy et al. [76]. The second approach applies statistical methods, in particular, Bayesian statistics and Bayes' theorem to predict the uncertain parameters and calibrate the model accordingly [63, 64, 77, 79]. In an attempt to infer the parameter values from the posterior distributions of uncertain parameters, Nagpal et al. [80] suggests an auto-calibrated model to reduce the manual effort in calibrating the UBEMs, while Kristensen et al. [69] implements a hierarchical setting to propose a multilevel parameter assessment which forms an optimal solution to infer the uncertain parameters. However, all the methods of calibrating UBEMs cannot be fit into these two categories; other different methods can be found in [81] and [82].

Nevertheless, model calibration methods do not suffice for reflecting on overall accuracy of an UBEM. In this respect, validation of the model against actual energy use data seems to be the only way to confirm the result of a model. However, except in a few examples, such as in [83] and [53], no explicit information on model validation is provided in existing studies.

2.3 Previous works

As regards the large number of studies aimed at developing improved UBEMs, summarizing all the relevant studies is beyond a few pages. Thus, in this section, it is intended to only review the most notable studies that led to the introduction of a new tool. For further reading, the reader is directed to Paper I. Furthermore, since the year 2019 when the review paper was written, there are a few additional studies that are deserved to be noted here.

2.3.1 UBEM simulation tools

The very first studies on building energy models and dynamic simulation of buildings emerged during the 70s and early 80s, such as Clarke [84]. Nonetheless, by doing a systematic review it is noted that the modern urban-scale building energy studies based on engineering methods can not be found until the early 21st century. Some of the examples of these early-stage engineering models are found to be published by Huang and Broderick [85] in which dynamic energy simulation of prototype buildings (or building archetypes) are conducted by DOE [86] and extrapolated over the whole stock, and Parekh [87] that specifically focused on establishing certain criteria in defining building archetypes. However, it was only after the development of SUNtool [88] and its successor CitySIM [73] that the attention moved to the usability of urban models of buildings as a tool to support the increasing demand for sustainable urban planning. In this respect, SUNtool and CitySIM [88] can be regarded as pioneering models (or tools) in the field of urban building energy modeling.

CitySIM

Developed at the Swiss Federal Institute of Technology of Lausanne (EPFL), CitySIM is a simulation tool for analysis of energy demand in buildings with respect to occupants' behavior, HVAC systems and urban microclimate and at different scales, from building to district and city. By receiving benefit from the geographical user interface (GUI) in Java, CitySIM calculates the building-related energy flows using a C++ solver in the background. Thermal models of buildings in CitySIM are originated from the R-C network analogy where the conducting walls transfer the heat between temperature nodes. On external surfaces, the temperature nodes are affected by microclimatic conditions, in particular solar radiation, and at the internal nodes, are designed to be reflective of the occupants' behavior and its stochastic nature. Based on the availability of geometrical information and individual building characterization, CitySIM seems to produce reasonable results [73, 89, 90].

SimStadt

Generally speaking, CitySIM can be regarded as a simulation platform that only handles dynamic simulations of buildings when the required information is given as input. Yet, this data is not always available. To round this problem, SimStadt [54], developed at the University of Applied Science Stuttgart, proposes a new modular workflow based on third party software, e.g., CitySIM, for conducting a multi-scale urban energy and environmental (CO_2 emission) analysis. To solve the complexities of handling data, using its pre-processing modules, the missing data is deduced from available information on typology and usage (archetype) or from probabilistic methods of interpolating from aggregated level data. In other words, it utilizes CitySIM while suggesting new methods to overcome its shortcomings. Furthermore, SimStadt makes use of the other already established tools to consider not only the buildings but also the energy systems. For instance, it makes use of the network analysis tool, Stenet [91] to evaluate the district heating and cooling networks and associated distribution losses. With the same approach, PV potential and renewable system integration are also considered in the tool. However, the main novelty of SimStadt, as compared to the similar studies of the time, is its approach in using a modern GUI for conducting fast and parallel calculations when computation power and power limitation was a big issue for many model developers.

CEA

However, SimStadt is not the only successful example of UBEMs that have been developed based on modular workflows. The integrated framework for analysis and optimization of buildings, developed by [74, 92], known as City Energy Analyst (CEA) is another example of such terminology that incorporates six different modules for building demand forecasting, resource availability assessment, simulation of conversion, storage and distribution technologies, bi-level optimization, and multi-criteria assessment. In terms of building-specific calculations, CEA takes an analytical approach in the physical description of dynamic heat and mass transfer along with buildings, systems, users, and the surrounding environment which is then corrected through statistical analysis with annual specific values for consumption in buildings, and classified using k-means clustering and illustrated in the output. This tool utilizes an innovative 4D interface in ArcGIS to facilitate visualization and dissemination of the results. Unlike SimStadt, CEA is developed in a single interface and a series of tailor-made models in Python.

umi and Boston UBEM

Not every UBEM is based on simplified mathematical models. Some UBEMs take full advantage of the validity and reliability of building simulation software in calculating energy demand in buildings. With a similar approach as

SUNtool, the urban modeling design platform called umi [93] is an UBEM with capabilities to evaluate operational building energy use, sustainable transportation choices, day-lighting and outdoor comfort at the neighborhood and city level. In this tool, Rhinoceros 3D CAD environment and its integrated visual programming environment, Grasshopper, are used as the modeling platform while EnergyPlus handles the subsequent dynamic simulation of buildings in the background. umi forms the basis for the UBEM for the city of Boston [53]. The Boston UBEM is a city-wide model that captures energy flows of more than 83000 buildings in the city of Boston. Due to the spatial scale of the model, it is not comparable with the other similar models. Using available datasets on building information and specific definitions of building archetypes, the building stock is modeled from characteristics of 52 use/age archetypes. As mentioned, umi [93] handles building-by-building modeling and simulation of thousands of buildings in 60 hours.

A summary of the main features of these models (or tools) is presented in Table 2.2.

2.3.2 Advancements in the field of UBEM

The Boston UBEM is not the only UBEM that applied the method in summarizing the building stock into building archetypes. In fact, most UBEMs employ various methods of finding a representative building, as described in Section 2.2.3. Evolving from purely deterministic approaches , recent studies leaning towards the application of machine learning for probabilistic classification or unsupervised clustering of building archetypes. Nonetheless, no machine learning or statistical method is applicable when not enough data is available. This implies the current trend in making use of available national databases and building stock surveys in defining the archetypes. For instance, Ali et al. [94] suggests a multi-scale archetype development for residential buildings from multi-level sources of data, i.e., national, city, regional, and district. Torabi Moghadam et al. [95] refers to geospatial data on building and household information when categorizing the buildings based on their main attributes.

As regards the availability of empirical national data, research interests have been turning to the Energy Performance Certificates (EPCs) and their valuable role in gathering buildings' information in one unified database [96, 45]. The energy performance certificate was first established in order to increase the awareness of energy performances of buildings in the EU [97] although nowadays, its strength in informing the important characterization of buildings receives increasing attention, particularly in the process of archetype development for an UBEM study. Ahren et al. [98] examine the Irish EPCs for the identification of 35 reference buildings representing the Irish predominant housing typology. Using Swedish EPC data Österbring et al. [99] classifies the building stock in the city of Gothenburg into use-type reference buildings that can be used for further analysis of the energy demand for heating and hot water use. Pasichnyi et al. [67] adopt a statistical approach in processing the EPCs and defining the building archetypes and suggest strategic analysis and planning for building energy retrofitting accordingly [100]. However, despite the usefulness of the EPCs, the associated uncertainties and proven deviations from real measurements [101] emphasize the necessity of a renewed certification system [102] that may benefit from BIM technology, big data techniques, and use of building smart-readiness indicators to increase accuracy, reliability and applicability of data [103].

Given the uncertainties of occupants' behavior, at the building level, a variety of occupancy models, from deterministic to stochastic have been developed that can generate a close to reality occupancy profiles, as found in Widén et al. [104], Fisher et al. [105, 106] and McKenna et al. [107]. For urban level studies, however, the urban occupancy modeling is still uncertain. Based on the review article that is written by Happle et al. [108], clearly in almost all existing UBEMs, the urban building occupancy is assumed to be similar to that of individual building archetypes. Besides, due to the complexity of stochastic models, it can be seen that the deterministic models are dominant. To solve the uncertainties of simplified treatments on urban building occupancy, the new generation of studies started to evolve from urban mobility models. At the time when the review article was written by the author, except [10, 109], and [73] in which the utilization of agent-based transport models in capturing the diversity of individual activities was conceptualized, no remarkable example has been found in this area. However, since then, several studies are taking the approach to integrate transportation and human mobility models into UBEMs. Barbour et al. [110] and Wu et al. [111] estimate absence or presence of building's occupants from cellphones and mobile positioning data. Based on overall information about individuals, e.g., students and teachers, Mosteiro-Romero [112] suggests a population-based model and assign a daily schedule to individuals in order to reach occupants' presence. Happle et al. [113] makes use of web mapping services, i.e., Google Maps and Facebook, to statistically prepare a schedule for occupancy in commercial buildings, e.g, retails and restaurants, at their locations. There is no doubt that integrating mobility models into UBEMs can solve the question of urban building occupancy, yet, all these studies still struggle to approach the stochastic nature of human activities at buildings. As suggested in Paper I, it is still a research gap in addressing occupancy profiles in UBEMs.

