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METRICS OF URBAN MORPHOLOGY AND THEIR IMPACT ON BUILDING ENERGY CONSUMPTION： CASE STUDIES IN SHANGHAI

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ABSTRACT

Urban form is a significant factor affecting building energy consumption and district energy efficiency design and its effects are difficult to quantify. This study aims to explore the effects of various urban forms on energy consumption at the community scale.

In this work, different urban forms for non-residential and residential districts were analyzed based on the generic form of buildings in Shanghai in terms of their overall energy consumption. Detailed simulations were carried out to quantitatively evaluate the impact of urban form on heating and cooling energy demand. The effect of morphological parameters including both building typology and urban morphology were examined using a dynamic building energy simulation tool, EnergyPlus.

Keywords: Urban form, Energy consumption, Morphological parameters, Office buildings, Residential buildings

NONMENCLATURE

Abbreviation	
FAR	*Floor area ratio*
S/V	*Surface-to-volume*
WWR	*Window-to-wall ratio*
SVF	*Sky view factors*
BIM	*Building information modeling*
EUI	*Energy use intensity*
TMY	*Typical meteorological year*

1. INTRODUCTION

In recent years, urbanization has significantly increased the capability of a city to further develop itself to meet the needs of migrating inhabitants. In a rapidly urbanizing world, the number of urban residents now exceeds half of the world's population, and this proportion is still rising[1]. According to the International Energy Agency (IEA), urban areas account for two thir ds of the global primary energy demand[2]. As one of the three terminal energy consumption sectors, buildings account for 32% of the total global energy consumption and 20–40% of the total energy consumption in developed countries[3][4]. With increasing urbanization rate and industrialization, energy consumption in the construction industry will continue to increase, which urgently calls for reduction in urban energy use and emissions.

In general, building energy consumption mainly depends on three factors: building design, systems efficiency, and occupant behavior. Baker and Steemers[5] reported that a well-planned urban area can benefit from efficient system design and energy-saving occupant behavior. Furthermore, Wener[6] argued that urban forms are less susceptible to the variation of occupant behavior compared with system performance. It therefore follows that urban form plays an important role in determining the energy consumption, and this contribution is difficult to quantify[7].

Parametric studies on the relationship between urban form and energy use mainly focus on two aspects: architectural form and the regional spatial structure. Architectural form refers to the shape and size of the building, including shading facility conditions and

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building orientation[8]. It also emphasizes the effects of the surface-to-volume (S/V) ratio, building height, passive zone ratio, and window-to-wall ratio (WWR) on building energy consumptions[9][10][11]. Regional spatial structure refers to the spatial arrangement of buildings, streets, and other open areas. The floor area ratio (FAR), building typology, site coverage, and sky view factors (SVF) are general indicators of the spatial structure, which specify the urban form and influence the district energy demand concurrently[12][13].

Many relevant studies mainly focused on some specific locations and climates, especially in heating dominated European cities. It was also observed that the energy performance of residential and non-residential districts was different for the same urban morphology. Since the effect of urban form on energy consumption strongly depends on regional differences and parameter interactions, existing researches did not address a number of issues, such as the synergy of morphological parameters, and recommended a preferred urban form over the rest. The aim of this study is to investigate the effects of various urban forms on building energy performance in a climate that has both heating and cooling requirements. In this study, the impacts of the urban forms were first quantified by simulating the generic forms of buildings at the community scale. Then, we compared the energy use at different settings of morphological parameters.

In this work, a group of geometrically simplified models were developed based on the actual forms of non-residential and residential districts in Shanghai. Detailed simulations were carried out to determine the heating and cooling energy consumption of buildings using EnergyPlus. Parametric simulations were conducted to explore the relationships between urban forms and energy consumption. Metrics of urban morphology

2. METRICS OF URBAN MORPHOLOGY

2.1 Paper structure

in Subsection 2.3, the simulation methodology, including geometrically simplified modeling of complex urban forms and the methodological framework of this study will be given. In this work, an array of simulation cases was generated to yield the correlation between urban form metrics and energy consumption. The detail simulation inputs, including simulated urban form, data input, and diversity factor will be illustrated in Subection 2.4. The simulation results of office communities and residential communities will be analyzed in Subsection 2.5.

2.2 The Scope of this work

The objective of this study is to quantify the relationship between urban morphological metrics and energy consumption.

