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Urban Building Energy Modeling with Parameterized Geometry and Detailed Thermal Zones for Complex Building Types

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Abstract: Urban building energy modeling (UBEM) has attracted wide attention to the requirement for global carbon emission reduction. This paper presents a UBEM tool, AutoBPS-Param, to generate building energy models (BEMs) with parameterized geometry and detailed thermal zones, especially for complex building types, considering the shading effect from surrounding buildings simultaneously. Three building number scales and four scenarios were analyzed in the hotel-related buildings in Changsha, China. For the prototype modeling of Scenario 1, eighteen prototype building energy models for six building types in three vintages were created, and their simulation results were aggregated based on their representative floor areas. For AutoBPS-Param of Scenario 4, the method created one EnergyPlus (Version: 9.3.0) model for each building. The geometry of the prototype model was scaled and modified based on the target building's length, width, and number of stories. The surrounding buildings were also added to the AutoBPS-Param simulation to better capture the urban dynamic impact. The results showed that the annual electricity and natural gas energy use intensity (EUI) of the pre-2005 HotelOffice prototype model was 172.25 and 140.45 kWh/m^2. In contrast, with the AutoBPS-Param method, the annual electricity EUIs of 71 HotelOffice buildings constructed before 2005 ranged from 159.51 to 213.58 kWh/m^2 with an average of 173.14 kWh/m^2, and the annual gas EUIs ranged from 68.02 to 229.12 kWh/m^2 with an average of 108.89 kWh/m^2. The proposed method can better capture the diversity of urban building energy consumption.

Keywords: energy simulation; prototype hotel building; AutoBPS-Param; EnergyPlus; urban building energy modeling

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1. Introduction

Buildings play an important role in people's lives and work, and the construction sector accounts for 28% of total global CO_2 emissions [1]. The building industry is an energy consumption giant [2]. Buildings in the city are always the main component considered when implementing carbon emission mitigation policies and have an enormous potential to reduce carbon emissions. Energy with low carbon emissions is critical for decarbonizing the urban building sector [3]. Seven out of ten people will likely live in urban areas by 2050, and cities account for more than 70 percent of global greenhouse gas emissions. And rapid urbanization is the source of increasing embodied carbon dioxide in the building sector [4]. Therefore, it is essential to multidimensionally and accurately evaluate the carbon emissions and energy consumption on a city scale.

Against the background of consuming a large volume of building energy, it is necessary to estimate the energy demand of buildings on a city scale. One popular method is urban building energy modeling (UBEM). UBEM, as defined by Reinhart and Cerezo Davila [5], is a building energy modeling method that covers a spatial scale from a city block to a district to an entire city. UBEM has top-down or bottom-up approaches [6]. UBEM evolved from building energy modeling (BEM), which has a long development history and consumes significant computing resources when applied to many buildings [7]. There are many studies on UBEM and on its use to conduct energy analysis. The applications of UBEM have four categories: urban planning and new neighborhood design, stock-level carbon reduction strategies, building-level recommendations, and building-to-grid integration [8]. Hong et al. [9] answered ten questions about UBEM, in which their analysis included the description of UBEM, a review of available UBEM tools, available urban datasets and data representation standards, sources of local weather data for use in UBEM, methods to couple multi-physics urban system models, calibration methods of UBEM, example applications of UBEM, and the main challenges of UBEM. In UBEM research, selecting the appropriate building stock aggregation method is crucial. Currently, there are two mainstream building stock aggregation approaches: prototype aggregation and building-by-building.

The prototype approach assesses building performance by analyzing a subset of prototype buildings [10]. The method employs reference building clusters according to specific features representing a series of buildings with similar properties, such as building type and vintage [11]. The prototype aggregation method calculates a building stock energy by multiplying the energy use intensity (EUI) of each building and their corresponding area at first, then summing up all types of prototype models. Many studies have evaluated energy consumption and EUI based on the prototype approach. Yang et al. [12] assessed the energy of 29,030 residential buildings in Leiden utilizing the Typology Approach for Building Stock Energy Assessment (TABULA) database via a prototype approach. An et al. [13] developed 151 prototype building models covering four residential buildings and eleven commercial building types in China. Carnieletto et al. [14] investigated the Italian building stock and developed 46 building prototypes for residential and office buildings. Buckley et al. [15] applied a prototype approach in UBEM to run the urban modeling interface (UMI) to test the efficacy of energy retrofitting policies for 9000 residential buildings in a European city. Deng et al. [16] selected twenty-two building types and three vintages as archetype buildings to represent 59,332 buildings, covering 87.4% of the city's total floor area. Li et al. [17] developed a modeling approach to estimate the energy consumption and carbon emissions of residential stock in the Chongqing municipality. The total energy saving of residential stock was calculated by multiplying stock floor area by EUI. As a part of the input for UBEM, prototype buildings are essential. They can conduct various analyses and applications such as building energy saving potential research, building design, building energy market evaluation, and building power policy-making [18]. One set of famous prototype buildings is the U.S. commercial prototype building models led by the Department of Energy (DOE). There are 16 commercial building types in 19 climate locations, and users can download the prototype buildings from the public website [19].

The building-by-building approach analyzes all buildings in the global stock environment [12,20]. This method models all the buildings in the stock while considering the mutual shading influence individually. It is essential to consider the bidirectional impacts between buildings and the urban environment [21]. Deng et al. [22] developed AutoBPS and simulated six types of buildings in Changsha city using the building-by-building method, and then conducted three energy saving measures. Johari et al. [23] observed a downward trend in the MAPE from building to district and city levels with single-family and multi-family buildings in different vintages. They considered the shading in over 12,150 buildings in the case study city of Borlänge when the building was in a dense urban area. Wen et al. [24] developed a SketchUp plug-in named MOOSAS-FastSolar to assess the shading effect from surrounding buildings and explore how the five parameters affect the building's energy, including orientation, distance, offset angle, length, and height. Garcia-Perez et al. [25] used the building-by-building and life cycle assessment methods to study and measure the renovation impact of low-energy efficient urban buildings. Saner et al. [26] proposed a multi-objective optimization model for urban building energy based on life cycle assessment, and the results showed that the model could be effectively used to calculate the greenhouse gas emissions and particulate matter emissions of urban buildings. Garreau et al. [27] developed a UBEM based on District MOdeller and SIMulator to optimize the energy consumption of urban structures. Prataviera et al. [28] have developed an open-source urban building energy simulation tool called EUReCA, which predicts the energy demand of metropolitan areas with a bottom-up approach and low computing resources. The results show that the prediction accuracy of building energy is good. Ali et al. [29] analyzed the advantages, disadvantages, opportunities, tools and methods of the UBEM method in predicting the energy consumption of urban buildings.

The existing UBEM research has many gaps. Firstly, the prototype building method ignored the energy influence of buildings with different geometries and the shading impacts from surrounding buildings. These gaps are due to incomplete data and the characteristics of the method. As for the incomplete data, obtaining the specific proportion of the distribution of thermal zoning inside the building is generally impossible. As for the characteristics of the prototype building method, although the building outline and surrounding building's shading data can be obtained, the prototype building uses a typical building to represent the entire building stock. Thus, the specific geometry of each building and the surrounding building's shading cannot be considered. In the potential application of this method, some things could be improved. For example, because the method ignores the shading from surrounding buildings, it cannot provide the correct guidance for installing lighting equipment. Secondly, the building-by-building method uses simple thermal zoning without detailed function types. This method usually sets a thermal zoning per floor and cannot model specific functional partitions. The building-by-building approach is not helpful if specific functional zones are renovated, such as laundry rooms and restaurants in hotel buildings.

To compensate for the gaps in previous studies, this paper presented a new UBEM tool, AutoBPS-Param, which considered the customized geometry with detailed thermal zonings and the shading impacts from surrounding buildings.

2. Methods

Figure 1 shows the research workflow of the paper. Firstly, the model establishment and energy simulation method via AutoBPS-Param was introduced. The method establishes the model according to the actual building information, including the length, width, story number, orientation, and the location and height of the surrounding buildings. The energy simulation introduced the non-geometric information required for simulation and the conversion process of the geometric model used for AutoBPS-Param. Secondly, the information collection and data processing for the case study city were described, including the geometry of the building, the climate information, and the built vintage information. The geometry information collected is in the Geographical JavaScript Object Notation (GeoJSON) format. The properties' data are converted to Comma-Separated Values (CSV) and JavaScript Object Notation (JSON) for AutoBPS-Param. Finally, the results are analyzed for the case study city. The results are analyzed with three scales and four scenarios. The case-building scale analyzes Scenarios 1–4. The HotelOffice building-type scale explores Scenarios 1, 3, and 4. All building scales compare energy in Scenarios 1 and 4.

2.1. Model Establishment via AutoBPS-Param

The Automated Building Performance Simulation (AutoBPS) application is a tool developed by Hunan University for various simulation functions. It is an urban building energy modeling tool developed in Ruby programming language to calculate urban building energy use, analyze energy retrofit scenarios, and evaluate rooftop photovoltaic (PV) potential, relying on OpenStudio and EnergyPlus [22]. Four function models exist in AutoBPS: AutoBPS-GEO, AutoBPS-OSS, AutoBPS-RM, and AutoBPS-PV. Wei et al. [30] showed AutoBPS-Param to present a rapid model for an existing shopping mall. Though Wei et al. [30] have shown the rapid establishment progress for a shopping mall using AutoBPS-Param, this paper further develops the AutoBPS-Param for complex different building types with pre-defined parameters.

