Impacts of Building Geometry Modeling Methods on the Simulation Results of Urban Building Energy Models

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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%

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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.

Keywords

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 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

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

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 and equipment, building operation and maintenance, indoor comfort criteria, and occupant behavior [22, 23]. Geometry zoning is part of the building envelope that influences building energy modeling results. One frequently asked question related to UBEM is "How do you calibrate your urban building energy models?" The current model calibration methods typically consider the ventilation rate, temperature setpoint, infiltration rate, equipment power density, lighting power density, occupant density, HVAC equipment efficiencies, window properties, and operation schedules as the most influential and uncertain input parameters for building energy models [24–26]. The current model calibration methods focus on adjusting the efficiency values and operation schedules of building systems rather than changing the building geometry [26–29]. Therefore, before working on the calibration of UBEM, this study explored the impacts of different geometry generation methods.

This study examined 940 buildings located in northeast San Francisco, California, United

States. This section introduces those case study buildings, the simulation workflow, and the development work to automate the large-scale building energy modeling and simulation for urban applications.

2.1 Case study buildings

The San Francisco Property Information Map [30] shows that San Francisco has 1,080 office buildings and 1,744 one-to-two story retail buildings smaller than 4,645 m^2 (50,000 ft^2). About one-third (940) of those office and retail buildings are located in northeast San Francisco, which includes six districts: Downtown, Nob Hill, Financial District, North Beach, Russian Hill, and Chinatown. In this study, those 940 buildings were modeled using different geometry generation methods, considering shading effects from the other 7,725 surrounding buildings in those districts (Figure 1). By integrating San Francisco public data, a building dataset was created for the 8665 buildings in northeast San Francisco [7]. The model contains a two-dimensional (2D) footprint, number of stories, building height, building type, and year built information for each building. Table 1 shows a summary of the 940 selected buildings with a total floor area of 6,648,099 m^2. The 278 large office buildings have the largest floor area (87%), while the small retail buildings have the largest number (292). Figure 2 shows the year built distribution for the 940 buildings. Most buildings (69%) were built before the 1930s.

Figure 1. 8665 buildings in northeast San Francisco

Table 1. Summary of the 940 office and retail buildings in northeast San Francisco

Building Type	Building Count	Total Floor area ($10^3 \, m^2$)
Small office (<2322 m^2 and <= 3 floors)	174	150
Medium office* (2322 to 9290 m^2, <= 5 floors)	148	475
Large office (>9290 m^2 or >=6 Floors)	278	5,786
Small retail (<1200 m^2 and <= 2 Floors)	292	148
Medium retail (1200 to 4645 m^2 and <= 2 Floors)	48	89
Total	940	6,648

* Note: The medium office building definition also includes buildings that are <2300 m^2 with four or five floors.
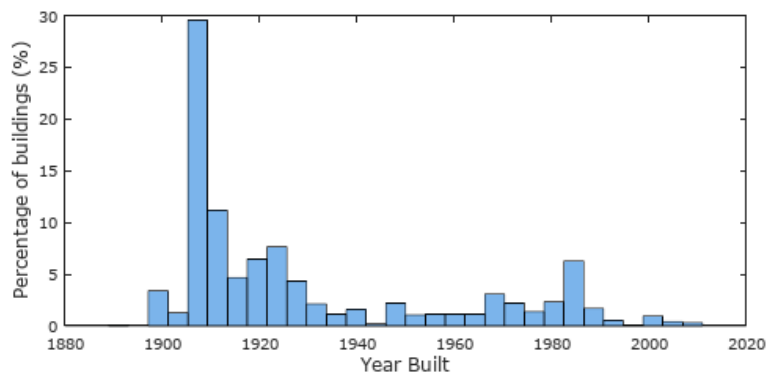
Figure 2. Distribution of year built for each of the 940 buildings

In the U.S. Department of Energy (DOE) reference buildings [31], retail building types and office building types are represented by a rectangular shape with different thermal zoning and a variety of stories. Figure 4 shows the distribution of the footprint area to border area ratio of the 940 buildings. The border is referred to as the smallest rectangular shape with a proper orientation that can entirely contain the building footprint. The footprint area-to-border area ratio ranges from 0.67 (5th percentile) to 1.0 (95th percentile) with a median of 0.97, which indicates that most of the buildings are similar to the rectangular shape. For the calculation of the footprint-to-border ratio, the building is first rotated according to its orientation and then compared to the area of the footprint with the rectangular border area to compute the ratio.
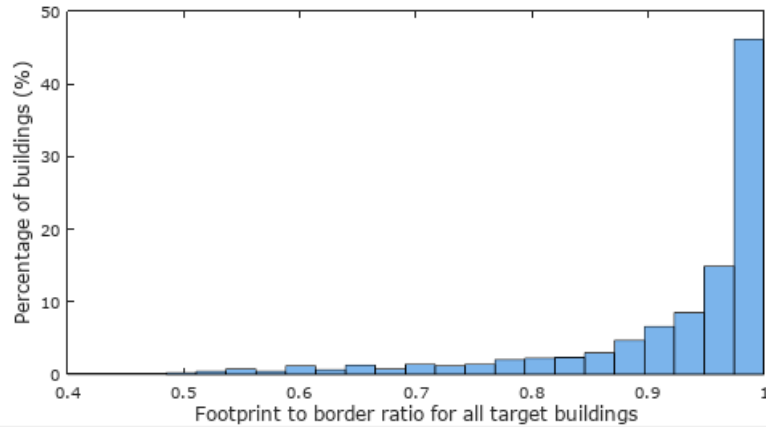
Figure 3. Distribution of footprint area-to-border area ratio for the 940 buildings

2.2 Simulation workflow

Figure 4 shows the major components of the UBEM in this study. The available building data

at urban scale provide the basic geometry information, the building type, and the year built of

each building. The 2D GIS-based building footprint, building height, and number of stories of

each building are used by the geometry modeling methods to generate the geometry for each

building. The building systems and their efficiency levels are inferred by their building type

and year built based on the local energy code and the prototype buildings. In San Francisco,

California Title 24 [32] is used to provide default building systems and efficiency levels.
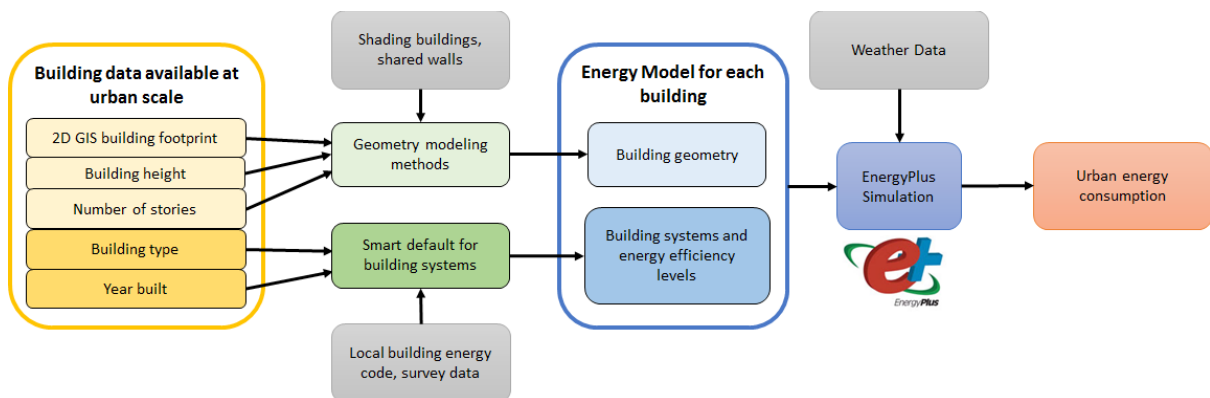
Figure 4. Major components of the urban building energy modeling

2.3 Geometry modeling methods

2.3.1 Floor multiplier

There are two considerations when establishing building geometry for energy models. First is

the modeling of multiple floors. The simulation time of detailed building energy models

strongly depends on the number of zones and surfaces. To speed up the simulation for high-

rise buildings, three representative floors are modeled when a floor multiplier is used; the top

floor, the ground floor, and a middle floor with the floor multiplier. This approach is also used

in the DOE reference building for large offices [31]. This simplification is based on the

assumption that all middle floors are the same or similar in terms of system characteristics,

use, and internal loads.

2.3.2 Floor zoning methods

The other consideration when establishing building geometry for energy models relates to the

thermal zoning of the arbitrary building footprint. There are three commonly used zoning

methods. The first method, named the ***OneZone method***, creates one zone for each floor

based on the given polygon of the floor shape. The second method, named the ***AutoZone***

method, automatically splits the building footprint into one or multiple core zones and

perimeter zones based on the ASHRAE 90.1 Appendix G guideline [33]. The third method,

named the ***Prototype method***, uses prototype building geometry and scales for the same floor

area, orientation, and aspect ratio as the target buildings. The office buildings (three sub-

types: small, medium, and large-sized) have a rectangular shape, and each floor includes four

perimeter zones, one core zone, and one plenum zone. The small retail building has a front

sale zone and a back storage zone, while the medium retail building has a sale zone, a storage

zone, an entry zone, and two accounting-office zones. The aspect ratio between the width and

length is adjusted to match the aspect ratio of the target building.

The simulation time of a detailed EnergyPlus model strongly depends on the number of zones and surfaces. The OneZone method creates the least number of zones per floor, while the AutoZone method normally creates more zones than the Prototype method. The use of the floor multiplier reduces the number of zones significantly, especially for high-rise buildings. The simulation results and the simulation time are evaluated in this study to determine the geometry generation methods for UBEM, considering the model accuracy as well as the computing performance.