2.3 Simulation Methodology

The complexity of the existing urban forms makes it difficult to compute all the details with any software. For simplicity, three archetypal building typologies were selected as the study objects based on the case study: pavilions, slabs, and courtyards [14]. These typical urban forms eliminate the complexities of real districts and provide a more systematic comparative analysis of morphological parameters[15].

Hence, the methodological framework of this study can be generalized by the following steps.

1) Select representative real non-residential and residential districts as the basis for the experiments and investigate urban forms with regard to their morphological characteristics.

2) Determine the morphological parameters to be examined, including building typologies, the range of FAR that generates an array of cases, and other architectural form parameters.

3) Specify the thermophysical, occupant-related, and operational properties of the buildings in accordance with the relevant standards.

4) Conduct energy simulations of a group of experimental models, including shading effect simulations. Calculate the annual energy use intensity (EUI) for heating and cooling using EnergyPlus simulation program[16].

2.4 Case Studies

Two case studies in Shanghai were selected to demonstrate the morphological characteristics of non-residential and residential districts, respectively. The classification of generic urban forms was combined with case study and urban planning criteria, thus generating an array of distinct models that can represent the common urban forms in Shanghai. Based on the case study, simulation models for parametric study were developed at a scale of 150 m × 150 m and 200 m × 150 m for non-residential and residential districts, respectively (see Figs 1-2). Parameters related to building typology, site coverage, FAR, and building height were determined in accordance with the case study and

Shanghai Urban Planning and Management Technical Regulations[17].

The non-residential sector is so diverse that this study focused on Shanghai office buildings—the predominant non-domestic building type. Three archetypal building typologies were examined under the same site coverage of 16.9%: the pavilion, the slab, and the courtyard (Fig.1). The ratio of the total building area to the floor area is determined to be in the range of 1.56–3.12 by specifying different number of floors (10, 15, and 20). The building height is in the range of 32.5–65 m, which represents high-rise offices in Shanghai. The orientation of the buildings is southward. With these distinct models, the effects of building typology and FAR on energy consumption can be investigated.

For residential quarters, various number of floors were specified for buildings with the same FAR of 2.0. By varying the height, orientation, and the distance of the buildings within residential quarters, the effects of morphological parameters other than the building typology were analyzed.

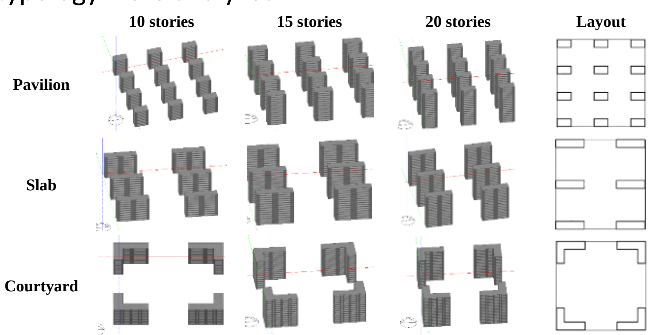

Fig 1 EnergyPlus models and layout of building typologies for official districts

For data input of the building level, the simulations were carried out according to the relevant thermal standards in order to conduct a parametric study. The morphological characteristics and building properties of the experimental models used in the simulation are given in Table 3.

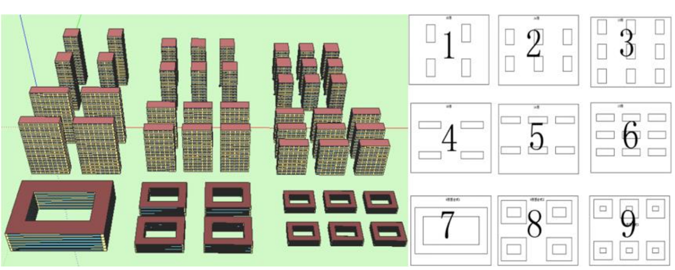

Fig 2 EnergyPlus models and layout of building typologies for residential quarters

Table 3
Morphological characteristics and building properties of the models.