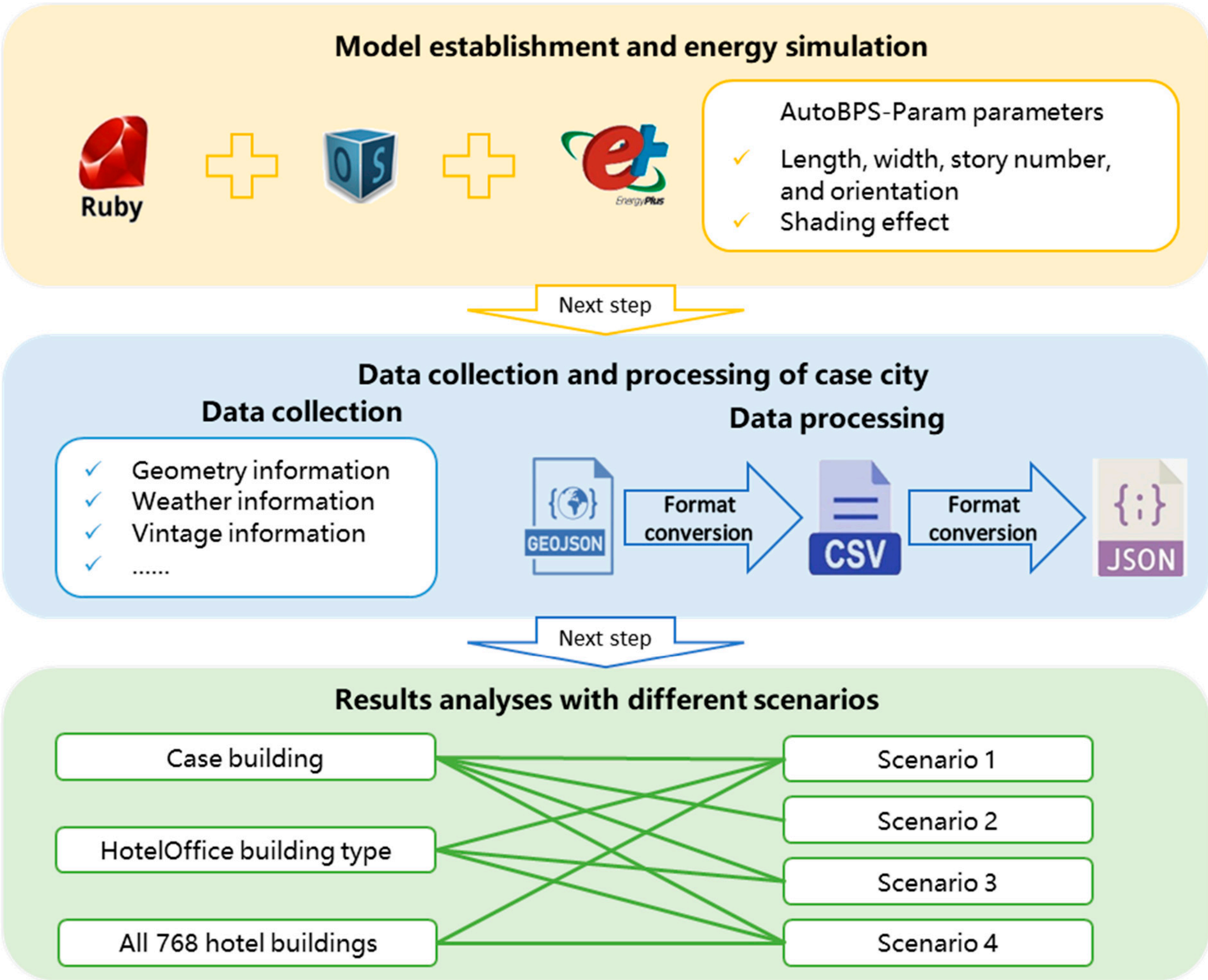


Figure 1. Workflow of the research.

Figure 2 shows three UBEM methods. Prototype aggregation simulates the energy of the whole city in two steps. Firstly, each prototype building's energy results are obtained by multiplying the representative floor area of each prototype building by the corresponding EUI. Secondly, the total energy of the whole city is summed up as various total prototype building energy. With the prototype method, each building type has a presentative EUI according to the building classification. Thus, the process does not consider the geometry discrepancy of each building. The simple thermal zone method calculates the energy consumption of each building with one-zone-per-building or one-zone-per-floor thermal zoning, including the shading impacts from the surrounding buildings. Martin et al. [31] compared the simplified and detailed EnergyPlus models in the urban context. The simple thermal zone method suits buildings with fewer functions and matches simple thermal zones such as office and residential ones. However, the method cannot represent the urban situation well for buildings with complex thermal zones, such as schools, shopping malls, and hotel-related buildings.

The AutoBPS-Param simulates the energy in the urban context with detailed thermal zones. For AutoBPS-Param modeling, the primary form of an actual building is a prototype without considering a shading building. Then, the prototype is parametrized with actual building geometric information based on the prototype building. Finally, the shading effect from surrounding buildings is considered. The geometry of each actual building is different. The total energy of all the buildings is calculated by summing up the energy consumption of each building with customized geometry information with the impact from surrounding buildings. The method considers the building's length, width, story height, number of stories, and orientation. In this paper, the closest ground distance between the target building and the surrounding building is less than three times the surrounding building's height.

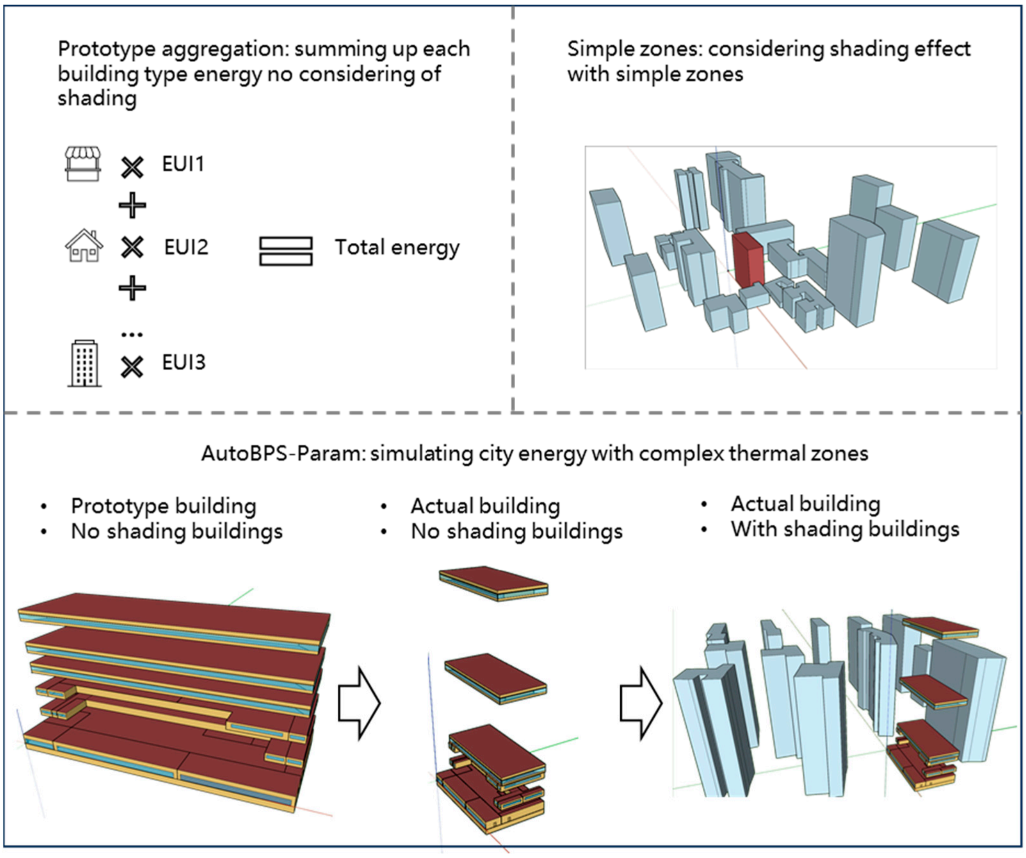


Figure 2. Comparison of different modeling methods.

2.2. Energy Simulation Description

The energy simulation requires geometry and non-geometry information inputs. The non-geometry information includes the built vintage and the climate zone. There are three vintages of hotel buildings: pre-2005, 2006–2014, and post-2015. The split of the three vintages refers to two national standards: Design Standard for Energy Efficiency of Public Buildings GB50189-2005 [32] and GB50189-2015 [33]. Buildings built in different years follow national standards and have specific envelope thermal properties and equipment efficiencies. Public buildings constructed before 2005 have no specific codes to follow; buildings built between 2006 and 2014 follow GB50189-2005; and buildings constructed after 2015 have to comply with the standard GB50189-2015 to achieve the goal of energy saving. Energy modeling also requires climate information inputs. The climate condition of a building can refer to the typical meteorological year (TMY) [34] data embedded in the AutoBPS. Chinese Standard Weather Data (CSWD) are suitable for estimating energy simulation in Chinese cities. For the case study, Changsha, China, is classified as a hot summer and cold winter climate zone according to the national standard code for Thermal Design of Civil Building GB 50176-2016 [35].

