World Academy of Science, Engineering and Technology
International Journal of Civil and Architectural Engineering
Vol:15, No:10, 2021

Geometric Simplification Method of Building Energy Model Based on Building Performance Simulation

Yan Lyu, Yiqun Pan, Zhizhong Huang

Abstract**—**In the design stage of a new building, the energy model of this building is often required for the analysis of the performance on energy efficiency. In practice, a certain degree of geometric simplification should be done in the establishment of building energy models, since the detailed geometric features of a real building are hard to be described perfectly in most energy simulation engine, such as ESP-r, eQuest or EnergyPlus. Actually, the detailed description is not necessary when the result with extremely high accuracy is not demanded. Therefore, this paper analyzed the relationship between the error of the simulation result from building energy models and the geometric simplification of the models. Finally, the following two parameters are selected as the indices to characterize the geometric feature of in building energy simulation: the southward projected area and total side surface area of the building. Based on the parameterization method, the simplification from an arbitrary column building to a typical shape (a cuboid) building can be made for energy modeling. The result in this study indicates that no more than 7% prediction error of annual cooling/heating load will be caused by the geometric simplification for those buildings with the ratio of southward projection length to total perimeter of the bottom of 0.25~0.35, which means this method is applicable for building performance simulation.

Keywords**—**Building energy model, simulation, geometric simplification, design, regression.

I. INTRODUCTION

NOWADAYS, modeling and simulation has become a widely used technical means for analysis of building energy consumption. The effect of modeling and simulation result depends on the accuracy of the model information [1]. For building energy model, which is a kind of complex system, it is inevitable to simplify appropriately in the process of modeling, and these simplification methods will also inevitably affect the accuracy of the output results of the model [2]. This is also one of the main sources of error between simulation results and actual data.

In practice, the simplification of building geometry in building energy model is the most common simplification method, because the detailed geometric information is often difficult to be obtained completely. At present, majority of work about geometric simplification of building is developed in the research field of building structure or architectural design. For example, Tribaleau et al. built a simplified model of the connector that reduced the time to build the CAD model to replace a local model of the connector describing its exact geometry and material properties by using equivalent method [3]. Li et al. proposed a structural simplification method: the structures of building models are classified into three categories: embedded structures, compositional structures, and connecting structures according to the convex/concave analysis [4]. Drechsler presented a simplification algorithm to reduce the number of polygons by iteratively replacing a group of polygons by a bigger polygon in the study of the numerical simulation of room acoustics [5]. A large number of engineering practices show that the accuracy loss caused by this simplification is acceptable in many cases [6], [7]. However, modelers still want to make sure how much this simplification will affect the results, or even to summarize a practical method as the guideline of the geometric simplification for building energy modeling. Some researchers have conducted related studies about this issue, and some examples will be introduced.

TABLE I
ABBREVIATIONS AND SYMBOLS IN THE PAPER

Abbreviations		Symbols	
hl	Heating Load	*Q*	Amount of Heat Transfer
cl	Cooling Load	*K*	Heat Transfer Coefficient
l	Heat Loss through Envelop	*A*	Area of Building Surface
g	Heat Gain through Envelop	*T*	Temperature
fa	Fresh Air	*SHGC*	Solar Heat Gain Coefficient
oc	Occupant	*α*	Ratio of the Southward Projected Area to the Total Side Surface Area
li	Lighting	*a, b, r*	Size parameters
eq	Equipment	*S*	Base Area
m	Wall	*P*	Relative Deviation between the Perimeter of a Non-rectangular Shape and That of the Typical Shape
w	Window	*D*	Relative Deviations of the Heat Gain and Loss between the Perimeter of a Non-rectangular Shape and That of the Typical Shape
rad	Radiative Heat		
i	Indoor Environment		
rec	Rectangle		
cir	Circle		
tri	Right Triangle		
L	L Shape		
enc	Enclosed Shape		
sem	Semi-enclosed Shape		
cut	Cutaway Rectangle		

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Ourghi et al. provided a simplified analysis method to predict the impact of the shape for an office building on its annual cooling and total energy use based on detailed simulation analyses utilizing several combinations of parameters such as building geometry, glazing type and area [8]. Ladenhauf et al. proposed a semi-automatic algorithm that the 3D representations of walls, slabs, windows, doors, etc. are reduced to a collection of surfaces describing the building's thermal shell, and this simplification also takes into account semantic constraints and expert knowledge [9]. Duan et al. analyzed the relationship between building shape coefficient and the cooling load of building, which derived a simplified formula to calculate envelop cooling load, and for different underside of the building the corresponding correction method is also proposed [10]. According to these research results, it can be seen that due to the complexity of the thermodynamic process of buildings, there is not yet a practical flow-based geometric simplification method for building energy simulation.

