A STUDY OF SHANGHAI RESIDENTIAL MORPHOLOGY AND MICROCLIMATE AT A NEIGHBORHOOD SCALE BASED ON ENERGY CONSUMPTION

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ABSTRACT

This study is to assess the impact of residential morphology and microclimate on energy use at the neighbourhood scale. At the scale of 200m×150m, based on the common residential forms in Shanghai, seven real residential districts are selected as research objects, including the garden houses, 6-storey flats, 14-storey flats, 28-storey flats, lane houses, slab-type apartments and high-rise buildings mixed, as well as high-rise buildings and super high-rise buildings mixed. The effects of residential morphology (e.g. building distance, density, etc.) and microclimate (e.g. wind speed, temperature, etc.) on building energy use are quantitatively assessed using EnergyPlus. In sum, data analyses of the comparison among the energy consumption of the seven distinct districts are usable for the optimal design of residential district in energy supply. Finally, a case study was carried out to analyze the effects of different morphology indexes on the energy balance in the same floor-area ratio (FAR).

INTRODUCTION

In recent years, urbanization has greatly increased the necessity for the city to further develop itself to accommodate the incoming inhabitants, which may promote the urban microclimate. Urban morphology is the foundation of the whole city, which can affect the energy consumption at different levels. In some cities, energy consumption per capita has grown at about the same rate as their spatial growth rate (Baynes and Bai, 2009). Linking the urban energy consumption with the urban form, density and morphology provides an opportunity to tackle the impact of each morphology index change.

In China, researchers recognized that spatial structure can impact the low carbon city development, which has been suggested by academia with empirical studies in most conditions. However, without actual data supports, it is impossible to analyze different urban spatial structures of the carbon emissions, so that it is difficult for the low carbon city to research into the “statistical, detectable and reportable” depth. A typical empirical research performed by Wong et al. (2011) is to study the effect of building energy consumption on the urban form in Singapore. With a long-term test, they concluded that the most significant factors on the influence of city air temperature are buildings, green space and hardening ground, as well as other related parameters, such as the Green Plot Ratio (GnPR), the Sky View Factor (SVF), the density of the adjacent buildings, the wall area, hardening surface area and reflectivity, etc. By adjusting these parameters properly, the building energy use could be reduced. The results showed that the Green Plot Ratio (GnPR) has the greatest impact on the building energy consumption, almost reducing 2 ℃ in temperature and causing a decline of 4.5% in the total building energy consumption compared with the baseline case. Other studies demonstrated that every reduction of 1 ℃ in outdoor air temperature may save 5% of the building energy consumption (Chen and Wong, 2006; Wong et al., 2009).

In other countries, researchers care relatively less about the relationship between urban spatial structure and energy consumption of residential buildings. But it is acknowledged that the urban density can affect energy consumption through the heat island effect, energy transport and storage. Larger area and more discrete buildings will result in more energy demand. Thus, the energy consumption of the highly dense area is relatively lower compared with the other situations. Kolokotroni et al. (2005) found that during typical hot weeks, a rural reference office has 84% cooling demand of a similar urban office in the same location in London. Greed (2004) specified two main types of residential density in the UK area: net and gross. Meanwhile, the results given by Salat (2009) showed that the main urban morphology factors which affect energy consumption are the building density, shape factor, passive volume, energy systems, and inhabitants' behaviors. A balanced view about the complicated impacts of morphologies, typologies, energy systems and inhabitants’ behaviors on energy loads and CO_2 emissions is presented, which allows for the optimization of the urban form in terms of the density, building configuration and morphology. Ewing and Rong (2008) have made a conclusion that the same household living in the sparse and detached house takes 54% more heating energy and 26% more cooling energy than living in the department or the terraced house. The LSE conclusions showed that Istanbul has the greatest variation both between and within morphology types, detached housing, high-rise apartment, gecekondu and compact urban block. Conversely, London and Paris exhibit smaller performance ranges between building types.

The main purpose of this paper is to evaluate the impact of residential morphology and microclimate on energy consumption at the neighborhood scale (200m×150m). Then, a case study in Shanghai which could evaluate the effects of different morphology indexes on the energy consumption of the 14-storey residential districts in the same floor-area ratio (FAR) was performed.

METHODOLOGY

Research object

Figure 1 shows the proportion of the house types from Shanghai Statistical Yearbook of 2013, which illustrates the category constitution of the residential buildings in Shanghai.