The geometry model is generated via the AutoBPS-Param tool using the parameterized method. Figure 3 shows the geometry conversion of an actual building to the AutoBPS-Param input model. The conversion process can be divided into four steps. In the first step, since the rectangular border around the actual building is different with different angles, the building needs to be rotated. The building is rotated from A_0 to A_1, and finally A_2, to obtain the final border rectangle with minimal border area. The second step is determining the actual building's orientation and border rectangle information after rotation. The orientation angle is determined by the angle change in the actual building from the original

A_0 orientation to final orientation A_2. The length and width of the final border rectangle are $L1$ and $W1$. The footprint to border ratio (FBR) is introduced to keep the actual building's geometry ratio. The FBR is calculated as in Equation (1):

$$FBR = \frac{\text{Footprint}}{L1 \times W1} \tag{1}$$

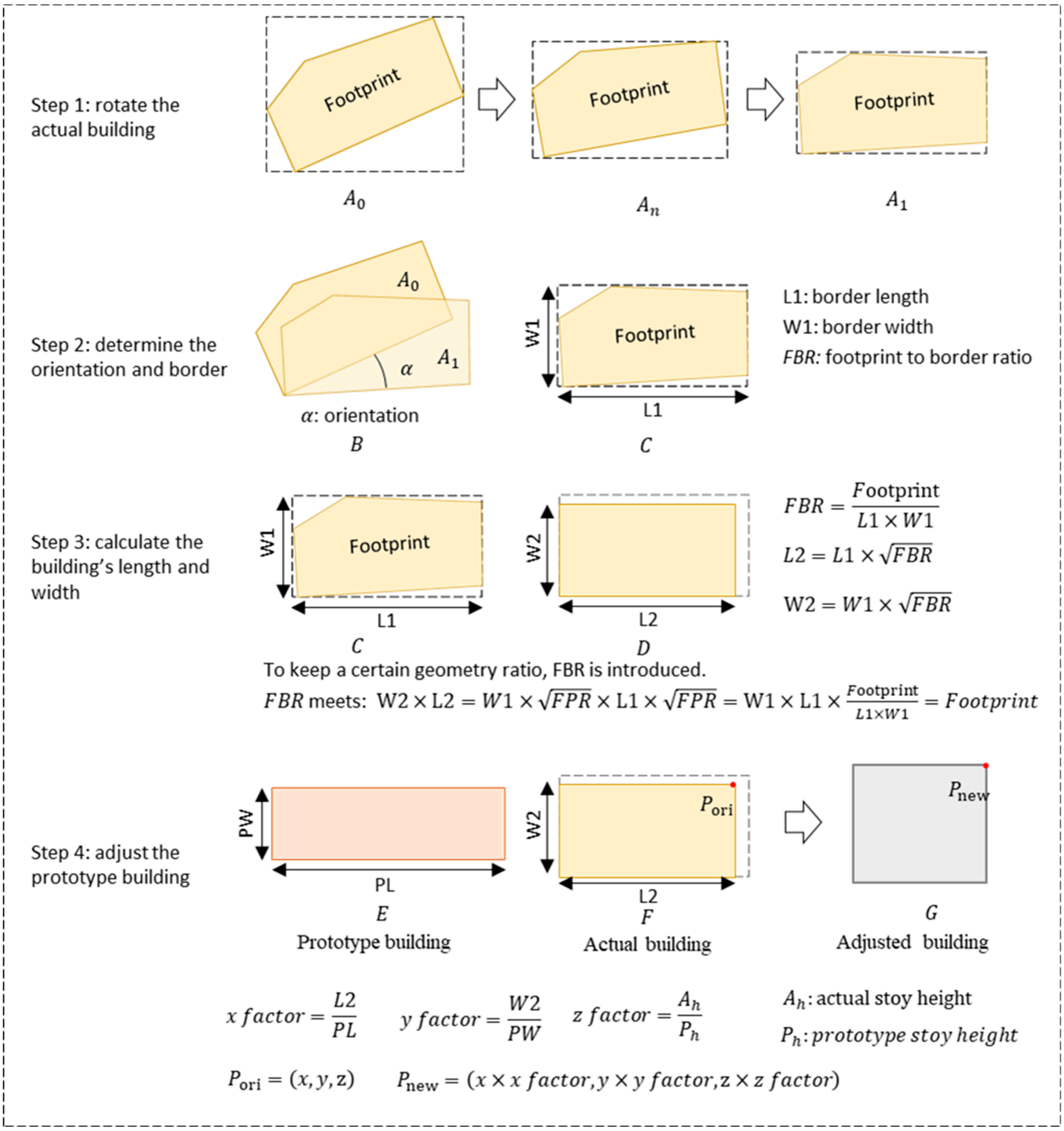


Figure 3. The geometry conversion of an actual building.

The third step is calculating the building's length and width. The equivalent length and width of the actual building are $L2$ and $W2$. $L2$ and $W2$ are calculated as in Equations (2) and (3):

$$L2 = L1 \times \sqrt{FBR} \tag{2}$$

$$W2 = W1 \times \sqrt{FBR} \tag{3}$$

The fourth step is adjusting the prototype building based on the actual building's equivalent length and width. The x factor, y factor, and z factor are calculated as in Equations (4)–(6):

$$x \text{ factor} = \frac{L2}{PL} \tag{4}$$

$$y \text{ factor} = \frac{W2}{PW} \tag{5}$$

$$z \text{ factor} = \frac{A_h}{P_h} \tag{6}$$

where $L2$, $W2$, PL, PW, A_h, and P_h are the actual building's equivalent length, actual building's equivalent width, prototype building's length, prototype building's width, actual building's story height, and prototype building's story height.

Finally, the original geometry coordinates of a point are assumed to be $P_{ori}(x, y, z)$ in graph F, and the coordinate of the adjusted actual building in graph G is $P_{new}(x \times x \text{ factor}, y \times y \text{ factor}, z \times z \text{ factor})$.

Table 1 shows the pattern of story number settings of the six hotel building types. The minimal story numbers for each building type are listed. All six hotel building types have the first, standard, and top stories. Buildings applied to the SmallHotel and LargeHotel prototypes template are all hotel buildings. Then, the buildings used in the other four prototype templates are of mixed use. The SmallHotelStore buildings have retail and restaurants on the first story. The HotelOffice, HotelMall, and HotelOfficeMall buildings contain the office story, shopping mall story, and the office and shopping mall story, respectively. The floor function distribution of the four mixed-used buildings is assumed to be the same as that of the top story. The story multiplier, the standard story number, is calculated as the total story number minus unique floors such as the basement story, the first story, the top story, and the bottom other function stories.

Table 1. The story multiplier of different hotel types.

	Prototype Building		Actual Building	
	Story Number; Composition	**Story Number**	**Story Number; Composition**	**Minimal Story Number**
SmallHotel	First story + standard story * 2 + top story; [1 + 2 + 1]	4	First story + standard story * ($n-2$) + top story; [1 + ($n-2$) + 1]	3
LargeHotel	Basement + first story + standard story * 7 + top story; [1 + 1 + 7 + 1]	10	Basement + first story + standard story * ($n-3$) + top story; [1 + 1 + ($n-3$) + 1]	4
SmallHotelStore	First story + standard story * 4 + top story; [1 + 4 + 1]	6	First story + standard story * ($n-2$) + top story; [1 + ($n-2$) + 1]	3
HotelMall	Five shopping mall stories + first hotel story + standard hotel story * 4 + top hotel story; [5 + 1 + 4 + 1]	11	Five shopping mall + first hotel story + standard hotel story * ($n-7$) + top story [5 + 1 + ($n-7$) + 1];	8
HotelOffice	Six hotel stories + first office story + standard office story * 4 + top office story; [6 + 1 + 4 + 1]	12	Six hotel stories + first office story + standard office stories * ($n-8$) + top office story; [6 + 1 + ($n-8$) + 1]	9
HotelOfficeMall	Five shopping mall stories + six hotel stories + first office story + standard office story * 4 + top office story; [5 + 6 + 1 + 4 + 1]	17	Five shopping mall stories + six hotel stories + first office story + standard office story * ($n-13$) + top office story; [5 + 6 + 1 + ($n-13$) + 1]	14

* n denotes the number of total stories; the building stories' layouts are in descending order.

Unlike the total of the archetype aggregation method, which calculates the energy by multiplying the total area by the EUI of the type, the parameterized method calculates the energy usage by summing the energy simulation results of each building.

2.3. Case City Data Collection and Processing

Changsha, China, was chosen as the case study city. Deng et al. [16] identified six types of hotel-related buildings in three built vintages in Changsha: SmallHotel, LargeHotel, SmallHotelStore, HotelMall, HotelOffice, and HotelOfficeMall. Figure 4 shows the geometry of the six types of hotel-related buildings. Although the geometries were all rectangular, the zone multipliers were used to simplify similar zones into thermal zones to speed up the simulation process. The prototype buildings' missing and blank stories have the same story thermal zone layout as the standard floor, which is not shown in Figure 4. The hotel vintage distribution of the six hotel types shows that most were built before 2005, followed by 2006–2014, and finally, post-2015.

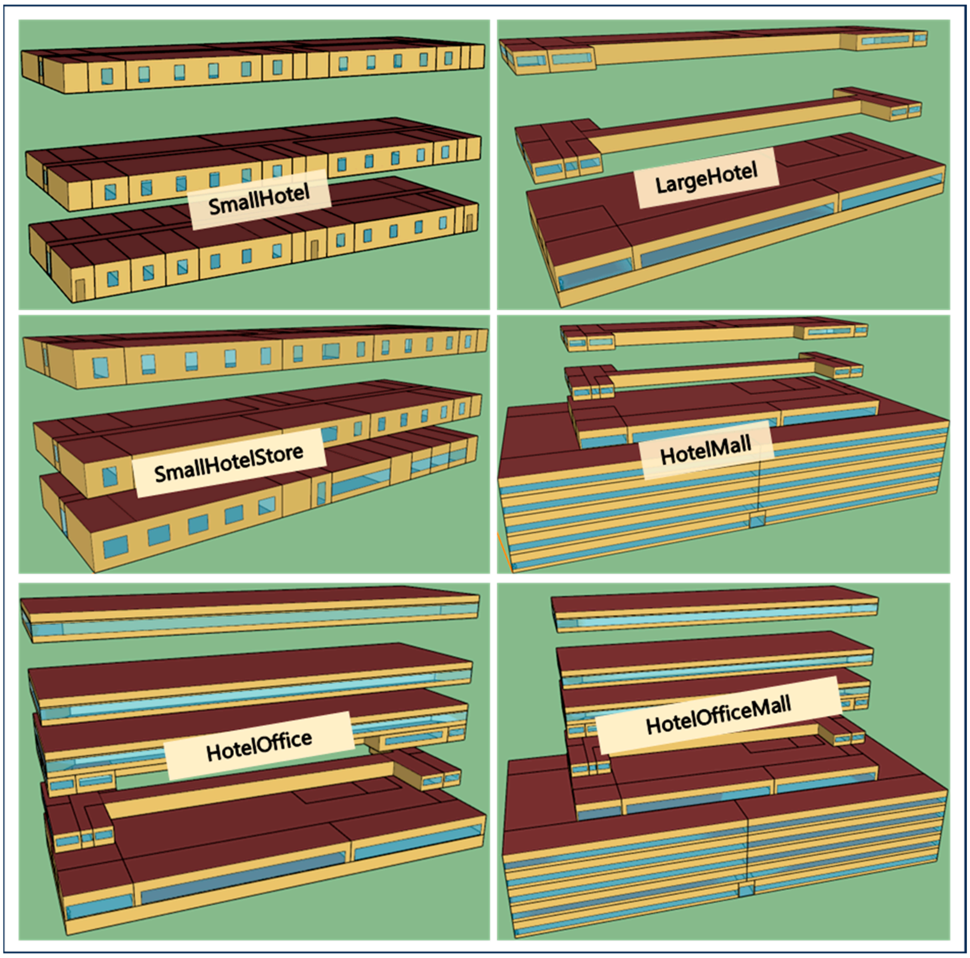


Figure 4. Geometry models of six hotel types.