Table 2.2. *Review of the main features of some of the notable UBEMs.*

Tool	Building type	3D city model	Archetype	Thermal model
SUNtool	Residential			R-C
CitySIM	Residential			R-C
CEA	All types	✓[2]	✓	R-C
SimStadt	All types	✓[1]	✓	CitySIM
umi	All types	✓	✓	EnergyPlus
Boston UBEM	All types	✓[3]	✓	umi

[1] CityGML LoD1 and LoD2.
[2] LoD1 from Open Street Maps
[3] LoD1 from available geometrical data

Tool	Occupancy	Microclimate	Energy system	Mobility	Scenario planning
SUNtool	✓[2]	✓[4]			
CitySIM	✓[3]	✓[4]			
CEA	✓[2]	✓[4]	✓		✓
SimStadt	✓[3]	✓[4]	✓		✓
umi	✓[3]	✓[4]		✓[5]	
Boston UBEM	✓[3]	✓[4]		✓[5]	✓

[2] Stochastic.
[3] Deterministic.
[4] Radiation model.
[5] Walkability.

Tool	Novelty	Platform	GUI	Year	Reference
SUNtool	First UBEM tools	JAVA	✓	2007	[88]
CitySIM	First UBEM tools	JAVA	✓	2009	[73]
CEA	Parallel computation	JAVA	✓	2015	[54]
SimStadt	Modular but single interface	ArcGIS	✓	2015-16	[74, 92]
umi	Daylighting and walkability models	Rhinoceros	✓	2013	[93]
Boston UBEM	Geo-spatioal extent	Rhinoceros	✓	2016	[53]

2.4 Research gaps

In an attempt to achieve a close to reality estimation of spatio-temporal energy use in cities, the field of urban building energy modeling has experienced considerable improvements, during the last decade. Yet, there is still a great deal of uncertainty about the choice of building simulation tools to be used for large-scale studies, the level of complexity of the thermal models, and the availability of good quality data on which to build the model. For this reason, the existing research gaps in the field have been identified as follows:

- Relying on the maturity of individual building energy models and the reliability of established building energy simulation tools, a large number of UBEM studies make use of one of the common BEM tools in their models. Although these BEM tools should be possible to use in large-scale studies, there is no comprehensive study that investigates their advantages and disadvantages as UBEM simulators. Paper II, therefore, aims to present a clear response to these questions by comparing some of the most common simulation tools with each other, all of them applied to the same case, and validating them against measured data.

- Due to the large number of buildings included in UBEMs, traditional multi-zone building models that are used in BEM studies are not applicable in UBEMs. While some model developers considerably reduce the complexity of the models to simplified single-zone models, others follow the ASHRAE guidelines in multi-zoning configuration, i.e., one core zone and several perimeter zones for each floor. Yet, there is no clear prescription on the proper level of complexity of the building models in an UBEM. This issue is the basis for Paper III, in which different zoning configurations and levels of model complexity are simulated and their effect on the resulting energy use is analysed and compared in the most common simulation tools.

3. Methodology and data

This chapter introduces the data, the case studies, and the method used in papers II, and III. Section 3.2 describes the fundamentals of the BEM simulation tools that are applied in the UBEM studies in papers II and III. In Section 3.2.4 the method suggested for comparison and validation of these BEM simulation tools for use in UBEM simulation is discussed, as in Paper II. Section 3.3 analyses the complexity and thermal zoning configuration of building models with respect to the scope of the UBEM, which is a summary of what is presented in Paper III.

3.1 Overview of available data

As mentioned, in UBEM, having access to good quality data is the main challenge for many model developers. In the appended papers to this thesis, various sources of data are exploited to overcome this issue. Depending on the data source, the accuracy, integrity and completeness of data can be different between datasets.

The data used in paper II comes from a previous study by Åberg et al. [114]. Detailed information on building construction and material as well as energy systems and secondary distribution systems were acquired from the private housing association HSB 53 brf Gräslöken [115] in the city of Uppsala, Sweden. The hourly heat use on substation level was also obtained from the district heating supplier company Vattenfall Heat AB [116]. This data was measured on the supply side and includes the total thermal energy used, flow rate, and inlet and outlet temperatures for the year 2015.

In Paper III, however, there was limited access to detailed data. Detailed information on building construction and blue prints have been provided by the municipal housing company Uppsalahem [117], while the assumptions on construction material were based on previous studies and available literature on the typology of Swedish buildings [118, 119].

3.2 Overview of BEM and simulation

As previously discussed in Section 3.2, the BEM-based urban building energy modeling forms the major part of the existing UBEM research. Traditionally,

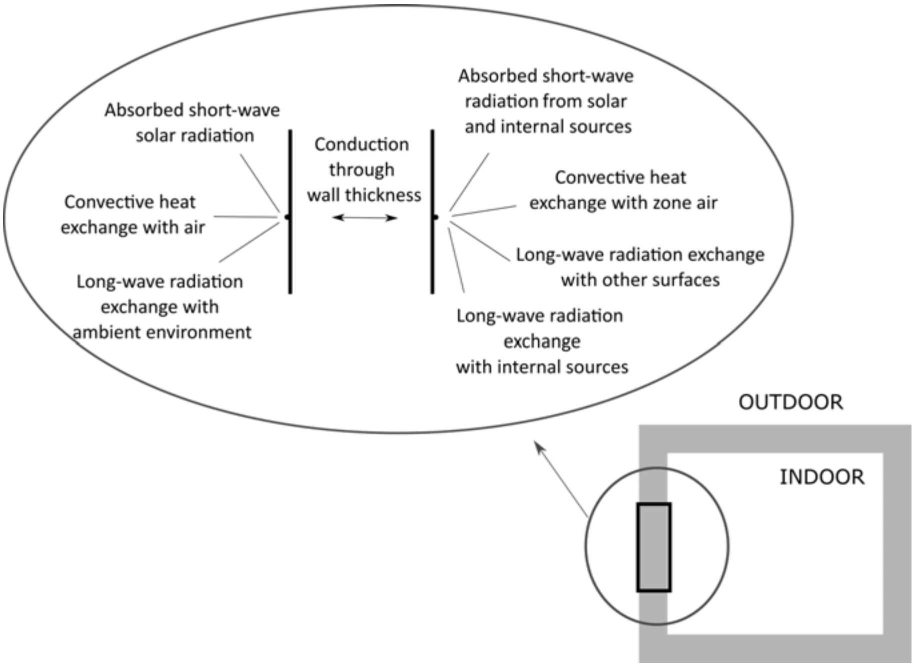


Figure 3.1. Illustration of the heat balance over building surfaces exposed to the ambient.

the BEM tools such as EnergyPlus, TRNSYS or IDA ICE, take full advantage of physical modeling and numerical simulation of heat and mass transfer throughout buildings. To be more focused on the thermal performance of a building, it can be stated that the core of these simulations is based on heat balance principals for every surface of the building. Figure 3.1 gives a simplified illustration of the components of the heat balance on a exposed surface of the building.

In general, the heat balance of the building is summarized into three parts, including heat balance of the external surfaces, heat conduction through the building envelope and heat balance on the internal surfaces.

3.2.1 Outside heat balance

An external surface, i.e., external surface of a wall or roof, basically incorporates the measures for heat exchange with the ambient,

$$Q_o = Q_{abs} + Q_{conv} + Q_{lw}, \tag{3.1}$$

where Q_o is the conduction heat into the wall, Q_{abs} is the absorbed solar radiation on the external surface, Q_{conv} is the representative for convective heat exchange with the air, and Q_{lw} is the long wave radiation exchanges between the wall and the surroundings.