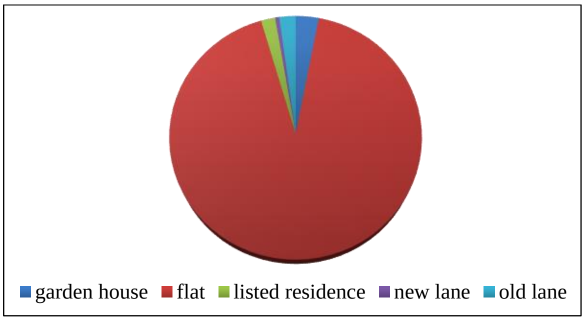

Figure 1 The residence type classification in 2012

As can be seen in Figure 1, the flat accounts for the largest proportion, followed by the garden house and the listed residence. Thus, seven residential districts are selected as research objects, including the garden houses, 6-storey flats, 14-storey flats, 28-storey flats, lane houses and two types of mixed houses.

Simulation Methodology

District construction load and energy prediction plays a key role in the process of regional energy planning, which are also an important method for estimation and analysis of regional carbon emissions and heat island effects. Regional construction load and energy consumption prediction require a forecasting model of energy consumption. Usually, there are two kinds of basic modelling methods: the top-down method and the bottom-up method. The top-down approach is to estimate the overall energy consumption of buildings, and then estimate the downscaling of time and space. While the bottom-up approach, which is utilized in this study, is the opposite. In other words, calculating the energy use of a single building takes priority over that of the regional scale. The bottom-up approach is divided into three types of models: physical models, statistical models, and hybrid models.

Procedure

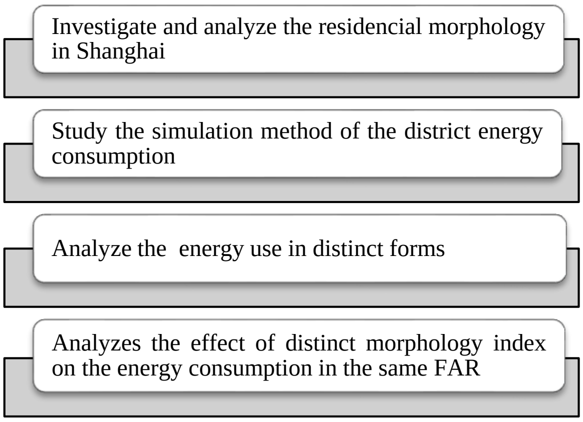

Figure 2 Procedure of the study

There are four main steps in the study (see Figure 2). In the first place, due to the selection of typical form types, the residential morphologies are investigated thoroughly in Shanghai. Then, the analysis in terms of the simulation results is carried out.

Input and output parameters

The input and output parameters of the model are shown in Figure 3. The input data is obtained from two ways – investigation (e.g. forms, HVAC types) and standards (e.g. envelop parameters).

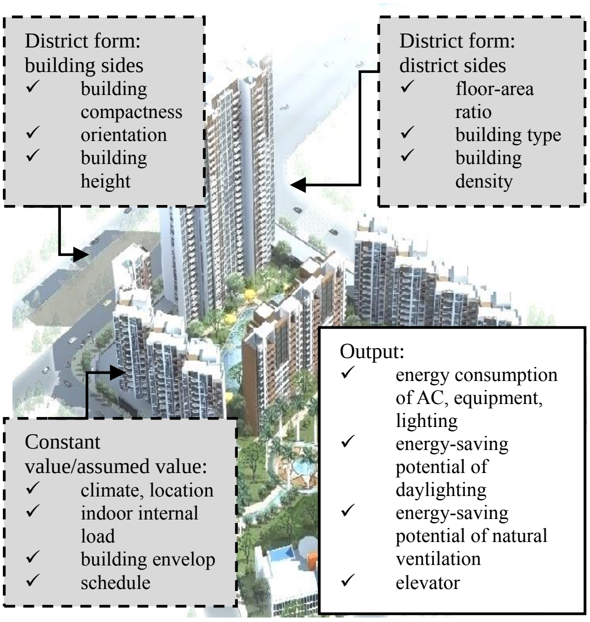

Figure 3 Input and output parameters

Simulation tools

EnergyPlus, which is developed by U.S. Department of Energy, has been widely applied in the studies of building energy simulation. EnergyPlus can simulate heating, cooling, lighting, ventilation, other energy flows, etc. Besides, EnergyPlus has many innovative simulation capabilities: time-steps less than an hour, modular systems and plant integrated with heat

