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A Parametric Study on the Community Form and Its Influences on Energy Consumption of Office Buildings in Shanghai

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Abstract

This paper aims to study the impact of community form on building energy consumption of commercial district. Building typology and FAR (floor area ratio) are two important morphology factors in district energy efficiency design. To explore how they influence building energy consumption, two major questions are concerning: (1) how a given FAR generates alternative building typologies that have different effects on energy consumption? (2) how increasing FAR affects building energy consumption generally? In this paper, a group of representative hypothetical models are built based on the form of actual office buildings in Shanghai. The energy consumption of three building typologies (the pavilion, the slab and the courtyard) are examined using DesignBuilder and EnergyPlus. The results suggest that, with the same building density, office building energy consumptions have a positive relationship with FAR, and different building typologies can lead to variations in energy consumption as well as energy-FAR relationship.

Keywords: Community form, Energy consumption, Building typology, FAR, Office building;

1. Introduction

In a rapidly urbanizing world, the number of urban dwellers exceeds half of the world's population, and the proportion is on the rise [1]. China has an urban population growth of more than 500 million people over the past 35 years [2], accompanied by sharp increase of energy use. According to IEA [3], urban areas account for two thirds of the global primary energy demand, which urgently calls for significant reductions in urban energy use and emissions.

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Buildings contribute a lot to the total energy consumption in cities with a rate of 32% on average and 20%-40% in developed countries [4,5]. In principle, building energy consumption mainly depends upon three type of factors: building design, systems efficiency and occupant behavior. Among them, building design has the most remarkable effect by leading 2.5 times variation in energy use [6]. It is also argued that urban context play equally important roles as these three factors in energy consumption, while the contribution of the urban form is not quantified on account of regional differences and variable interactions [7].

Efforts have been made to explore the impact of urban form by using parametric study to examine the effect of morphology factors within community scale. Building typology and FAR are two important morphological parameters identifying community form by specifying the surrounding environment, building compactness and spatial characteristics. The floor area ratio reflects the total building capacity on a piece of land, which is usually used to measure land development intensity. The formula (1) shows the definition of FAR. It is also explained as formula (2), where building density equals to floor area/planning area.

$$\mathrm{FAR} = \frac{\text{Total Building Area}}{\text{Floor Area}} \tag{1}$$

$$\mathrm{FAR} = \text{building density} \times \text{floor numbers} \tag{2}$$

Quantities of researches have been conducted focus on these two morphological parameters. Steemers [8] assessed the energy trend and implications of varying FAR by applying the lighting and thermal (LT) method. Salat [9] investigated the influences of building typology on energy efficiency using statistical analysis based on a large case study in Paris. Rode et al. [10] used digital elevation model (DEM) simulation to study the effect of morphological parameters on heating energy demand of residential buildings. The energy-FAR relations of offices with different building typologies have been examined by conducting a series of parametric simulation experiments in Quan et al.'s research [11]. Detailed simulations were carried out on geometrically simplified models to calculate the impact of building typology on total energy demand in Tereci et al.'s research [12]. However, these researches reveal significantly different findings about the relationship between community form and building energy use.

This paper tries to explore how community form influences building energy consumption concerning two main questions: (1) how building typology affects energy consumption with a given FAR, (2) how increasing FAR influences building energy use. With the help of dynamic simulation software DesignBuilder and EnergyPlus, a group of representative hypothetical models are built based on the form of actual office buildings in Shanghai. The energy consumptions of three basic building typologies are examined: the pavilion, the slab and the courtyard [13]. The energy-FAR relationships with different building typologies are also studied.

2. Methods

The methodological framework of this study can be generalized as the following steps:

1) Select a representative actual office building as the experimental basis and determine the morphological parameters to be examined, including building typologies and the range of FAR that will generate an array of cases.

2) Specify the thermophysical, occupant related and operational characteristics of the building following the relevant standards.

3) Conduct energy simulations of a series of experimental models using dynamic simulation software DesignBuilder4.7 and EnergyPlus8.4. Calculate annual energy use intensity (EUI) for cooling and heating of each model.

2.1. Morphological parameter settings

Based on the form of actual office buildings in Shanghai, a group of representative hypothetical models are built within an area of 150m×150m. The practical building groups are located in the west of Shanghai Hongqiao Central Business District (Fig.1).