II. Method and Principle

From the analysis of physical principles, the impact of building geometry on energy consumption is due to its impact on the heating and cooling load of the HVAC system. As shown by (1) and (2), the heating and cooling load of HVAC system can be divided into several different parts [11], where the part of the heat gain and loss through the building envelope is exactly determined by the geometric and thermal properties of the building.

$$Q_{hl} = Q_{loss} + Q_{fa} - Q_{oc} - Q_{li} - Q_{eq} \tag{1}$$

$$Q_{cl} = Q_{gain} + Q_{fa} + Q_{oc} + Q_{li} + Q_{eq} \tag{2}$$

It means that the impact of building geometry for energy modeling can be analyzed in accordance with the heat gain and loss through the envelope. If the heat gain and loss of two buildings with different shape are approximately equal, they are considered to be equivalent geometry for building energy modeling. Following this principle, this paper can make such a simplification of building geometric model in energy simulation: using the equivalent geometric cuboid building for modeling instead of detailed building model to run simulation when high precision results are not required. Therefore, the essence of the simplification method is to determine the quantitative relationship between the heat gain and loss and the geometric properties of the building.

According to heat transfer laws, (3)-(5) are used to explicate three main ways of heat gain and loss through the envelope: the heat transfer through walls, the heat transfer through windows, and the solar heat gain through windows [12].

$$Q_m = K_m A|T_i - T_m| \tag{3}$$

$$Q_w = K_w A|T_i - T_w| \tag{4}$$

$$Q_{rad} = SHGC \cdot A(T_i - T_{rad}) \tag{5}$$

Obviously, there is a linear proportional relationship between heat gain/loss and the surface area, and also between heat gain/loss and heat transfer (or solar heat gain) coefficient. It means that the thermal properties (related to heat transfer coefficient) and geometric properties (related to surface area) are not coupled in the calculation of heating and cooling load. However, how much the building geometry affects the equivalent temperature difference between two sides of the envelope is still uncertain, and it is exactly the main question discussed in this study. Therefore, this paper firstly sets a typical building model whose thermal properties are invariant, and then develops the study on the basis of this typical model by changing the geometric properties of this building. The impact of geometric changes is expressed in the form of the varying proportions of the heat gain/loss through the envelope relative to the baseline. Essentially, this is the application of the control variable method.

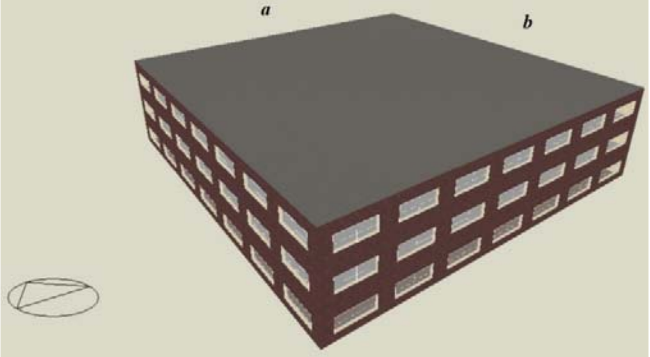

Fig. 1 Geometric Model of the Baseline Building (Rectangle)

TABLE II
PARAMETERS OF THE ENVELOPE OF THE BASELINE BUILDING MODEL

Envelope	Materials	Parameters
Outer Wall	20 mm Cement Plaster 340 mm Bricks 100 mm Aerated Concrete 20 mm Cement Plaster	U-value = 0.888 [W/m^2.K]
Rooftop	20 mm Asbestos Cement Plate 20 m Cement Plaster XPS-R 20 mm Cement Plaster 140 mm Reinforced Concrete 20 mm Cement Plaster	U-value = 0.638 [W/m^2.K]
Window	Two-layer Hollow Glass; Aluminum Window Frame	U-value = 2.73 [W/m^2.K] SHGC = 0.4

The study focuses on the common office building in Shanghai, so the thermal properties of an office building located in Hongqiao Business District, Shanghai are used as the input variables of the baseline building model (as illustrated by Fig. 1). All building information is listed in Tables II and III. For the convenience of research, it is assumed that all buildings are cylindrical, which is reasonable for practicality. In addition, due to this assumption the thermal properties of the typical floor of the building can be analyzed without considering the specific building height. Therefore, only a three-floor building model is required to be built when running simulation for any case in this study. The second floor in the model is the typical floor, and thus all results discussed later are the simulation results of the second floor of the building model.