Table 1 Settings of EnergyPlus simulations

Building type	Total building area (m²)	Floor-area ratio (FAR)	Floor space (m²)
Garden houses	13260	0.44	2210
6-storey flats	33078	1.10	5513
14-storey flats	62832	2.09	4488
28-storey flats	171360	5.71	6120
Lane houses	96948.3	3.23	19390
Slab-type and high-rise mixed	87520	2.90	6695
High-rise and super high-rise mixed	104720	3.49	4910

balance-based zone simulation, multi-zone air flow, thermal comfort, water use, natural ventilation, as well as photovoltaic systems. Therefore, EnergyPlus 8.1 is utilized in this study.

Case study

We conducted two case studies to demonstrate the effect of the residential morphology. The first case shows the energy consumption of distinct residential region morphology in Shanghai at the neighborhood scale (200m×150m). The other is the analysis of the effects of different morphology indexes on the energy consumption of the 14-storey residential districts in the same FAR.

ANALYSIS OF ENERGY USE OF SEVEN DISTRICT RESIDENTIAL TYPES

The research on the morphology of the residential district is based on seven typical real districts in Shanghai, including the garden houses, 6-storey flats, 14-storey flats, 28-storey flats, lane houses, slab-type apartment and high-rise building mixed, as well as high-rise building and super high-rise building mixed.

Building information

All the district models share the same planning area (30000m²). Table 1 illustrates the setting of typical models. The selected residential district and types are depicted in Figure 4.

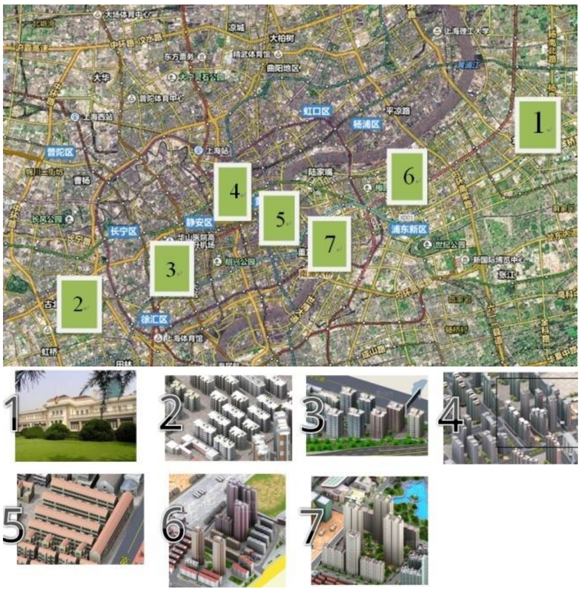

Figure 4 Seven district types

Schedule

The schedule is set from the prototypical model in Shanghai. The data of heating and cooling period is set based on the Shanghai residential energy saving standard (DGJ08-205-2011). The heating period is from September 1st to February 28th next year. The cooling period is from June 15th to August 31th. The data of the prototypical model is collected through investigating hundreds of residential buildings in Shanghai. Given different constitutions of human rest time, totally four scenarios are conducted to reflect the phenomenon (see Table 2). The schedule of this study is the weighted average value based on the area with all scenarios, as shown in Figure 5.

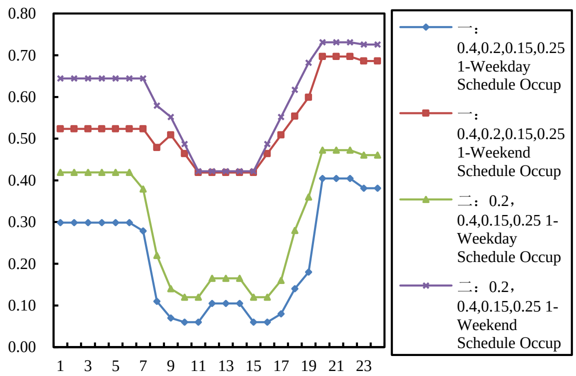

Figure 5 Schedule

Table 2 Assumption of residential usage scenarios

NO	USAGE CONDITION
Scenario 1	Weekday night, weekends
Scenario 2	Weekday, weekends
Scenario 3	Weekday noon
Scenario 4	Weekends

Day lighting and natural ventilation

This study considers the daylighting by setting the reference point of daylighting control at the center of each building at 200lx. If the luminance value of the reference point is larger than 200lx, the daylighting control will be available to close the lights.