2.3.3 Shading and Adjacency

Neighborhood buildings are modeled as shading surfaces in EnergyPlus to evaluate solar shading effects between buildings. The basic algorithms are first introduced in Chen, et al. [7]. When the closest ground distance of the target building and a surrounding building is less than 2.5 times of the surrounding building's height, the surrounding building may shade the target building and is therefore considered as a shading building of the target building. The height multiplier (2.5) is calculated based on a sun angle of 21.8°, which covers 83% of working hours (9 am to 5 pm) for San Francisco (longitude 37.77°N). A polygon simplification was performed to determine an equivalent polygon with fewer vertices/points for the shading buildings, which significantly reduce the simulation time without influencing the simulation results. Chen, et al. [7] modeled all surfaces of the shading buildings (Figure 5 (a)) and used floor multipliers for tall buildings. In this study, EnergyPlus simulations were significantly slowed down or even sometimes crashed when every floor of tall buildings and all surfaces of the shading buildings were used, due to the increasing complexity of shading calculations. To solve this problem, a shading surface pre-processing algorithm is developed

and implemented to determine the effective shading surfaces (Figure 5 (b)). The algorithm loops through all shading surfaces and removes the surfaces that are blocked by other shading surfaces. The simulation time for the example building in Figure 5 was reduced from 7 minutes to 2 minutes when only the effective shading surfaces were modeled.
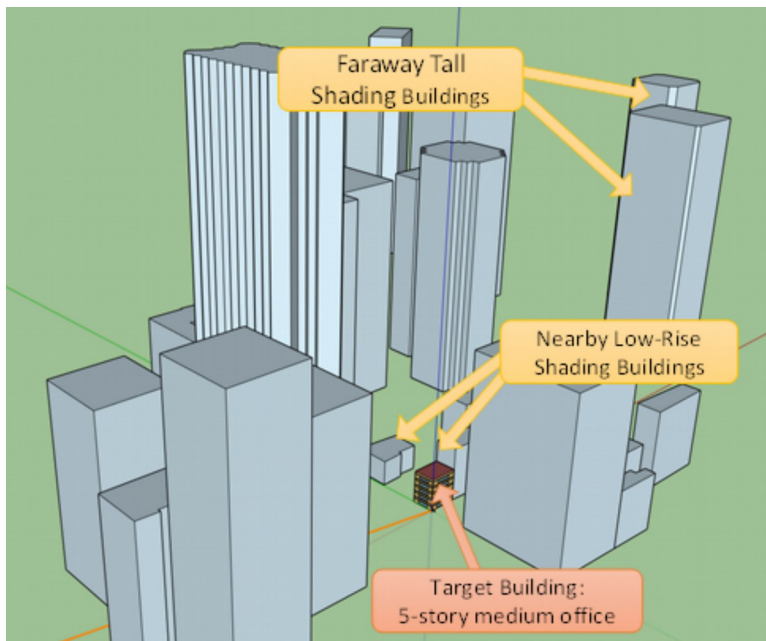
(a) Shading buildings, source: [7]
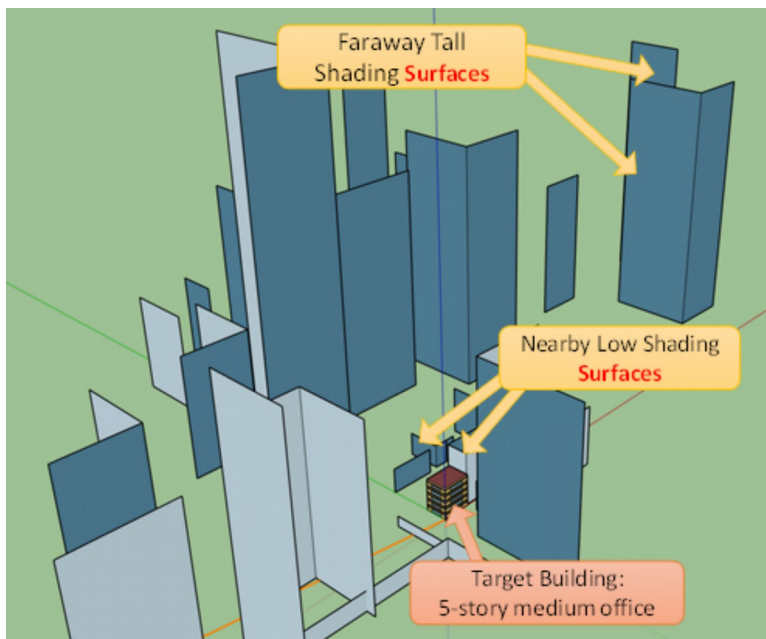
(b) Effective shading surfaces

Figure 5. EnergyPlus models for an example building using different shading modeling methods

Shared/adjacent walls are detected between two adjoining buildings based on the GIS information. First, the model searched for and identified adjacent walls for each target wall. In this study, two walls are adjacent when the distance between them is less than 0.5 meters. A margin of 0.5 meters is used to address the GIS data quality issue. All the adjacent walls' area are then added together; the target wall is determined to be a shared wall if the adjacent area is more than 50% of the target wall's area. Those shared walls are modeled as adiabatic surfaces without windows [7]. For the OneZone and AutoZone methods, the detailed building footprint is used to detect the shared walls; in Prototype method, prototype geometry (e.g., rectangular shape for office and retail buildings) is used. The models using the Prototype method have same floor area as those using the OneZone or AutoZone methods; however, they may have quite different exterior wall and window area.

2.4 Pixel-based autozoning algorithm

ASHRAE 90.1-2013 appendix G table G.3.1-8 [33] introduces a thermal zoning method when the HVAC zones and systems have not yet been designed or information is not available. The interior and perimeter spaces should be separated, and the interior spaces should be located greater than 5 m (about 15 ft) from an exterior wall. The perimeter spaces should be located within 5 m (15 ft) of exterior walls. A separate zone shall be provided for each orientation. The method can be used as an alternative to creating thermal zones for UBEM as there is usually lack of detailed thermal zoning information.

A novel pixel-based algorithm is developed to split an arbitrary polygon into multiple perimeter and core zones, which complies with the ASHRAE 90.1 requirements. The main idea of the algorithm is to use the discrete element method (DEM), which is normally applied

in the Computational Fluid Dynamics (CFD) simulation. First, a 2D space that contains the arbitrary polygon is meshed into small grids (e.g., 20cm * 20cm) to determine the status of each grid. There are four possible states of each grid element, including outside the polygon, in the perimeter area (inside the polygon and close to exterior walls), in the core area (inside the polygon and far away from exterior walls), and on the boundary of the core area. The 2D space can be drawn as an image with different colors for different states. Each element represents one pixel in the image, and the calculation is preformed at the pixel level. The algorithm is named a pixel-based autozoning algorithm.

There are four steps in the pixel-based autozoning algorithm (Figure 6). Step (a): fill in the indoor space with white pixels. Step (b): separate the perimeter space in dark gray and core space still in white. Step (c): separate the boundary of the core space in white and inner space in light gray. Step (d): simplify the boundary of the core space and split into thermal zones. The pixel-based autozoning algorithm is easy to implement and can work for arbitrary shapes. The detailed algorithm of each step is introduced next.

(a)   (b)   (c)   (d)
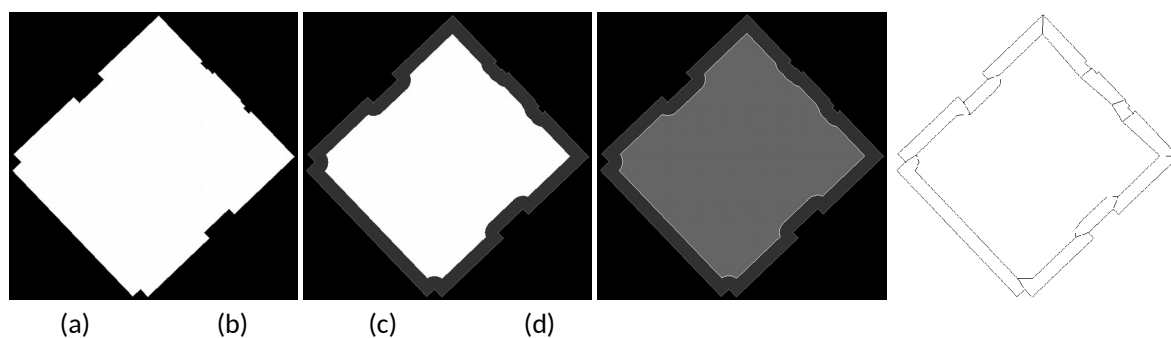
Figure 6. Pixel-based autozoning algorithm procedures

2.4.1 Step (a): fill in the indoor space with white pixels

For the coordinate system of the image, the horizontal X-axis represents the longitude, while the vertical Y-axis represents the latitude (Figure 7 (a)). All pixels are set to black by default, which is the color for pixels outside the polygon. For each line of the building polygon, the

line is first drawn as black in the image, and then swapped from black to white or from white to black for all pixels directly below the pixels on the line. A pixel (P1) is directly below another pixel (P2) when their X values are the same, but the Y value of P1 is smaller than that of P2. When the polygon is closed, the indoor and outdoor spaces are split with black and white colors (Figure 7). The black pixel represents the boundary or outdoor space, while the white pixel represents the indoor space.

2.4.2 Step (b): separate the perimeter space in dark gray and core space in white

For each white pixel, check the distances of the white pixel with all black pixels, if any distance is less than the perimeter zone depth threshold (e.g., 5 m), change the white pixel to dark gray color, which is the perimeter area color.

2.4.3 Step (c): separate the boundary of the core space in white and inner space in light gray

For each white pixel, check whether the pixel is on the boundary of the core area, and change the color of inner space into light gray.