As shown in Table 1, the AutoBPS-Param has a minimal story number requirement for each building type. The raw data contained buildings that may not meet the requirements. In addition to the story number requirement, the minimum length requirements were 29 m for the SmallHotel and SmallHotelStore and 35 m for the other four types. The minimal width was set as 10 m. After filtering, 786 out of 1319 buildings were selected, as listed in Table 2 for the UBEM study.

Table 3 shows the prototype geometry information, including the length, width, and height of the standard story and the number of stories.

Figure 5 shows the data processing workflow from the acquired data format to the input JSON file format for AutoBPS-Param. The information obtained is in the GeoJSON format and covers the Changsha 68,583 building geometry information. GeoJSON [36] is a geospatial data interchange format based on JSON. It defines several types of JSON objects and how they are combined to represent data about geographic features, properties, and spatial extents. The geometry type in the Changsha GeoJSON file is MultiPolygon and contains geometry objects and additional properties. Each building is assigned an ID stored in properties. The other properties in the GeoJSON file include the building type, the vintage, the footprint area to border ratio, and the orientation. The geometry in the GeoJSON file describes the geometry type and the MultiPolygon coordinates.

Table 2. Raw and filtered Changsha hotel buildings number.

	Raw Number/After Filtering			
	Pre-2005	**2006–2014**	**Post-2015**	**Total**
SmallHotel	426/300	178/109	71/32	675/441
LargeHotel	25/22	14/11	3/3	42/36
SmallHotelStore	164/118	46/33	5/3	215/154
HotelMall	35/7	16/7	4/2	55/16
HotelOffice	195/71	104/42	17/6	316/119
HotelOfficeMall	10/0	6/2	0/0	16/2
				1319/768

Table 3. Geometry information of six hotel-related models.

	Standard Story's Length (m)	**Standard Story's Width (m)**	**Standard Story's Height (m)**	**Number of Stories**
SmallHotel	53.86	18.29	2.74	4
LargeHotel	75.87	23.53	3.05	10
SmallHotelStore	53.86	18.29	2.74	6
HotelMall	75.87	23.53	3.05	11
HotelOffice	75.87	23.53	3.05	12
HotelOfficeMall	75.87	23.53	3.05	17

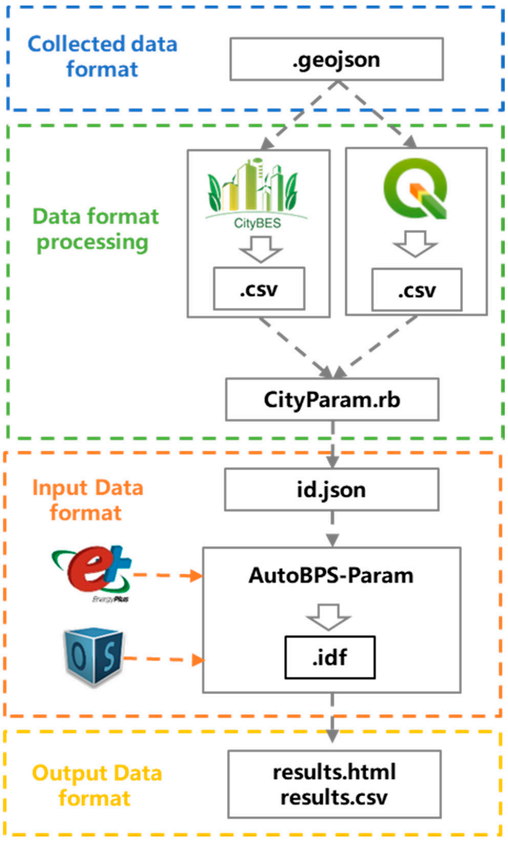


Figure 5. Data-processing workflow.

This paper processes the collected data in two ways: One, the GeoJSON file, including 68,583 building geometry information, is input into the City Buildings, Energy, and Sustainability (CityBES) tool, leading to the CSV file with the target building geometry and the surrounding shading building information. Specific geometry features include the center latitude, the center longitude, etc., of the target building, and the shading buildings' ID. Two, the GIS information, including the building type and built year stored in GeoJSON, is output by the conversion function in QGIS from GeoJSON to the CSV format. CityBES is a web-based platform developed by Lawrence Berkeley National Laboratory (LBNL) that is freely available to any U.S. city [37]. It can automatically generate UBEM based on a city's GIS dataset in GeoJSON or City Geography Markup Language (CityGML). The tool can process the GeoJSON data to output the CSV file that contains the GIS data for UBEM simulation. Then, the two CSV files containing information for a building with the same ID are processed with the Ruby script to obtain the AutoBPS-Param-required input JSON format.

When obtaining the input JSON file for each building with a unique ID, the AutoBPS-Param leverages the EnergyPlus and OpenStudio that embeds in the AutoBPS. OpenStudio [38] supports whole-building energy modeling using EnergyPlus. By inputting data and simulating the model, users can obtain energy consumption in HTML, CSV, etc.

2.4. The EnergyPlus Mathematic Model

EnergyPlus is an energy analysis and thermal load simulation program developed and maintained by DOE that engineers, architects, and researchers use to model energy consumption—for heating, cooling, ventilation, lighting and plug and process loads—and building water use [39]. The heating/cooling loads in the room are shown in Figure 6. The load considerations for thermal zones include heat transfer through envelopes, solar heat gains, load from lighting and equipment systems, occupants' heat load, fresh air heating/cooling load, and heating/cooling load due to door and window air infiltration.

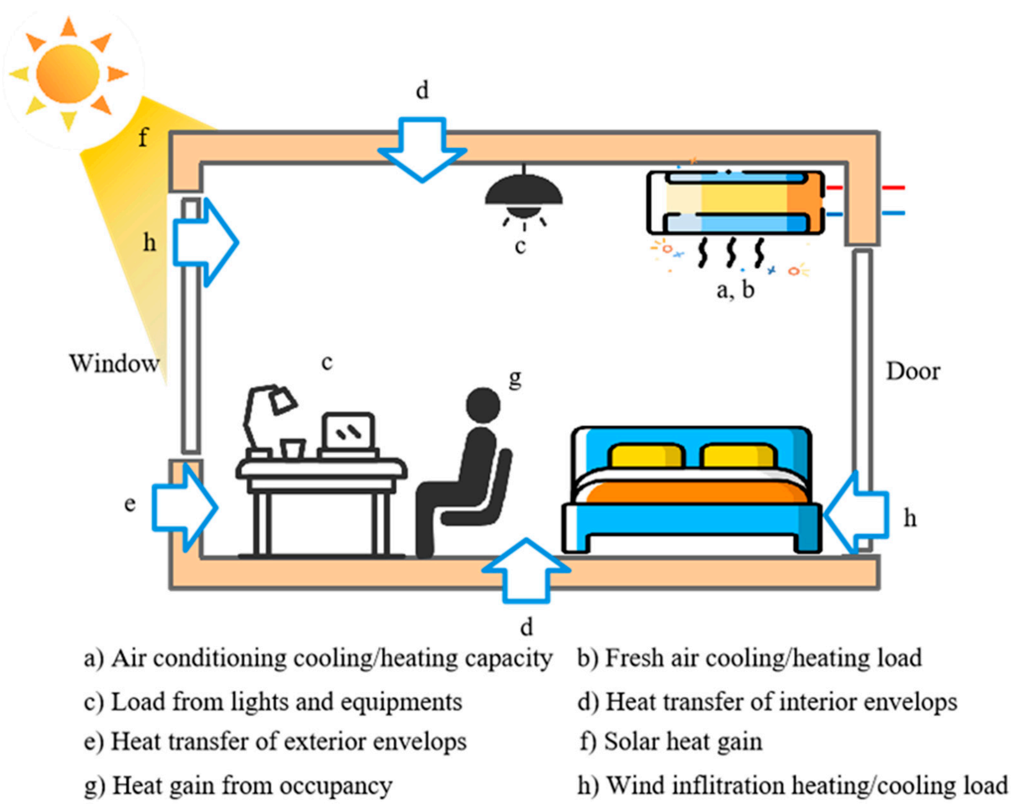


Figure 6. Composition of indoor air-conditioned loads.

Figure 7 illustrates the coupling calculation between thermal zones, air loop systems, and central plant systems. The time step for room load calculation can be adjusted, with a minimum value of 1 min. Taking summer conditions as an example, EnergyPlus calculates the cooling load of each thermal zone based on the temperature setpoints. Various HVAC systems are available to meet the load demand, and the fan coil unit system is used as an example below to explain the load coupling calculation. After calculating the thermal load, EnergyPlus checks whether the output capacity of the fan coil unit can meet the cooling load requirements while the chiller regulates the water flow rate to the fan coil unit. If the load exceeds the chiller's capacity, the room temperature will increase, prompting EnergyPlus to recalculate the room cooling load and adjust circulation. In cases where the chiller cannot supply the required chilled water, the chilled water outlet temperature will rise, and EnergyPlus will recalculate the water flow rate of the fan coil unit.