Natural ventilation is also considered. According to the standard, the time from January 1st to February 18th and from June 15th to August 31th is the air conditioning period for heating and cooling. Thus, the natural ventilation can be used in the rest time. During the air conditioning period, if the outdoor air

Table 3 Output of the energy consumption (I)

Building type	Initial energy consumption (kWh/m²)	Day lighting saving (kWh/m²)	Natural ventilation saving (kWh/m²)	Total energy consumption (kWh/m²)
6-storey	21.18	-0.14	-1.49	19.55
Garden house	53.77	-10.50	-4.79	38.48
14-storey	21.35	-0.52	-0.86	19.97
28-storey	21.02	-0.19	-0.92	19.91
Lane house	22.19	-0.19	-1.30	20.70
Mixed type 1	29.91	-0.88	-1.90	27.13
Mixed type 2	29.70	-0.95	-1.56	27.19

Table 4 Output of the energy consumption (II)

Building type	HVAC	Lighting	Equipment	Lift
6-storey	5.88	4.91	8.19	0.57
Garden house	25.50	4.76	8.22	0.00
14-storey	5.70	4.83	7.92	1.51
28-storey	5.75	4.90	8.04	1.22
Lane house	7.72	4.84	8.14	0.00
Mixed type 1	13.04	4.04	8.17	1.88
Mixed type 2	13.28	3.88	8.17	1.70

temperature is less than 28 ℃ and the wind speed is less than 3m/s, natural ventilation could be operated. The outdoor air temperature and the wind speed is obtained from the hourly data of typical meteorological year (TMY).

Results

In Tables 3-4 and Figure 6, the garden house costs the most energy use than other districts, followed by the mixed house, lane house and 14-storey building. Besides, the 14-storey building, 28-storey building and 6-storey building share similar results. The daylight saving of the garden house ranks the first as well as the natural ventilation. The garden house consumes the most HVAC energy consumption, and the mixed house takes the second place.

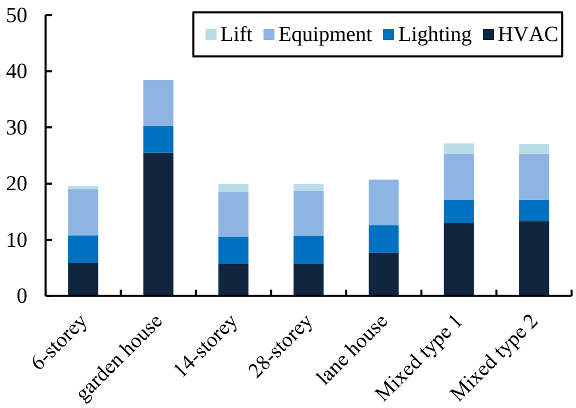

Figure 6 Energy consumption of the seven districts

Daylighting is related to the window and the shading. If the shading area is smaller, the daylighting energy-saving potential will be more. The result shows that the garden house saves nearly 10kWh/m² in the daylighting, and the lane house is the least due to its conferted shading effect.

The garden house also takes the first place in the energy saving of natural ventilation, followed by the 6-storey building and the lane house. The high-rise building has its shortage on the natural ventilation because of its height. The wind speed will vary with the height. When its height reach to the specific value, we cannot open the window for ventilation due to the excessive wind speed. Thus, the energy saving of natural ventilation is mainly obtained in the multi-storey building and the low-rise building.

As can be seen from Table 4, the HVAC system and equipment cost the main part of the total energy consumption. The energy consumption of lighting is in the third place, at around 4kWh/m². The garden house is equipped with the VRV (variable refrigerant volume) system, which could cost the most energy consumption among all the other houses. Other houses utilize the split air conditioner. Mixed types also consume more energy on the HVAC system. The lighting on the low-rise houses costs more proportion of the total energy consumption than the high-rise houses. Based on the new standard, houses with no less than 6 storeys must be equipped with lifts. Thus, the energy use of the lift is another aspect which need to satisfy the total population of the building and the waiting time of the lift.

Table 5 and Figure 7 show the results of total energy consumption against floor-area ratio (FAR).

We select the FARs of the seven types and their total energy consumption to figure out whether there is a relationship between the two factors (see Table 5). Figure 7 is the line graph displaying the correlation intuitively.