2.4.4 Step (d): simplify the boundary of the core space and split into thermal zones.

Following steps (a) through (c), the remaining while pixels are on the boundary of interior zones. Coordinates (pixel location) for the white pixels are collected, starting with any pixel in the pool, and searing the surrounding pixels in the pool until looping back to the starting point. A polygon is then created for all pixels in the loop. If there are pixels remaining in the pool, start another process to create another polygon for another interior zones. Then, use the simplify_rb ruby gem [34] to reduce the number of points in the complex polygon, making use of an optimized Douglas-Peucker algorithm [35]. The interior polygon in Figure 6 (c) includes 1014 pixels, which is simplified into 26 points/lines.

The final step of the algorithm is to connect the interior polygons with the original building polygon to create thermal zones. For each interior point, first, find its closest exterior point. The line connecting the interior point and the closest exterior point should not intersect with any other lines in the interior or exterior polygons. When multiple interior points are close to

the same exterior point, only the interior point that is closest to the exterior point is used. Then, link all the interior points with their associated exterior points to divide the space into multiple zones. Figure 8 shows the autozoning results of four sample buildings.
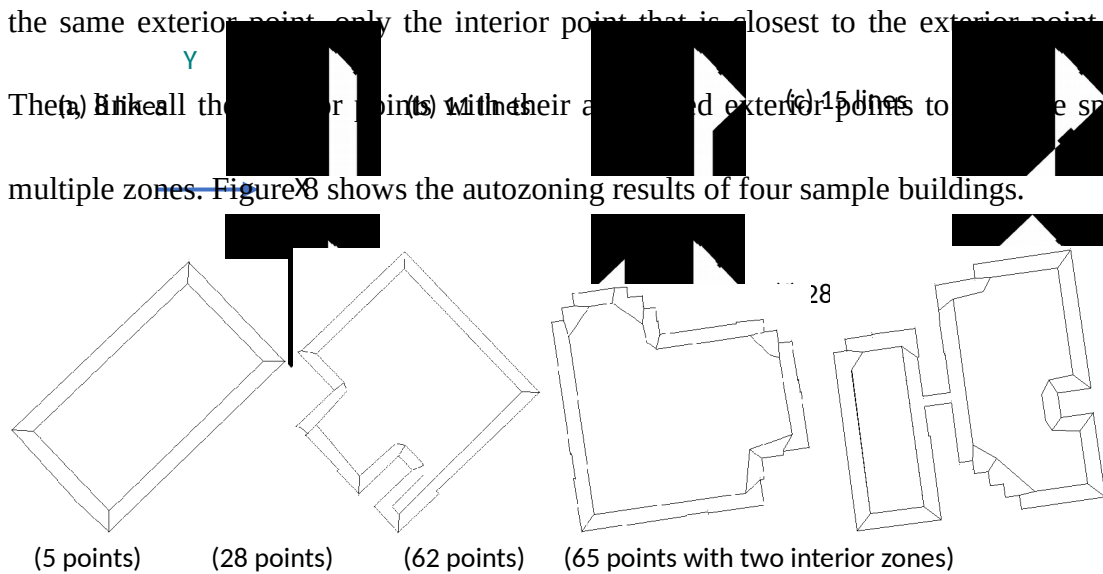

| (5 points) | (28 points) | (62 points) | (65 points with two interior zones) |

Figure 8. Sample results of the autozoning algorithm

2.5 Prototype zoning method

The prototype zoning method needs to detect the orientation and aspect ratio of the building.

To calculate the orientation and aspect ratio of the building, rotate the building from 0 to 90 degree clockwise with one-degree interval (Table 2). For every rotation, calculate the area of the rectangular boundary that contains the building. Then find the rotation degree with the least boundary area as the preliminary result (e.g., 57° for the building in Table 2). Next, search one degree above and one degree below the preliminary result (56° to 58°) with an interval of 0.1 degrees to determine the orientation with a resolution of 0.1 degrees. For example, the orientation and aspect ratio are 57.5° and 1.779 accordingly for the building in Table 2.

Table 2. Schematic diagrams to demonstrate the building orientation and aspect ratio calculation algorithm

Schematic					
Orientation (°)	0	15	37	57	57.5

Normalized boundary area	1.00	1.12	0.95	0.655	0.653
Aspect Ratio (height/width)	0.764	0.924	1.211	1.755	1.779

2.6 Building systems

The building systems and their efficiency values are determined based on the building type,

vintage, climate, and the local building energy code or standard (California Title 24, in this

study, for San Francisco). Table 3 shows the default configurations of HVAC systems for

each building type.

Table 3. Default HVAV system type for each building type

Building type	**HVAC system**	**Cooling**	**Heating**	**Fan control**	**Reheat**
Small office and small retail	Packaged single zone rooftop air conditioner	Direct expansion (DX) coil, single speed	Gas heating coil	Constant volume	No reheat
Medium office and medium retail	Packaged variable air volume (VAV) for each floor	DX coil, two speed	Hot water coil, boiler	VAV	Hot water coil, boiler
Large office	Central VAV for each floor, with a central plant of chillers and boilers	Chilled water coil, chillers	Hot water coil, boiler	VAV	Hot water coil, boiler

2.7 Climate impact on the simulation results

Weather conditions have strong impacts on the building energy performance. For this study,

two additional weather conditions were applied to all buildings to evaluate the impacts of

geometry modeling methods under different weather conditions. Those 8665 buildings (940

target buildings and 7725 surrounding buildings) were assumed to be located in Chicago,

Illinois (cold climate, ASHRAE climate zone 5A) and Miami, Florida (hot climate, ASHRAE

climate zone 1A). Besides changing the weather files, the ASHRAE standard 90.1 efficiency

requirements are applied to provide the default building systems and efficiency values based

on the climate zones. The typical meteorological year (TMY) 3 weather files from EnergyPlus Weather Data website[4] for San Francisco international airport (724940), Chicago O'Hare international airport (725300), and Miami international airport (722020) are used for the simulation.

2.8 The modeling and simulation environment

All the models are created and simulated using the City Building Energy Saver (CityBES), an open web-based data and computing platform for UBEM [7,36–38]. CityBES is built upon Commercial Building Energy Saver (CBES) [39–41] to create energy models in EnergyPlus [42] for each building. Chen, et al. [7] introduced the detailed generation and simulation of urban building energy models using CityBES. First, the three zoning methods and the use of floor multiplier are integrated into the CityBES platform so that users can select different zoning methods and decide whether or not to use the floor multiplier on the simulation-setting page. Then, all the EnergyPlus models are run on a CityBES server, which can run 62 simulations simultaneously using 62 cores. The server has Intel® Xeon® CPU E5-2699 v3 @ 2.30 GHZ (2 processors), 256 GB memory, with 64-bit Windows 7 Operation system.

3 Results

Table 4 summarizes the simulation runs for each building type. For the small and medium office and retail buildings, nine simulations were run for each building: the combination of three climate zones and three zoning methods. For the large office, 18 simulations for each building were run: the combination of three climate zones, three zoning methods, and with or without using the floor multiplier. The total number of simulations is 10,962 for each iteration.

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4 https://energyplus.net/weather

Table 4 Summary of simulation runs of each building type

	Building Count	Climate Zone	Zoning Method	Floor Multiplier	Number of Simulations
Small Office (SO)	174	3	3	1	1,566
Medium Office (MO)	148	3	3	1	1,332
Large Office (LO)	278	3	3	2	5,004
Small Retail (SR)	292	3	3	1	2,628
Medium Retail (MR)	48	3	3	1	432
Total					10,962

3.1 Comparison of cases with and without use of the floor multiplier

The large office buildings have multiple floors and can use the floor multiplier in the energy

modeling. The percentage differences are calculated based on Equation 1.

$$Percentage\,Difference = \frac{result\,with\,floor\,multiplier - result\,without\,floor\,multiplier}{result\,without\,floor\,multiplier} \times 100$$

Eq. 1

3.1.1 Comparison of simulated energy use

There are two types of energy uses in the case study buildings: electricity and natural gas. For

the source energy calculation, the source energy factors used in the study are 3.14 for

electricity and 1.05 for natural gas [43]. For all cases, the differences in the annual electricity

and source energy use between the models with and without using the floor multiplier are

about ±2.5% with a median close to 0% (Figure 9 and Figure 10). For the San Francisco and

Miami cases, the differences in natural gas use range from -0.4% (5th percentile) to 3.4% (95th

percentile) with a median of 0.5% (Figure 10). For the Chicago cases, the differences in

natural gas use are larger with a median value of -3.7% for the OneZone method and -4.9%

for the AutoZone method. For the Chicago Prototype zoning case, the differences in natural