(a) Morphological characteristic

	Office buildings	Residential buildings
Planning area	150 m × 150 m	200 m × 150 m
Site density	16.90%	11.11–33.3%
FAR	1.5–3.2	2.0
Building height	32.5–65m	18–54m

(b) Building Envelope

	Office buildings	Residential buildings
U-Roof	0.5 W/(m^2·K)	0.8 W/(m^2·K)
U-Wall	0.8 W/(m^2·K)	0.93 W/(m^2·K)
U-Window	2.0 W/(m^2·K)	5.78 W/(m^2·K)
WWR	0.4	0.2

Taking the diversity of occupant's schedule in each residential building into account, a scenario analysis-based approach was proposed to define diversity factor of residential buildings (Table 4). Daily schedules of occupancy, lighting, appliance and air conditioning were determined in each scenario. Besides, considering the proportion of each scenario in a residential building, two proposals were assumed (Table 5).

Table 3
Scenarios assumed in residential buildings

	User usage
Scenario 1	Weekday evenings and weekends at home
Scenario 2	Weekday and weekend at home
Scenario 3	At noon on weekdays at home, weekends are not at home
Scenario 4	Weekday is not at home, weekend at home

Table 4
Proposals with different proportion of scenarios.

	Proposal 1	Proposal 2
Scenario 1	0.4	0.2
Scenario 2	0.2	0.4
Scenario 3	0.15	0.15
Scenario 4	0.25	0.25

The energy consumption of a 6-story typical residential apartments as model with two aforementioned proposals was simulated respectively. The results demonstrate the difference in total energy consumption due to different proposals is 4.8%, which is relatively small. Therefore, in the following discussion, diversity factor is not a factor to consider.

2.5 Results

2.5.1 Office Buildings: Influence of building typology

By specifying different number of floors in the buildings, three classes were developed based on FAR (low, medium, high classes). The energy demand of three building typologies at different floor area ratios are presented in Table 5 For low FAR classes, the pavilion type consumed the highest energy for heating among the three building typologies, while the slab and the courtyard types had comparable heating energy demand. The results also indicate a close relation between the S/V ratio and heating energy consumption: the pavilion type had the largest S/V ratio and the highest heating demand. It is not difficult to understand that building surface areas increase with increasing S/V ratio, thus leading to a high amount of heat loss from the envelope in winter.

Table 5

Heating and cooling energy demand of office buildings with different building typologies.

Building typology	Layout	FAR	S/V ratio	Heating energy demand [kWh·m^{-2}·a^{-1}]	Cooling energy demand [kWh·m^{-2}·a^{-1}]
10-story pavilion	+ 10		0.27	14.78	13.54
10-story slab	+ 10	1.56	0.22	14.60	13.21
10-story courtyard	+ 10		0.21	14.61	13.34
15-story pavilion	+ 15		0.26	14.80	13.54
15-story slab	+ 15	2.34	0.21	14.60	13.24
15-story courtyard	+ 15		0.20	14.60	13.38
20-story pavilion	+ 20		0.25	14.82	13.51
20-story slab	+ 20	3.12	0.21	14.62	13.24
20-story courtyard	+ 20		0.19	14.60	13.38

In terms of the cooling demand, the slab type had the lowest energy consumption. Owing to higher solar elevation angle in summer, most of the solar radiation is concentrated on the eastern and western walls and windows. Hence, the south-oriented slab office buildings obtained less solar heat gains for smaller surface areas in the east and west. On the other hand, the courtyard office buildings that are subjected to mutual shading by adjacent buildings had a lower cooling demand than the pavilion type.

Similar results were observed for the medium and high FAR classes. In other words, the pavilion type offices required significantly higher energy for both heating and cooling, while the south-oriented slab buildings yielded the best performance in terms of the sum of heating and cooling energy demand.

2.5.2 Office Buildings: Influence of Floor Area Ratio

The experiments were further extended to investigate the influence of FAR on the energy consumption of office buildings. The energy–FAR relationships of three building typologies are shown in Fig 6 (left). The results show similar trends in the energy–FAR relationships and a uniform total EUI ranking for different FAR settings: Courtyards<Slabs<Pavilions. In terms of the trend of the curves, the results show a positive relationship between FAR and the energy consumption per area of all building typologies. For a range of FAR of 1.56–3.12, the EUI of the pavilion type, slab and the courtyard types had approximately a linear positive correlation with FAR.

