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Constructing prototypical building models based on the similarity theory coupled with entropy weight method

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Because of the lack of established prototypical models in China, evaluations or predictions of the impact of changes in building codes, appliance and equipment standards, new building technologies, materials, or even design solutions are normally based on particular selected or customized models that vary greatly in different studies, thus jeopardizing the validity of the results. As a step to address this, this study developed a coupled method of the similarity theory and the entropy weight coefficient method to construct prototypical building models that represent the building stock. To present such a constructing method, we adopted apartment buildings in cold climates in China as an example. This research firstly collected a series of architectural design documents of apartment buildings in cold climates in China and performed a statistical analysis of their apartment layout features and other associated design data to achieve a statistical building model. Subsequently, a statistical model was introduced to further simplify the statistical building model's dimensions and thermal properties of the building envelopes and attain the prototypical building models. The effectiveness of the extracted prototypical model for general building energy analysis is presented. Given the availability of design data and surveys, this method of constructing prototypical building models based on the similarity theory can be implemented into other types of building prototypical model development (e.g., office building, single-family house, etc.).

Introduction

In most cases, analyses of residential buildings are influenced by building shape, envelope enclosure, building dimensions, and the number of apartment units. In the study of building energy benchmarking, a baseline building model is usually first studied and then used to examine energy performance with various design and system options. Therefore, this modeling process of the baseline model is often very complex because the baseline model should represent a category of buildings in a specific area. To undertake pertinent analyses of buildings in specific areas, simplify the calculation process, and obtain useful representative conclusions, it is necessary to conduct in-depth analyses of existing building models and summarize the prototypical building models.

In the similarity theory, a model must be similar to the prototype in terms of both the geometric and physical elements (Sheng et al. 2014). This theory is an important research tool and extensively applied in the fields of coastal engineering (Hughes and Mansard 1996), physics, computer technology (Marin et al. 2009; Bublievsky et al. 2015; Horaites et al. 2015; Robert et al. 2015; Ciccariello 2016; Qing et al. 2016; Qiu et al. 2016), simulation technology (Wen 2005; Benson et al. 2015; Roads and Mozer 2017), and biological study (Liu et al. 2015; Kumar et al. 2016) and is regularly identified as an effective research method. In the area of building and construction, the theory of similarity is primarily used when researching building structures. For instance, Liu and Meng (2005) used the theory to simplify the structure of reinforced concrete buildings down to a three-degrees-of-freedom spring–mass vibration system for seismic design. Shao et al. (2008) employed the theory to study harmful gas emission in chemical experiments and predict the emission rules for high concentrates of harmful gases. Wang et al. (2010) used the theory and computational fluid dynamics software to obtain a simple method for predicting the average velocity and particle concentration of indoor air flow.

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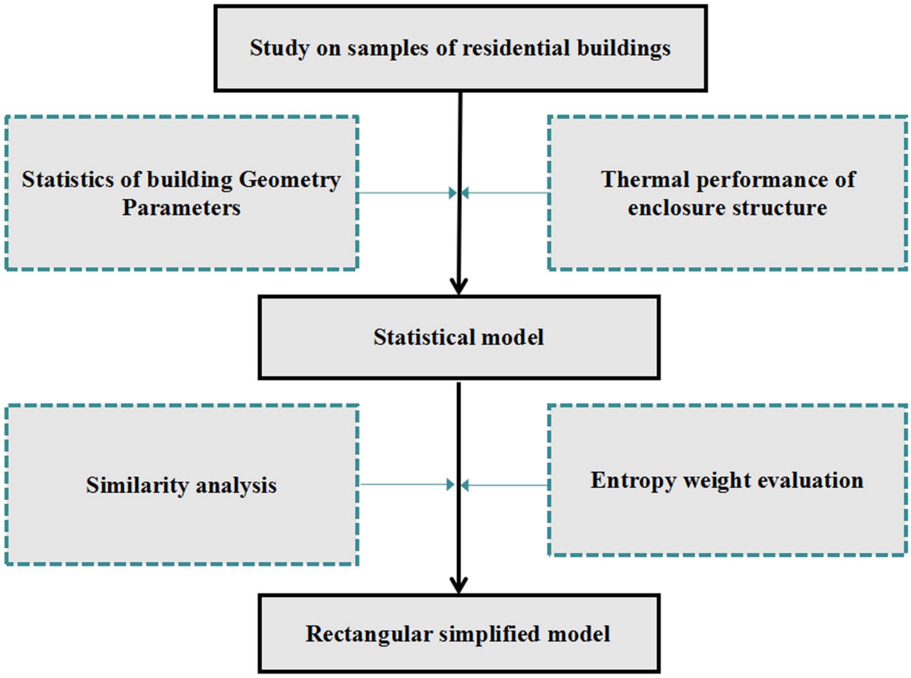

Fig. 1. Combined analysis diagram of the similarity principle and the entropy weight method.

Based on analysis of the 1999 and 2003 Commercial Building Energy Consumption Survey and expert opinions of the existing building stock, the U.S. Department of Energy, working with Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, and the National Renewable Energy Laboratory, has established 16 commercial building benchmark models for different climate regions (Deru et al. 2006; U.S. Department of Energy 2006; Hendron 2008). This provides some standardization and starting points for researchers to conduct building energy studies. Furthermore, in 1995, the Hong Kong Government defined the prototypical model of commercial buildings based on the characteristics of local buildings (Hong Kong SAR Government 1995; Yik et al. 1998; Lam 2000; Yu and Chow 2001; Huang and Niu 2015a). With the application of the prototypical model, various researchers analyzed the effects of different building materials and technologies on building energy efficiency (e.g., aerogel glazing's energy performance; Huang and Niu 2015b; Lee et al. 2015).