gas use are significant with a median of -14.2% and many outliers greater than 30%.
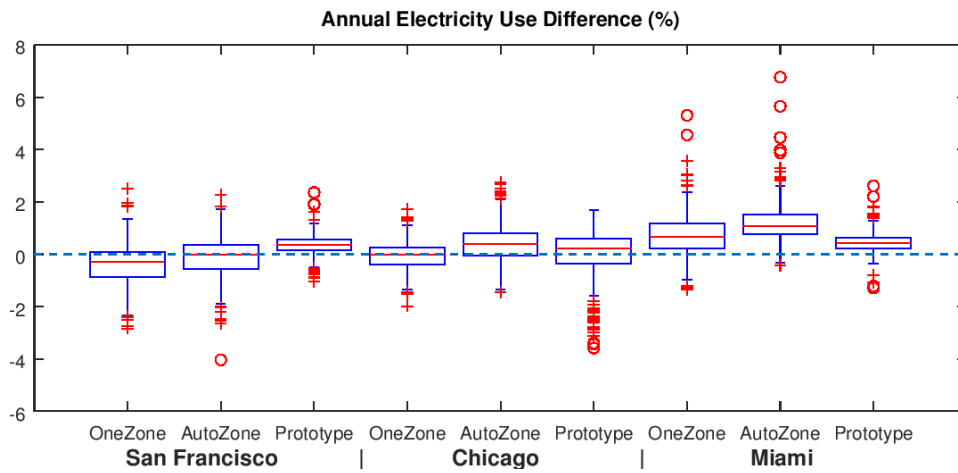
Figure 9. Differences in the annual electricity use between the cases with and without using the floor multiplier
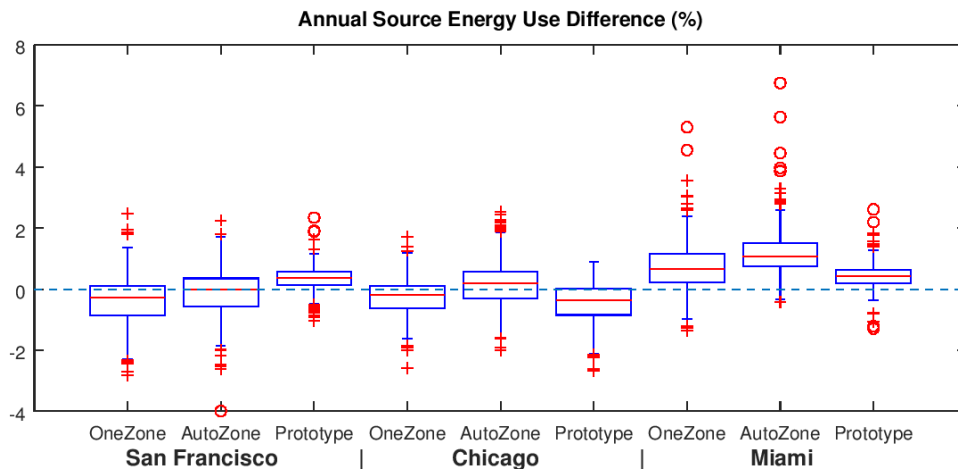
Figure 10. Differences in the annual source energy between the cases with and without using the floor multiplier
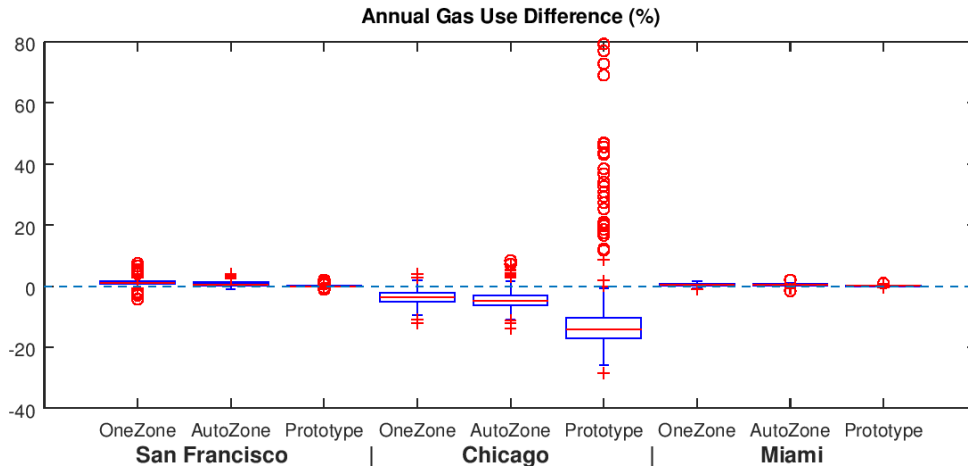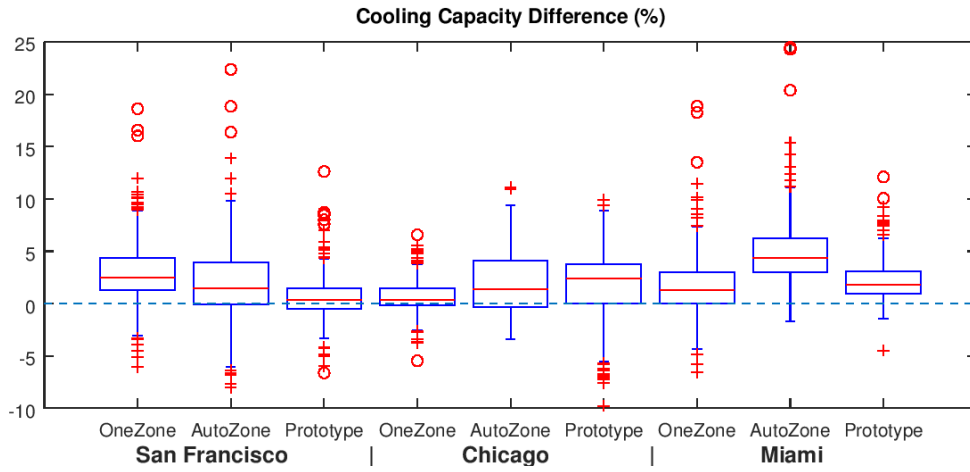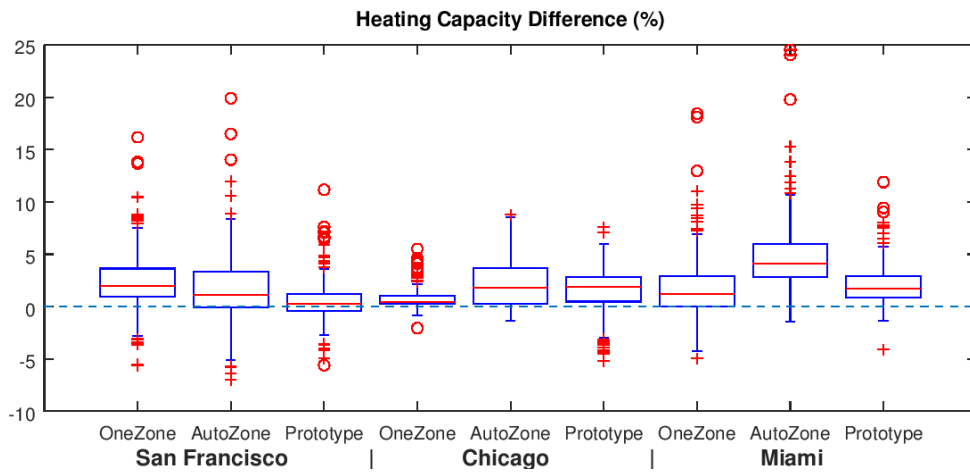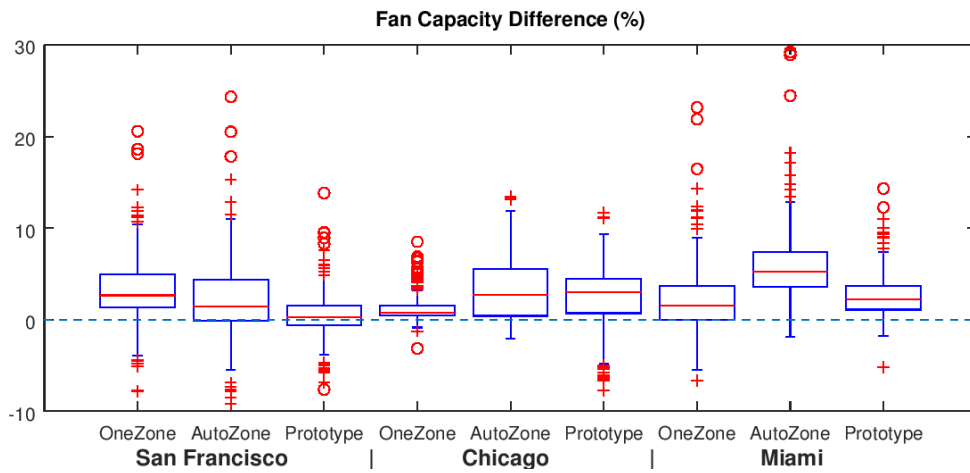
Annual Gas Use Difference (%)

Figure 11. Differences in the annual gas use between the cases with and without using the floor multiplier

In summary, the floor multipliers have less influence on the annual electricity or source energy across the three climates; however, the influence on the annual heating gas use is much greater, especially for the Chicago cold climate with the Prototype zoning method.

3.1.2 Comparison of autosized equipment capacities

Autosizing is used in EnergyPlus to determine equipment capacities based on peak thermal loads for all simulations. The equipment capacities are calculated based on the peak space heating and cooling loads using the design day weather data, with details available in the EnergyPlus Engineering Manual [44].

For all cases, the cooling capacity differences range from -5.5% (5th percentile) to 10.2% (95th percentile) with a median of 1.8%; the heating capacity differences vary from -3.3% (5th percentile) to 9.7% (95th percentile) with a median of 1.6%. The fan capacity differences vary from -4.9% (5th percentile) to 12.2% (95th percentile) with a median of 2.2%.

Cooling Capacity Difference (%)

Figure 12. Differences in the cooling capacities between the cases with and without using the floor multiplier

Heating Capacity Difference (%)

Figure 13. Differences in the heating capacities between the cases with and without using the floor multiplier

Fan Capacity Difference (%)

Figure 14. Differences in the fan capacities between the cases with and without using the floor multiplier

In summary, the floor multipliers have some but not significant impacts on the cooling, heating, or fan capacities.

