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Computing energy performance of building density, shape and typology in urban context

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Abstract

This paper aims to better understand the impact of urban context on building energy consumption. The factors of external shading, shapes generated from zoning ordinances, and local climate are examined concerning three main questions: (1)how density influences building energy consumption generally, (2) how a given density generates alternative building shapes that have different impacts on energy performance, and (3) how different typologies affect the energy-density relationship. To answer them, a series of parametric simulation experiments are conducted based on Martin and March's urban block structure. For more than 14,000 hypothetical models located at the Portland urban grid, the energy consumptions for the purposes of cooling and heating are simulated using AutoCAD script, MATLAB and EnergyPlus 8. The results suggest that, different from the common perceptions, building energy consumptions for cooling and heating purposes do not always have a negative relationship with density. Instead, the energy consumption has a negative relationship with density before a turning point, and then the relationship changes to be positive. Also with the same FAR, different building cover ratio and typologies can lead to large variations in energy consumption. By the experiments on different building shapes generated by urban frit, it was found that even with the same typology, the building energy consumption can still vary significantly. Finally, the exploration of climate factors indicates that in both Portland and Atlanta, the findings are similar except that the energy-density relationship is weaker in Atlanta than in Portland.

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Keywords: energy performance; building density; building typology; urban block structure; urban frits; urban context

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1. Introduction

Building energy use has a large share of the total energy consumption in cities. It is argued that at least four factors affect energy performance of buildings: building design, HVAC system, occupancy behavior and urban contexts [1]. Among them, the urban context plays a critical role by specifying the surrounding environment, the local climate, and building shapes. However, research in the field of building energy has generally been divided between the city level and the building level [2, 3], with neither of them sufficiently addressing the importance of urban contexts. A few attempts that tried to bridge the two, but they didn't consider how building shapes and surrounding environment could vary at a given site.

This paper tries to fill such gaps by using a parametric study to explore how density, building shapes and building typology jointly influence building energy performance within urban contexts. Three major questions are addressed: (1) How increasing density affects energy performance, (2) how a given density generates alternative building shapes based on zoning parameters of FAR (floor area ratio) and Coverage (cover ratio), and (3) how a given setting of FAR and Coverage lead to various energy performances with different building typologies. Shape possibilities within typology and climate factor are also examined.

2. Method

2.1. Parametric Experiment Settings

The method of operating performance measure of building and urban context discussed here is built upon the fundamental work presented in *Urban Space and Structure* [4]. Following Martin and March's modeling method, a dynamic 3 × 3 urban block matrix is designed as the experimental framework with the Portland downtown grid (200 ft × 200 ft block with 60 ft wide street). The central block is the focus, while the eight surrounding blocks provide the urban context. The buildings on the blocks are considered to be office buildings with the shape as prism and each floor height as 13 ft. FAR ranges from 0 to 20, Coverage from 0% to 100% and building height from 0 to 40. Factors other than shapes are fixed with the common settings of office buildings suggested by DesignBuilder 3.2 and EnergyPlus 8. Four building typologies are studied: the Pavilion, SlabH (horizontal slab), SlabV (vertical slab) and Courtyard (Fig 1).

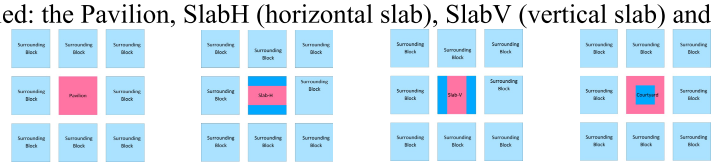

Fig. 1. The four typologies locating at the center block (a) Pavilion; (b) SlabH; (c) SlabV; (d) Courtyard

2.2. Modeling and Simulation

The experiment models are generated using AutoCAD 2013 C# script and MATLAB 2013a. EnergyPlus 8.0008 is used to run the experiments to calculate the energy demand density of annual cooling and heating of the sample building. To explore shape possibilities, urban frit, a bottom-up model to automatically generate building shapes, is introduced to advance Martin and March's archetypal method. It uses cellular grid patterns to enumerate all possible and distinct building shapes [5, 6].

3. Analysis

3.1. Density and Energy

The Isolated Scenario (without surrounding buildings) and Shading Scenarios (with surroundings) are examined in the experiments, assuming Pavilion typology (Coverage: 50%, FAR: 0.5 – 20). The results suggest significant external shading effect and segmented relationship between energy consumption and density: the energy decreases with increasing density at first, and after a turning point, begins to increase.