TABLE III
OTHER PARAMETERS OF THE BASELINE BUILDING MODEL

Type	Ideal Load Cooling and Heating System	
Cooling/heating operation period	Cooling Period	Jun 1 to Sep 30
	Heating Period	Nov 1 to Mar 31
Control parameters	Thermostat set-point when occupied	Summer/Winter: 26°C/ 20°C
	Thermostat set-point when not occupied	Summer/Winter: 37°C/12°C
Operating Schedule	0:00~6:00; 20:00~24:00	0
	7:00	0.1
	8:00; 13:00~14:00	0.7
	9:00~12:00; 15:00~18:00	1
	19:00	0.3

After the baseline (rectangle) building model has been built, this paper focuses on how to describe the changing of the building geometry. Firstly, the main shapes of building in design should be considered. And the shape of building base is needed to be cared about due to only cylindrical buildings are considered in this study. Thus, totally 6 other common shapes of buildings are designed as illustrated in Fig. 2: circle (also ellipse), right triangle, L-shape, enclosed shape, semi-enclosed shape, and cutaway rectangle. The size parameters are also marked in the figure. Then, another parameter is used to describe some more detailed geometric features of a building. In this study, the ratio of the southward projected area to the total side surface area of the building (α) is selected as the describing parameter. For example, the rectangle will be a square when the ratio is 0.25 and a rectangle with aspect ratio of 3:2 when the ratio is 0.3; as for perfect circle the ratio will be about 0.3183 ($1/\pi$); if the south-north axis of the circle building is changed into the long axis of ellipse the ratio of the circle building will be less than $1/\pi$; and if the east-west axis is the long axis the ratio will be more than $1/\pi$. As shown in (6)-(12), this paper summarizes the calculation formulas of the ratio for all 7 kinds of shapes of buildings. By using these formulas in reverse, the specific settings of geometric parameters when modeling for any given number of the ratio can be also determined.

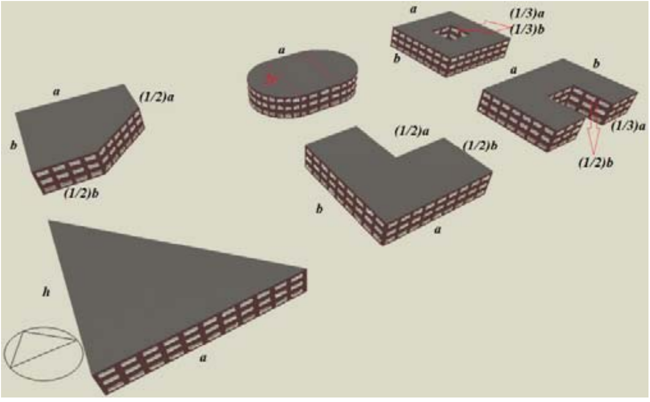

Fig. 2 Six Other Common Shapes of Building Base

$$\alpha_{rec} = a/(2a + 2b) \tag{6}$$

$$\alpha_{cir} = (a + 2r)/(2a + 2\pi r) \tag{7}$$

$$\alpha_{tri} = a/(a + h + \sqrt{a^2 + h^2}) \tag{8}$$

$$\alpha_{L} = a/(2a + 2b) \tag{9}$$

$$\alpha_{enc} = (\tfrac{4}{3}a)/(2a + 2b + \tfrac{2}{3}a + \tfrac{2}{3}b) = a/(2a + 2b) \tag{10}$$

$$\alpha_{sem} = a/(2a + 3b) \tag{11}$$

$$\alpha_{cut} = a/(\tfrac{3}{2}a + \tfrac{3}{2}b + \tfrac{1}{2}\sqrt{a^2 + b^2}) \tag{12}$$

Next, the parameter α and the base area (S) are used as the input of these formulas to compute the size of each shape of building for modeling. This paper sets 3 levels of α (0.25, 0.3, and 0.35) and also 3 levels of S (400 m^2, 1600 m^2, and 2800 m^2). Each combination of these two parameters corresponds to 7 kinds of shapes. It leads to total 63 kinds of shapes of buildings for analysis (as listed in Table IV). By modeling and running simulation in DesignBuilder (the computation engine is EnergyPlus), the final results of these 63 cases are obtained.