Daylighting control was included in the models to investigate the effects of FAR on the utilization potential of daylight in office buildings. Results suggest that the positive energy–FAR relationships still hold when daylighting control is taken into account (see Fig 6 right). The energy use intensity gap between different typologies decreased when daylighting was used. In addition, the total EUI savings of daylighting decreased from 16.03% to 15.64% when FAR increased from 1.56 to 3.12 for pavilion type offices. Similar reductions in the energy saving ratios can be observed for the slab and courtyard typologies. For the same floor area, it is possible for the low-rise and mid-rise building groups to maintain solar access rights to all buildings in a district, while taller buildings are more likely to obstruct the availability of daylight from each other, thus diminishing the energy savings of daylighting control. Hence, for office buildings, energy consumption increased with increasing FAR mostly due to reduced availability of daylight.

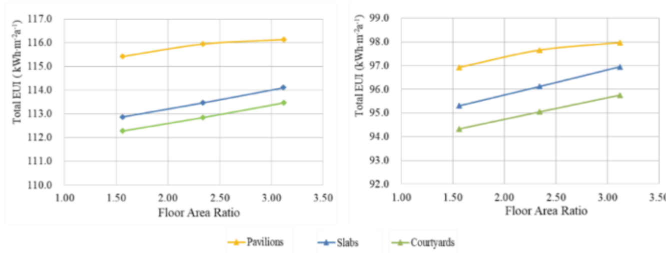

Fig 6 Energy–FAR relationship of three building typologies without (left) and with (right) daylighting

2.5.3 Residential building: Influence of building typology

The multi-story, middle height, and high-rise dwellings are common residential forms in Shanghai at a

FAR value of 2.0. Thus, the building heights were determined as 10-story, 14-story, and 18-story to generate the pavilion type and slab type dwellings, and 6-story for the courtyard houses. The heating and cooling energy demand of the residential quarters with different typologies are shown in Fig.7 and Fig 8, respectively. In each building typology group, the S/V ratio increased as the building serial number increased.

The simulation result of the heating energy demand indicates similar energy consumption trends for different building typologies (see Fig 7). That is, the heating energy demand of the residential buildings increased with increasing S/V ratio. A comparison of buildings with the same number of floors (Buildings 1 and 4, 2 and 5, 3 and 6, Fig. 7) indicate that the slab typology had slightly higher energy consumption than the pavilion typology. Multi-story courtyard houses had the least energy demand for heating as a result of receiving more sunlight on the surfaces and losing less heat through the envelope.

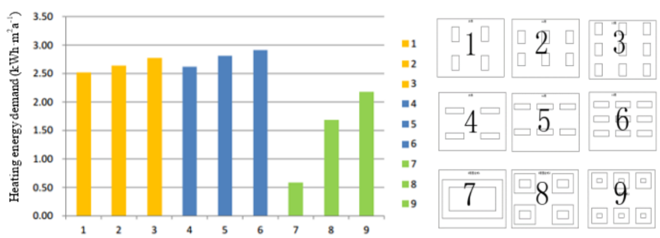

Fig 7 Heating energy demand of residential buildings with different building typologies

On the other hand, the simulation result shows similar cooling energy consumptions for three building typologies (see Fig 8), except building 7. The traditional courtyard house with the largest yard inside (Buildings 7, Fig 8) had up to 55–60% higher cooling demand than other residential buildings because the large open space and low building height expose both the inside and outside building surfaces to solar radiation.

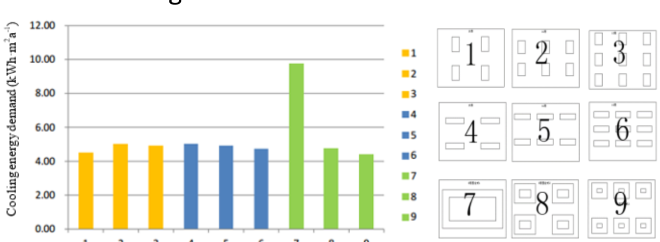

Fig 8 Cooling energy demand of residential buildings with different building typologies

2.5.4 Residential building: Influence of other factors

The experiments were further extended to examine the effect of different building heights on energy consumption with equal FAR. The pavilion type residential quarters consisting of three rows of 14-story apartments were selected as the baseline simulation scenario. The building height was varied by specifying different floors to the three rows of buildings to generate distinct simulation scenarios (see Fig 9).