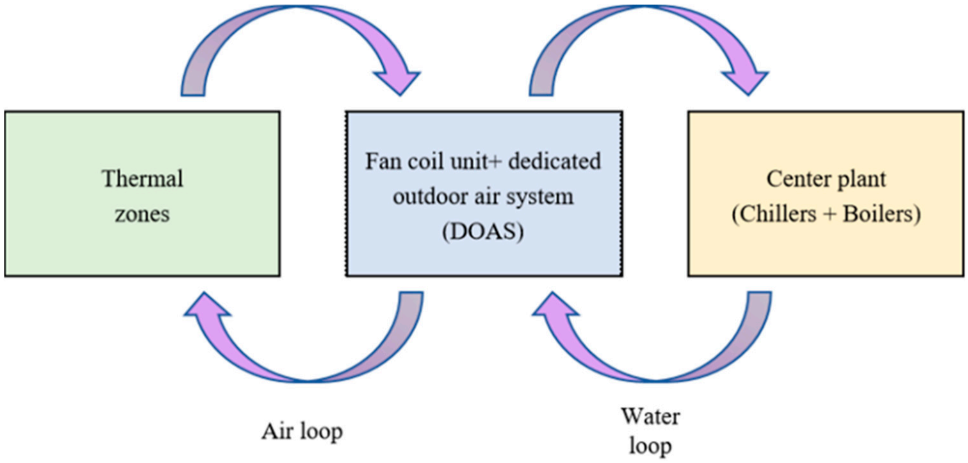


Figure 7. Schematic of dynamic control calculation of EnergyPlus.

The objects of the HVAC system in this paper are as follows. The detailed descriptions of the HVAC systems can be seen in the EnergyPlus Engineering Reference for the complex calculation of the specific HVAC modules.

(1) Chiller: The chiller model used in this study is the Electric Chiller Model Based on Condenser Entering Temperature (object name: Chiller:Electric: EIR). The model utilizes performance data provided by the user for design conditions, along with three performance curves (curve objects) for cooling capacity and efficiency, to determine the operation of the chiller under off-design conditions [39].
(2) Mini-split heat pump: the heat pump model used in this study is the air-to-air heat pump (object name: AirLoopHVAC:UnitaryHeatPump: AirToAir).

3. Results

The hotel buildings in Changsha are chosen as the case study buildings. First, the simulation results of a single hotel building were demonstrated in detail. Then, the simulation results of 119 HotelOffice buildings were analyzed to show the electricity and natural gas EUI distributions. Finally, the simulation results of the 768 buildings were discussed. Table 4 shows four simulation scenarios that transform a prototype building energy model to match a target building.

Table 4. Four scenarios' description.

Scenarios	Scenario Description
Scenario 1 (Prototype scenario)	Prototype model
Scenario 2	Modify building length and width based on Scenario 1
Scenario 3	Modify story number and orientation based on Scenario 2
Scenario 4 (AutoBPS-Param scenario)	Add shading buildings based on Scenario 3

Table 5 shows the coefficient of performance (COP) in different systems. There are two types of HVAC systems in six hotel-related buildings. The geometry of the SmallHotel and SmallHotelStore types are similar, and their thermal zones are simple, mainly including guestrooms, stairs and storage. Therefore, the two building types have the mini-split heat pump as the HVAC device. The SmallHotelStore adds retail and shops on the first floor based on SmallHotel.

Table 5. COP values among different HVAC systems.

HVAC System	Building Types Using the System	Built Year	Cooling COP/Heating COP of Heat Pump	Chiller COP/Boiler Efficiency
Mini-split heat pump	SmallHotel, SmallHotelStore	Pre-2005	2.2/1.9	-
		2006–2014	2.3/1.9	-
		Post-2015	2.9/2.2	-
Chiller + boiler	LargeHotel, HotelMall, HotelOffice, HotelOfficeMall	Pre-2005	-	4.2/0.8
		2006–2014	-	5.1/0.89
		Post-2015	-	5.6/0.9

3.1. Simulation Results of a Single Case HotelOffice Building

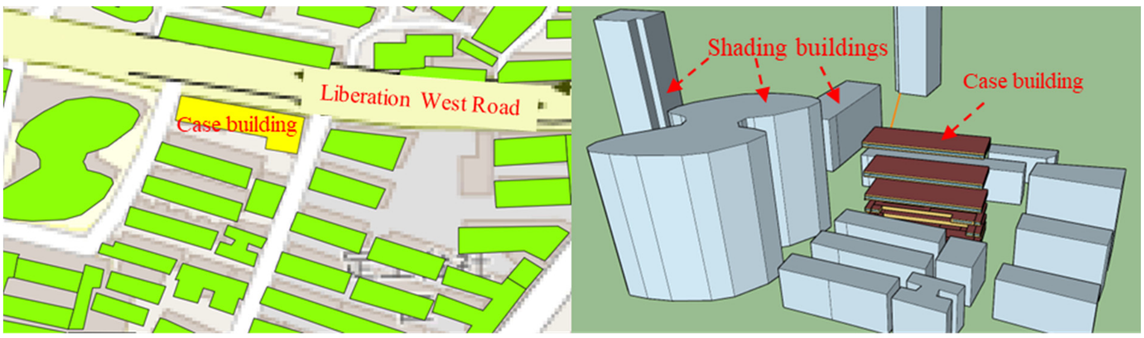
A HotelOffice building is chosen to show the simulation results under four different modeling scenarios in this part.

3.1.1. Brief Description of the Case HotelOffice Building

Table 6 shows the basic information of the case hotel building. The case study HotelOffice building is located in the downtown area of Changsha City, as shown in Figure 8. Figure 8a shows the planned view of the hotel's location on the map via QGIS, while Figure 8b shows the geometry model of the case building with the surrounding buildings in the SketchUp tool. The geometric models of Figure 8a,b are slightly different, and the transformation process is introduced in Figure 3.

Table 6. Case study building description.

Building Description	Value
Type	HotelOffice
Year built	Pre-2005
HVAC system	Chiller + boiler
Thermal zone types	Banquet, Basement, Café, Corridor, Guest room, Kitchen, Laundry, Lobby, Mechanical, Retail, Storage, Office



(a): The planned view of the case building via QGIS

(b): Case building with the surrounding buildings by SketchUp tool

Figure 8. The geographical location of the case building.

3.1.2. Simulation Results of the Case Building

Table 7 describes the parameters of the geometry model of the case building in the four scenarios. The conversion from Scenario 1 to 2 changes the length and width of the prototype to match the case building. It can demonstrate the impact of changes in the building shapes on energy consumption. The conversion from Scenario 2 to 3 changes the story number and the orientation to match the case building. The conversion from Scenario 3 to Scenario 4 presents the shading impacts from surrounding buildings.

Table 7. Model parameters of different scenarios for the case building.

Scenario	Length (m)	Width (m)	Number of Stories	Orientation (°)	Modeling Shading Buildings?
Scenario 1	75.87	23.53	12	0	No
Scenario 2	61.87	20.72	12	0	No
Scenario 3	61.87	20.72	17	11.2	No
Scenario 4	61.87	20.72	17	11.2	Yes

Figure 9 shows the four scenarios' electricity and natural gas EUI and their total usage. The electricity EUI of the four scenarios are 172.25, 180.44, 178.73, and 176.12 kWh/m^2, respectively, and the natural gas EUI of the four scenarios are 140.45, 154.88, 123.16, and 126.28 kWh/m^2, respectively.

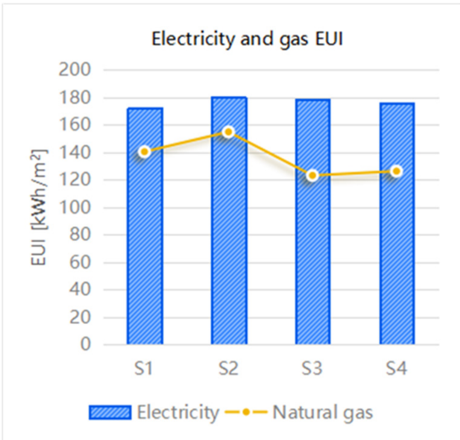


Figure 9. Electricity and natural gas EUI of four scenarios.

3.2. Simulation Results of 119 HotelOffice Buildings

One of the six hotel building types, the HotelOffice building type, is chosen to evaluate the distribution ranges of the electricity and natural gas EUI. Scenarios 1, 3, and 4 are selected to show the energy change magnitude for the HotelOffice building type. The conversion from Scenarios 1 to 3 presents the geometry change and the conversion from Scenarios 3 to 4 shows the shading impacts. The minimum story number of HotelOffice is 9. For HotelOffice, Table 2 shows that the building numbers after filtering in three vintages are 71, 42, and 6, respectively.

3.2.1. Geometry Parameters Distribution of the 119 HotelOffice Buildings

Figures 10–12 show the 119 HotelOffice buildings' geometry parameter distribution, including the number of stories, orientation, length (x factor) and width (y factor). Figure 10 shows that buildings with 10, 20, and 30 stories are the most common, with 19, 15, and 14 buildings, respectively. The orientation distribution of the 119 HotelOffice buildings is shown in Figure 11. The orientations of most buildings are close to 0° facing south or north. The distribution characteristics of building orientation align with the geographical features of southern China. Figure 12a,b shows the building geometry distribution. The median length and width of the HotelOffice buildings are 55.31 and 27.37 m. The length and width of the prototype HotelOffice building are 75.87 and 23.53 m; therefore, the median x factor and y factor are 0.73 and 1.16 according to Equations (4) and (5). The aspect ratio is the ratio of the building length to width.

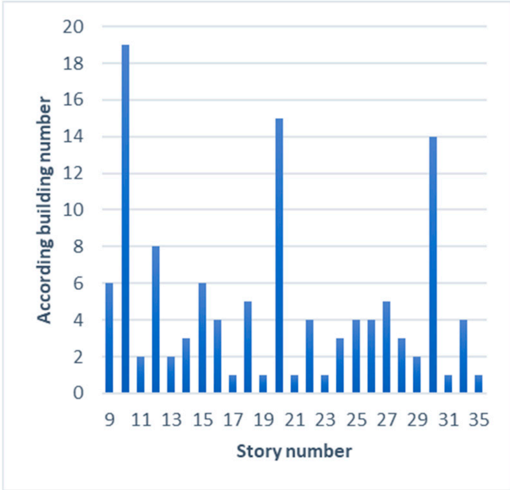


Figure 10. Distribution of story numbers.