TABLE IV
SETTINGS OF ALL CASES FOR ANALYSIS

α	S [m^2]	Rectangle	Circle	Triangle	L-shape	Enclosed	Semi-E	Cutaway
0.25	400	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
0.30	400	Case 8	Case 9	Case 10	Case 11	Case 12	Case 13	Case 14
0.35	400	Case 15	Case 16	Case 17	Case 18	Case 19	Case 20	Case 21
0.25	1600	Case 22	Case 23	Case 24	Case 25	Case 26	Case 27	Case 28
0.30	1600	Case 29	Case 30	Case 31	Case 32	Case 33	Case 34	Case 35
0.35	1600	Case 36	Case 37	Case 38	Case 39	Case 40	Case 41	Case 42
0.25	2800	Case 43	Case 44	Case 45	Case 46	Case 47	Case 48	Case 49
0.30	2800	Case 50	Case 51	Case 52	Case 53	Case 54	Case 55	Case 56
0.35	2800	Case 57	Case 58	Case 59	Case 60	Case 61	Case 62	Case 63

III. SIMULATION RESULT

As an example, the simulation results of Case 1-7 are listed in Table V. In this table, a new variable is denoted as P, which refers to the relative deviation between the perimeter of a non-rectangular shape and that of the typical shape (rectangle). The relative deviations of the heat gain and loss between them (D) have also been calculated. Fig. 3 is drawn with P as the x-axis and D as the y-axis. Each case corresponds to a point in the figure, and a regression line can be then obtained (the regression equations are listed in Table VI). The time scale of model calculation is year-round.

TABLE V
SIMULATION RESULTS OF CASE 1-7

α	0.25	S [m^2]	400		
	Heat Gain [GJ]	Heat Loss [GJ]	P	D_g	D_l
Rectangle	168.1912	119.6448	0	0	0
Circle	152.3059	110.1595	-0.11377	-0.09445	-0.07928
Triangle	188.2917	131.1452	0.207107	0.11951	0.096121
L-shape	180.0311	127.3807	0.154701	0.070396	0.064657
Enclosed	213.1886	151.3847	0.539601	0.267538	0.265285
Semi-enclosed	194.3149	137.3268	0.369306	0.155322	0.147788
Cutaway	166.2581	118.3518	-0.00923	-0.01149	-0.01081

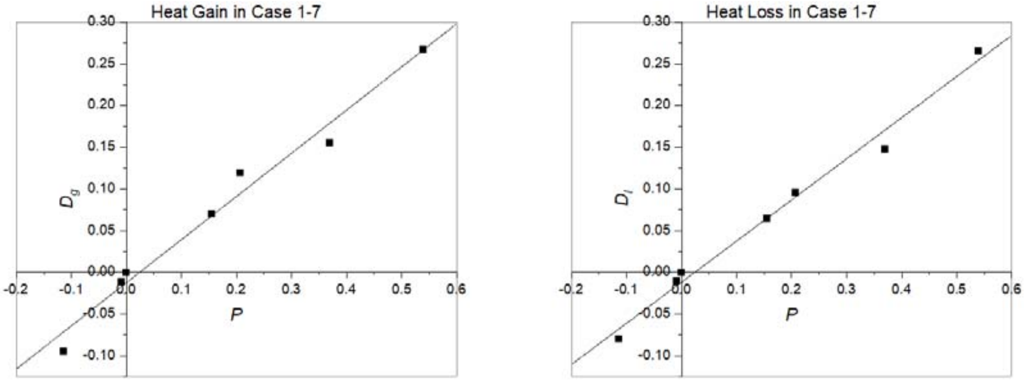
Heat Gain in Case 1-7
Heat Loss in Case 1-7