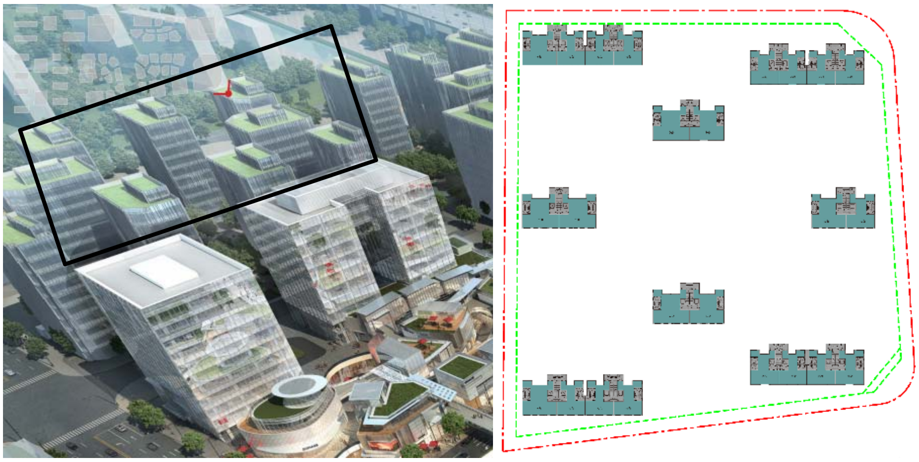

Fig. 1. (a) The sketch and (b) plan of the office building in Shanghai Hongqiao.

With a given building density of 16.9%, three archetypal building typologies are studied: the pavilion, the slab and the courtyard (Fig.2). FAR ranges from 1.56 to 3.12 by specifying different number of floors (10, 15 and 20) and building height ranges from 32.5m to 65m. The orientation of the buildings are south.

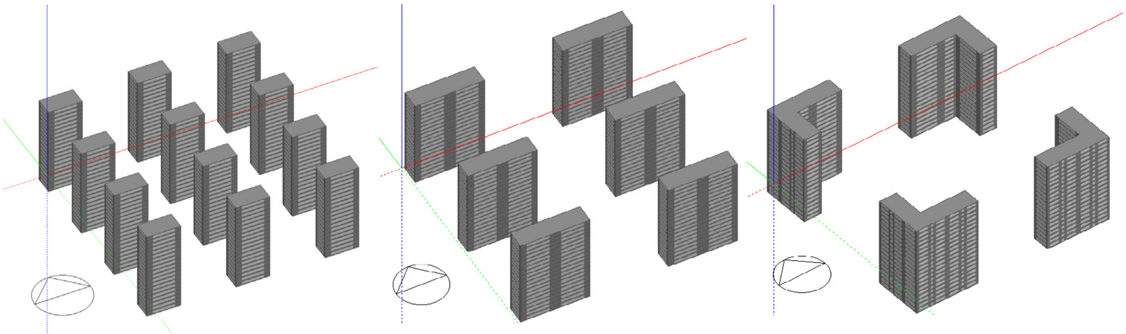

Fig. 2. *The geometrical models of three building typologies (a) Pavilion; (b) Slab; (c) Courtyard.*

2.2. Climatic data

The simulations are conducted for the city of Shanghai, which can be treated as a typical zone in hot-summer-and-cold-winter area of China. The heating period starts from October 1st to February 28th, while the cooling period starts from June 15th to August 31st. The TMY (Typical Meteorological Year) weather data of Shanghai is used in the simulations.

2.3. Detailed building information

Detailed building information(Table A1) and operational schedules(Fig.A1) required by the energy modeling other than building typology are fixed and determined according to the local energy efficiency standards.

2.4. Elevator energy use

In general, elevator energy demand of high-rise office buildings should be included in total energy use as process load. Elevator design parameters have been determined in accordance with practical office building requirement and following the relevant criterions (Table A2). The elevator energy consumption of each models are calculated as shown in Table 1.

Table 1. Elevator energy use calculation.

Typology	Elevator power (kW)	Number of elevators	Operation time (h/day)	Operation days	Demand factor	Diversity factor	Electricity consumption (kWh/a)	Energy use per area (kWh/m^2)
10-stories Pavilion	11	24	12	260	0.25	0.85	175032	5.03
15-stories Pavilion	15	36	12	260	0.22	0.78	289112	5.54
20-stories Pavilion	18.5	48	12	260	0.2	0.72	398961	5.73
10-stories Slab	11	18	12	260	0.22	0.78	106008	3.02
15-stories Slab	15	30	12	260	0.2	0.67	188136	3.58
20-stories Slab	18.5	48	12	260	0.19	0.56	294788	4.2
10-stories Courtyard	11	16	12	260	0.2	0.72	79073	2.25
15-stories Courtyard	15	28	12	260	0.19	0.59	146896	2.78
20-stories Courtyard	18.5	48	12	260	0.18	0.48	239376	3.4

2.5. Daylighting control

Daylighting control is considered in the models to study the influences of community form on the utilization potential of daylight. Two monitoring points are set in the perimeter zone (5m depth) of each floor with the height of 0.8m. The lighting control strategy is 3-stepped control and the illuminance setpoint is 500 lux at the reference points.