3.2.2 Heat conduction through building envelope

Fourier's law specifies the heat conduction proportional to the magnitude of the temperature gradient,

$$q = -k\frac{\partial(x,T)}{\partial x}, \tag{3.2}$$

where q is the conductive heat flux, k is the conductivity of the material and $\frac{\partial(x,T)}{\partial x}$ is the spatial gradient of temperature in one-dimensional form [120]. In order to capture the heat conduction through the building envelope, e.g., walls, and solve the partial equations, conduction transfer function (CTF) and response factor methods are the dominant methods for estimation of transient heat transfer in most BEM tools [121]. In response factor, the material thermal response is a linear system that is related to time series of current and past temperature and heat flux. In CTF, additionally, the current temperature and heat flux is connected to the past outputs which considerably reduces the computation time [122].

3.2.3 Inside heat balance

As for the outside, the inside heat balance is calculated on the internal surface of the walls, roofs, and floors as

$$Q_i = Q_{abs} + Q_{conv} + Q_{lw}, \tag{3.3}$$

where Q_i is the conduction though the wall. Due to contribution of internal sources of energy, e.g., lighting, Q_{abs} is the absorbed short-wave radiation from diffused solar as well as internal sources. In this equation, Q_{lw} refers to the long-wave radiation exchange between internal surfaces of the building as well as internal sources of energy, e.g, occupants,equipment and lighting. Finally, Q_{conv} is the heat convection to the air flows in the building.

Methods for calculating each components of the heat balance in buildings is different from one tool to the other. Besides systematic differences in the way that a simulation tool conducts the energy model of a building, these differences in the fundamental heat balance equations contribute to variations in the results that can be obtained from each tool.

3.2.4 Comparison of simulation tools

Among various BEM software, only some are compatible with the scope of the UBEM. In general, there are technical barriers for the application of some of the tools that limit them to individual building modeling and make them unable to cope with urban energy studies. An overview of BEM tools that could potentially be used for UBEMs and their most relevant features from an UBEM point of view was presented in [19, 123]. Nevertheless, it seems that only a few are actually capable of handling UBEMs with all their complexities. An overview of the most feasible tools, IDA ICE, TRNSYS and EnergyPlus, that have been used in Papers II and III, is given as follows.

EnergyPlus [124] is an open-source building energy simulation software that estimates the need for heating, ventilation, and air conditioning of buildings using a variety of systems and resources. TRNSYS [125] is a dynamic simulation software that enables users to study the behaviour of transient and dynamic systems. Having an extensive library and an organized simulation environment makes TRNSYS a flexible tool that can be used in many applications from building energy modeling to system energy analysis and solar energy studies. IDA Indoor Climate and Energy (IDA ICE) [126] is a dynamic multi-zone simulation software which accurately models buildings, systems, and controllers in order to maintain the thermal comfort of the building occupants.

Despite the fact that these tools have many similar features, they can be very different in their fundamentals, especially when it comes to calculation of the heat balance and its components.

Calculations of outside heat balance

Absorbed solar radiation, Q_{abs}, as a factor of incoming solar radiation, is defined as,

$$Q_{abs} = \alpha A(I_b + I_d), \tag{3.4}$$

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, respectively, on the wall surface, in IDA ICE and EnergyPlus, direct and diffuse incident radiations are mainly assessed based on ASHRAE guidelines [127] and Perez model [128], while TRNSYS gives the possibility of choosing between sets of common methods such as, the Perez model [129] or the Hay and Davies model [129].

Convective heat transfer on external surfaces is determined based on the convective heat transfer coefficient as

$$Q_{conv} = h_c A(T_{air} - T_{wall}), \tag{3.5}$$

where h_c is the convective heat transfer coefficient, A is wall area, T_{air} is the ambient air temperature and T_{wall} is the wall surface temperature. 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. As default, EnergyPlus calculates the total convective heat transfer coefficient as the sum of coefficients for forced and natural convection with respect to the local wind speed and wind direction. In TRNSYS, on the other hand, the convective heat transfer coefficient is assumed as either a user-defined variable to be static or time-dependant or to be calculated internally. The internal algorithms calculate the convective coefficient with respect to the surface inclination and heat flux.

The long-wave radiation exchange with the surrounding environment can be generally written as

$$Q_{lw} = Q_{lw,sky} + Q_{lw,ground} + Q_{lw,air}, \tag{3.6}$$

with $Q_{lw,sky}$, $Q_{lw,ground}$ and $Q_{lw,air}$ being the components of radiation exchange with sky, ground and the air respectively. Generally, the radiation exchange with the surrounding is estimated using

$$Q_{lw,x} = \varepsilon \sigma F_x A (T_x^4 - T_{wall}^4), \tag{3.7}$$

where ε is the long-wave emittance of the surface, σ is the Stefan-Boltzmann constant, A is the surface area, F_x is the view factor between the sky, air or ground and T_x represents the temperature of the sky, air or ground, while T_{wall} is the surface temperature. Using Equations 3.6 and 3.7, the long-wave radiation exchange with the surrounding is calculated accurately in EnergyPlus. In IDA ICE, however, the long-wave radiation exchange with the air, $Q_{lw,air}$, is ignored from these equations. Calculation of the radiation exchange is conducted slightly different in TRNSYS, with T_x in Equation 3.7 being the fictive sky temperature and representing not only the sky temperature but also the ground temperature and the view factor between the sky and the surface. In this method, based on the definition of the fictive sky temperature, both ground and sky long-wave radiation exchange with the surface are summarized under one term.

Calculation of heat conduction through building envelope

Calculation of the heat transfer through opaque and transparent surfaces of the building envelope, e.g., walls, and windows, plays a principal role in the differences that can be seen later in the results from Paper II and III.

In IDA ICE, the calculations of the CTF function is simplified through designating fewer thermal nodes to the heat transfer surfaces. Using an optimized thermal-electrical analogy of heat conduction for a given thermal resistance-capacitance (R-C) network with only three capacitance, IDA ICE conducts an optimization method to estimate the model parameters. On the other hand, TRNSYS and EnergyPlus take full advantage of CTF methods and response factor in calculating the heat conduction through the opaque surfaces. However, each uses a distinctive solver. TRNSYS utilizes the direct root finding methods [130] and treats the surfaces as black-boxes with no need for information on temperature variations inside the surface. EnergyPlus, however, makes use of the state space methods in solving the analytical CTF models [122]. By assigning multiple temperature nodes to the heat transfer surface, in EnergyPlus the heat flux through the wall is calculated from one node to the other. Descretizing the wall into multiple nodes is expected to reduce the length of CTF series and thus the computation cost to some extent. More information on differences in calculation and solving the heat conduction transfer through the building envelope is found in Paper III.

Calculation of the inside heat balance

As for calculation of the outside heat balance, the components of the heat balance equations on internal surfaces, Equation 3.3, are estimated differently in each tool. Convective heat transfer to the zone air and convective heat transfer coefficient follows almost the same terminology as outside convective heat transfer in TRNSYS and EnergyPlus. In IDA ICE, however, the convective heat transfer is estimated from the slope of the surface, and the temperature gradient between the internal air and the internal surfaces.

The absorbed short-wave radiation is determined as a function of transmitted solar radiation through windows

$$Q_{abs} = XI_{dif}, \tag{3.8}$$

with X being the absorption matrix in IDA ICE, the transposed of Gebhart matrix [131] in TRNSYS and the relative absorption of the surfaces multiplied to the window area in EnergyPlus and I_{dif} the solar radiation transmitted through windows.

In calculation of the internal long-wave radiation exchange, EnergyPlus assumes the inside air to be as completely transparent to long-wave radiations, the internal surfaces of the buildings to be grey-bodies and all the radiation to be diffuse. Then rely on a unique coefficient for all reflections, absorptions and re-emissions from other surfaces in the zone, EnergyPlus calculates the rediative exchange in the building. In TRNSYS, and based on its standard-level calculation methods, the radiation exchange is approximated from the star method [122], for a hypothetical temperature node in middle of the room. In this methods, not only the radiative exchange but also the convective heat is also contributed to the temperature node. In IDA ICE, the long-wave radiation is proportional to the radiosity and the properties of the black-body surfaces.

In addition to these differences in the principal methods of calculating heat transfer, there are systematic differences in how the modeling procedure is conducted.

Ground coupling
To model the heat transfer from the building to the ground below the slab or the basement in IDA ICE, it is suffice to determine the average annual ground temperature as well as slab and soil properties. According to ISO 13370 [132], IDA ICE calculates the heat resistance of layers below the building construction and, accordingly, the heat transfer through them. If the standard weather datasets are used, the respective annual ground temperature is assumed automatically. 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. Depending on the building model and desired accuracy, ground coupling models with different level of complexity can be used, e.g., Type 49 for approximation of the slab on grade, or Type 77 for calculation the soil temperature. More components for calculation of both slab and basement heat transfer are found in the TESS library [125]. However, computing time is greatly influenced by choosing alternative components. In EnergyPlus, different ground coupling concepts exist. The two associated auxiliary tools for basement and slab modelling in EnergyPlus, conduct an accurate calculation of heat transfer and boundary temperatures [124].