Fig. 3 Regression Line According to Case 1-7

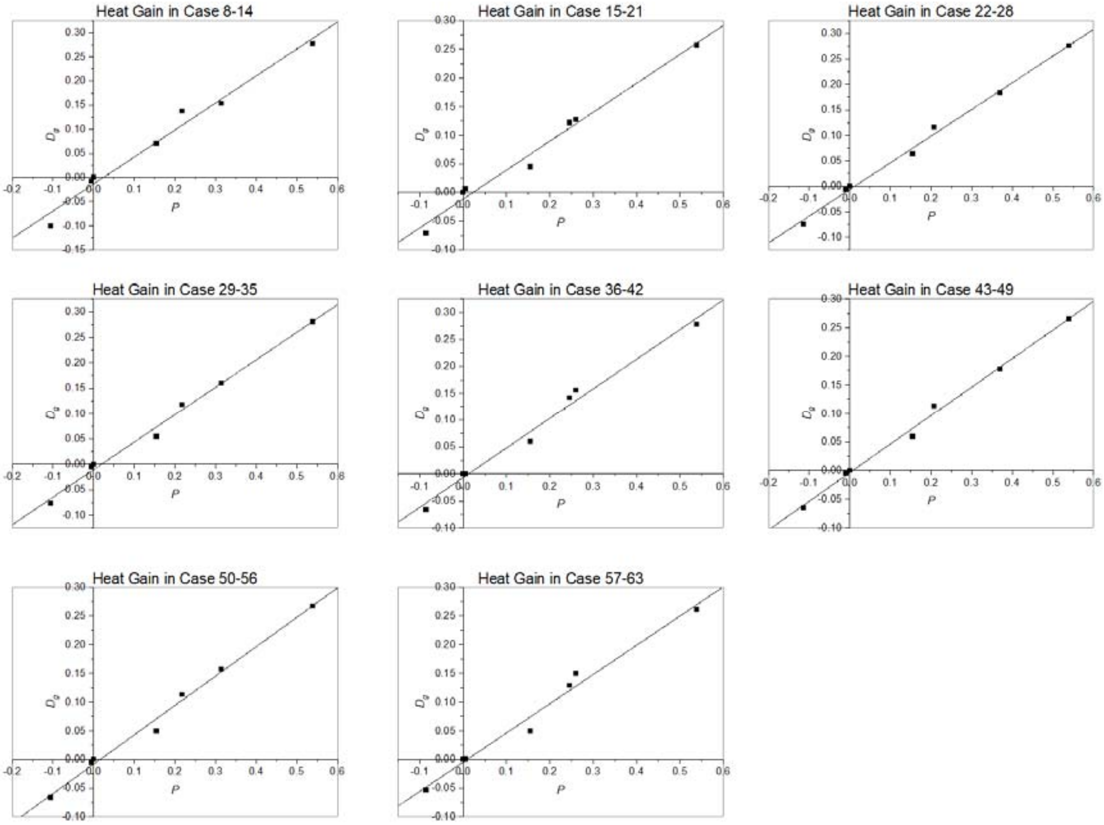
Heat Gain in Case 8-14
Heat Gain in Case 15-21
Heat Gain in Case 22-28
Heat Gain in Case 29-35
Heat Gain in Case 36-42
Heat Gain in Case 43-49
Heat Gain in Case 50-56
Heat Gain in Case 57-63

Fig. 4 Regression Line According to Case 8-63 (Heat Gain)