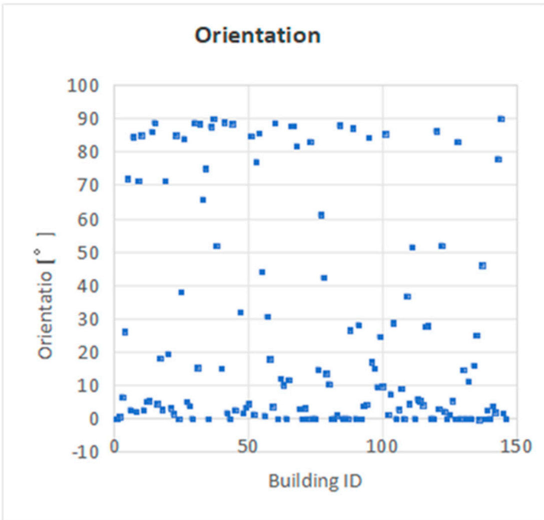


Figure 11. The parameter distribution of orientation.

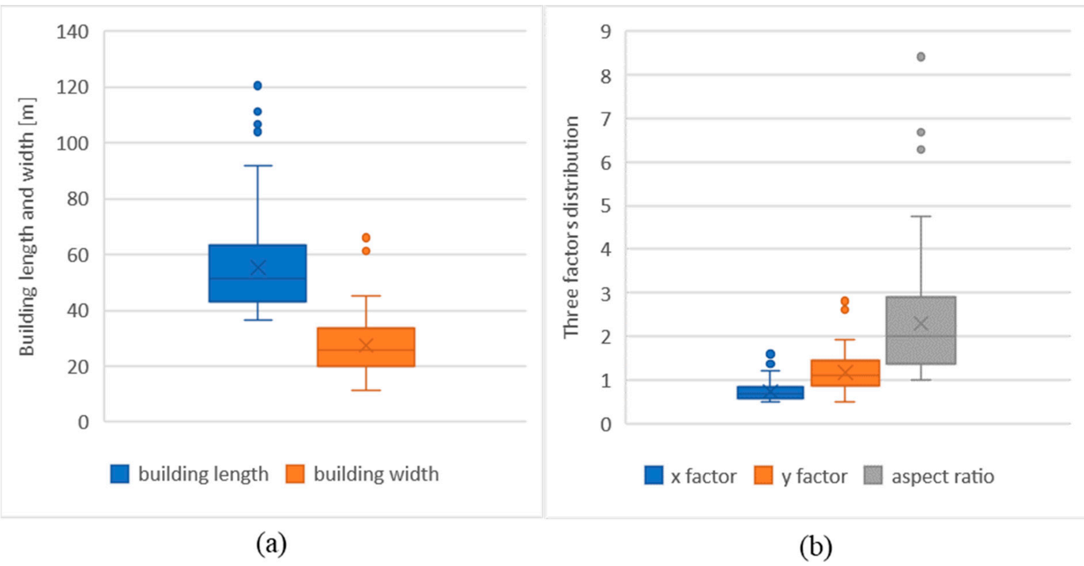


Figure 12. Parameter distribution of 119 HotelOffice buildings: (**a**) the building length and width distribution; (**b**) the *x* factor, *y* factor, and aspect ratio distribution.

There are five extreme outliers in Figure 12b. To better understand the characteristics of the outliers, the five outliers' length, width, and aspect ratio are presented in Figure 13. The upper footprints of the five buildings in Figure 13 are the actual building footprints, and the lower building footprints are the footprints after conversion. The conversion process is shown in Figure 3. Buildings c, d, and e have a relatively large aspect ratio and are within our screening criteria (length ≥ 35 m and width ≥ 10 m); therefore, they are shown as outliers in Figure 12b.

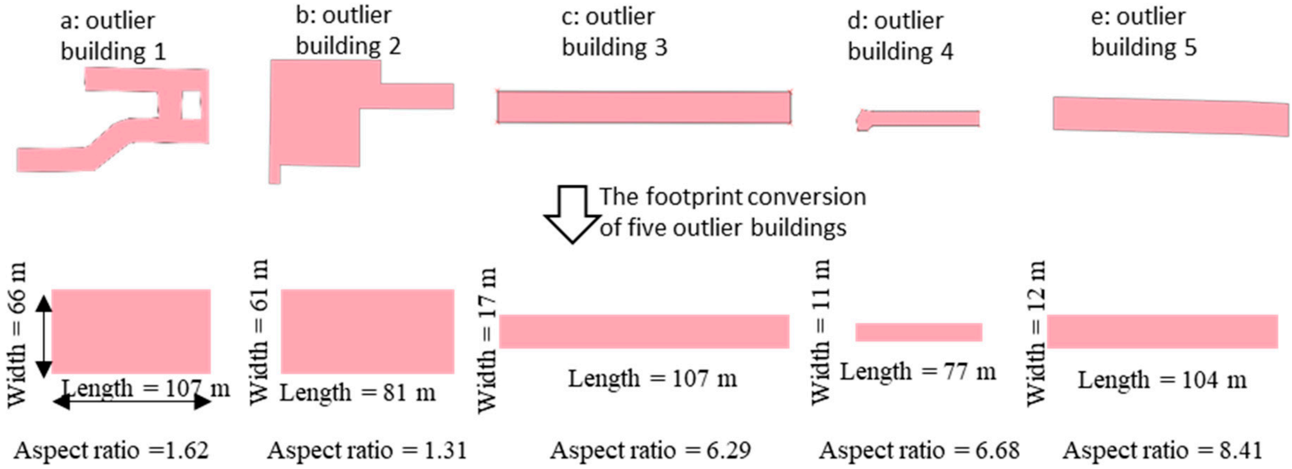


Figure 13. Five outliers in Figure 12b.

3.2.2. Simulation Results of Scenarios 1, 3 and 4 for the 119 HotelOffice Buildings

Scenarios 1, 3, and 4 are chosen to show the simulation results affected by the geometry modifications (length, width, story number, and orientation) and the shading surfaces from the surrounding buildings. Figure 14 shows the average electricity and natural gas EUI of 119 HotelOffice buildings in three vintages for the three scenarios. In Scenario 1, the average electricity and gas EUIs before 2005 were 172.25 and 140.44 kWh/m^2. In Scenario 3, the average electricity and gas EUIs before 2005 were 174.92 and 107.12 kWh/m^2, while in Scenario 4, the two values are 173.14 and 108.89 kWh/m^2. For natural gas EUI in three vintages, the difference between Scenario 1 and 3 is much more significant than that between Scenario 3 and 4. The natural gas EUI differences between Scenario 1 and 3 in three vintages are 33.32, 16.49, and 21.40 kWh/m^2. The natural gas EUI differences between Scenario 3 and 4 in three vintages are 1.77, 0.50, and 0.76 kWh/m^2. The most significant natural gas EUI is 33.32 kWh/m^2 between Scenario 1 and 3 for pre-2005 vintage. The average electricity EUI differences are relatively small compared to those in natural gas EUI between Scenario 1 and 3. Figure 14 shows that the geometry change (from Scenario 1 to 3) significantly impacts the natural gas EUI. The shading impacts of the surrounding buildings (from Scenario 3 to 4) on electrical and natural gas EUI are similar, with an impact of approximately 1 kWh/m^2. However, the parameterized model with surrounding buildings can be used to better evaluate the energy-saving potential of lighting-related energy conservation measures, such as installing occupancy sensors for lighting control, installing daylighting sensors, adding blinds, etc.

3.3. Simulation Results of the 768 Hotel-Related Buildings in Changsha

This section compares the energy consumption results of the prototype aggregation (Scenario 1) and AutoBPS-Param methods (Scenario 4). The comparison of results is divided into two parts: one compares the electricity and natural gas EUI of six types of hotel buildings in the three vintages, and the other compares the total energy consumption of the 768 buildings.

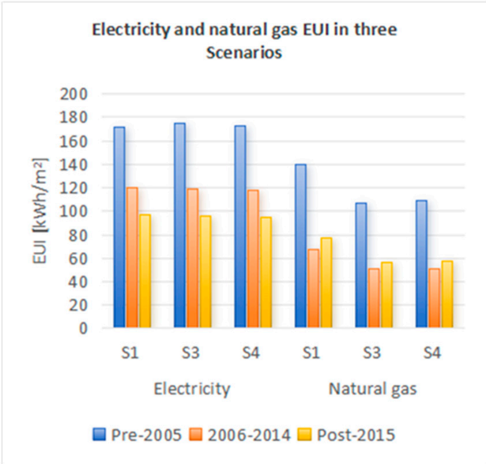
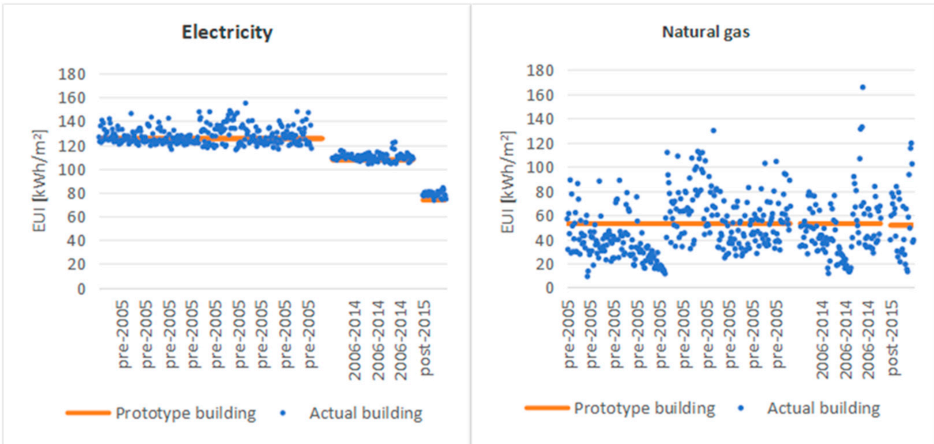


Figure 14. Average electricity and natural gas EUI of 119 HotelOffice buildings for Scenarios 1, 3, and 4.