Shading analysis
Analysis of shading from nearby buildings or surrounding obstacles and its effects on building performance is one of the sources of differences between the tools. Using the SkechUp [133] plugin for building's form and external shadings, TRNSYS acquires the geometrical information of the shading obstacle. However, implementation of shading analysis from SkechUp file generator is not feasible for TNSYS 17. In TRNSYS 18, this feature has been included, yet, the building model does not consider the influences of shading obstacle on the heat performance of the building as effectively. Instead, it is suggested to add the external components for shading models provided in the TRNSYS library. With application of a similar SketchUp Plugin for EnergyPlus, or by determination of the geometry of the shading obstacle in the site location, shading analysis in EnergyPlus is easily conducted. Due to the increase in complexity of the model, the computation time increases slightly. IDA ICE does the shadings analysis differently. By importing the site plan in 3D format or by drawing the obstacles, IDA ICE includes the shadings and performs the simulation automatically.

Occupancy and use profile
In calculation of the metabolic heat gain of occupants, all four tools have the same methodology using ASHRAE standards [127] and taking just the convective heat into consideration. However, the main challenge is to define

annual schedules for hourly based activities and presence of buildings' occupants. IDA ICE can accept hourly schedules for week days or weekends as well as months. However, while specifying the hourly or even daily profiles seems impractical, importing any external file to its database is impossible. Thus, the only way is either to use constant or predefined schedules or just rely on the low resolution profile development. In EnergyPlus and TRNSYS, the procedure brings no difficulties for the user and it would be possible to import the schedules or load profiles by just importing a text file to the programs.

Number of buildings

In TRNSYS and EnergyPlus it is impossible to model and analyze one building at a time. However, IDA ICE as a BEM tool is capable of handling the energy modelling of buildings at larger scales e.g., district level up to a limited number of thermal zones (300 simple zones and 70 detailed zone).

Time step and simulation

In terms of accepting sub hourly data both in input and output, IDA ICE and TRNSYS have no limitations, even for considerably small time steps e.g., seconds. Similarly, EnergyPlus can handle minute-based time steps although for receiving the best output from the tool hourly or at least 10-minute resolution is suggested.

Given the importance of BEM simulation tools and their usefulness in UBEM, in Paper II, a comparative study on the validity of the dominant BEM tools, i.e., IDA ICE, TRNSYS, and EnergyPlus, for being used as the main simulation core of the UBEM is determined. In order to explore their advantages and disadvantages in large-scale studies, a district-level energy model of 32 district heated multifamily buildings was developed in the three tools.

In this study, it has been tried to make the models as similar as possible in order to be comparable. Some of the assumptions and conducted methods in Paper II, are linked to this point. For instance, due to limitations of IDA ICE in handling hourly load profiles input to the model, the occupancy profile, i.e, occupant presence, household electricity and lighting as well as DHW, and its contribution to internal heat gain was calculated separately from the models and added to the final results later. In this study a stochastic occupancy load generator developed in [104] was used.

3.3 Model complexity and zoning configuration

As mentioned, to overcome the complexity of simulating a large number of building models, in the UBEM the aim is to abstract the buildings and their

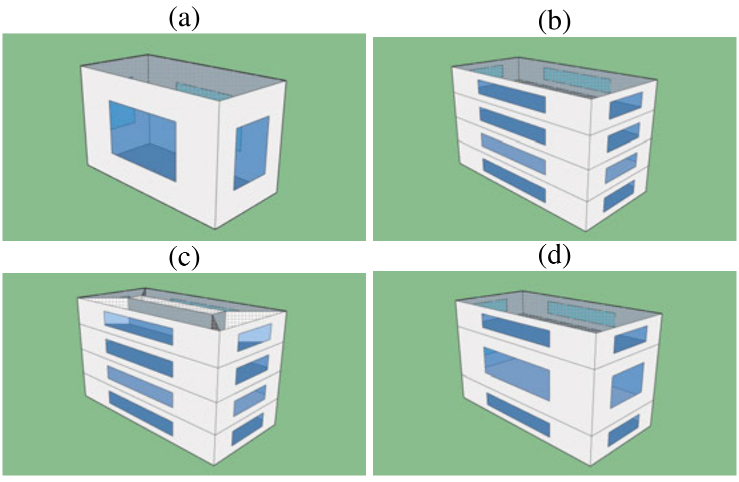


Figure 3.2. Thermal zoning configurations in UBEM: (a) single-zone model (1 zone per building), (b) multi-zone model (1 zone per floor), (c) multi-zone model (5 zone per floor) and (d) multi-zone model (3 zones per building: one for bottom floor, one for top floor and one for all middle floors).

systems, and estimate their performance without having to deal with all their details. Some examples of such simplification are reducing the number of thermal zones or reducing the level of detail in the building models. However, the exact effectiveness of theses alternative methods is not clear in existing research. The risk of defining too simple models is to increase the uncertainty and decrease the accuracy.

To untangle these questions about model complexity in an UBEM, in Paper III, some of the most common zoning configurations and levels of detail are systematically compared. The single-zone model is traditionally one of the simplest ways of describing a building by a set of equations. Differences in heating and air conditioning as well as influences of inner walls of the building are neglected and it is assumed that the whole building can be described as one thermal zone. The windows are also modelled based on the corresponding window-to-wall ratio (WWR) on every external wall. Figure 3.2(a) illustrates the single-zone model. Although a single-zone model (1 zone per building) cannot, in most cases, be an accurate representation of an individual building, it improves the computation cost to a large extent, and might be accurate enough on an aggregated urban scale.

The second approach is to assign one thermal zone for every floor of the building, as shown in Figure 3.2(b) (1 zone per floor). Defining a simplified multi-zone model is expected to slightly capture the contribution of internal building elements, e.g., adjacent floors, but still run the simulation in an acceptable time. The third and very common method towards multi-zone modeling follows the ASHRAE guidelines for envelope setting and zoning

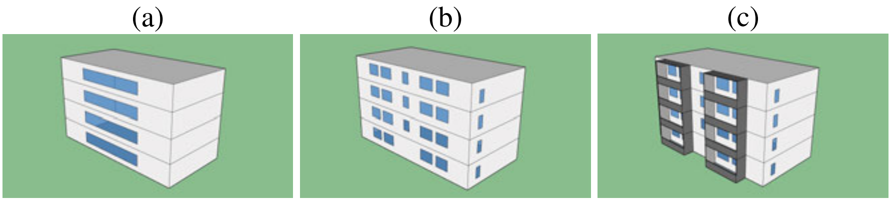


Figure 3.3. Level of detail in building modeling: (a) LoD1, Shoe-box model of the building with 25% window area on long walls, (b) LoD2*, Detailed building model excluding the shading components, (c) LoD3, Detailed building model with precise geometry of windows and shading components

configuration. According to ASHRAE 90.1, Appendix G [127], different thermal zones are assumed for perimeter and interior spaces that are at least 4.6 m away from the exterior or semi-exterior walls. This means, for a square base building, that at least 5 thermal zones, i.e., one core and four perimeter zones, are required for every floor of the building (5 zones per floor), as visualized in Figure 3.2(c) (5 zones per floor).

In addition to these three configurations, when tall buildings are of interest, there is anther alternative in which the building is divided into three main thermal zones. One thermal zone is assigned to the ground-coupled or the bottom floor of the building while a second one represents the top floor that is adjacent to the exposed roof. All the intermediate floors are considered as one big zone (3 zones per building). Figure 3.2(d) illustrates this.

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). This level of simplification, however, may lead to inaccuracy of the results and, therefore, further calibration might be needed to compensate for the deviations from the measured data. Thus, in Paper III, the LoD of the building construction and its impacts on the simulated energy demand is analyzed in depth. In this study, three levels of detail, namely LoD3, LoD2*, and LoD1, are considered, as shown in Figure 3.3. Accordingly, LoD3 implies a detailed building model with precise components and geometries. In LoD2*, the geometry of windows is kept as in LoD3 but the balconies and shading components are excluded from the model. Finally, LoD1 represents a simplified shoe-box model with 25% WWR [1].

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

[1] The WWR varies between 20% and 25% as a typical value for the window area in buildings of similar type.

Figure 3.4. Overview of the area with 32 buildings modeled in Paper II. Different building types colored in green, representing building type A and blue showing building type B.

3.4 Overview of case studies

3.4.1 Case study 1

In Paper II, a neighborhood in Uppsala, Sweden, with 32 buildings of two different types (here defined as types A and B) is considered for modeling and validation of the respective BEM tools when applied to UBEM simulation, see Figure 3.4. These buildings are connected to the city's district heating system through a local substation and a secondary heat distribution system, from which the thermal energy is transferred to the buildings. A detailed description of the buildings and the distribution heating systems are given in [114].