3.1.3 Comparison of simulation time

The simulation speed-up factor is defined in Equation 2. The simulation speed-up factor is about 2.1 when the OneZone method is used and 3.1 when the AutoZone or Prototype methods are used (Table 5).

$$SimulationSpeedUpFactor = \frac{Simulation\,time\,without\,using\,floor\,multiplier}{Simulation\,time\,using\,floor\,multiplier} \qquad Eq.\ 2$$

Table 5. Differences in the simulation time between the cases with and without using the floor multiplier

Zoning method	Climate zone	Simulation time per building (minutes)		Simulation speed up factor
		With floor multiplier	**Without floor multiplier**	
OneZone	SF	4.6	9.5	2.1
OneZone	Chicago	4.1	8.6	2.1
OneZone	Miami	4.0	7.8	2.0
AutoZone	SF	8.0	25.9	3.2
AutoZone	Chicago	7.2	23.8	3.3
AutoZone	Miami	6.5	20.8	3.2
Prototype	SF	5.3	15.8	3.0
Prototype	Chicago	4.9	15.3	3.1
Prototype	Miami	4.5	13.5	3.0

3.2 OneZone method vs. AutoZone method

This section compares the simulation results using the OneZone method with those using the AutoZone method. The detailed models that did not use the floor multiplier are used for the comparison. Of the total, 284 buildings have a width close to or less than 10 m. Those buildings cannot be further divided into core zones and perimeter zones, including 78 small offices, 25 medium offices, 168 small retails, and 13 large offices. Therefore, only 656 buildings are included in this comparison. The percentage differences in this section are calculated based on Equation 3.

$$Percentage\ Difference = \frac{result\ using\ OneZone\ method - result\ using\ Autozoning\ method}{result\ using\ Autozoning\ method} \times 100$$

Eq. 3

3.2.1 Comparison of total annual space cooling and heating loads

Compared to the AutoZone method, the OneZone method results in 2.4% (5th percentile) to 17.4% (95th percentile) less space cooling loads with a median of 7.5% (Figure 15), and 0% to 79.7% smaller space heating loads with a median of 19.5% (Figure 16). For core zones without exterior walls, they typically require cooling all year round to remove the heat generated by occupants, lights, and equipment; while the perimeter zones with exterior walls and windows may require heating during winter and cooling during summer depending on the climate conditions. When using the OneZone method, the cooling and heating loads from the core and perimeter zones may be canceled out and result in less space cooling and heating loads compared to the AutoZone method. The OneZone method should be used with caution as it can underestimate the peak cooling and heating loads thus equipment capacities as well as energy use.
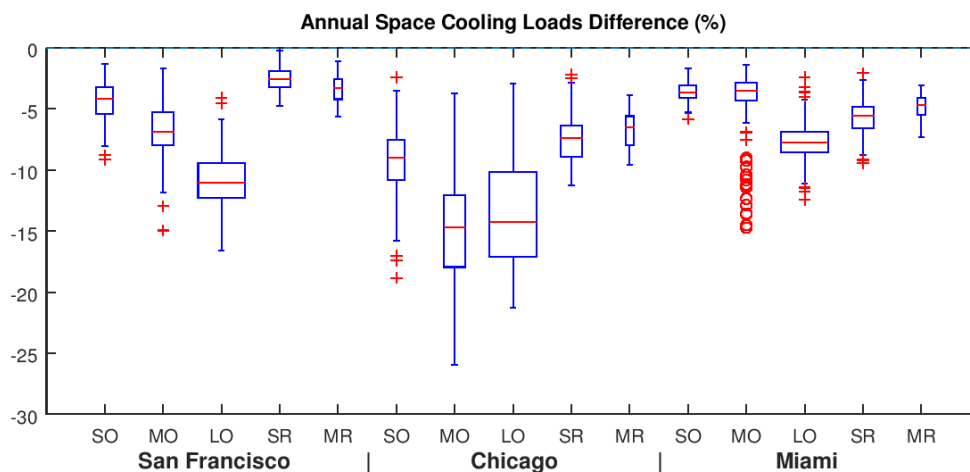
Figure 15. Differences in annual space cooling loads between the cases using the OneZone and the AutoZone methods

27
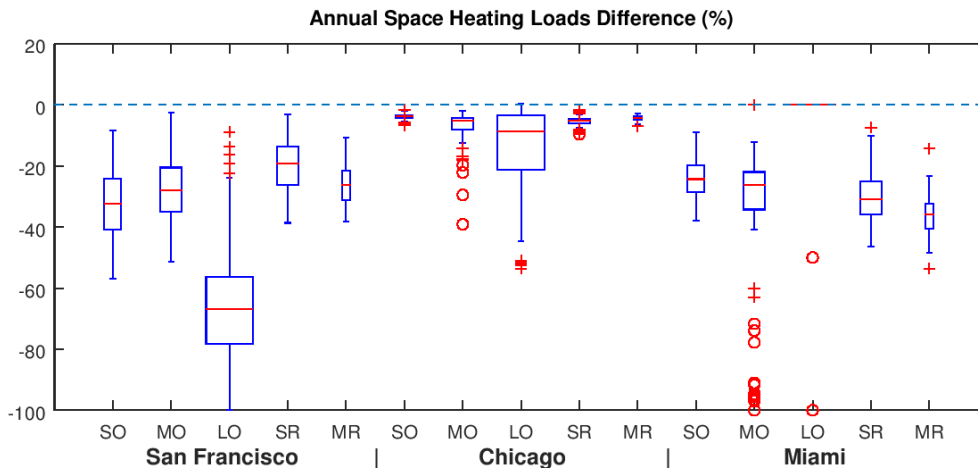
Figure 16. Differences in annual space heating loads between the cases using the OneZone and the AutoZone methods

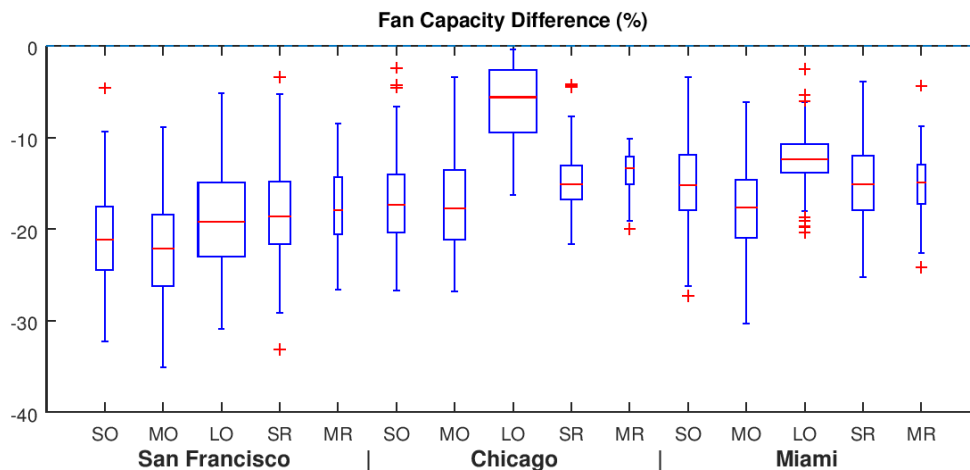## 3.2.2 Comparison of equipment capacities

The equipment capacity using the OneZone method is less than using the AutoZone method, except the cooling capacity for some buildings. Compared to the AutoZone method for all three climate zones, the OneZone method results in 0.1% to 22.8% less cooling capacity (Figure 17a), 2.4% to 20.6% less heating capacity (Figure 17b), and 3.7% to 25.9% less fan capacity (Figure 17c). Lower space heating and cooling loads using the OneZone method leads to lower equipment capacity.

(a) Cooling capacity

Heating Capacity Difference (%)
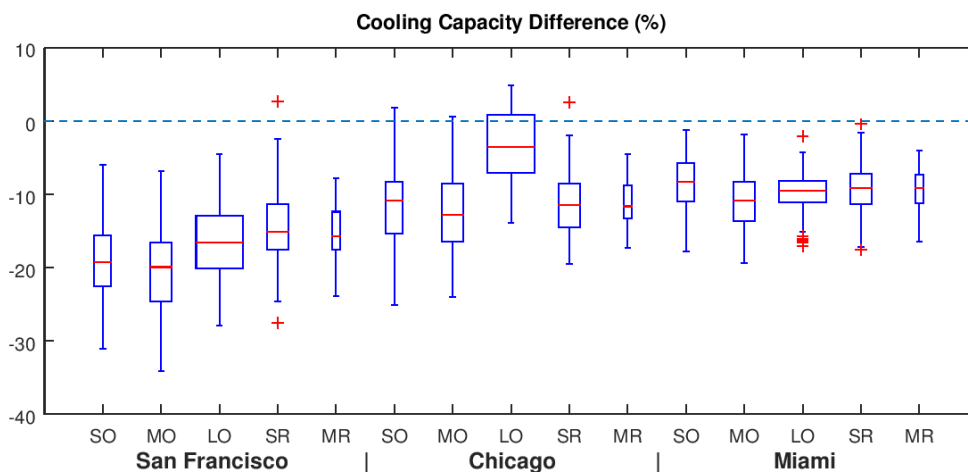
(b) Heating capacity
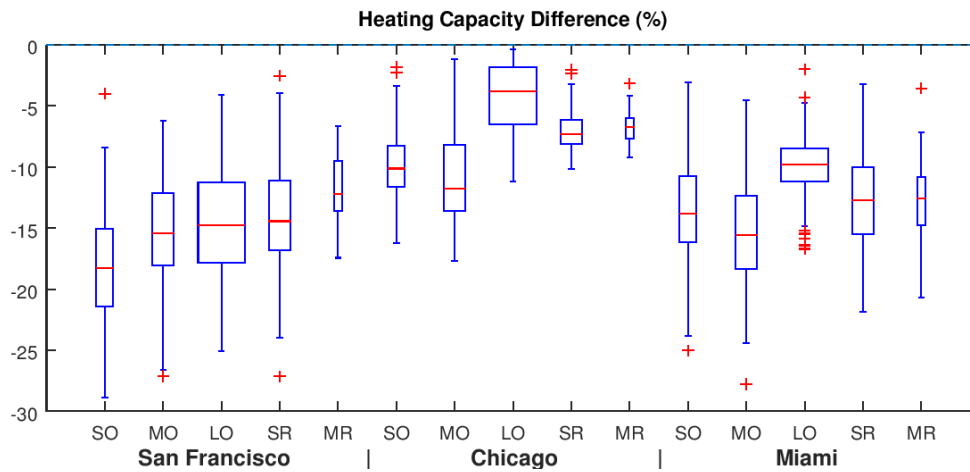
Fan Capacity Difference (%)

(c) Fan capacity

Figure 17. Differences in the autosized equipment capacities between the OneZone and the Autozone methods

3.2.3 Comparison of total energy use

The space heating and cooling loads need to be removed by the HVAC systems to maintain

zone thermostat settings for occupant comfort requirements. The annual source energy is

1.2% to 6.5% less for the Chicago climate and 1.4% to 8.4% less for the Miami climate.