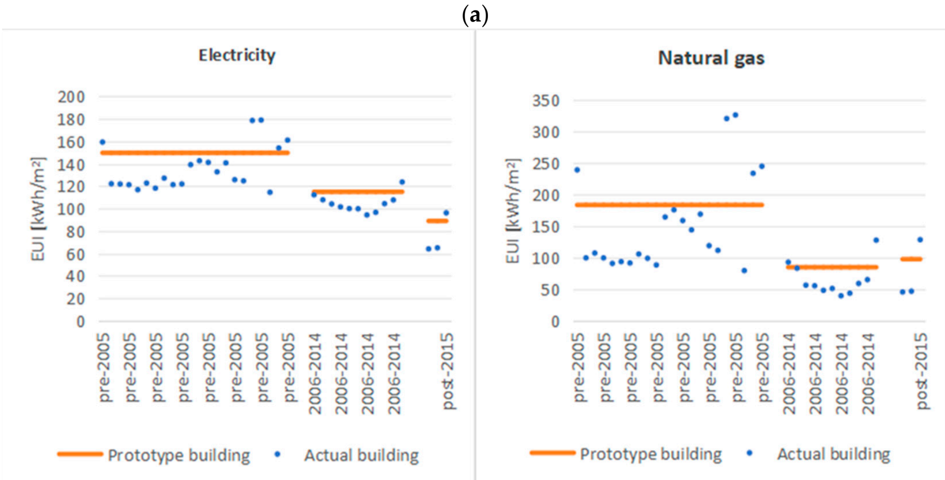
3.3.1. EUI Results of Six Hotel-Related Building Types

Figure 15a–e shows the three vintages' electricity and natural gas EUIs for five hotel-related building types. Because only two buildings belong to the HotelOfficeMall building type after filtering, the electrical and natural gas EUI of the two buildings are listed in Table 8.



SmallHotel

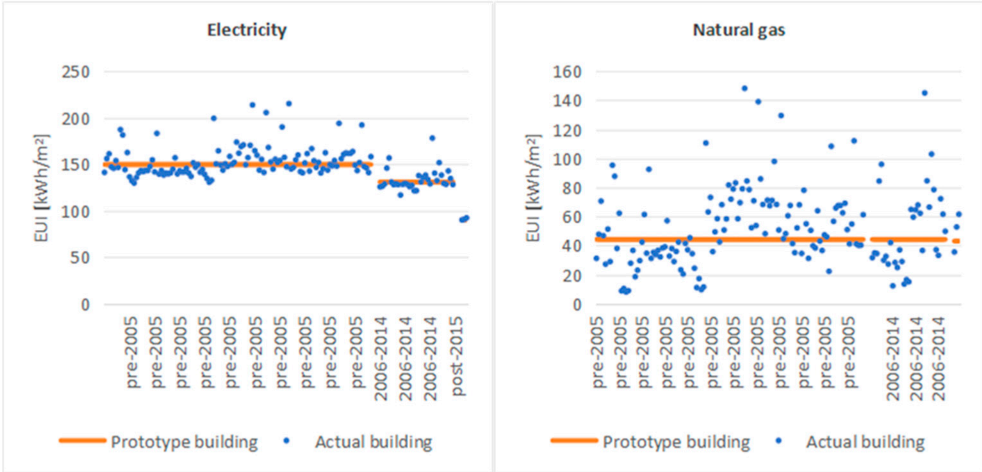
(**a**)



LargeHotel

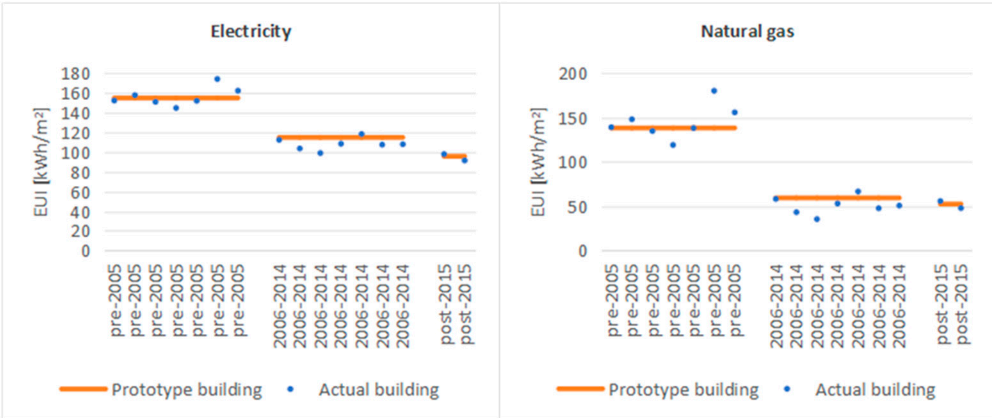
(**b**)

Figure 15. *Cont.*



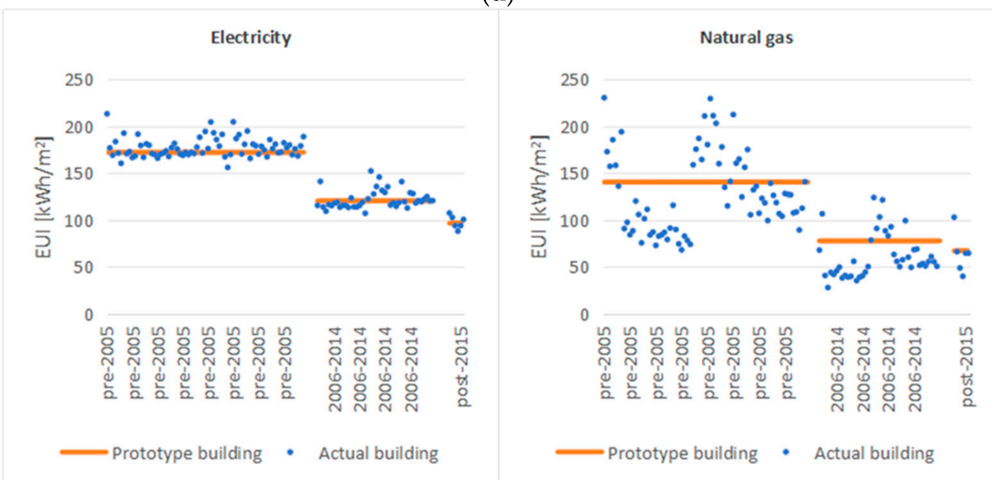
SmallHotelStore

(**c**)



HotelMall

(**d**)



HotelOffice

(**e**)

Figure 15. EUI comparison of six hotel-related buildings. (**a**) SmallHotel energy comparison between prototype (Scenario 1) and actual buildings (Scenario 4). (**b**) LargeHotel energy comparison between prototype (Scenario 1) and actual buildings (Scenario 4). (**c**) SmallHotelStore energy comparison between prototype (Scenario 1) and actual buildings (Scenario 4). (**d**) HotelMall energy comparison between prototype (Scenario 1) and actual buildings (Scenario 4). (**e**) HotelOffice energy comparison between prototype (Scenario 1) and actual buildings (Scenario 4).

Table 8. Comparison of EUI between two methods of HotelOfficeMall type.

HotelOfficeMall Buildings	Year Built	Prototype Building Electricity EUI (kWh/m^2)	Actual Building Electricity EUI (kWh/m^2)	Prototype Natural Gas EUI (kWh/m^2)	Actual Building Natural Gas EUI (kWh/m^2)
Building 1	2006–2014	113.51	112.68	48.02	41.35
Building 2	2006–2014	113.51	110.39	48.02	38.76

The dots in Figure 15a–e represent the target buildings' electricity and natural gas EUI, and the horizontal lines represent the electricity and natural gas EUI of the prototype building energy models. Three building types, SmallHotel, SmallHotelStore, and HotelOffice, have a large number of buildings, as shown in Figure 15a,c,e. For the HotelOffice building type constructed before 2005, the electricity EUI of actual buildings ranged from 159.51 to 213.58 kWh/m^2 with an average of 173.14 kWh/m^2, and the gas EUIs ranged from 68.02 to 229.12 kWh/m^2 with an average of 108.89 kWh/m^2. The overall electricity EUI of the six hotel types ranges from 55 kWh/m^2 to 215 kWh/m^2, and natural gas ranges from 8 kWh/m^2 to 240 kWh/m^2.

3.3.2. EUI Validation

To validate the simulation results, the results simulated using AutoBPS-Param are compared with the measured values and limited values in the Chinese national code Standard for Energy Consumption of Building (GB 51161-2016) [40]. Table 9 lists some EUI electricity and natural gas energy consumption ranges from the literature. Except for SmallHotel and LargeHotel, the other four building types are all hybrid buildings, and it is necessary to consider the EUI indicators of two or more building types. In Table 9, the data in the calculated EUI column was not listed in the literature and was calculated using Equation (7) [41,42] to obtain the total energy consumption to facilitate energy comparison. Table 9 shows that the overall energy is within the measured range.

Table 9. Simulated and measured EUI.

		Location	Hotel Numbers	Electricity EUI [kWh/m^2]	Natural Gas EUI [kWh/m^2]	Calculated Total EUI [kWh/m^2]	Measured Total EUI [kWh/m^2]
Simulated EUI		Changsha	768	55–215	8–240	62–373	-
Measured hotel EUI	Wang et al. [43]	Wujiang	7	80–119	10–23	87–134	-
	Ding et al. [44]	Chongqing	48	-	-	-	40–319
	Sheng et al. [42]	HSCW	127	-	-	-	140–245
	Yao et al. [45]	Shanghai	45	-	-	-	84–360
	Standard [40]	HSCW	-	90–240	-	90–240	-
Measured office EUI	Standard [40]	HSCW	-	55–110	-	55–110	-
	Wei et al. [46]	Changsha	45	12–160	-	-	12–160
	Jing et al. [47]	HSCW	15	50–108	-	-	-
Measured shopping mall EUI	Standard [40]	HSCW	-	70–225	-	70–225	-

HSCW presents hot summer and cold winter area; standard presents the national code Standard for Energy Consumption of Building (GB 51161-2016).