The buildings in this area are multifamily buildings with two heated floors and an unheated attic. However, for the sake of simplicity necessary in UBEMs, in this study the unheated attic was not considered as a part of the building model and rather merged to the external roof. The buildings of type A have an average heated floor area of 906 m^2 and window area of 102 m^2, while the buildings of type B have 1019 m^2 heated floor area and 109 m^2 window area.

3.4.2 Case study 2

In Paper III, three different buildings chosen to be representative of the typical Swedish district heated multifamily buildings constructed during early 1970s were considered for further study. Detailed characteristics of these buildings are can be found in Paper III.

- Building A: *Multifamily building with 2 floors*.
  Building type A is a residential multifamily building with 2 floors and 699 m^2 heated area. According to the latest EPC, total energy use (including the energy used for space heating, domestic hot water and operational electricity) in this building is 109780 kWh or 157 kWh/m^2y, for a normal year.

- Building B: *Multifamily building with 3 floors*
  As previously mentioned, building type B is also a district heated multifamily building built in 1972. This building has 3 heated floors with 1498 m^2 heated floor area. Similarly, overall energy use for a normal year is calculated to be 235209 kWh or 157 kWh/m^2y, in this building.

- Building C: *Multifamily building with 8 floors*
  In addition to the low-rise multifamily buildings, in this study a high-rise building with 8 heated floors and an unheated basement is also analyzed. The normal year energy consumption for this building is reported to be 896738 kWh/y which equals to 173 kWh/m^2y. Its total heated floor area is 5197 m^2.

4. Results

In this chapter, concluding results from Papers II, and III are presented in brief. Section 4.1 summarizes the results from the comparison and validation of the most common BEM simulation software to be potentially used as the main simulation core of the intended UBEM. Section 4.2 provides a summary of the investigation of zoning configurations and level of detail in thermal models of buildings and their impact on simulated energy demand.

4.1 Comparison of simulation tools

This section summarizes the most important results from modeling and simulation of a case study area, in the BEM simulation tools IDA ICE, TRNSYS, and EnergyPlus and reflects on their validity and reliability in large-scale studies. The full results are presented in Paper II. Here there are slight changes in measures and indicators for analyzing the results, as compared to Paper II. Furthermore, the results on the performance of the BEM software VIP-Energy are excluded here. As stated in Paper II, the functionality of this tool for large-scale studies is limited and, thus, despite its strong correlation with the measurement data, it is excluded from this summary and from subsequent analyses.

Following the suggested methodology in Section 3.2.4, the energy model of a neighborhood with 32 district heated multifamily buildings was implemented in IDA ICE 4.8, TRNSYS 17, and EnergyPlus 8-7-0. IDA ICE is capable of handling more than one building model in every simulation studio and gives the user the opportunity to easily move from individual-level to district-level studies. This is in contrast with TRNSYS and EnergyPlus, in which every building model is treated individually. This means that, for the latter simulation tools, in order to reach the district-level energy performance of buildings, the obtained results from individual buildings need to be aggregated externally.

The final results from modeling and simulation of the buildings with two heated thermal zones and an ideal heating system[1] maintaining the room temperature constantly at 22°C are presented in the following.

Figure 4.1(a) shows the annual heat use calculated in the three tools, IDA ICE, TRNSYS and EnergyPlus, as compared to the measured data for the year

[1] An ideal heating system is a room unit that maintains the room temperature at the set temperature without giving any information on actual physical specifications of the room unit.

2015. Overall, the simulation results from all three tools seems to be in a reasonable approximation to the measurements. It is observed that IDA ICE and TRNSYS tend to overestimate the demand by 18% and 15% respectively, whereas EnergyPlus results in 13% lower energy use. To be more precise, while the actual heat use over the whole neighborhood is 3.48 GWh/y (115 kWh/m^{2}y), it is calculated to be 4.1 GWh/y (136 kWh/m^{2}y) for IDA ICE, 4.03 GWh/y (133 kWh/m^{2}y) for TRNSYS, and 3.03 GWh/y (100 kWh/m^{2}y) for EnergyPlus.

The same conclusion is drawn from the analysis of the correlations of the hourly simulated results form TRNSYS and EnergyPlus versus measured data, as seen in Figure 4.1(b) and presented in Table 4.1. Yet, IDA ICE indicates weaker correlation with measurements, in particular when the hourly heat demand is higher than 600 kWh/h. Clearly, during heating hours, IDA ICE highly overestimates the demand, while at low heating hours it gives a scattered profile with an overall tendency of underestimating the demand. Although on an annual basis IDA ICE and TRNSYS result in very similar numbers, on hourly basis it can be seen that TRNSYS has a more consistent profile with lower variability as compared to IDA ICE. However, it has a positive bias in estimating the heat use.

Table 4.1. *Correlation of the simulation results with measurement data.*

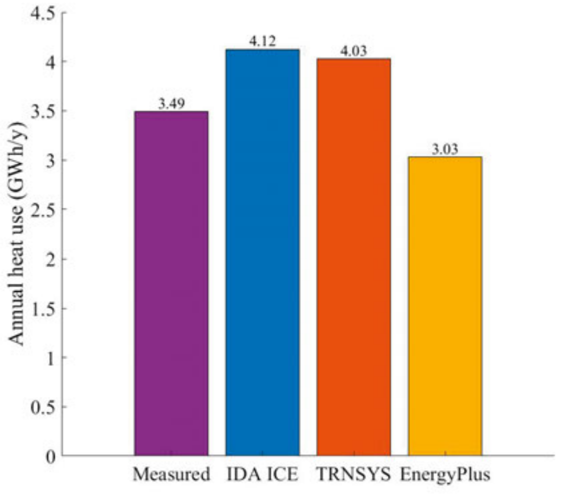
Tool	MAE	RMSE	R^2
IDA ICE	72	203	0.80
TRNSYS	61	130	0.83
EnergyPlus	52	117	0.83

Figure 4.2 demonstrates the heat use profile that is simulated in the three tools as compared to the measurements over the course of a year. Figure 4.2(a) demonstrates the deviation of the results from the measurements (ε), calculated as

$$\varepsilon = Q_s - Q_m, \tag{4.1}$$

where Q_s is the simulated heat use and Q_m is the actual heat use that is measured at the district heating substation. This figure is presented with hourly time resolution. Following the results presented in Figure 4.1(b), here, the high diurnal and seasonal variability of the simulated results in IDA ICE is also evident. On the other hand, in TRNSYS and EnergyPlus the variability is less extreme and more consistent throughout the whole year. While the deviation of the results from measurement data (ε) can go beyond $\pm$0.5 MWh/h ($\pm$0.016 kWh/m^{2}h) in IDA ICE, it mainly fluctuates between $\pm$0.3 MWh/h ($\pm$0.009 kWh/m^{2}h) for TRNSYS and EnergyPlus. In Figure 4.2(b), comparison of the daily heat demand profiles from the tools with respect to actual use per each day is presented. Clearly, all three tools follow the same trend as the measurements, with EnergyPlus being closest to the actual data. Despite differences in magnitude, EnergyPlus and TRNSYS behave very similarly.

(a)



(b)