The theory of similarity is an effective research method; however, thus far it has not been widely used in the study of constructing prototypical building models. This study proposes a combined entropy weight and similarity analysis method for prototypical model development. In the present article, a statistical building model is obtained through collection of design data and surveys. Then, geometric and physical information entropy is employed to derive the objective weights of the evaluation criteria and a similarity analysis method is employed to obtain simplified prototypical models that conform to the statistical model's energy performance. A specific case—apartment buildings in cold climates in China—is selected to present the proposed prototypical model development method and procedure. The remainder of the article is structured as follows. The following section describes the proposed method and algorithm steps. A case of prototypical model development is then used to demonstrate the feasibility and practicability of the proposed method. The final section concludes this research since 2006.

The entropy weight method and the similarity theory

Buildings are complex systems. Quantitative analysis of a building's architectural features tends to be inaccurate because there are aspects that cannot be precisely described by numbers and mathematical models; instead, this must be accomplished by using general simplified model systems and numerous building information datasets. The Shannon entropy method is used to determine the disorder degree of a system (Shannon 1948). The smaller the entropy value is, the smaller the disorder degree of the system is. Based on Shannon's entropy concept, the entropy weight method (Hwang and Yoon 1981; Klir and Yuan 2005) is according to the amount of information to determine the index's weight under a fuzzy environment with unknown attributes weight information, which is one of the objective fixed weight methods. In this article, the entropy weight method is adopted to determine the weight of the index for building simplified prototypical models. On the other hand, similarities in the characteristics of architectural archetypes and target buildings can be effectively identified and calculated by the similarity method, which is based on needs of comparable models and the characteristic values of the building model obtained from the entropy weight evaluation procedure. The basic analytical procedure for engaging the similarity principle and the entropy weight method is shown in Figure 1.

Similarity analysis

In this study, similarity is defined by hybrid features in terms of building energy performance, geometry, and envelope features, which are further explained later. Our similarity analysis approach is as follows:

1. To select targets (e.g., M and N) and identify similar elements and their characteristic values.
2. To establish similar systems $M = \{m_1, m_2, \ldots, m_k\}$, $N = \{n_1, n_2, \ldots, n_l\}$, where m_k is the element of system M, and n_l is the element of system N.
3. To perform similarity analysis. According to the fuzzy mathematical theory, fuzzy correspondence universally exists among the elements. The correspondence can be described through a matrix $A = (a_{ij})_{k\times l}$.

$$\bar{A} = \begin{array}{c} \begin{matrix} m_1 & m_2 & \ldots & m_k \end{matrix} \\ \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1k} \\ a_{21} & a_{22} & \ldots & a_{2k} \\ \ldots & \ldots & \ldots & \ldots \\ a_{l1} & a_{l2} & \ldots & a_{kl} \end{bmatrix} \begin{matrix} n_1 \\ n_2 \\ . \\ n_l \end{matrix} \end{array} = (\mathrm{a_{ij}})_{k\times l} \tag{1}$$

where $0 \le a_{ij} \le 1$, a_{ij} is the similar element characteristic, namely, similarity. When the corresponding elements are not similar, $a_{ij} = 0$. Otherwise, $a_{ij} = 1$.

$$\mathrm{a}_{ij} = \frac{\min\{M_j(m_i), N_j(n_\mathrm{i})\}}{\max\{M_j(m_i), N_j(n_i)\}} \tag{2}$$

where $M_j(m_i)$ and $N_j(n_i)$ depend on the specific conditions. According to the degree of membership and fuzziness, after the evaluation is determined, the binary relative method is adopted to determine the specific value.

The elements with similar characteristics in the systems are selected to establish the simplified matrix relation as follows:

$$\bar{A}' = \begin{array}{c} \begin{matrix} m_1 & m_2 & \ldots & m_g \end{matrix} \\ \begin{bmatrix} a_{11} & a_{12} & \ldots & a_{1g} \\ a_{21} & a_{22} & \ldots & a_{2g} \\ \ldots & \ldots & \ldots & \ldots \\ a_{g1} & a_{l2} & \ldots & a_{gg} \end{bmatrix} \begin{matrix} n_1 \\ n_2 \\ . \\ n_g \end{matrix} \end{array} = (\mathrm{a_{ij}})_{g\times g} \tag{3}$$

where $0 \le a_{ij} \le 1$.

Entropy weight evaluation

Based on the entropy weight theory (Hernandez et al. 2008; Wang and Beltran 2016), we integrated the above similarity analysis into the entropy weight evaluation procedure, which is shown below:

1. Assume that there are m objectives to be evaluated during the model simplification process and there are n indices for each objective, then the evaluation matrix is $X = (x_{ij})_{mn}$.
2. The evaluated matrix X is normalized to obtain the normalized matrix B, whose elements are

$$b_{ij} = (X_{ij} - X_{\min})/(X_{\max} - X_{\min}) \tag{4}$$

where $X_{\max}$ is the most satisfactory value of different scheme index parameters in the same index and $X_{\min}$ is the most unsatisfactory value of different scheme index parameters in the same index.