However, results are more complex for San Francisco due to its mild climate. Although the

OneZone method results in lower space heating and cooling loads for all building types

(Figure 18), it does not result in less source energy use for all building types due to the use of different HVAC system types. Detailed explanations are provided in the next section.
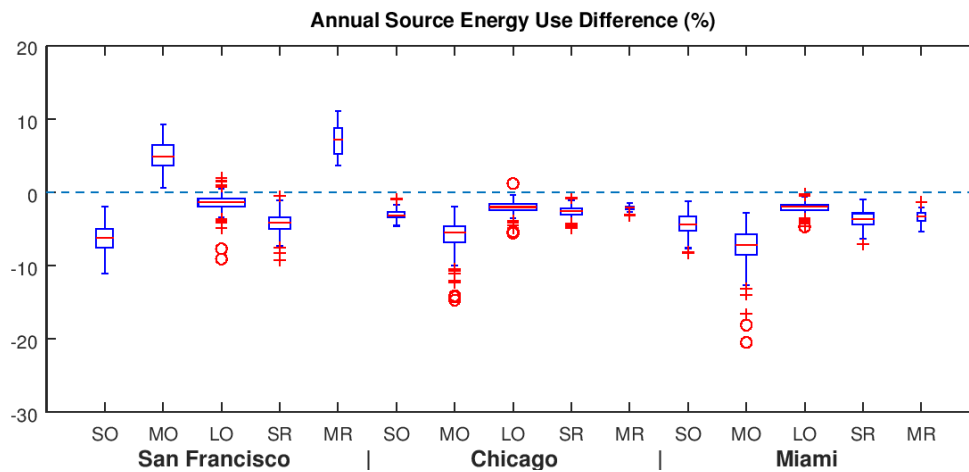
Figure 18. Differences in the annual source energy use by building type

3.2.4 Explanation of source energy use results for the San Francisco climate

For the San Francisco climate, small office and small retail use packaged, single-zone rooftop air conditioning systems, one system for each zone. Therefore, for the small office and small retail, the OneZone method results in 3.4% to 9.2% and 1.7% to 6.6% less source energy use compared to the AutoZone method, respectively. The large office uses a central plant to provide chilled and hot water for air handling units on each floor. For the large offices, the OneZone method typically results in less source energy than the AutoZone method with a median of 1.4%. The medium office and medium retail use packaged variable air volume (VAV) systems. For those two building types, the OneZone method results in 2.4% to 9.2% more source energy use compared to the AutoZone method. One medium office was selected to further investigate the unexpected trend of source energy use.

Figure 19 shows the surrounding environment and the autozoning results of the selected

medium office building. The building footprint is split into seven perimeter zones and one core zone. Among the seven perimeter zones, two zones do not have exterior walls due to shared walls with surrounding buildings. The rest of the five perimeter zones with exterior walls and windows are referred to the exterior zones in the following discussion. The building has five floors, and the third floor, one day during summer (June 24), is selected for detailed analysis.
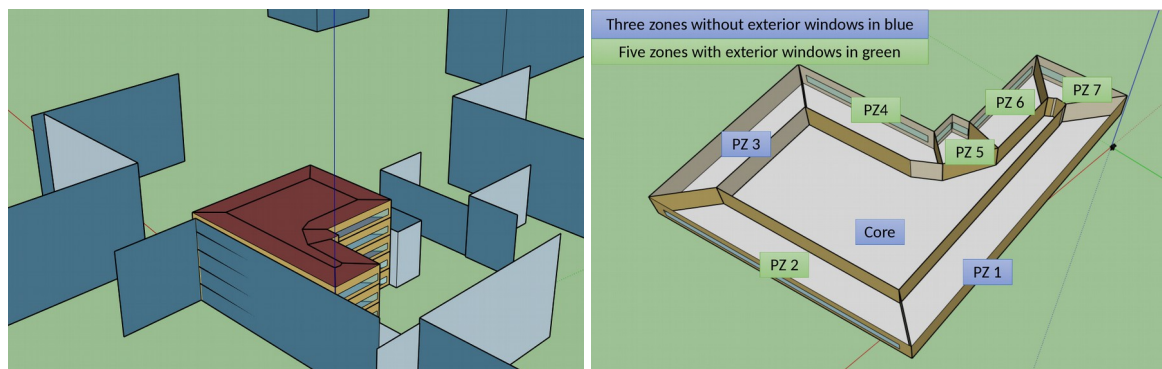
(a) with surrounding shading surfaces   (b) autozoning results with shared walls

Figure 19. Geometry of the medium office building

The outdoor air temperature varies from 11.6°C to 19.2°C on June 24, Wednesday. The thermostat setpoints are 21.11°C for heating and 23.89°C for cooling from 6:00 to 24:00 for weekdays. Figure 20 shows the zone air temperature on June 24 for the eight zones using the AutoZone method and the single zone using the OneZone method of the third floor. For the OneZone method, the zone air temperature slightly drops from the cooling setpoint (23.89°C) to 23.0°C before 6 AM (Figure 20). However, for the AutoZone method, the zone air temperature of the exterior zones drops much faster during the night, and it is below the heating setpoint for some zones that trigger heating during the early morning. The trend is similar throughout the whole year due to the mild climate of San Francisco. During the

31

winter, air temperature of the single zone drops to 21.7°C for the OneZone method, while the zone air temperature for the exterior zones all drop below the heating setpoint, the lowest at 17.6°C.
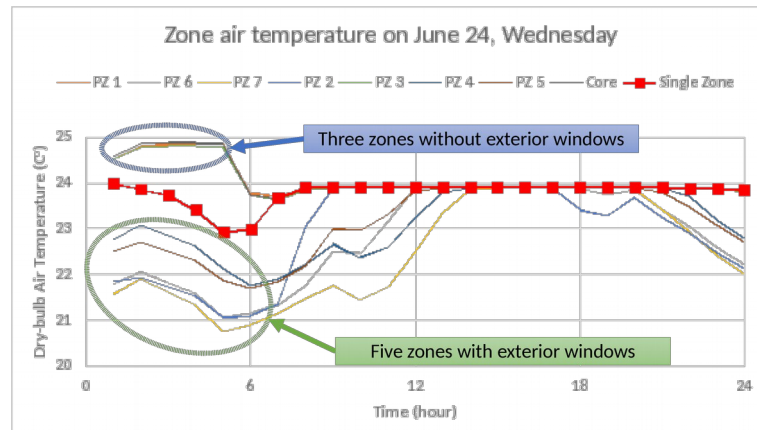

Figure 20. Zone air temperature on June 24 for zones on the third floor

The total space heating and cooling loads are very close between the two zoning methods (Figure 21). For the OneZone method, the fan runs at full speed from 9:00 to 19:00. However, for the AutoZone method, the exterior zones do not require HVAC service for several hours during the morning and late afternoon. The OneZone method, therefore, consumes more fan energy compared to the AutoZone method (Figure 22). For the central multi-zone VAV systems, the return air from different zones is mixed before reaching the air handling unit. Therefore, the air from the perimeter zones provides free cooling for the core zones, while the air from the core zones provide free heating for the perimeter zones. For example, the space heating loads shown in Figure 21(b), can be removed by the mixed air without consuming heating energy. Compared to the single zone system, the multi-zone VAV system uses less energy when zones have mixed heating and cooling demands. Therefore, the AutoZone method consumes less energy for some buildings due to the lower fan energy consumption and the benefit of mixed air to cancel out some cooling and heating loads.
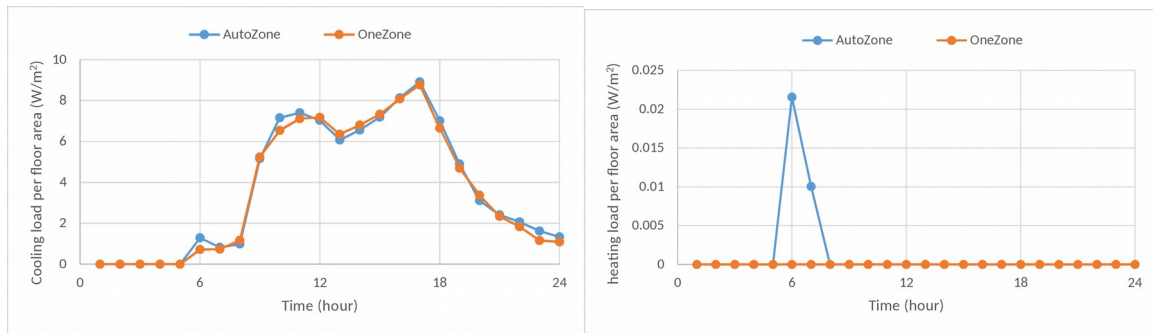
(a) Space cooling loads　　　　　　　　(b) Space heating loads

Figure 21. Third-floor space cooling and heating loads for the two zoning methods
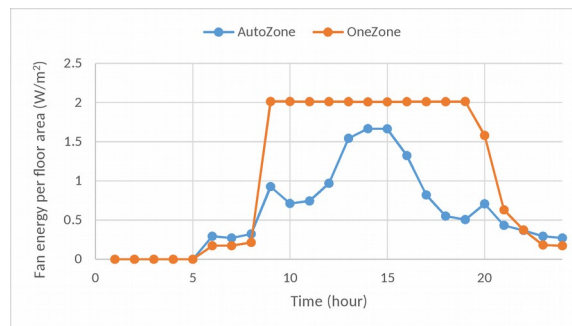

Figure 22. Third-floor fan electricity use per floor area for the two zoning methods

3.2.5 Comparison of simulation time

The simulation time of one model includes creating the EnergyPlus input file, running the EnergyPlus model, and extracting and saving the simulation results. It also includes the autozoning time for the AutoZone method. On average, running a model takes about 5.1 minutes using the OneZone method and 11.7 minutes using the AutoZone method. Using the OneZone method can save about half of the simulation time.