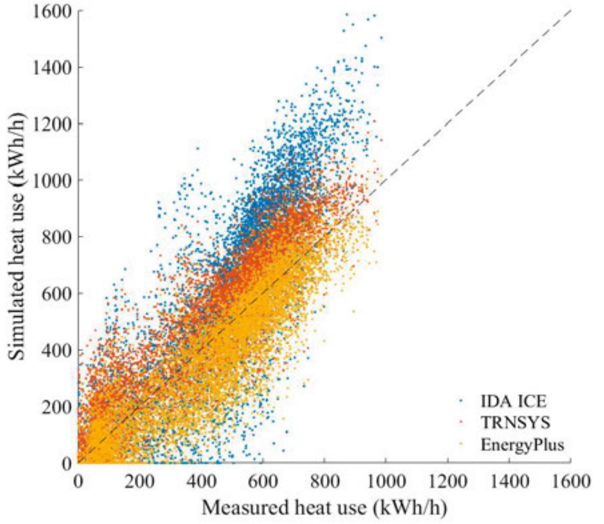
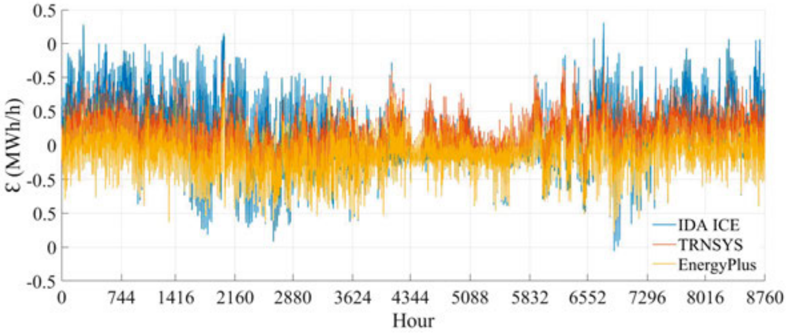
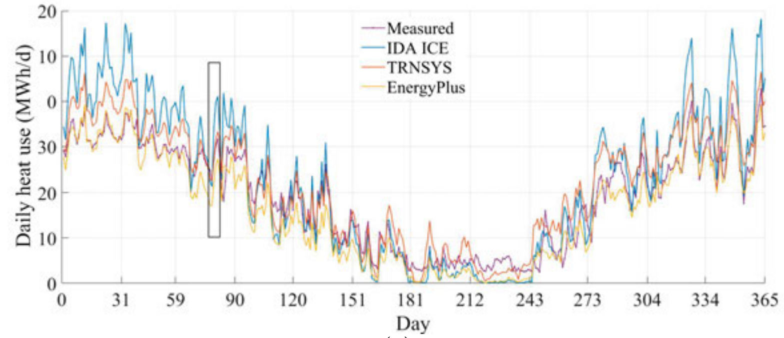


Figure 4.1. Validation of the simulation results from IDA ICE, TRNSYS and EnergyPlus against measured heat use data: (a) is the total heat used in the year 2015, and (b) shows the scatter plot that indicates the correlations between simulated and measured values for all 8760 hours of the year.

(a)



(b)



(c)

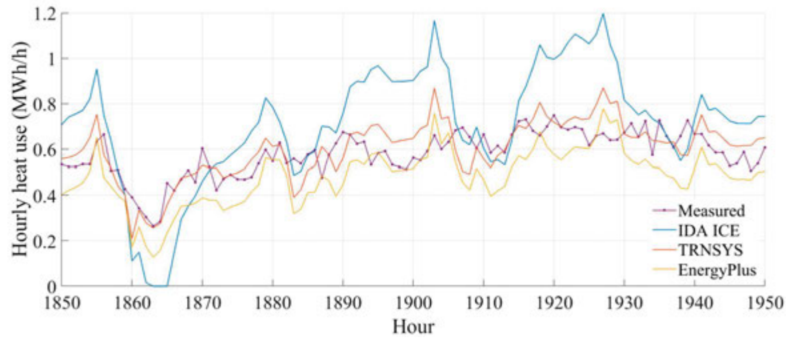


Figure 4.2. Validation of hourly heat use profile from IDA ICE, TRNSYS and EnergyPlus against hourly measurement data: (a) is the hourly deviation profile of the simulation results from measurements, and (b) is the daily heat use profiles with subplot (c) zooming in on 200 hours of the profile with higher time resolution (hourly resolution).

Considering the analogy of the simulation tools in calculating the heat balance in the building (Section 3.2), the main reasons in observed discrepancies between the results lie in the contribution of solar energy heat gain and thermal losses through building envelope model. As compared to TRNSYS and EnergyPlus, in IDA ICE, simplified thermal zone models result in higher sensitivity of the values to the ambient condition, particularly when there is solar radiation. The same observation is reported by Nageler et al. [134]. The second reasoning is related to the influence of the thermal mass of the building envelope and thermal responses to short term variations in the ambient condition. As can be seen in the results from Paper III, reduced thermal mass of the building in IDA ICE increases the total heat use in the building and at the same time increases the variability of the hourly heat use profile in response to diurnal and hourly changes in the ambient conditions. Finally, ground coupling and limitations in proper calculation of the heat exchange with the ground lead to higher energy use in TRNSYS and IDA ICE as compared to EnergyPlus in which the use of an auxiliary slab model improves the results.

4.2 Model complexity and zoning configuration

Following the suggested method in Paper III, analysis of the different zoning configurations and model complexity was conducted using the same three BEM simulation tools IDA ICE 4.8, TRNSYS 18 and EnergyPlus 9.1. The simulations were conducted for a normal year [2] and with hourly time steps.

4.2.1 Zoning configuration

Figure 4.3 illustrates the results from the energy modeling of building type A, multifamily building with two floors, with different zoning configurations in IDA ICE, TRNSYS and EnergyPlus. Figures 4.3(a)-(c) present the daily average heat demand for 365 days of the year with a close-up of hourly heat use for an example day in winter. In these figures, daily and seasonal variations of the results with respect to the ambient conditions can be clearly observed. Finally, Figures 4.3(d) shows the total annual heat demand that is aggregated from dynamic simulation of the models in the different tools.

Considering Figure 4.3(a)-(c), it can be concluded that EnergyPlus gives no major changes in the annual results when the zoning configuration is changed. On the contrary, IDA ICE is more influenced by the total number of thermal zones in the building. As a result, for the 1 zone per building model it calculates 8% higher annual thermal energy demand as compared to the 5 zones per floor model. The same trend can be seen in the case of TRNSYS. This means that in comparison to EnergyPlus, in IDA ICE and TRNSYS, there is

[2] A normal year describes the average climate for a given place and time period, i.e., one year.

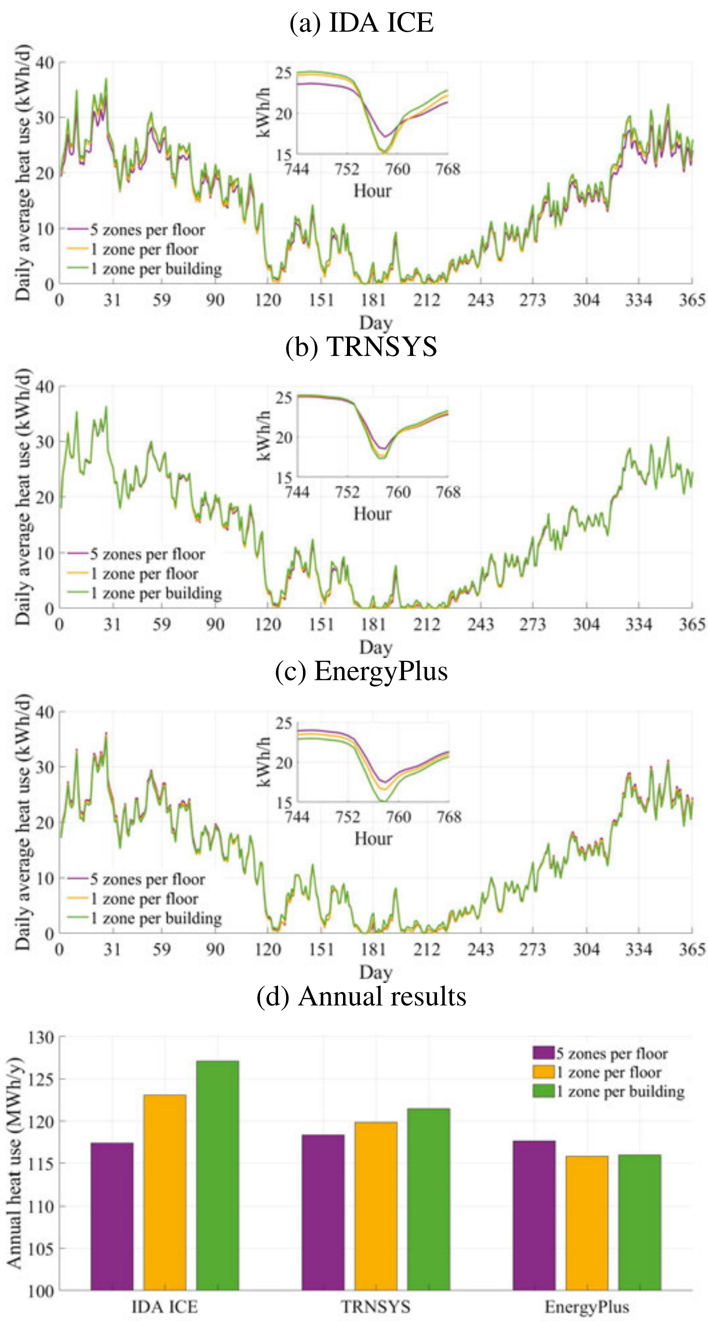


Figure 4.3. Comparison of zoning configuration of the case study building type A in different tools: subplots (a), (b), and (c) represent the results for daily average heat use over the coarse of a year with a zoom-in on hourly heat use for an example day in winter. Subplot (d) compares the results of annual heat use.

a systematic tendency to over-estimate the heat use when the simplest zoning configuration is applied.