3. Based on the entropy concept, the entropy value of each index M_j can be obtained as

$$M_j = -\left(\sum_{i=1}^{m} f_{ij} \ln f_{ij}\right)/\ln m(i = 1, 2, \ldots, m; j = 1, 2, \ldots) \tag{5}$$

$$f_{ij} = \frac{b_{ij}}{\sum_{\mathrm{i}=1}^{m} b_{ij}}. \tag{6}$$

To make $\ln f_{ij}$ meaningful, it is generally assumed that when $f_{ij} = 0$, $f_{ij}\ln f_{ij} = 0$. However, when $f_{ij} = 1$, $\ln f_{ij}$ is also equal to zero, which is apparently unrealistic and incompatible with the concept of entropy. So modification of f_{ij} is required, which is defined as $f_{ij} = \frac{1+b_{ij}}{\sum_{i=1}^{m}(1+b_{ij})}$. Then, the entropy weight W_j of the jth evaluation index is

$$W_j = \frac{1-M_j}{n - \sum_{j=1}^{n} M_{ij}}. \tag{7}$$

The entropy weight matrix is

$$W = (W_j)_{1\times n}.$$

4. The index matrix C of weight

$$C = (b_{ij})_{mn} \times (W_j)_{1\times n} = (C_{ij})_{mn}. \tag{8}$$

5. The ideal point is chosen, and the optimal standard value p_j^* for each row in the weight matrix C is selected:

$$p_j^* = \left(C_{ij}^*\right)(i = 1, 2, \ldots, m; j = 1, 2, \ldots, n), \tag{9}$$

where C_{ij}^* is the optimal index for each column in the system.

6. The proximity value T_i to the ideal point is

$$T_i = 1 - \frac{\sum_{j=1}^{n} C_{ij} p_j^*}{\sum_{j=1}^{n} (p_j^*)^2}, \tag{10}$$

where smaller T_i value indicate a better option, and $0 < T_i < 1$.

The criteria of the entropy evaluation method developed in this research are as follows:

a. When the entropy value of one building parameter's similarity index is 1, the entropy weight is 0, and the index does not offer information to the decision making, which can be canceled.
b. The smaller the entropy value of one building parameter, the larger the entropy weight, indicating that the index is more important and vice versa. Furthermore, $0 \le W_j \le 1$, $\sum_{j=1}^{n} W_j = 1$.

Table 1. Basic boundary factors of the physical building environment.

Number	Item	Content	Comment
1	Building type	Apartment	Accounts for the largest portion of residential buildings
2	Floor number	Multistory (low-, middle-, and high-rise)	Most common classifications
3	Energy savings requirement	From 2003 onward, the completed buildings that fulfilled the national three-step energy-savings requirement	The newly completed buildings are mainly in this phase and representative
4	Climate	Cold region	Has certain research groundwork
5	Building location	Beijing and Tianjin	The urban residential area is densely populated and has universality
6	Building orientation	North–south direction	Has the potential to utilize solar energy
7	Building type and layout	Board type, one ladder, two households	This type, compared to other types of portfolio models, has ideal living environment characteristics with good ventilation and lighting conditions. It is easy to distribute energy, more suitable for zero-energy building operation, and the ideal residential apartment type
8	Geometrical shape	Regular and linear shapes	Most apartment units are based on such geometric shapes
9	Area	Room building area as the principal area, taking traffic space into consideration	This is in accordance with the real estate market operation mode at this stage
10	Annual energy consumption	Comprehensive energy consumption, including heating and cooling	Building energy consumption is an important indicator for the study of building energy systems and is a research prerequisite

Developing prototypical apartment buildings in cold climates in China

Construction of the statistical model

This study selected apartment buildings from 29 communities located in Beijing and Tianjin, two central cities in northern China, to research and analyze. Beijing and Tianjin are located in cold regions in China. Respectively, they are the capital city and the economic center of the country. A survey of the buildings in these two cities offered significant documentation. The architectural documents used in the survey were obtained from various design institutes, real estate development enterprises, and construction companies in Beijing and Tianjin. The preliminary conclusions obtained from the survey can be found in Table 1.

Statistical analysis of the geometric parameters. This research addressed apartment buildings in cold climates in northern China and analyzed a total of 40 apartment buildings in Tianjin and Beijing. In the process of this work, it was determined that small and medium-sized apartments were more popular; therefore, this study took small and medium-sized apartments in multistory apartment buildings as the main research topic. Due to the climatic characteristics and architectural culture of northern China, residential buildings in Tianjin and Beijing were consistently located in the north–south direction. This research collected 40 design samples from the survey data and analyzed them thoroughly. The survey results are shown in Figure 2.

The analysis indicated that the average area of the apartments was 90.42 m^2 with 95% confidence interval of 88.38–94.79 m^2; the average depth was 12.26 m with a 95% confidence interval of 11.77–12.98 m; and the average width was 7.79 m with 95% confidence interval of 7.68–8.15 m. The analysis results are shown in Figure 3.

Statistical analysis of the envelope properties. Based on an investigation of 40 sample apartment buildings in Beijing and Tianjin, it was determined that the structures were mainly built with frame shear walls and the insulation was primarily external. From the results of the statistical analysis on the design data, the average heat transfer coefficient of the walls was 0.58 W/(m^2·k), with a confidence region of 0.53–0.63 W/(m^2·k). The average heat transfer coefficient of the roofs was 0.41 W/(m^2·k), with a confidence region of 0.39–0.43 W/(m^2·k). The average heat transfer coefficient of the doors was 1.5 W/(m^2·k), with a confidence region of 1.47–1.51 W/(m^2·k). The average heat transfer coefficient of the exterior windows was 2.7 W/(m^2·k), with a confidence