3. Results

This section presents the energy consumption results of the array of experimental models. The Basic Scenario (without daylighting controls) and Daylighting Scenario (with daylighting) are examined in the experiment. Generally, EUI values represent the annual energy use intensity without daylighting controls. The natural gas consumptions for space heating have been converted into the equivalent electricity consumptions with the coefficient of 65.9% following the local standards.

3.1. Building typology and energy

Three building typologies are generated and studied with a given setting of density (16.9%) and FAR range (1.56-3.12). The simulation results suggest that the Pavilion consumes the most energy for both heating and cooling, while there is no much difference between the Slab and the Courtyard (Table 2). Among the energy consumptions for end-use, elevator energy use intensity varies significantly of three building typologies. Results also show the uniformed total EUI ranking with different settings of FAR: Courtyard<Slab<Pavilion. However, the Pavilion has the largest amount of energy savings as daylighting is used, followed by the Courtyard and the Slab.

Table 2. *Annual energy use intensity of three building typologies*.

Typology	FAR	S/V ratio	EUI for heating ($kWh/m^2 \cdot y$)	EUI for cooling ($kWh/m^2 \cdot y$)	EUI for elevators ($kWh/m^2 \cdot y$)	Total EUI ($kWh/m^2 \cdot y$)	Daylighting energy savings
10-stories Pavilion		0.27	14.78	13.54	5.03	115.42	16.03%
10-stories Slab	1.56	0.22	14.60	13.21	3.02	112.87	15.57%
10-stories Courtyard		0.21	14.61	13.34	2.25	112.28	15.99%

15-stories Pavilion		0.26	14.80	13.54	5.54	115.94	15.77%
15-stories Slab	2.34	0.21	14.60	13.24	3.58	113.46	15.29%
15-stories Courtyard		0.20	14.60	13.38	2.78	112.84	15.77%
20-stories Pavilion		0.25	14.82	13.51	5.73	116.13	15.64%
20-stories Slab	3.12	0.21	14.62	13.24	4.20	114.10	15.03%
20-stories Courtyard		0.19	14.60	13.38	3.40	113.46	15.61%

3.2. Building typology, FAR and energy

The results suggest a positive relationship between FAR and energy use of all building typologies (Fig.3). With the same building density, energy consumption of the Pavilion generally increases and saturates with increasing FAR, while energy use of the Slab and the Courtyard have approximately linear positive correlation with FAR. Similar results can be found when daylighting control is taken into consideration. Moreover, the EUI gap between different typologies reduces as daylighting is used.

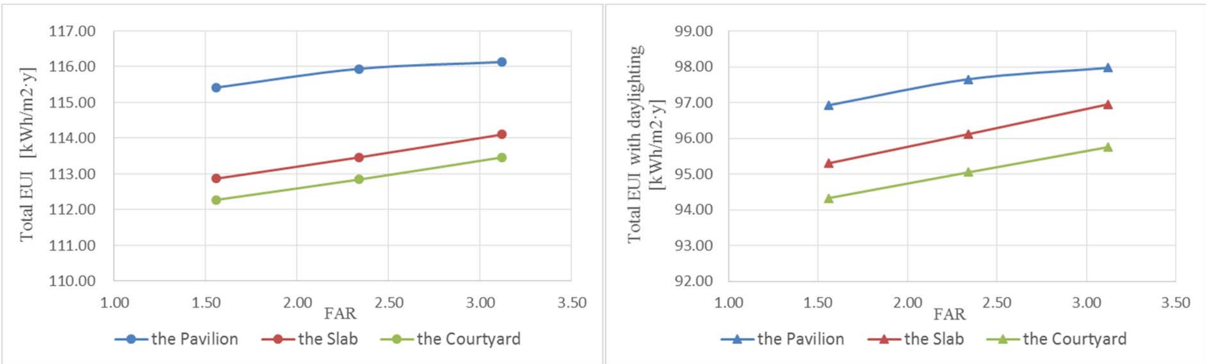

Fig. 3. Energy-FAR relationship of three building typologies without (a) or with (b) day lighting.