It can be concluded from Figure 7 that there exists a strong positive correlation between the two variables. Therefore, we could easily predict the total energy consumption of a specific building type according to the corresponding value of FAR.

Table 5 Relationship between total energy consumption and FAR

Building type	FAR	Total energy consumption (10000kWh)
Garden house	0.44	51.02
6-storey	1.10	62.78
14-storey	2.09	125.48
28-storey	5.71	341.18
Lane house	3.23	200.68
Mixed type 1	2.91	237.44
Mixed type 2	3.49	284.73

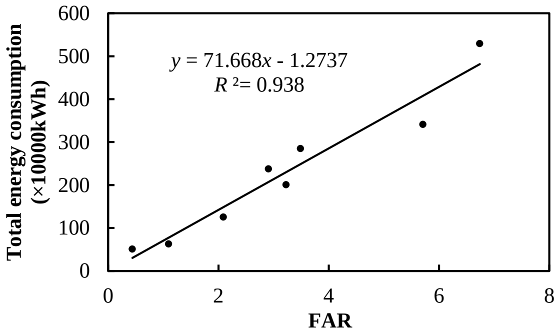

Figure 7 Relationship between total energy consumption and FAR

THE EFFECTS OF DIFFERENT MORPHOLOGY INDEXES ON THE ENERGY CONSUMPTION OF 14-STOREY FLAT RESIDENTIAL DISTRICTS IN THE SAME FAR

This section analyses the relationship between energy consumption and four spatial characteristics, which describes the different samples of urban morphology. The parameters are building distance, building height, orientation and building density. The case study was carried out based on the typical 14-storey flats as mentioned above. The FAR of the model is set as two, meaning that the planning area is 200m×150m and the total building area is 60000m^2.

Building distance

The building distance of the baseline model is 50m. While the distance is changed to be 10m, 20m, 30m, 40m, and 60m respectively in order to compare the energy consumption. The related results are shown in Figure 8.

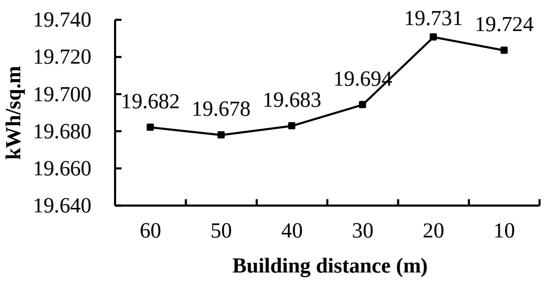

Figure 8 Relationship between building distance and energy consumption

As can be seen in Figure 8, different building distances may lead to different energy use. The energy consumption increases with decrease of the building distance. Besides, the resulting energy consumption appears to be approximately the same numerical value.

Building height

This subsection shows the results of energy demand against building height. The buildings are divided into four different building height scenarios for simulations, as shown in Figure 9 and Table 6.

There is a slightly negative correlation between the building height and energy demand (see Figure 10). There is no significant difference in the energy demands of buildings between Scenario 2 and Scenario 3 – both averages are around 19.72kWh/m^2. However, as can be seen in Figure 10, a smaller difference in the building heights may lead to a less energy consumption.

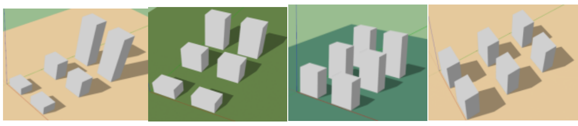

Figure 9 Scenarios of building height (from left to right is Scenario 1, Scenario 2, Scenario 3 and Baseline)

Table 6 Scenarios of building height

Scenario	Front row	Middle row	Third row
Scenario1	6-storey	14-storey	22-storey
Scenario2	10-storey	14-storey	18-storey
Scenario3	12-storey	14-storey	16-storey
Baseline	14-storey	14-storey	14-storey

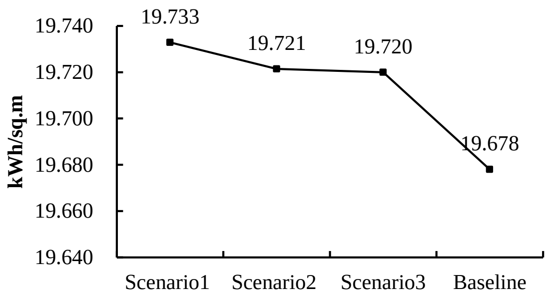

Figure 10 Relationship between energy consumption and building height

Orientation

The orientation of the baseline model is south. Figure 11 illustrates how the building north axis rotates to correspond with one of the major axes of an actual building. The energy consumption is simulated every 15 degree.