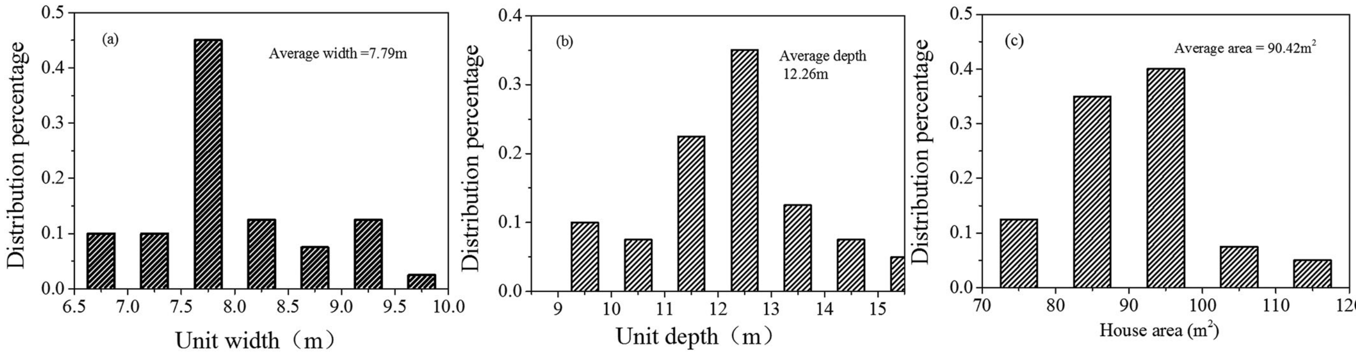

Fig. 2. Geometric parameter distribution of residential buildings.

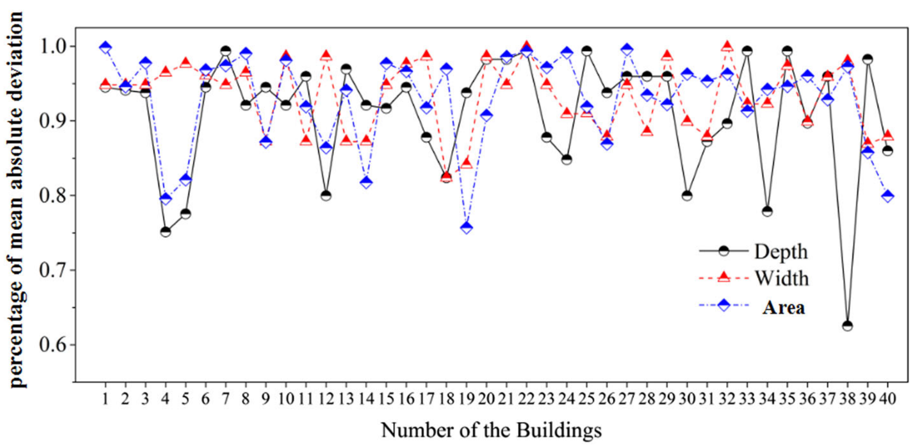

Fig. 3. Data and typical value similarity analysis diagram.

region of 2.47–2.70 W/(m^2·k). The average heat transfer coefficient of the ground was 0.5 W/(m^2·k). The average heat transfer coefficients of the walls, roofs, doors, and windows were 0.5, 0.41, 0.5, and 2.7 W/(m^2·k), respectively. The analysis results are shown in Figure 4.

Establishment of the statistical model. In addition to the above geometric and thermal properties analysis, we analyzed design data on window-to-wall (WWR) ratios and orientations. Per the *Design Standard for Energy Efficiency of Residential Buildings in Severe Cold and Cold Zones* (MOHURD 2010), WWRs of apartments must be lower than 0.3, 0.35, and 0.4 for north, east and west, and south sides, respectively. Our statistical results on all collected design data showed that the average WWRs are 0.20, 0.01, 0.35 for north, east and west, and south sides, respectively. In addition, the design standard recommends that all residential buildings in northern China should be oriented on the east–-west axis for daylight access and heat gains in winter. This orientation recommendation is also consistently reflected by our findings of the statistical analysis on the collected design data. Consequently, these parameters were considered in our model development.

The statistical model established based on the above statistical analysis of design data surveys is shown in Figure 5; its main parameters are the width, depth, and area of the apartment type. This statistical model can represent typical

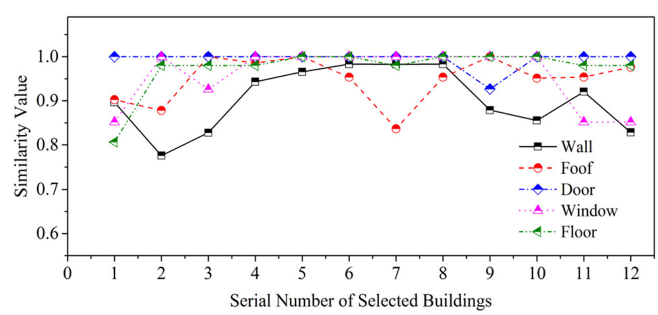

Fig. 4. Heat transfer coefficient similarity analysis of the typical building envelope.

apartment buildings in Beijing and Tianjing. We also defined each material layer of building envelope elements to match the associated heat transfer coefficients in the statistical model.

Selection of the suitable alternative for prototypical models

In the previous steps, we established the statistical model of apartment buildings based on the collected design data. It can be seen from Figure 4 that the typical or statistical apartment layout has a complex shape and geometry, which is not needed for the main purpose of evaluating the impact of changes in building codes, appliance and equipment standards, etc. In this prototypical model construction process, we intended to simplify the statistical apartment model into a rectangular model (see Figure 6) that conformed to the energy performance of the statistical model and maintained the statistically average values of envelope thermal properties as well. Because the change in geometric parameters might inevitably affect the energy consumption of buildings, the selection of the suitable alternative for the simple rectangular model was conducted using the proposed coupled method—the entropy weight evaluation and the similarity theory. Two sets of data were involved in this evaluation and selection procedure, including layout geometric parameters and resulting building energy consumption.