4. Discussion

The parametric study reveals how community form affects energy consumption of office buildings for the hot-summer-and-cold-winter climate. With the same building density of 16.9%, office building energy consumptions have a positive relationship with FAR and the Courtyard has the best energy performance among three building typologies, followed by the Slab and the Pavilion.

On one hand, the energy demand for heating mainly depends on the thermal properties of the envelope as well as the solar heat gain on the facade of the buildings. In Shanghai, the southern walls and windows of the buildings usually receive more solar radiation in the winter due to the altitude and azimuth of the sun. Among three building typologies, the Pavilion has the largest S/V ratio which results in great amount of heat loss from the envelope in the winter. Along with the small solar radiation area on the southern surface on account of the shading between the buildings, the Pavilion consumes the most energy for heating.

On the other, the ventilation and shading conditions play important roles in determining the cooling energy demand of the buildings in Shanghai. With the higher solar elevation angle, most of the solar radiation concentrated on the eastern and western walls and windows in the summer. Compared with the Courtyard, the south-oriented slab buildings have smaller surface area on the east and west, which reduces the energy use for cooling. However, the large amount of heat gain through the envelope as well as the compact arrangement causing heat accumulation within the community have led to the highest cooling energy consumption of the Pavilion.

Moreover, elevator energy consumptions are indispensable parts of the total energy use in high-rise buildings, which could be easily neglected. The number and the operation pattern of elevators vary a lot with different form of office buildings, which results in distinction between elevator energy demands. In this experiment, the elevator energy use intensity of the Pavilion, the Slab and the Courtyard decreases successively for total number of elevators required by the buildings reduces as well as the demand factor and the diversity factor (Table 1). It follows that with the equivalent total building area, reducing the number of buildings within the community facilitates reduction in elevator energy demand. Since the elevator consumption is the most remarkable factor affecting the total EUI of three building typologies, the approximately linear FAR-energy relations presented in this study mainly depend on the increase of elevator energy use with higher building height.

This study also examines the energy saving potential of daylighting with different community form. The availability of daylight is generally related with the interaction of buildings within the community, the less the building blocks each other the more daylight is available to the buildings. The arrangement of monitoring point and control strategy of the daylighting systems are important factors influencing the energy savings beyond shading conditions. It can be concluded from the results that the Pavilion benefits from daylighting effectively while the energy saving potential of the Slab is limited.

The experiments have been conducted to explore the community form that has better energy performance for sustainable urban design. However, this study only focus on the influence of building typology and FAR with a certain building density, which cannot represent various form of office buildings in Shanghai. Another element that limits this study's scope is that the range of FAR excludes the respectable ultra-high-rise buildings in Shanghai. Therefore, further research could extend the range of morphological parameters.

5. Conclusion

This study reveals how community form influence building energy consumption of commercial district in Shanghai by using parametric study. A group of experimental simulations are conducted using EnergyPlus to better understand the role of community form in district energy efficiency design. Two major questions are addressed: how building typology affect energy consumption and what is the relationship between FAR and energy consumption?

Regarding the questions above, the present study has demonstrated that: (i) The Courtyard has the most efficient energy performance under the density of 16.9%, followed by the Slab and the Pavilion. (ii) With FAR in the range of 1.56 to 3.12, the energy consumption of three building typologies have positive relations with FAR, and energy use of the Pavilion generally increases and saturates with increasing FAR while energy-FAR relationship of the rest two typologies are approximately linear. (iii) Elevator energy use of high-rise buildings are notable factors in affecting energy consumption of different building typologies. (iv) The utilization of daylighting in the Pavilion facilitates reduction in energy consumption effectively.

Hence, it follows that the Courtyard and the Slab are recommended typologies in energy efficiency design of high-rise office buildings in Shanghai for the local conditions of density, FAR and climate. These two building typologies have smaller S/V ratios and better shading conditions, which assist to store and dissipate heat in cold-winter-and-hot-summer area. Moreover, optimal district energy performance can be achieved through improve the design of the elevator systems and the utilization of day lighting.

These findings can provide reference for future urban planning and district energy efficiency design in areas with climatic conditions similar to Shanghai. While this study mainly focus on high-rise offices with a certain density, respectable ultra-high-rise buildings as well as different building density settings could be covered in the experiment. These could be included in further research.

Appendix A. Building input parameters

Table A1. *Detailed building information*.