The building orientation changes primarily because of the variation of the acceptance toward solar radiation. Figure 12 shows that the minimal energy consumption occurs when the building faces south.

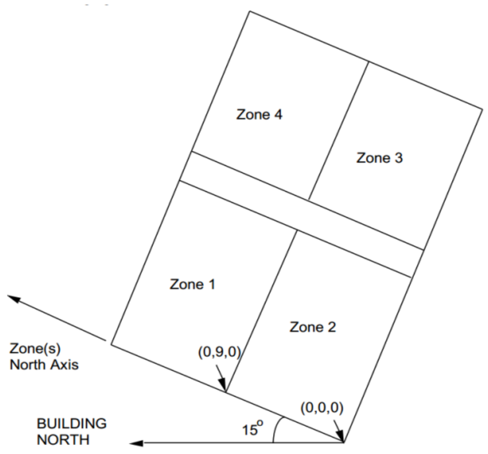

Figure 11 Building north and the rotation

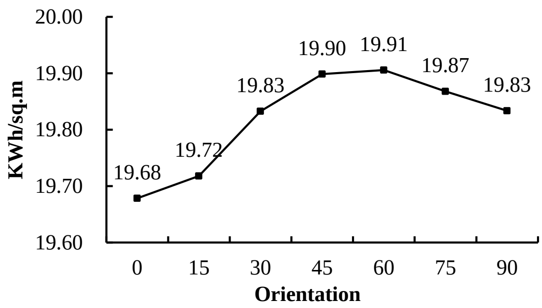

Figure 12 Relationship between energy consumption and orientation

Building density

This subsection shows the results of energy use against building density. Building density means the proportion of the total building bottom space and planning space. With the same total building area and floor space of each building, the buildings are divided into 4 scenarios for simulations respectively, as shown in Table 7. The baseline case is the typical 14-storey buildings as mentioned before.

Table 7 Scenarios of building density

Scenario	**Building density**	**Storey**	**Quantity**
Scenario1	0.0242	84	1
Scenario2	0.0484	42	2
Scenario3	0.0968	21	4
Baseline	0.1452	14	6

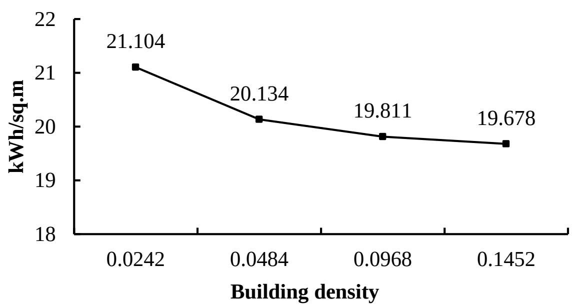

Figure 13 Relationship between building density and energy consumption

It can be concluded from Figure 13 that there exists a strong negative correlation between the two variables. That is to say, the energy consumption per unit area decreases with the increase in density of buildings. Based on this analysis, with the same building area ($60000m^2$), the energy use can be totally different. Among all the variables presented in this subsection, building density shows the strongest correlation with energy demand. Therefore, it is of importance to set an appropriate building density.

VALIDITY AND RELIABILITY

This section presents the validity and reliability test through the model calibration and the verification of the simulated results. The prototypical model is calibrated to meet the data of the Shanghai Statistical Yearbook. We tuned the lighting power, equipment power and other factors to calibrate the model.

The typical types of the residential building are selected based on the Shanghai Statistical Yearbook of 2013. Moreover, the final model is based on the field investigations and measurements. In the last five years, the energy consumption of the residential buildings has reached a stable level, at about 30kWh/(m^2 a). The total energy consumption and the sub-entry energy consumption of those models are close to the data of Shanghai Statistical Yearbook. The energy consumption of China is lower than that of the developed countries. This is mainly because the inhabitants in China always open the windows for ventilation, and have less consciousness to use air-conditioner in winter or summer, especially in winter. According to the results, a household living with a low density causes more energy consumption. This conclusion is the same as the previous description (Ewing and Rong, 2008). Likewise, the heating consumption of the buildings has less relationship with the building types. The conclusion is similar to the results from LSE (2011) in London.