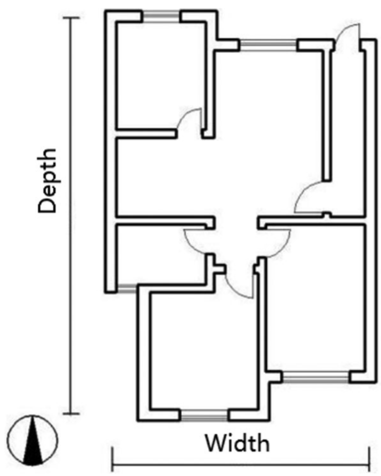

Fig. 5. Layout of the statistical model.

Before conducting this procedure, we had to obtain the energy performance data of the statistical model. The simulation model (Figure 7) was constructed using DesignBuilder software (Design-Builder Software Ltd, https://designbuilder.co.uk/), and the boundary conditions were defined as follows: location = Tianjing, latitude = 39.1°, height of floor = 2.8 m, and building area = 91 m^2. The materials selected for the envelope thermal properties are shown in Table 2. Additionally, in winter it was assumed that coal-fired boilers would provide central heating, households housed three people, the heating boiler efficiency rate was specified at 0.7, the heating temperature was 18°C (MOHURD 2010), and the interior corridor temperature was a set to 12°C. In summer, a regular air conditioner cooling mode was adopted, the actual cooling temperature of the rooms was 25°C, and the coefficient of performance (COP) value of the air conditioner system was 3.3 (AQSIQ 2010). The cooling period was 92 days, from June 15 to September 15, with daily openings set at 11:00 a.m. and midnight (AQSIQ 2010). The heating period was 118 days, from November 15 to March 1 (see TUCC 2013). Other systems were set as follows: the mechanical ventilation model, auxiliary system energy consumption, and domestic hot water model were off, but the natural ventilation model was turned on.

Table 2. Thermal calculation parameters of the envelope structures.

Name	Construction		Heat transfer coefficient K [W/(m^2.K)]
External wall	1.20-mm cement mortar 2.70-mm expanded polystyrene board 3.200-mm reinforced concrete walls 4.20-mm cement mortar		0.58
Interior walls	1.20-mm cement mortar 3.200-mm reinforced concrete walls 4.20-mm cement mortar		1.34
Roof	1.6-mm waterproof Styrene Butadiene Styrene (SBS) membrane layer 2.20-mm 1:3 cement mortar leveling layer 3.30-mm slope made by cement mortar with expanded perlite 4.70-mm extruded polystyrene board 5.10-mm reinforced concrete board 6.20-mm white mortar surface		0.41
Window	General broken-bridge aluminum insulating glass (6 + 12 + 6)		2.7
Door	Finished triproof door filled with 30-mm rock wool insulation		1.5
Floor	Perimeter	120-mm reinforced concrete board and 70-mm extruded polystyrene board Perimeter-equivalent heat transfer coefficient	0.08
	Nonperimeter	120-mm reinforced concrete board and 70-mm extruded polystyrene board No perimeter-equivalent heat transfer coefficient	0.04

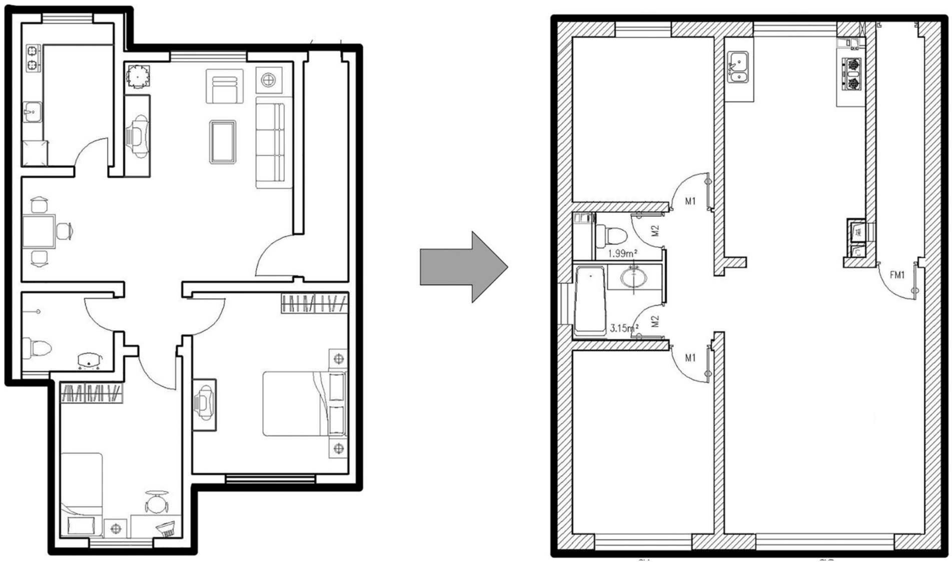

Fig. 6. The statistical model is simplified as a simple rectangular model.