Basic Information		Building Envelope		Internal Load			HVAC System	
planning area	22500m^2	roofs U-value	0.5 W/m^2·K		office	other area	system type	fan-coil with DOAS
floor area	3801.6m^2	exterior walls	0.8	occupant	8m^2/人	10m^2/人	indoor design	cooling 25℃/

		U-value	W/ m^2·K				temperature	heating 20℃
building density	16.90%	window to wall ratio	0.4	lighting power density	11W/ m^2	14W/ m^2	operation time	7:00~18:00
FAR	1.5~3.2	Windows U-value	2.0 W/ m^2·K	equipment power density	20W/㎡	0	cooling equipment	water-cooled screw chiller: COP=5.0
floor height	3.25m	Shading coefficient	0.35	min. fresh air	30 m³/人·h	10 m³/人·h	chilled water temperature	7℃/12℃
							condensed water temperature	30℃/35℃
							Heating equipment	gas-fired hot water boiler: efficiency=88%
							hot water temperature	85℃/60℃

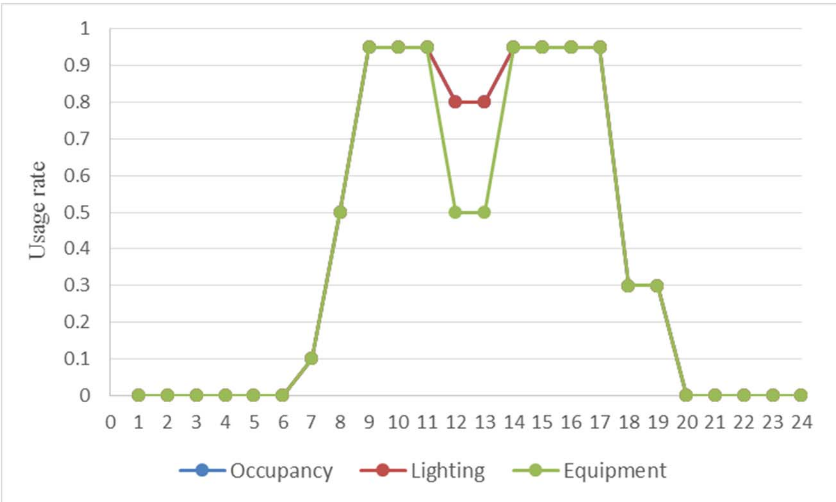

Fig. A1. *Internal loads schedules (occupant schedule is the same as lighting's).*

Table A2. *Elevator design parameters.*

	Occupant density (m^2/p)	Attendance rate	Average running interval (s)	Carrying capacity in 5 min	Velocity (m/s)	Load capacity (kg)	Numbers per building
10-stories Pavilion					1		2
15-stories Pavilion					1.5		3
20-stories Pavilion					1.75		4
10-stories Slab	8	70%	≤60	≥12%	1	1000 (13 persons）	3
15-stories Slab					1.5		5
20-stories Slab					1.75		8
10-stories Courtyard					1		4

15-stories Courtyard	1.5	7
20-stories Courtyard	1.75	12

References

[1] United Nations: World Urbanization Prospects: the 2014 Revision, UN Department of Economic and Social Affairs, Population Division, New York NY, 2014.
[2] The Economist, Urbanisation: Moving on up 2014.
[3] International Energy Agency, World energy outlook 2008, Technical Report, International Energy Agency, Paris, 2008.
[4] IPCC Working Group III, IPCC Fifth Assessment Report: Mitigation of Climate Change, IPCC, Berlin, Germany, 2014.
[5] L. Pérez-Lombard, J. Ortiz and C. Pout. A review on buildings energy consumption information, Energy and Buildings. 40 (2008) 394-398.
[6] N. Baker and K. Steemers. Energy and Environment in Architecture, E&FN Spon, London, 2000.
[7] C. Ratti, N. Baker and K. Steemers. Energy consumption and urban texture, Energy Buildings. 37 (2005) 762-776.
[8] K. Steemers. Energy and the city: density, buildings and transport, Energy and Buildings. 35 (2003) 3-14.
[9] S. Salat. Energy loads, CO_2 emissions and building stocks: morphologies, typologies, energy systems and behaviour, Building Research & Information. 37 (5-6) (2009) 598-609.
[10] P. Rode et al. Cities and energy: urban morphology and residential heat-energy demand, Environment and Planning B: Planning and Design. 41 (1) (2013) 138-162.
[11] S.J. Quan et al. Computing energy performance of building density, shape and typology in urban context, Energy Procedia. 61 (2014) 1602-1605.
[12] A. Tereci, S. T. E. Ozkana and U. Eicker. Energy benchmarking for residential buildings, Energy and Buildings. 60 (2013) 92-99.
[13] L. March and L. Martin. Urban Space and Structures. Cambridge University Press, Cambridge, UK, 1972.