Refer to 4.3(d), on the annual basis with more complex zoning configuration, i.e., 5 zones per floor, all three tools tend to produce very similar results, where the deviation between the annual values from each tools is less than 1%. When reducing the number of thermal zones to 1 zone per floor and 1 zone per building, the heat use profiles start diverging from each other to the extent that in the simplest model, i.e., 1 zone per floor, IDA ICE gives 9% and 5% higher annual values as compare to EnergyPlys and TRNSYS, respectively.

As mentioned in Section 3.2, in all three tools, estimations of the heat demand in a building is conducted using numerical heat transfer equations. However, the differences in underlying methods for calculations of the heat transfer components, leads to observed deviations in the simulated results from each tool. On account of these differences, in IDA ICE, exclusion of the thermal mass of the building from the building envelope leads to higher sensitivity of the building envelope to diurnal and hourly variations in the ambient condition and thus, higher variability in the simulated result. On overall, this could result in higher annual thermal energy demand in IDA ICE when a single-zone building is modelled. With increase in the number of the thermal zones, and including internal building components, e.g., internal floors, ceiling and walls, the effects of thermal mass of the building can be covered to some extent. This is the main reason why with 1 zone per floor model and 5 zones per floor model, the estimated heat demand from IDA ICE becomes closer to that of TRNSYS and EnergyPlus.

For building type B, multifamily building with three floors, the results are very similar to the ones for building type A and hence are not shown here, and the same conclusions can be drawn. EnergyPlus gives the most robust results with respect to changed zoning configuration. However, IDA ICE still estimates the heat use for 1 zone per building model to be 15% higher than EnergyPlus and TRNSYS.

Figure 4.4 shows a comparison of the simulation results for the energy model of building type C, multifamily house with 8 floors, with different zoning configurations in the three simulation tools IDA ICE, TRNSYS and EnergyPlus. Here, it can also be noticed that with the increase in the number of the floors to 8, the results of the 1 zone per floor model get closer to those of the 5 zones per floor model. In this case, the deviation between the 1 zone per building and 5 zones per building models reaches almost 0% in all three tools. However, while thermal zoning plays a negligible role in EnergyPlus and TRNSYS, in IDA ICE it still has a considerable impact on the results. As seen in Figures 4.4(a) and 4.4(d), the calculated total space heating demand in IDA ICE is equal to 128.85 MWh/y or 212 kWh/m^{2}y with 1 zone per building, while it reduces to 113.62 MWh/y or 187 kWh/m^{2}y with having 5 zones per floor. This means that there is a 14% difference in the results for detailed compared to simplified zoning configuration in IDA ICE. For the case study

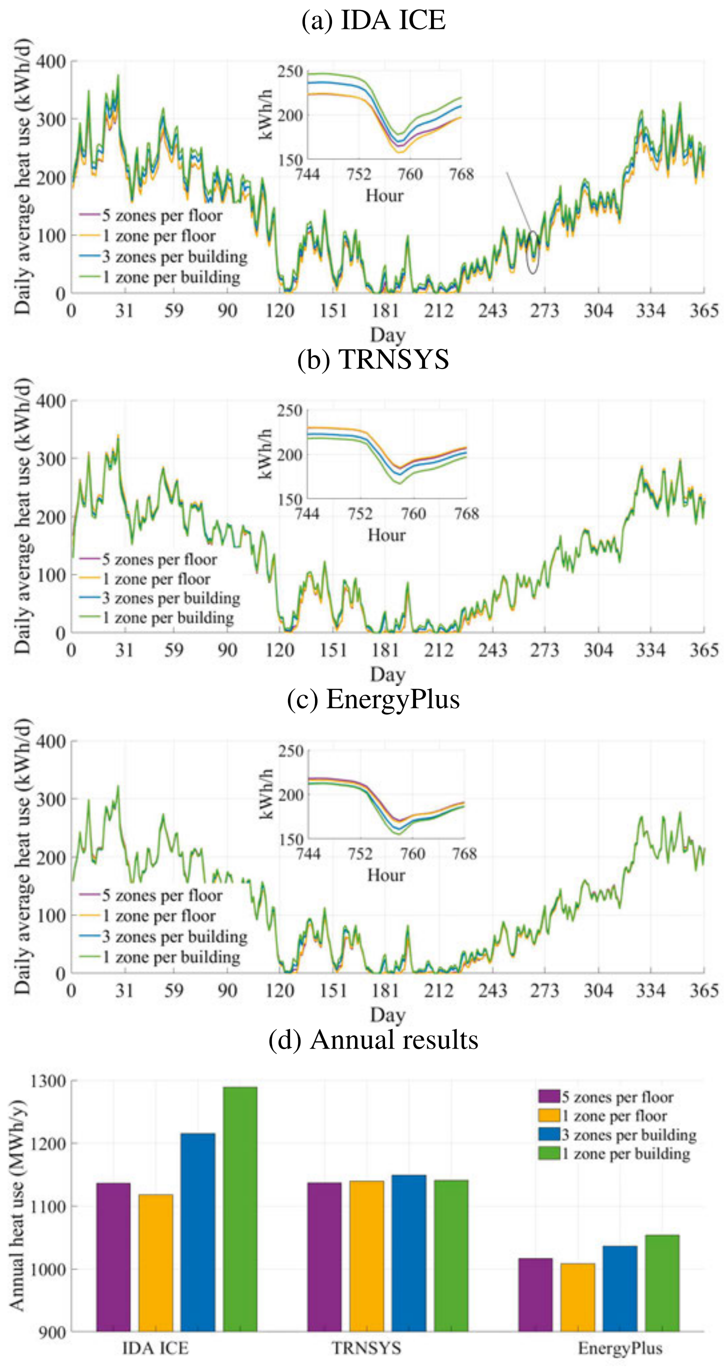


Figure 4.4. Comparison of zoning configuration of the case study building type C in different tools: subplots (a), (b), and (c) represent the results for daily average heat use over the coarse of a year with a zoom-in on hourly heat use for an example day in winter. Subplot (d) compares the results of annual heat use.

building type C, EnergyPlus gives smaller values as compared to IDA ICE and TRNSYS.

Following the same justification for Building A and as a result of increased thermal mass of the building, the simulated heat demand for 1 zone per floor gets closer to the values for 5 zones per floor model. In addition to the influence of the thermal capacity of the building on stability of the heat demand, the other clear trend here in this figure is the differences in the estimated heat demand in EnergyPlus as compared to IDA ICE and TRNSYS. The motivation for this can be provided from the discussion on ground-coupling and use of different methods in calculation of the heat flux to the ground. In EnrgyPlus the auxiliary basement tool is used which can result in accurate calculations of the heat transfer from the basement to the ground. In IDA ICE, the approximation of the heat conduction to the ground follows ISO 13370 guidelines [132]. In the case of TRNSYS, rely on standard component library and unavailability of a proper standard component for modeling the ground-coupled basement, the slab model Type 49 has been used instead. With this, some deviations from the accuracy in the result is expected.

As mentioned, in high-rise buildings, zoning configuration can be different from low-rise buildings. As regards the complexity of the model and the computation time associated with the large number of thermal zones, in addition to the previous configurations, the 3 zone per building is also evaluated for this case, which is visualized in Figure 4.4(a)-(d). It can be seen that the performance of a 3 zone per building model is quite similar to a 1 zone per building model, which might suggest that even a single-zone building model could be used. However, a major advantage of having 3 zones per building instead of 1 zone per building is its applicability in mixed-use buildings where lower floors have a different use profile from the upper floors.

4.2.2 Level of detail

Figure 4.5 shows simulation results for a building model with three different levels of detail, i.e., LoD3, LoD2*, and LoD1, in IDA ICE, TRNSYS and EnergyPlus. The illustration of the annual heat use, Figure 4.5(d), proves that on overall, the mean absolute percentage deviation (MAPD) of LoD2* and LoD1 from LoD3 is 25% and 21% for IDA ICE and 25% and 20% for EnergyPlus, while for TRNSYS it is only 8% and 3% respectively.