Considering different constitutions of human rest time, totally four scenarios are conducted to reflect this phenomenon (see Table 2). The simultaneity usage coefficient is also taken into consideration since the same schedule is not available for the buildings in the same district. We conduct two plans, as can be seen in Table 8. The simultaneity usage, however, is used to balance the buildings distinction on schedule of the air-conditioning operating time and human behaviours. The district of the 6-storey buildings is selected as the sample for evaluating to what extent the simultaneity usage may affect the energy consumption.

Through calculation, the energy consumption of Plan 1 is $22.96kWh/m^2$, while that of adopting Plan 2 is $25.16kWh/m^2$. To explain the difference of every building, we suppose that five buildings utilize Plan 1, while five buildings utilize Plan 2. The result is $24.06kWh/m^2$. Related energy consumption can vary about: (24.06－22.96)/22.96 = 4.8%.

Table 8 Settings of the schedule plans

	NO	PROPORTION
PLAN 1	Scenario 1	0.4
	Scenario 2	0.2
	Scenario 3	0.15
	Scenario 4	0.25
PLAN 2	**NO**	**PROPORTION**
	Scenario 1	0.2
	Scenario 2	0.4
	Scenario 3	0.15
	Scenario 4	0.25

It can be concluded that the simultaneous coefficient have some impact on the energy consumption due to a variation of about 5% in total energy use. However, it is not the key factor of the district energy use. Therefore, in this study, we ignore the effect of the simultaneity usage.

CONCLUSIONS

This research displays how morphology can affect the energy consumption in two aspects. One is to select seven types of typical residential morphology in Shanghai to study the energy consumption at the neighborhood scale (200m×150m). The other is to analyze the effects of different morphology indexes on the energy consumption of the 14-storey residential districts in the same FAR.

The research on the morphology of the residential district is based on real typical districts in Shanghai, including the garden houses, 6-storey flats, 14-storey flats, 28-storey flats, lane houses and two types of mixed houses. The garden house costs the most total energy consumption than other districts, followed by the mixed house, the lane house and the 14-storey building. In addition, the 14-storey building, 28-storey building and 6-storey building share similar results. The energy saving through daylighting in the garden house ranks the first as well as the natural ventilation. The energy use of the mixed buildings consumes just below that of the garden house. The lane house does not seem to have the daylighting energy-saving potential. Besides, natural ventilation in high-rise buildings is less useful.

From Comparison between FAR and total energy consumption, we can find that these two indexes have a linear relationship. That is, the higher the FAR, the higher the total energy use. The linear equation is $y = 71.668x - 1.2737$ ($R^2 = 0.938$), where y is the 10000 times of the energy consumption (kWh), and x is the FAR. Different types of building morphology result in distinctively different energy consumption values. The building distance, building height, orientation and building density are found to be good indicators of morphology, which may correlate well with the energy use. While among the four index, the best performance is the building density, followed by the orientation. In addition, the building height and building distance seem to have no significant relationship with energy consumption.

It can be concluded that the most energy-efficient residential district design should be all the buildings with the same medium height, a south orientation, and relatively complicated appearances.

REFERENCES

Baynes T, Bai X. 2009. Trajectories of change: Melbourne’s population, urban development, energy supply and use from 1960–2006. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Chen Y., Wong N. H. 2006. Thermal benefits of city parks. Energy and Buildings, 38: 105-120.

Ewing R., Rong F. 2008. The impact of urban form on U.S. residential energy use. Housing policy debate, 19(1): 1-30

Greed C. 2004. Introducing Planning. Continuum International Publishing Group, London.

Kolokotroni M., Giannitsaris I., Watkins R. 2005. The effect of the London urban heat island on building summer cooling demand and night ventilation strategies. Solar Energy, 80: 383-392.

LSE cities, EIFER, Urban Morphology and Heat Energy Demand [R]. CITIES AND ENERGY. 2011: 4-4

Salat S. 2009. Energy loads, CO_2 emissions and building stocks: morphologies, typologies, energy systems and behaviour. Building Research & Information, 37(5-6): 598-609.

Wang J., Ma J. 2013. Shanghai Statistical Yearbook. China Statistics Press [in Chinese].

Wong N. H., Jusuf S. K., et al. 2011. Evaluation of the impact of the surrounding urban morphology on building energy consumption. Solar Energy, 85(1): 57-71.