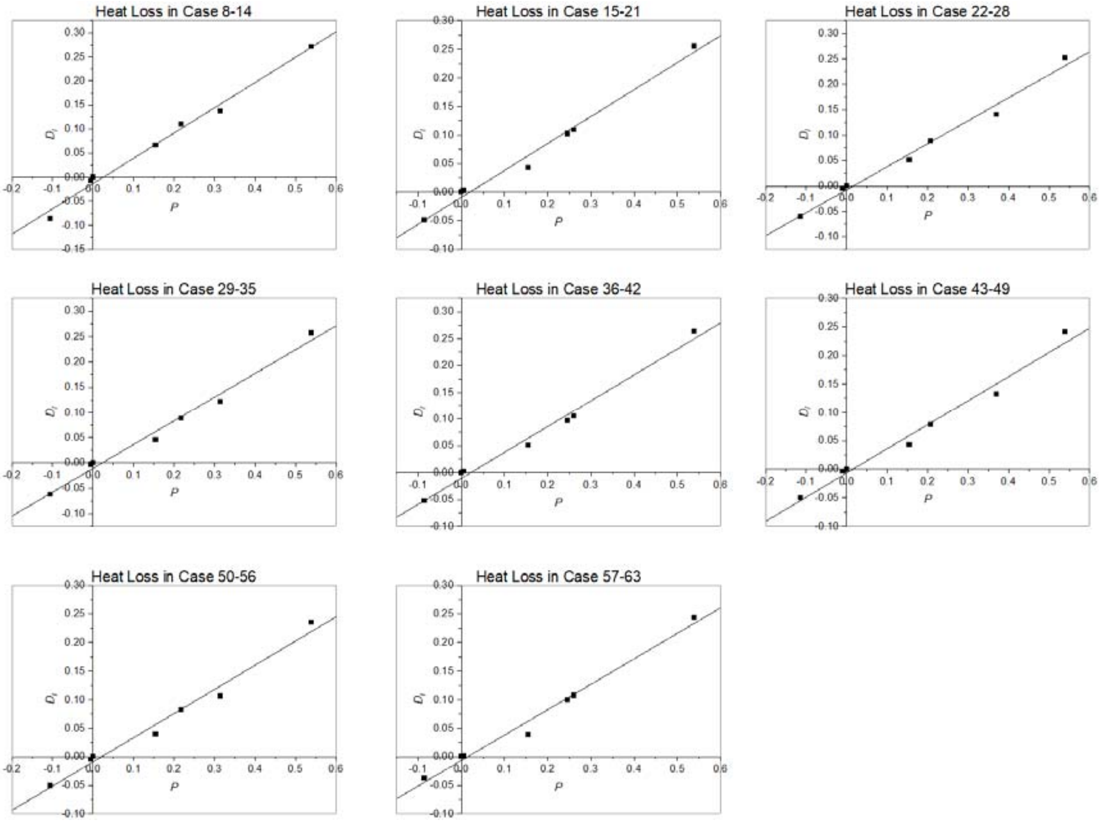

Fig. 5 the Regression Line According to Case 8-63 (Heat Loss)

TABLE VI
REGRESSION EQUATIONS OF FIG. 3

	Equations	R^2
Heat Gain	D_g=0.5172P-0.0124	0.9784
Heat Loss	D_l=0.4932P-0.0118	0.9878

TABLE VII
REGRESSION EQUATIONS OF FIGS. 4 & 5

	Heat Gain		Heat Loss	
Case Group	Equations	R^2	Equations	R^2
Case 8-14	D_g=0.5596P-0.0135	0.9766	D_l=0.5252P-0.0134	0.9895
Case 15-21	D_g=0.5044P-0.0112	0.9821	D_l=0.4717P-0.0092	0.9878
Case 22-28	D_g=0.5238P-0.0064	0.9946	D_l=0.453P-0.0077	0.9877
Case 29-35	D_g=0.5406P-0.0106	0.9915	D_l=0.4694P-0.0109	0.9861
Case 36-42	D_g=0.5499P-0.0067	0.9851	D_l=0.483P-0.0107	0.9876
Case 43-49	D_g=0.4993P-0.0036	0.9946	D_l=0.4236P-0.0066	0.9818
Case 50-56	D_g=0.5119P-0.0082	0.9914	D_l=0.4231P-0.009	0.9813
Case 57-63	D_g=0.509P-0.0047	0.982	D_l=0.4451P-0.0066	0.9846

IV. DISCUSSION AND CONCLUSION

According to Fig. 3 and Table VI, there is obviously a clear linear correlation between P and D. By using a similar approach to deal with the results of other cases, other 8 sets of similar figures (Figs. 4 & 5) and also their regression lines and equations (Table VII) are obtained. It can be found that the slopes of all regression equations are about 0.5 and the intercepts are almost zero (the line crosses the origin). According to it, an equivalent simplification method can be summarized: for an arbitrary cylindrical building, modelers can use instead a rectangle building model with the same base area, perimeter of building base and ratio of the southward projected area to the total side surface area.

The following instruction shows the specific operation to use this simplification method in building energy simulation:

1. Calculate the ratio of the southward projected area to the total side surface area (α) and the perimeter of the building base of the original building.
2. Select a rectangle building with the same ratio and perimeter as the equivalent model, and then determine its specific size and total building area.
3. If the building area of the original model is smaller than the equivalent one, remove part of the building interior, which means that in model settings, there is not any light, equipment, occupant and HVAC system in this part, and also insulated with the outside. After the removal, the base area of the original and the equivalent model should be the same.
4. If the building area of the original model is larger than the equivalent one, select a circle building with the same ratio and perimeter as the equivalent model for the area of circle is larger than square with the same perimeter. And then perform operation similar to Step 3.

Finally, we apply this method on the simulation results of all 63 cases obtained in this study, and find that the maximum error of the annual heat gain of the building is less than 7%. So far, such a conclusion can be drawn that the geometric simplification method from an arbitrary column building to a

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typical shape (a cuboid) building for energy modeling is reasonable, and this simplification would only lead to the error that is less than 7% for those buildings with the ratio of southward projection length to total perimeter of the bottom of 0.25~0.35, which covers most situations.

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