Figure 4.5(a)-(c) suggests that these slight deviations between the LoD2* and LoD1 with LoD3 mainly occur during the warmer periods of the year when the solar altitude is higher and the incident solar radiation through windows can be reduced by the shading objects considerably. However, in case of TRNSYS, as been already mentioned in Section 3.2, the software does not consider the impact of the shading obstacles on heat performance of the build-

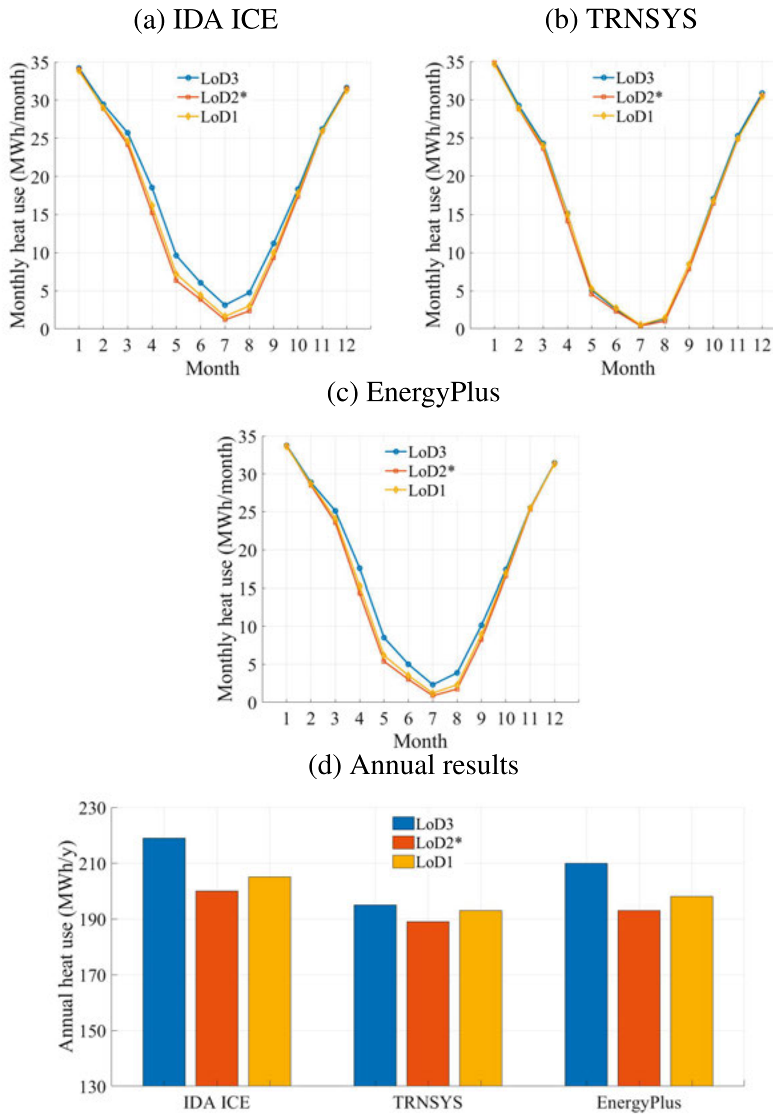


Figure 4.5. Results from comparison of the levels of detail in building energy model in different tools. Subplots (a), (b) and (c) illustrate the monthly results for IDA ICE, TRNSYS and EnergyPlus. Subplot (g) shows the annual heat all three LoDs and simulation tools.

ing effectively and as a result, no distinguished differences is seen in the result from simulation of the building with three LoDs.

Overall, based on the definition of the level of detail given in Paper III, LoD1, i.e., the shoe-box model of a building, can deviate by 25% from the detailed building models annually. However, this deviation between the results is basically seen when the heating demand is less.

5. Discussion and future work

This chapter contributes to the discussion around the results from Paper II and Paper III. Furthermore, a future outlook and further suggestions on future work is presented in this chapter.

5.1 Discussion

In this thesis a review of the state-of-the-art of the field of urban building energy modeling is summarized in Paper I. From conception to implementation, Paper I contributes to comprehensive survey of the existing UBEMs, identifies challenges and opportunities, and presents an outlook for future developments. In Papers II and III, the overriding aim is to provide the basis for development of a simple but still accurate UBEM.

According to the findings from Papers II, and III, it can be observed that not every BEM tool handles the complexities involved in of urban building energy modeling. Even though most validated and commercialized BEM tools can generate very accurate and close-to-reality energy models of individual buildings, when it comes to urban building energy modeling their capabilities become restricted. From the three building energy simulation tools that have been evaluated in Paper II, and later in Paper III, only EnergyPlus could meet almost all the requirements for development of a simple yet accurate UBEM.

Considering all the features that have been discussed in Paper II and Paper III, including modeling approach, and calculations around heat balance of a building, EnergyPlus seems a most suitable tool to be used in simplified, but rather accurate UBEMs. The short computation time in EnergyPlus is also another merit. While it only takes a few seconds to conduct a simple single-zone model simulation in EnergyPlus, it reaches to some minutes for IDA ICE and TRNSYS. Thus, the overall computation time for large number of buildings increases considerably.

Finally, as presented in Paper III the deviation of single-zone building models from detailed multi-zone models can be negligible on building level studies. This means that, on the aggregated level and for city-scale energy modeling, the simplified zoning configuration does not adversely influence the accuracy of the result. With this being said, it is more likely to have even more simplifications in the models and yet reach the results with an acceptable accuracy. In this respect, the the level of detail (LoD) of the building model should not be an issue on the aggregated level although it is still possible to make use of correction factors and calibration methods in considering the shading objects adjacent to the building, such as balconies.

5.2 Future work

The field of urban building energy modeling is still under further development and this opens up significant opportunities for contributions to the advancement of UBEMs. Here follow a few possible directions for future work.

- Data collection is one of the biggest challenges in UBEM. In the absence of detailed information on buildings, the availability of national databases for geographical and property information together with information on energy performance certifications can be expected to facilitate the modeling procedure considerably. For this reason, the future outlook to this work is to analyze the possibility of developing an UBEM using available national databases and determine their validity and reliability in UBEM studies.

- Abstracting the building stock into a few building archetypes seems to be an optimal solution for reducing the complexity and extent of UBEMs. Except for a small number of studies, a majority have relied on deterministic classification of buildings based on variables such as type and year of construction. However, deterministic methods cannot represent the diversity of buildings and thus the second outlook to this work is to make use of machine learning techniques in probability classification of building stock and finding the most representative building archetypes.

- As inferred from the review of the state-of-the-art, most UBEMs are lacking a comprehensive perspective in reflecting on urban energy systems. Existing models focus more on buildings with some including the energy systems and microclimate. Yet, no UBEM is found that integrates different elements of urban energy system in one framework. This means that there is a need for a more comprehensive urban model that extends the definition of an UBEM and encompasses not only the buildings but also the urban human mobility and transport, urban energy systems (both renewable and conventional), and distribution (both heat and electricity) as well as urban microclimate. Therefore, an outlook for future work is to develop a more comprehensive model that can be referred to as urban and decentralized energy model (UDEM).

6. Conclusion

This thesis contributes to the state-of-the-are of the urban building energy models. UBEMs have emerged from the need for city-wide energy planning for a low carbon and energy efficient built environment. From individual buildings to district and city levels, an UBEM provides insight into the energy performance of buildings, identifies effective energy efficiency measures and building integrated renewable energy technology solutions.

Among different methods of developing an UBEM, a BEM-based model, which benefits from already established building energy simulation techniques in conducting city-scale studies, seems promising. The results of this thesis provide simulation evidence that on aggregated levels (district- or city-level), the building energy simulation software, EnergyPlus, gives the least deviations from measured data. According to the simulation results of an UBEM for a case study neighbourhood, it is concluded that the root mean squared error (RMSE) from hourly measurements is calculated to be 117 kWh for EnergyPlus, while it reaches to 130 kWh and 203 kWh for TRNSYS and IDA ICE, respectively. In terms of applicability, capability and accuracy, EnergyPlus can also have more advantages over the others when used in UBEMs.

From the results of this thesis, it is also concluded that for the scope of urban building energy modeling, simplified zoning configurations and lower levels of detail, i.e., 1 zone per building model with LoD1 (or single-zone shoebox models), can generate accurate estimations of the heat use on individual building-level. It is also expected that in an UBEM and on aggregated levels the deviations between estimated results and actual data become smaller as the differences from simplified building models would be averaged out over.

Acknowledgement

I would like to express my sincere gratitude to my supervisor Joakim Widén and my co-supervisor Joakim Munkhammar for their endless support. Your insightful feedback and constant encouragement helped me a lot throughout this process. I also wish to thank my co-authors–beside Joakim Widén and Joakim Munkhammar– Annica Nilsson, Magnus Åberg, and Guiseppe Peronato, for their valuable contribution to my work. It has been a pleasure working with you. I also appreciate working and collaborating with my master thesis supervisors and later co-authors, Chris Bales and Emmanouil Psimopoulos. I gratefully acknowledge the members of UBMEM work group, and all my colleagues at the division of Civil Engineering and Built Environment. Thank you for interesting discussions and practical guidance.

And finally, to my dearest husband and my best friend forever, thanks for believing in me and supporting me unconditionally.

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