Table 6. Differences in simulation time using two zoning methods

Climate zone	Simulation time per building (minutes)		Simulation speed up factor
	OneZone Method	**AutoZone Method**	
San Francisco	5.4	12.8	2.4
Chicago	5.0	11.8	2.4
Miami	4.8	10.6	2.2

3.3 Prototype method vs. AutoZone method

The detailed models without using the floor multiplier are used for the comparison. All the

940 buildings are included in this analysis. Compared to the AutoZone method, the

differences in the annual source energy use are -12.1% (5th percentile) to 19.0% (95th

percentile) with a median of -2.1% for the Prototype method (Figure 23). Large ranges of

differences are also found for space cooling and heating loads (Figure 24), as well as

equipment capacities (Figure 25).
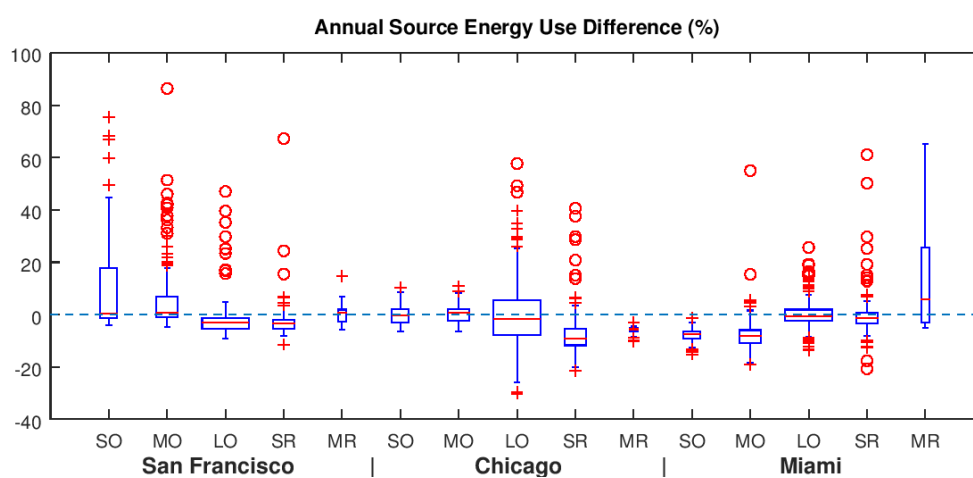
Figure 23. Differences in annual source energy use by building type
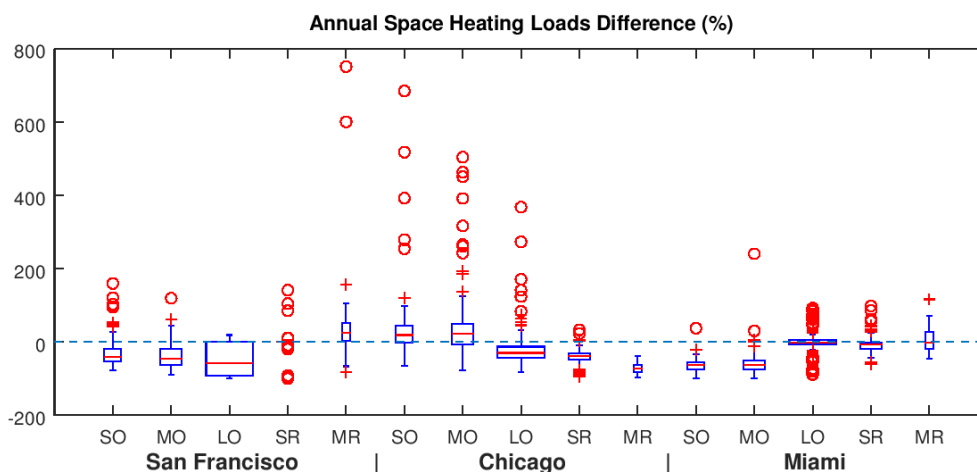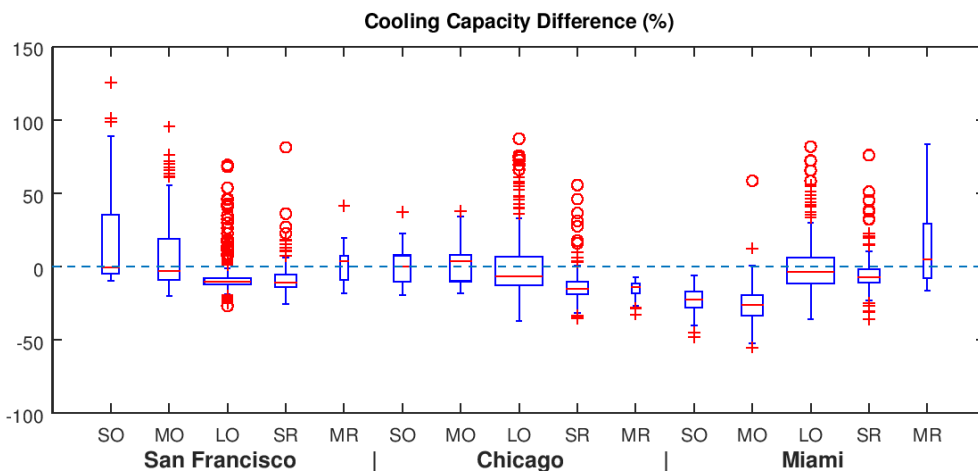

(a) Space heating loads
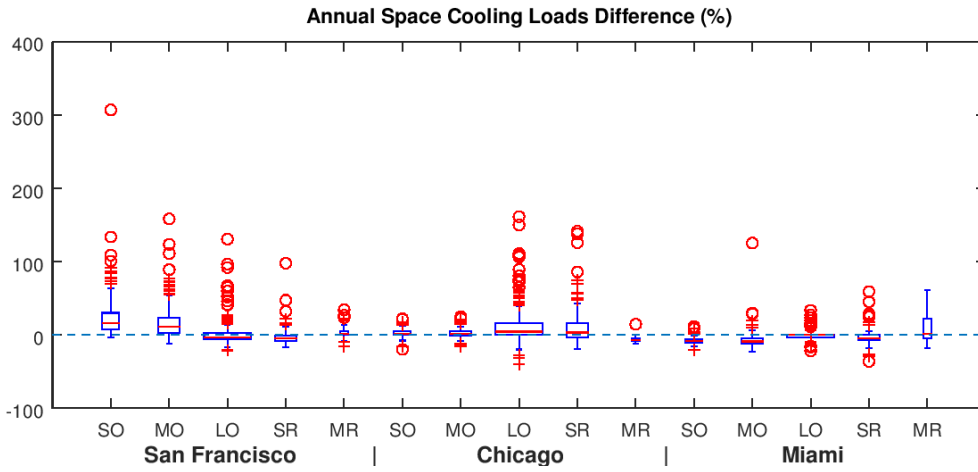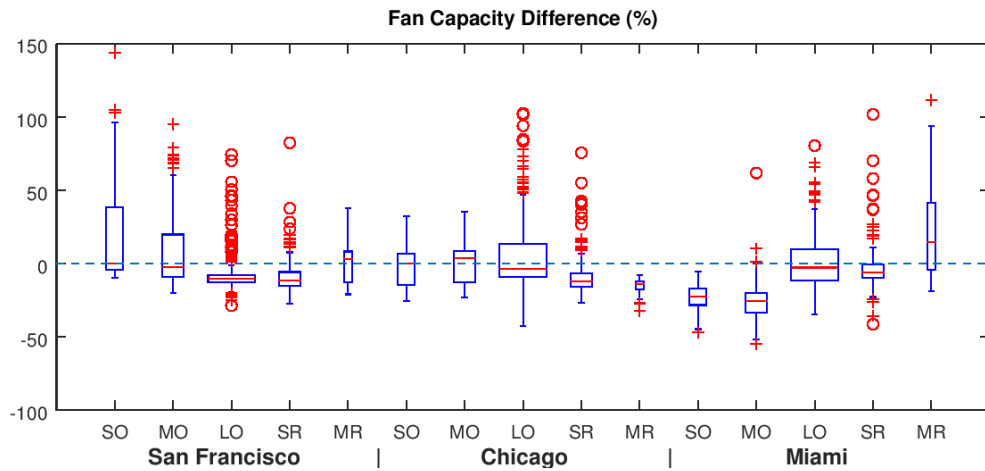
(b) Space cooling loads