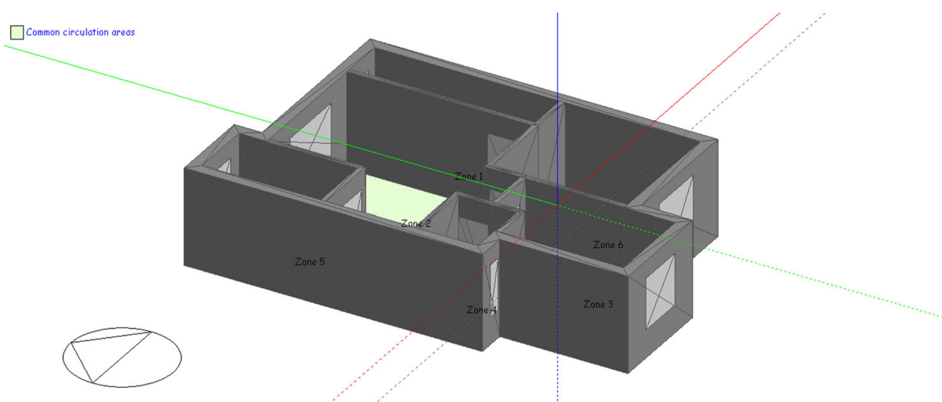

Fig. 7. DesignBuilder model of the statistical model.

Subsequently, the following steps were conducted to evaluate and select the parameters for the rectangular model (i.e., prototypical model):

1. Establishment of the parameter set: Firstly, we chose representative geometric parameters such as width of the model, depth of the model, area of the model, energy use density, window area of the southern façade ($A_{\text{window\_south}}$), window area of the northern façade ($A_{\text{window\_north}}$), and building orientation. Secondly, we established a set with these parameters: $U =$ (width [m], depth [m], unit area [m^2], energy density [kWh/(m^2)], $A_{\text{window\_south}}$, $A_{\text{window\_north}}$, building orientation). Among these variables, we defined the dimensionless value "1" as the north–south orientation of the building and employed this value for all cases. Based on the orientation recommendations section 5.0.1 of the *Code of Urban Residential Areas Planning and Design* (MOHURD 2016), all urban residential buildings should be orientated north–south. This is also consistent with our own data collection results. Furthermore, we performed energy calculations and simulations in order to determine the energy density value of the statistical model. Table 3 presents the parameters of the statistical model and the four proposed simplified models.
2. Similarity analysis: The similarity processing was needed for the parameters of the simplified layouts. Compare the similarity of the parameters of the four simplified schemes with those of the statistical model; the similar datasets of the four simplified layouts are as follows:

$$S_{srs-1} = \{1.000,\ 1.000,\ 0.936,\ 0.927,\ 1.000,\ 1.000,\ 1.000\}$$

$$S_{srs-2} = \{1.000,\ 0.935,\ 1.000,\ 0.991,\ 1.000,\ 1.000,\ 1.000\}$$

$$S_{srs-3} = \{0.937,\ 1.000,\ 1.000,\ 0.981,\ 0.940,\ 0.940,\ 1.000\}$$

$$S_{srs-4} = \{0.975,\ 0.967,\ 1.000,\ 0.986,\ 0.970,\ 0.970,\ 1.000\},$$

where S represents the similarity dataset.

3. Comprehensive evaluation using the entropy weight method: A comprehensive entropy weight evaluation method was used to evaluate each layout. The results obtained during this comprehensive evaluation process are shown in Table 4.

Table 3. Building parameters to be considered for similarity analysis.

Model	Width (m)	Depth (m)	Unit area (m^2)	Energy density [kWh/(m^2)]	Window area of southern façade (m^2)	Window area of northern façade (m^2)	Building orientation
U_{st}	7.9	12.3	91	7606.16	7.74	5.31	1.00
U_{srs-1}	7.9	12.3	97	8203.35	7.74	5.31	1.00
U_{srs-2}	7.9	11.5	91	7675.03	7.74	5.31	1.00
U_{srs-3}	7.4	12.3	91	7748.72	7.25	4.97	1.00
U_{srs-4}	7.7	11.8	91	7712.61	7.54	5.17	1.00

Where U_{st} is the statistical model, U_{srs-} is the simplified rectangle models.

Table 4. Comprehensive evaluation calculation parameters.

Layout	Evaluation index							Remark
	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	
U_{srs-1}	1.000	1.000	0.936	0.927	1.000	1.000	1.000	Evaluation matrix
U_{srs-2}	1.000	0.935	1.000	0.991	1.000	1.000	1.000	
U_{srs-3}	0.937	1.000	1.000	0.982	0.940	0.940	1.000	
U_{srs-4}	0.975	0.967	0.993	0.986	0.970	0.970	1.000	
B_{ij}	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 4
U_{srs-1}	1.000	1.000	0.000	0.000	1.000	1.000	0.000	Normalized Matrix
U_{srs-2}	1.000	0.000	1.000	1.000	1.000	1.000	0.000	
U_{srs-3}	0.000	1.000	1.000	0.852	0.000	0.000	0.000	
U_{srs-4}	0.603	0.492	0.891	0.924	0.500	0.500	0.000	
F_{ij}	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 6
U_{srs-1}	0.303	0.308	0.145	0.148	0.308	0.308	0.250	Normalized Matrix
U_{srs-2}	0.303	0.154	0.290	0.295	0.308	0.308	0.250	
U_{srs-3}	0.151	0.308	0.290	0.273	0.154	0.154	0.250	
U_{srs-4}	0.243	0.230	0.274	0.284	0.231	0.231	0.250	
M_{ij}	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 5
M	0.976	0.975	0.976	0.977	0.975	0.975	1.000	Normalized Matrix
W_{ij}	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 7
W	0.164	0.172	0.164	0.157	0.171	0.171	0.000	Normalized Matrix
C_{ij}	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 8
U_{srs-1}	0.164	0.172	0.000	0.000	0.171	0.171	0.000	Compound weight index matrix
U_{srs-2}	0.164	0.000	0.164	0.157	0.171	0.171	0.000	
U_{srs-3}	0.000	0.172	0.164	0.134	0.000	0.000	0.000	
U_{srs-4}	0.099	0.085	0.146	0.145	0.086	0.086	0.000	
P^*_j	Width*	Depth*	Area*	Energy density*	A_{window_south}*	A_{window_north}*	Orientation*	Equation 9
P^*	0.164	0.172	0.164	0.157	0.171	0.171	0	Ideal point
Layout	U_{srs-1}		U_{srs-2}		U_{srs-3}		U_{srs-4}	Equation 10
T_i	0.398		0.177		0.534		0.446	Proximity of optimization value

Note: *Refers to the parameters calculated by Equations 1–7 rather than original design parameters.

