Applied Energy 215 (2018) 717–735

Contents lists available at ScienceDirect

Applied Energy

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

Impacts of building geometry modeling methods on the simulation results of urban building energy models

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HIGHLIGHTS

- Three zoning methods were presented, evaluated and compared in the UBEM context.
- Influences of using a floor multiplier in urban building energy modeling are studied.
- 940 office and retail buildings in San Francisco were simulated with 3 zoning methods.
- Modeling each floor as one zone underestimates thermal loads and equipment capacity.
- Zoning methods have a significant impact on the simulated energy use of UBEM.

ARTICLE INFO

Keywords:
Urban building energy modeling
EnergyPlus
Geometry representation
Zoning method
CityBES
Floor multiplier

ABSTRACT

Urban-scale building energy modeling (UBEM)—using building modeling to understand how a group of buildings will perform together—is attracting increasing attention in the energy modeling field. Unlike modeling a single building, which will use detailed information, UBEM generally uses existing building stock data consisting of high-level building information. This study evaluated the impacts of three zoning methods and the use of floor multipliers on the simulated energy use of 940 office and retail buildings in three climate zones using City Building Energy Saver. The first zoning method, OneZone, creates one thermal zone per floor using the target building's footprint. The second zoning method, AutoZone, splits the building's footprint into perimeter and core zones. A novel, pixel-based automatic zoning algorithm is developed for the AutoZone method. The third zoning method, Prototype, uses the U.S. Department of Energy's reference building prototype shapes. Results show that simulated source energy use of buildings with the floor multiplier are marginally higher by up to 2.6% than those modeling each floor explicitly, which take two to three times longer to run. Compared with the AutoZone method, the OneZone method results in decreased thermal loads and less equipment capacities: 15.2% smaller fan capacity, 11.1% smaller cooling capacity, 11.0% smaller heating capacity, 16.9% less heating loads, and 7.5% less cooling loads. Source energy use differences range from -7.6% to 5.1%. When comparing the Prototype method with the AutoZone method, source energy use differences range from -12.1% to 19.0%, and larger ranges of differences are found for the thermal loads and equipment capacities. This study demonstrated that zoning methods have a significant impact on the simulated energy use of UBEM. One recommendation resulting from this study is to use the AutoZone method with floor multiplier to obtain accurate results while balancing the simulation run time for UBEM.

1. Introduction

More than half of the world's population (54% in 2014) lives in urban areas [1]. Today's cities consume more than two-thirds of the world's primary energy and account for more than 70% of global greenhouse gas (GHG) emissions [2]. Working toward a sustainable future, many cities have adopted ambitious long-term GHG emissions reduction goals. For example, San Francisco planned to reduce GHG emissions by 40% and 80% below the 1990 level by 2025 and 2050 accordingly [3]. New York City also committed to reducing GHG emissions by 40% and 80% below 1990 level by 2030 and 2050, respectively [4]. The building sector in the United States accounts for about 40% of the nation's total primary energy consumption and GHG emissions [5]. In cities, buildings can consume up to 75% of total primary energy [6]. Retrofitting the existing building stock to improve energy efficiency and reduce energy use is a key strategy for cities to

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https://doi.org/10.1016/j.apenergy.2018.02.073
Received 6 November 2017; Received in revised form 4 January 2018; Accepted 8 February 2018
Available online 20 February 2018

reduce GHG emissions and mitigate climate change [7,8].

Urban Building Energy Modeling (UBEM) refers to the application of physics-based building energy models to predict operational energy use as well as indoor and outdoor environmental conditions for groups of buildings in urban context. UBEM tools can be used to support urban planning, retrofit analysis of building stock, improve building operations, and design district energy systems [9,10]. Reinhart and Davila [11] performed a comprehensive review of UBEM case studies and pointed out that multi-zone dynamic thermal models using simulation engines such as EnergyPlus, DOE2, TRNSYS, and IDA-ICE may be necessary for evaluation of detailed urban design scenarios as well as urban-scale building retrofit analysis.

Having a city building dataset is a key component to creating an UBEM. There are two major parts of a building energy model. The first part relates to the building geometry, including the building shape, building height, number of stories, and thermal zoning. The second part relates to the building systems and their operation conditions, such as envelope construction, interior and exterior lighting, plug loads, heating, ventilation and air conditioning (HVAC) systems, central plant, and server hot water systems [12–14]. Many cities in the United States have web portals that provide open city datasets for public use. For example, San Francisco's open data portal[1] provides the Geographic Information System (GIS) building geometry information including the footprint and height of each building in the city. It also provides the building characteristics, such as year built, number of stories, and building type. Similar building data can be found in other U.S. cities (e.g., Chicago[2] and New York City.[3]). With UBEM, building systems and their efficiencies are often determined based on building type, building size and year built, referring to the national or local building energy codes and standards and survey data when available. Three-dimensional (3D) information is required for detailed building energy models; however, it is often difficult to get such detailed 3D geometry data. It is also difficult to get detailed thermal zoning for each building for UBEM. Cities may have the 3D point clouds data (e.g., LIDAR data); however, it is difficult to use directly to generate the 3D geometry of the building. Typical building geometry data available for UBEM include the GIS-based building footprint, building height, and number of stories for each building.