The simulation results for total energy consumption according building height are shown in Fig 9. Scenario 1, which is the most remarkable in building height difference, consumed the highest energy, while the baseline scenario with the same building heights had the lowest energy demand. Therefore, residential quarters with small differences in building height are recommended in Shanghai.

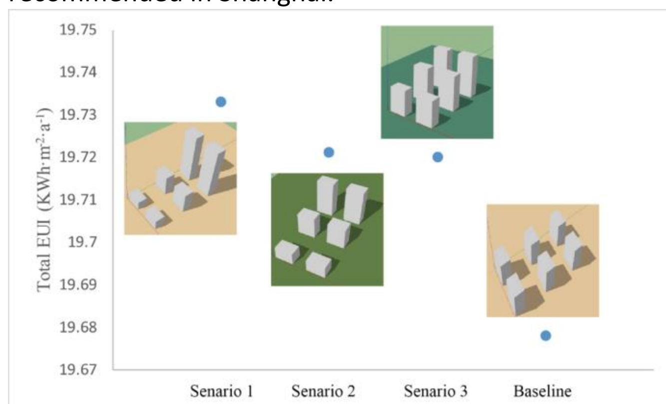

Fig 9 Energy consumption of residential buildings with different building heights

Additionally, the impact of building orientation and building distance were investigated in this paper, and the results were presented in Fig 10 and Fig 11, respectively.

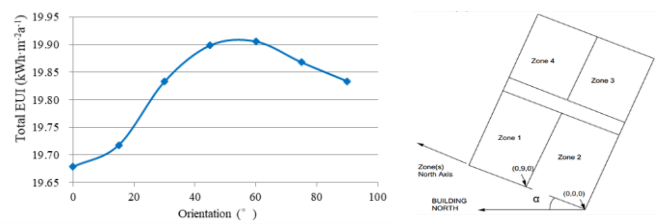

Fig 10 Energy consumption of residential buildings with different orientations

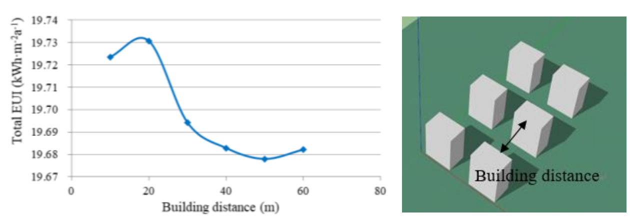

Fig 11 Energy consumption of residential buildings with different building distances

2.6 Discussion and conclusions

In this study, the energy efficient-oriented morphological metrics was determined to characterize the various urban forms, and the influence these metrics on the building energy consumption of office and residential districts in Shanghai was investigated using parametric study. The energy consumption of a group of experimental simulation models with generic urban forms were calculated using EnergyPlus. The effects of building typology on energy consumption, the energy–FAR relationships with different building typologies, and the effects of architectural form parameters were carefully analyzed. By this work, the significant and relative insignificant morphological parameters are identified for both residential and office communities.

For office buildings, the present study demonstrated that: (i) generally the courtyard type offices had the best energy performance under different FAR settings, followed by the slab type, and the pavilion typology. (ii) The energy consumption had positive correlations with FAR. (iii) The utilization of daylighting facilitated reduction in energy consumption effectively, as it reduced artificial lighting energy use as well as cooling load. Therefore, the courtyard and the slab are recommended typologies for high-rise office buildings in Shanghai for the local conditions of urban density, FAR, and climate. Moreover, optimal district energy performance can be achieved through improving the utilization of daylight.

For residential buildings, the results indicate that: (i) the most significant impact factor is building typology, the influence of which were balanced between the benefits from decreased heat losses and the non-benefits of reduced solar availability, and traditionally enclosed courtyard houses are not recommended. (ii) Among the architectural form parameters, building orientation also had an impact on the variation of energy consumption and N-S orientation had an overall advantage in reducing energy use compared to other orientations. (iii) Increasing the differences in the building height resulted in increase in the energy consumption. (iv) The energy consumption decreased as the building distance decreased and the optimal building distance seems to be at 50 m for a group of 42 m high pavilion type residential buildings with FAR value of 2.0. In conclusion, south oriented middle high-rise residential quarters with aligned building height as well as a relatively complex façade structure are preferred in the community design of Shanghai.

This study neglected the impacts of the underlying surface and afforestation on the energy consumption of an urban area. It should be involved in the future work.

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