The total energy can be calculated as in Equation (7):

$$Q = Q_E + aQ_N + bQ_S + cQ_C + dQ_H + eQ_D + fQ_G \tag{7}$$

where Q, Q_E, Q_N, Q_S, Q_C, Q_H, Q_D and Q_G are the annual consumption of electricity, natural gas, steam, chilled water, hot water, diesel oil and gasoline, respectively, kWh/a. The conversion coefficient values of a-f are 0.66, 0.23, 0.40, 0.07, 0.66, 0.66, respectively.

3.3.3. Total Energy Consumption of the 768 Hotel-Related Buildings

Table 10 shows the six hotel types' representative floor areas and electricity and natural gas EUI in three vintages via prototype aggregation. The total floor area for a building type is the total floor area of all buildings belonging to the building type. The total electricity usage of the six types is 597.80, 758.98, 193.00, 141.87, 564.13, and 14.53 GWh, respectively.

The total natural gas usage of the six types is 262.58, 175.46, 58.96, 102.36, 416.47, and 6.17 GWh, respectively. Using the prototype aggregation approach, the total electricity and natural gas usage of 768 buildings was calculated to be 1672.56 GWh and 1021.99 GWh.

Table 10. The total energy via prototype aggregation.

	Year Built	Total Floor Area (km^2)	Prototype Electricity EUI (kWh/m^2)	Total Electricity Usage (GWh)	Prototype Natural Gas EUI (kWh/m^2)	Total Natural Gas Usage (GWh)
mallHotel	Pre-2005	3.99	125.34	500.64	52.95	211.49
	2006–2014	0.76	107.45	81.65	52.94	40.23
	Post-2015	0.21	73.69	15.52	51.55	10.86
	All vintages			597.80		262.58
LargeHotel	Pre-2005	0.72	149.69	107.24	183.51	131.47
	2006–2014	0.37	114.93	42.21	84.77	31.14
	Post-2015	0.13	88.94	11.73	97.53	12.86
	All vintages			161.18		175.46
SmallHotelStore	Pre-2005	1.02	149.74	152.79	44.24	45.14
	2006–2014	0.29	131.01	38.47	44.23	12.99
	Post-2015	0.02	90.26	1.74	43.09	0.83
	All vintages			193.00		58.96
HotelMall	Pre-2005	0.53	149.74	79.02	138.25	72.96
	2006–2014	0.42	131.01	55.37	59.30	25.06
	Post-2015	0.08	90.26	7.49	52.34	4.34
	All vintages			141.87		102.36
HotelOffice	Pre-2005	2.20	172.25	379.79	140.44	309.65
	2006–2014	1.39	120.52	167.46	67.11	93.25
	Post-2015	0.17	96.72	16.88	77.76	13.57
	All vintages			564.13		416.47
HotelOfficeMall	2006–2014	0.13	113.51	14.58	48.02	6.17
	All vintages			14.58		6.17
The sum of six building types				1672.56		1021.99

Table 11 shows the electricity and natural gas usage simulated using AutoBPS-Param. The six hotel buildings' electricity consumption is 355.43, 143.79, 187.56, 132.5, 561.96, and 14.31 GWh, respectively. The natural gas usage of the six hotel buildings is 110.39, 137.05, 47.05, 94.89, 321.1, and 5.13 GWh, respectively. The total electricity and natural gas are 1395.55 and 715.61 GWh.

Table 11. The total energy comparison via prototype (Scenario 1) and AutoBPS-Param (Scenario 4).

	Year Built	Total Electricity Energy (GWh)		η (%)	Total Natural Gas Energy (GWh)		η (%)
		AutoBPS-Param	Prototype		AutoBPS-Param	Prototype	
SmallHotel	Pre-2005	253.02	500.64	49.46%	75.56	211.49	64.27%
	2006–2014	85.98	81.65	5.30%	27.26	40.23	32.24%
	Post-2015	16.43	15.52	5.86%	7.57	10.86	30.29%
	All vintages	355.43	597.80	40.54%	110.39	262.58	57.96%
LargeHotel	Pre-2005	95.27	107.24	11.16%	102.36	131.47	22.14%
	2006–2014	38.34	42.21	9.17%	24.25	31.14	22.13%
	Post-2015	10.18	11.73	13.21%	10.44	12.86	18.82%
	All vintages	143.79	161.18	10.79%	137.05	175.46	21.89%
SmallHotelStore	Pre-2005	148.04	152.79	3.11%	35.96	45.14	20.34%
	2006–2014	37.77	38.47	1.82%	10.19	12.99	21.56%
	Post-2015	1.75	1.74	0.57%	0.90	0.83	8.43%
	All vintages	187.56	193.00	2.82%	47.05	58.96	20.20%
HotelMall	Pre-2005	79.51	79.02	0.62%	70.28	72.96	3.67%
	2006–2014	45.17	55.37	18.42%	20.37	25.06	18.72%
	Post-2015	7.82	7.49	4.41%	4.24	4.34	2.30%
	All vintages	132.5	141.87	6.60%	94.89	102.36	7.30%
HotelOffice	Pre-2005	381.75	379.79	0.52%	240.10	309.65	22.46%
	2006–2014	163.60	167.46	2.31%	71.03	93.25	23.83%
	Post-2015	16.61	16.88	1.60%	9.97	13.57	26.53%
	All vintages	561.96	564.13	0.38	321.1	416.47	22.90%
HotelOfficeMall	2006–2014	14.31	14.58	1.85%	5.13	6.17	16.86%
	All vintages	14.31	14.58	1.85%	5.13	6.17	16.86%
The sum of all building types		1395.55	1672.56	16.56%	715.61	1021.9	29.97%

The relative energy difference percentage η in Table 11 is introduced to compare the energy difference in energy consumption simulated using the two methods. It is calculated as in Equation (8):

$$\eta = \frac{|E_{BPS} - E_{pro}|}{E_{pro}} \quad (8)$$

where E_{BPS} and E_{pro} are the total electricity or natural gas simulated via AutoBPS-Param and the prototype method.

The total electricity is larger than the natural gas simulated using the two methods. Table 11 shows that whether in electricity or natural gas, the total energy consumption simulated using the AutoBPS-Param method is lower than that simulated via the prototype. The difference may be owing to a more detailed geometric model and consideration of the surrounding effect. For the electricity energy differences between the two methods, the most considerable difference percentage η appears in the SmallHotel before 2005 building type with 49.46%, and the most minor energy appears in the HotelOffice before 2005 with 0.52%. It shows enormous electricity energy differences in SmallHotel buildings built before 2005 and minor energy differences in buildings in HotelOffice buildings built before 2005. The SmallHotel buildings built before 2005 have large numbers. Therefore, there are significant geometric differences and significant energy differences. For natural gas energy differences, the most prominent and minor difference appears in SmallHotel built before 2005 and HotelMall built after 2015, respectively.

4. Conclusions

This paper uses the newly proposed AutoBPS-Param tool to generate customized building energy models with complex thermal zones and shading impacts from surrounding buildings. The results are analyzed from three cases: a single building, a building type of HotelOffice with 119 buildings, and all building types with 768 buildings in Changsha. For the case study building, the results show that the positive annual electricity EUI differences between Scenario 1 and Scenario 2, Scenario 2 and Scenario 3, and Scenario 3 and Scenario 4 are 8.19, 1.71, and 2.61 kWh/m^2, respectively. The annual natural gas EUI differences are 14.43, 31.72, and 3.12 kWh/m^2, respectively. It shows that the electricity energy difference between the different scenarios is smaller than the natural gas energy difference. The scenario change from Scenario 2 to Scenario 3 with story numbers and orientation change brought the most significant difference of 31.72 kWh/m^2.

For the case building type HotelOffice, the electricity and natural gas EUI of 71 HotelOffice buildings built before 2005 were 172.25 and 140.44 kWh/m^2 via thw prototype method (Scenario 1), while using the AutoBPS-Param method (Scenario 4), the two values were 173.14 and 108.89 kWh/m^2. The average natural gas EUI difference is 33.32 kWh/m^2 between Scenarios 1 and 4 for the 71 HotelOffice buildings built before 2005. The average electricity EUI differences are relatively small compared to the difference in natural gas EUI between Scenario 1 and 3 for the HotelOffice buildings, which is about 1 kWh/m^2. For all three scenarios, the impact of modifying the geometry on the urban building energy consumption is far more significant than that of adding the shading surfaces of the surrounding buildings.

Finally, the electricity and natural gas consumptions of each hotel-related building type in three vintages are simulated and compared via the prototype aggregation and AutoBPS-Param methods. According to prototype aggregation, the total electricity and gas are 1672.56 and 1021.99 GWh, respectively, while using AutoBPS-Param, the total electricity and gas are 1395.55 and 715.61 GWh. The biggest and smallest electricity energy difference percentages η between the two methods were 49.46% and 0.52%. The biggest and smallest natural gas energy difference percentages η between the two methods were 64.27% and 2.3%. This shows enormous electricity energy simulation differences between the two methods in SmallHotel buildings built before 2005 and minor energy differences in HotelOffice buildings built before 2005.

5. Discussion

This paper introduced the AutoBPS-Param model establishment and compared the results of two model establishment methods: prototype and AutoBPS-Param. The energy of a single building, a building type, and buildings of all types in a city can be simulated via AutoBPS-Param. AutoBPS-Param models were established and supported by the existing city data. Thus, abundant data are necessary. With more data, energy simulation will be faster and more accurate. In the future, the models established using AutoBPS-Param can be used to conduct energy analyses such as energy saving, photovoltaic production potential, and demand response potential.

There are some limitations in this study. The geometric shapes of the prototype buildings are all rectangular. Thus, this method only works well for buildings with a footprint-to–board area ratio close to 1.0, which indicates that the building shape is similar to a rectangular shape. For buildings with shapes other than rectangular, additional prototype models with representative geometry shapes may need to be added. In the future, we will continue to expand this method, making it less restrictive on geometry to broaden the scope of AutoBPS-Param. We will continue to grow AutoBPS-Param to cover other buildings with complex thermal zones, such as shopping malls, schools, and other building types.

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Conflicts of Interest: The authors declare no conflict of interest.

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