The optimal proximities T_1, T_2, T_3, and T_4 of the four layouts are 0.398, 0.177, 0.534, and 0.446, respectively. The lowest proximity (T_2) refers to the best option of the four rectangular layouts, which was selected as the prototypical model (i.e., layout) of apartment buildings.

Implementation of the prototypical model

Through the above steps, we obtained the simple rectangular layout as the prototypical model. However, the actual building types existed in a variety of combinations. We could expand this simple layout with different spatial combinations covering the forms common to most apartment buildings. This procedure is also consistent with the schematic design procedure at the early stage of the architectural design of multistory apartment buildings in China. A common question proposed by architects is the best energy-efficient design option among these combinations. In addition, by comparing the energy performances of different design combinations of the established prototypical models, we could examine whether the prototypical modeling complies with the basic heat transfer principles.

As shown in Figure 8, the rectangular simplified model can be transformed into a single-layer model of layout A

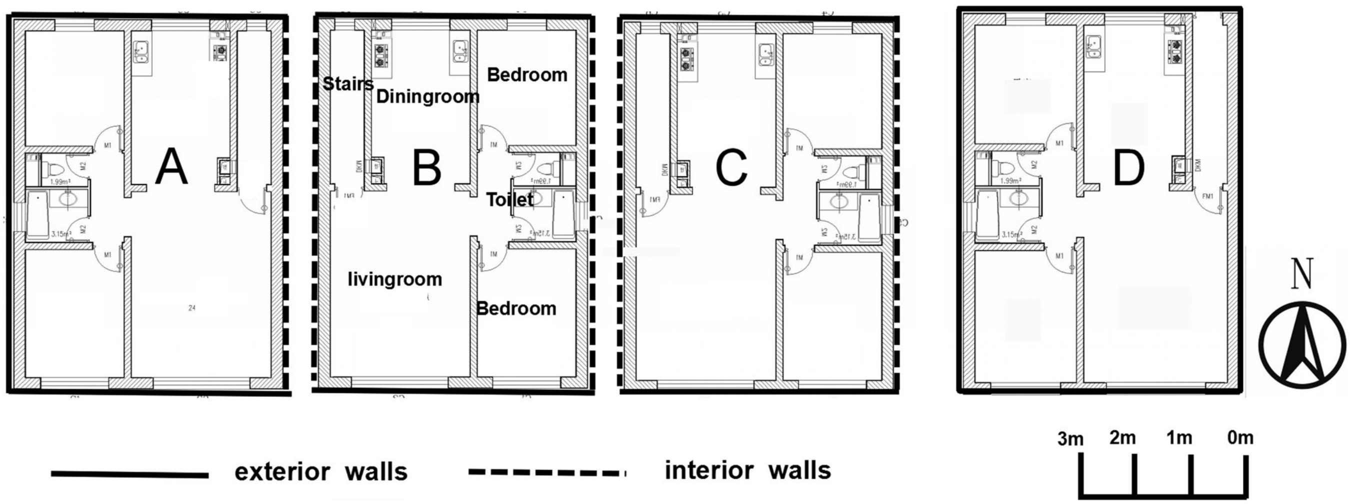

Fig. 8. Four possible exterior wall settings of the layout.

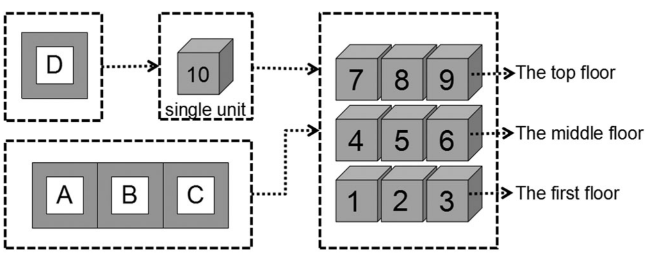

Fig. 9. Ten design options (placements of layouts A, B, C, and D).

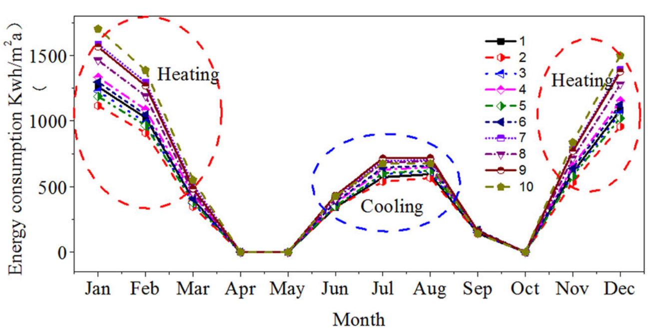

Fig. 10. Energy use density by month for the ten design options.