Several studies have been done to evaluate the impacts of geometry modeling methods on the simulation results of individual buildings. Martin et al. [15] compared the simulated cooling demand of a 6-floor office building in Singapore using three different models when coupled with an urban canopy model, including the shoebox model (one rectangular zone for the whole building), the multi-floor model (one rectangular zone per floor), and the detailed model (one core zone and four perimeter zones per floor). The mean absolute percentage error of cooling demand between the detailed model and the shoebox model is more than 10%, while it is about 3% between the detailed model and the multi-floor model. The tropical climate of Singapore determines that all zones require cooling almost at all times. For colder climates, some core zones may require cooling while the perimeter zones may require heating simultaneously, leading to the cancellation of some cooling and heating loads when using the shoebox or the multi-floor model. This may lead to significant under-prediction of thermal loads and equipment capacity. Further investigation is required to study the performance of the multi-floor model in other climates.

Smith et al. [16] described a method to automatically generate an energy model from an architect's basic massing model during the conceptual design stage. The basic massing model was made of regular cubic shapes. Each cubic shape was sliced into multiple floors, and each floor was further divided into a core zone and four perimeter zones. Dogan et al. [17] presented a general algorithm for a rapid model generation to automatically convert arbitrary building massing models into multi-zone building energy models. Design tools (such as eQuest and Bentley AECOsim) also provide some functionality to create or split buildings into perimeter and core zones [17]. Those methods can be categorized as geometry processing-based methods (e.g., offset the line, find the intersection, trim the line) to handle typical geometries (e.g., rectangular and L-shape), which are normally used in the early design stage where the building data comes from design and are of good quality. However, buildings in a city are of different arbitrary shapes. For UBEM, the GIS-based building footprint data normally have quality issues, containing noises in data that lead to problems in applying the geometry processing-based methods. Therefore, new methods with more robustness need to be developed to handle that GIS-based city building footprint data.

For high-rise buildings, the ground floor and the top floor are usually modeled explicitly, while the middle floors are modeled as a "typical" floor with a floor multiplier. Environmental factors such as air temperature and wind speed change with altitude, and the urban environment imposes additional environmental factors due to shading and reflections from surrounding buildings [18]. Ellis and Torcellini [19] used EnergyPlus to simulate and compare the energy impacts of several environmental factors that vary with altitude for one building. Results showed that environmental factors have a significant effect on total annual building cooling and heating energy use. The accuracy of using floor multipliers to reduce input data was also studied. Researchers concluded that simulating a single floor with a multiplier can provide accurate enough results for an entire building, as long as the floor is near the midheight of the building. Computing resources required to run these models (in addition to UBEM) are significant and present a challenge, especially when detailed energy models are used to evaluate the energy performance of many energy conservation measures (ECMs). Dogan and Reinhart [20] developed a Shoeboxer algorithm to cluster similar spaces in a neighborhood into shoebox units and simulate each unit separately. The floor area can be further divided into a core and perimeter regions by offsetting the floor edges inwards by a specified perimeter depth.

This study evaluates the differences between simulation results for different geometry modeling methods in urban building energy models. The goal is to provide insight and guidance regarding geometry modeling methods, with consideration of model accuracy as well as computing performance. This study first introduced a novel pixel-based method to generate core zone and perimeter zones automatically for arbitrary building footprint data. Then, three geometry modeling methods were compared, including the one zone per floor: the pixel-based autozoning method and the prototype building method (e.g., rectangular shape with core and perimeter zones for office buildings). Impacts of using floor multipliers on the simulated energy use of large office buildings were also considered.

2. Methods

Unlike modeling a single building, where a modeler can collect detailed information about the building, UBEM are usually generated using existing building stock data. Available building stock data typically contain high-level building geometry and characteristics information, such as building footprint, building height, number of stories, building type (use type), and year built. A building energy model has two main parts: the geometry and the building systems. Buildings with similar use type, vintage (year built), and size can be organized into archetypes, and an archetype database can be created based on local energy codes combined with measured or surveyed data. For UBEM, the details of building systems are typically generated based on archetypes.

There are six driving factors to energy use and occupant comfort in buildings [21], including weather, building envelope, building systems

[1] https://datasf.org/.
[2] https://data.cityofchicago.org.
[3] https://data.cityofnewyork.us.