3.2. Density, Coverage and Energy

The Coverage is further introduced into the experiment following Coverage = FAR / Floor number. The simulation result shows that with the same FAR such as 3, the overall building energy generally decreases and saturates with increasing Coverage. A further set of experiment are done to examine how energy performance responds to FAR under different Coverage settings. The results suggest Under all Coverage settings, the segmented energy-density relationship still holds, as shown in Fig 2. However, the significances of the trend, the magnitudes and the turning points are different with various Coverages.

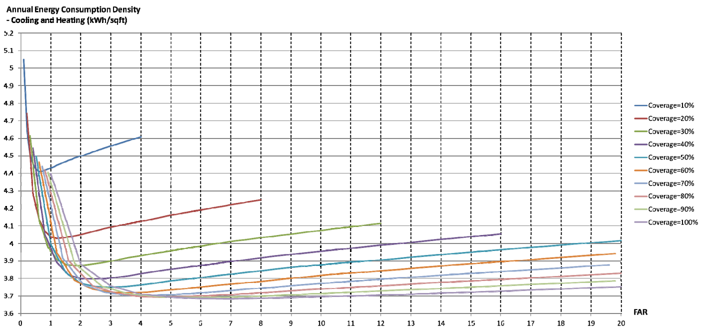

Fig. 2. Energy-FAR relationship with different Coverage settings

3.3. Density, Coverage, Typology and Energy

The experiments are further extended to include all four typologies. The results show all typologies have similar trends of energy-density relationship and within-density energy variation. The question of "which building typology has better energy performance" for sustainable urban design which goes beyond Martin and March's search for most economic urban forms [2, 7] is further studied by experiments. Results show two energy consumption rankings against FAR: SlabH<Pavilion<SlabV<Courtyard and Pavilion<SlabH<SlabV<Courtyard. In either ranking, Courtyard consumes the most energy, while SlabV follows it. The competing results between SlabH and Pavilion change with different Coverages.

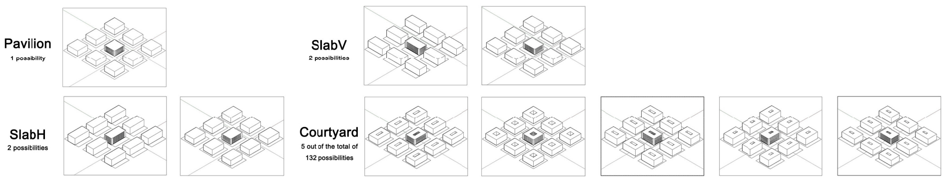

Fig. 3. Shape possibilities generated by Urban Frit with FAR=3 and Coverage=50%

Urban Frit is further used to generate find possible building shapes in the same typology using the 8 ft x 8 ft grid (Fig 3). Experiment results suggest that the number of possible shapes and the variation range could be very large, especially with complex shapes such as Courtyard.

3.4. Climate factor

Urban climate is another urban context factor that influences building energy consumptions [8]. Comparison experiments in Atlanta (Mixed Humid Climate Zone) and Portland (Marine Climate Zone) suggest similar findings in except the weaker energy-density relationship in Atlanta than in Portland.

4. Conclusions

This theoretical study reveals how urban contexts influence building energy performance. Three main questions are answered: how increasing density affects energy performance, how cover ratio impacts energy performance with given density, and how typology influences energy performances with a given setting of FAR and Coverage.

For the first question, different from the commonly conceived energy-density relationship among scholars, this study finds that this relationship is a segmented one that the energy consumption decreases with increasing FAR before FAR reaches a specific turning point, and then the relationship reverses. Such a relationship applies to both Isolated and Shading Scenarios but the energy consumption levels differ.

For the second and the third questions, the study points out that FAR is not the only factor that influences the energy performance. Even with the same FAR, building shapes can vary significantly with different Coverages and typologies, which lead to different energy consumptions. Generally the energy consumption decreases with increasing Coverage, and the Courtyard consumes the most energy while Pavilion or SlabH consumes the least depending on the settings. Furthermore, even with the same typology, possibilities of building shapes still result in significant variations of energy consumption.

The answers are tested in Portland and Atlanta to explore the influence of the climate factor. The energy-density relationship is weaker in Atlanta than in Portland, but the general patterns are similar.

There are still other variables that could be introduced to the study, such as orientation, setback, urban heat island effect, activity schedule, etc. These could be of interest in future studies.

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