Figure 24. Differences in space cooling and heating loads
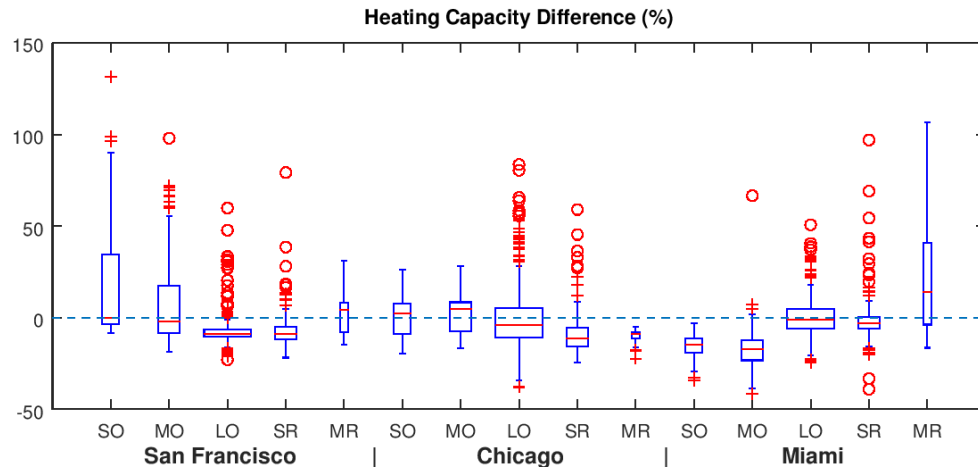
(a) Heating capacity

(b) Cooling capacity

(c) Fan capacity

Figure 25. Differences in autosized equipment capacity

On average, running an EnergyPlus model takes about 6.3 minutes using the Prototype zoning method and 8.8 minutes using the AutoZone method. Using the Prototype method takes about one-third less time.

Table 7. Differences in simulation time using the two zoning methods

Climate zone	Simulation time per building (minutes)		Simulation speed up factor
	Prototype Zoning Method	AutoZone Method	
San Francisco	6.6	9.6	1.5
Chicago	6.4	8.9	1.4
Miami	5.8	8.0	1.4

The Prototype method creates buildings with the same floor area as the target building. However, the exterior wall area, excluding the shared adiabatic walls, is very different due to the different shape and different shared walls (Figure 26). Significant outliners remain that have quite a different exterior wall area using the AutoZone method compared to the Prototype method. The algorithm to detect the shared walls for the Prototype method needs to be improved.
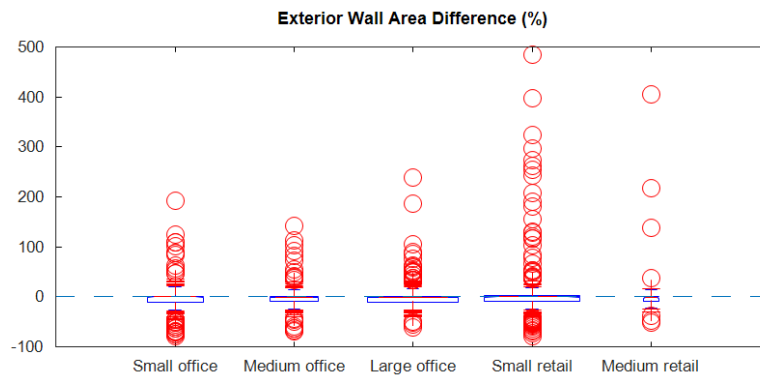
Figure 26. Differences in the exterior wall area by building type

3.4 Comparison of simulated results with measured data for the San Francisco climate

Of the 940 buildings, 359 have measured annual energy usage data from the San Francisco

Existing Commercial Building Energy Performance Ordinance, including the site energy use

intensity (EUI), source EUI, and greenhouse gas emissions. Figure 27 and Table 8 compare

the measured site EUIs with the simulated ones for San Francisco climate. The simulated

results can capture the total site energy use or overall/average site EUI (Table 8); however,

current UBEM cannot match the site EUI distributions with the measured data. The simulated

site EUIs range from 126 to 319 kWh/m^2, while the measured site EUIs range from 25 to

1400 kWh/m^2. The building systems and their efficiency values are determined based on the

building type and vintage, which represent the average conditions among peer groups. This

may lead to smaller ranges of site EUI distribution for simulated results compared with
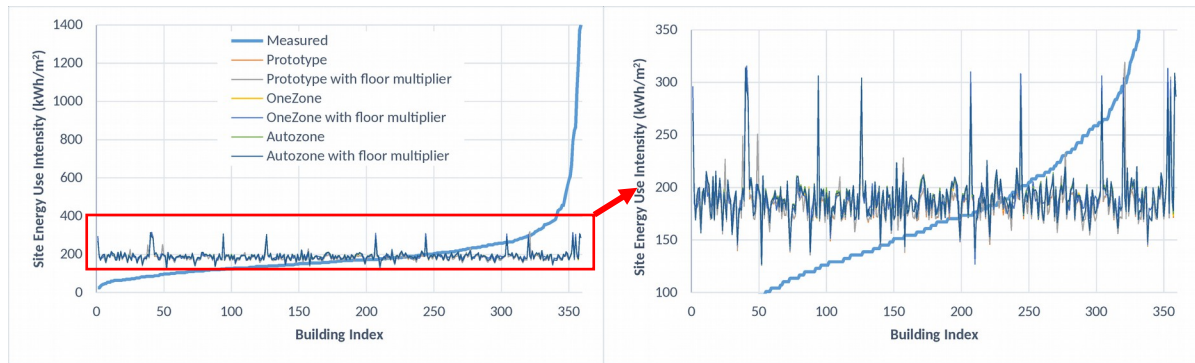
measured data.

Figure 27. Comparison of measured data and simulated results for the site EUI

Table 8. The average site EUI of the measured data and simulated results

Data source	Zoning method	Floor multiplier	Overall Site EUI (kWh/m²)	Total site energy use (GWh)	Percentage difference with measured data
Measured			186.0	942.6	
Simulated	Prototype	No	179.2	908.5	-3.6%
	Prototype	Yes	180.1	913.1	-3.1%
	OneZone	No	184.3	934.0	-0.9%
	OneZone	Yes	183.5	930.3	-1.3%
	AutoZone	No	186.1	943.2	0.1%
	AutoZone	Yes	186.0	943.1	0.0%

4 Discussion

The current AutoZone method does not split the buildings with a width less than 10 m. Different criteria should be used to create thermal zones for those small buildings. For example, simply splitting the building into two zones. The AutoZone method creates perimeter zones for shared walls, which may not be necessary (e.g., the PZ 1, PZ 3, and core zones in Figure 19 can be combined as a single zone). The AutoZone method can handle arbitrary building footprints, including concave shapes or curve surfaces; it cannot process polygons with holes. As detailed 3D geometry information for the buildings is not available, the AutoZone method only uses the 2D building footprint, number of stories, and building

height to create the 3D geometry for energy models. It cannot handle tilt walls or buildings with multiple floor layouts.

The simulated results can capture the total energy use of the buildings. However, without detailed calibration, they cannot match the site EUI distribution of the measured data. One reason is the measured annual site energy use of the buildings across multiple years and the weather file used for the simulation is the San Francisco TMY3 (which represents the historical average rather than any actual year's weather conditions). Another reason leading to the discrepancy of results is that the simulated results have not been calibrated using city's publicly available building energy data. It is important to calibrate the UBEM results with the measured data. There is an on-going effort to develop calibration methods for UBEM based on the city's public available annual energy use disclosure data.

5 Conclusions

This study evaluated the impacts of three geometry zoning methods on the simulated building performance in the urban context, including the space heating and cooling loads, the autosized equipment capacities, and the annual energy uses. It is the first study to evaluate the impacts of building zoning on the simulated building performance at the urban scale. The geometry modeling methods include zoning methods to create thermal zones and the usage of floor multiplier. Simulation results show that the energy use in tall buildings is almost the same between the cases with and without the use of the floor multiplier. This is based on the assumptions that middle floors have the same internal heat gain and HVAC systems, while the simulation time for using the floor multiplier is only 30% to 50% of those without using the floor multiplier.

Compared with the AutoZone method, the OneZone method results in 15.2% less fan capacity, 11.1% less cooling capacity, 11.0% less heating capacity, 16.9% less space heating load, and 7.5% less space cooling load; while the source energy use difference ranges from -7.6% to 5.1% with an average of -2.5%. The OneZone method results in lower space heating and cooling load compared to the AutoZone method, which leads to lower energy consumption in many cases. Using the AutoZone method, some exterior zones do not need HVAC service for some period, leading to lower fan energy use compared to the OneZone method. During the early morning, when the exterior zones may require heating and the core zones require cooling, the multi-zone VAV systems mix the return air and may reduce the cooling to the core zones and heating to the exterior zones.

Although the Prototype method uses the same floor area as the building footprint, the different shared wall conditions and the different shapes lead to large differences in exterior wall area and window area. Larger differences are found for the space cooling and heating loads, the equipment capacities, and the energy use. It is therefore not a good idea to model the building using the Prototype shape when the building footprint is available.

This study demonstrated that zoning methods have a significant impact on simulated energy use in buildings. The commonly used Prototype method for UBEM may not be accurate enough. Two recommendations are suggested for future UBEM studies:

- Use the AutoZone method to split the core and perimeter zones to better represent the dynamic performance of urban buildings.

- Use the floor multiplier for tall buildings to significantly save the simulation time while maintaining good accuracy compared to the detailed model for each floor as

long as the middle floors have similar internal loads, HVAC systems, and operating conditions.

The three zoning methods and the use of floor multiplier are implemented into the CityBES platform (citybes.lbl.gov) for public use, which enables researchers and practitioners to evaluate the impacts of building geometry modeling methods on the simulation results of urban building energy models in other cities and climate zones, and to choose the appropriate zoning method for their applications.

6 Acknowledgment

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