(three exterior walls with a western façade), layout B (two exterior walls), layout C (three exterior walls with an eastern façade), and layout D (four exterior walls). In addition, different locations (i.e., at the first floor contacting the ground, the middle floor sandwiched between other spaces, or the top floor exposed to solar radiation) for the unit will be possible in real design options, as shown in Figure 9. This combination procedure resulted in ten different multistory apartment design options:

Option 1—Layout A on the first floor
Option 2—Layout B on the first floor
Option 3—Layout C on the first floor

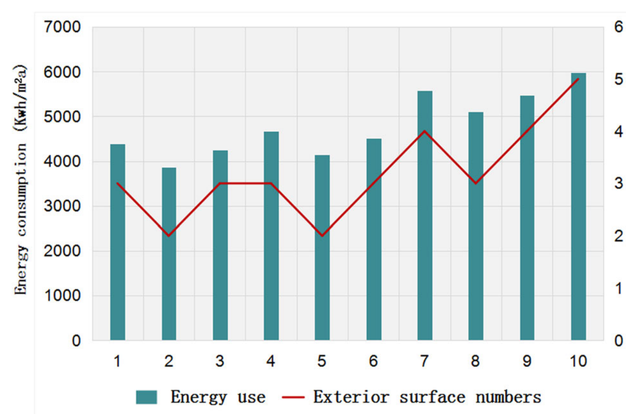

Fig. 11. Heating energy use and exterior surface number for the ten design options.

Option 4—Layout A on the middle floor
Option 5—Layout B on the middle floor
Option 6—Layout C on the middle floor
Option 7—Layout A on the top floor
Option 8—Layout B on the top floor
Option 9—Layout C on the top floor
Option 10—Layout D with four exterior walls.

Then, we performed energy modeling and simulation in DesignBuilder in order to understand the characteristics of the energy use of these different multistory apartment design options.

Energy consumption density by month for these ten building models is shown in Figure 10. January, February, March, November, and December were the heating seasons (in red). In descending order, the heating consumption sequences for the design options were as follows: 10, 7, 9, 8, 4, 6, 1, 3, 5, and 2. June, July, August, and September were the cooling seasons. In descending order, the energy consumption for each design option was as follows: 9, 7, 8, 10, 6, 4, 5, 3, 1, and 2.

Figures 11 and 12 present the correlation between the exterior surface number of each design option and the

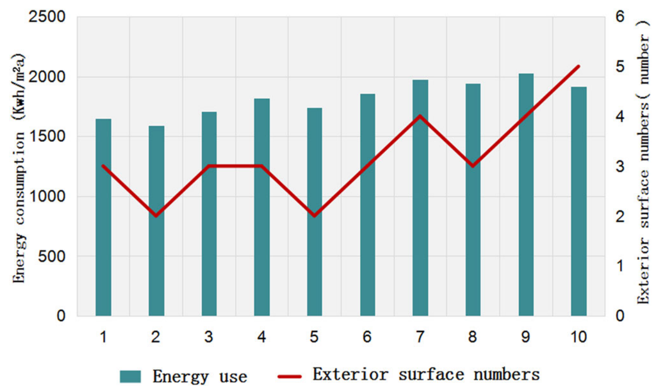

Fig. 12. Cooling energy use and exterior surface number for the ten design options.

energy use in winter and summer, respectively. It was found that in the heating season the main factor affecting building energy consumption was the number of walls in contact with the outdoors. In the cooling season, building energy consumption was not only related to the number of walls in contact with the outdoors. However, it is worth mentioning that design option 10 has slightly lower cooling energy use in summer compared to options 9, 7, and 8, even though it has four exterior walls. This is because the cooler site ground temperatures (13 °C in simulation settings) relative to the interior floor temperatures in the other three options were much more beneficial to reducing the cooling energy use in summer.

Thus, through the analysis of the energy use trends of the ten design options in this case study, we could conclude that the established prototypical models basically followed the heat transfer principles.

Conclusion

China has not established prototypical building models until now. Building models selected for evaluations or predictions for the main purpose of evaluating the impact of changes in building codes, appliance and equipment standards, new technologies, materials, or design solutions vary greatly, thus jeopardizing the validity of the results. In the building energy area, especially benchmarking and design improvement strategies projects (e.g., Hernandez et al. 2008; Wang and Beltran 2016), energy performance analysis relies on the existence and accuracy of prototypical models. The establishment of a prototypical building model in this research aims to address this challenge.

In this article, we first developed a prototypical building model construction method that combines entropy weight and similarity analysis to quantify the weight of each evaluated index in a complex system (i.e., building model). The approach is computationally simple and its underlying concept is rational and comprehensible, thus facilitating its implementation in a computer-based system.

Subsequently, we present a practical workflow of constructing prototypical models: firstly, to collect design data samples in a given building type and climate zone; secondly, to conduct statistical analysis on design data, in terms of architectural geometry, building envelope design parameters (e.g., WWR), and envelope physical properties; thirdly, to form the statistical model using the statistics of the design data; fourthly, using the statistical models, to provide design variations or generate design options (which can be done through, e.g., genetic algorithms, parametric design methods); and, lastly, to execute the entropy weight method and the similarity analysis to attain the prototypical building models that comply with the energy performance and characteristics of the statistical models.

To illustrate the above construction workflow, we used design data on 40 apartment buildings in cold climates in China, generated a statistical model, proposed several representative prototype options, and employed the developed entropy evaluation method to identify the prototypical model. Further, the identified prototypical model was preliminarily used in an energy analysis and comparison work to demonstrate its usage and the reasonableness of results. The resultant prototypical model is limited by the given design data and proposed prototype options. Therefore, based on this preliminary establishment study, from a long-term perspective, we plan to collect large sample size of different building typologies (ranging from residential to commercial sectors) and then develop a series of prototypical models that can represent the Chinese building stock and serve the purpose of energy performance analysis and sustainable design studies.

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