Simulating the impact of urban morphology on energy demand in blocks- A case study of dwellings in Nanjing

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Abstract

This study aims to explore the impact of urban morphology on the energy demand of urban residential blocks, using dynamic simulation tools—HTB2 and Virvil Sketchup Extension. The study was conducted in Nanjing, a city with a hot-summer and cold-winter climate that was under great challenges of reducing heating and cooling energy consumption. In particular, the simulation was applied to 35 residential blocks characterized by four types including point-type, line-type, courtyard-type and hybrid-type. Seven indicators were chosen to reveal each block's morphological features and total energy use intensity (EUI) was adopted to assess energy demand. Through correlation analysis and multiple regression analysis, this study verified a quantitative correlation relationship between urban morphology features and energy performance of buildings at block scale. Building density was the only factor that could significantly affect the total EUI of point-type and line-type residential blocks, while building orientation was the only factor affecting the total EUI of hybrid-type residential blocks significantly. No indicators could significantly affect the total EUI of the courtyard-type residential blocks. It should be noted that surface-to-volume ratio was the only factor that could significantly affect the total EUI of all urban blocks, regardless of block morphological types. Overall, this study provides a reference for urban planners and designers to reduce building energy consumption at the master planning stage. Moreover, this study also suggests a general method for analysing the impact of urban morphology on building energy consumption in blocks.

Keyword: *Simulation; Urban Morphology; Energy Use Intensity; Hot-summer and Cold-winter Area*

Introduction

Reducing energy consumption of buildings has been widely recognised as one of the primary approaches to carbon neutrality. Previous studies have mostly discussed this issue from the perspective of individual buildings, based on which a large number of reliable architectural design guides have been developed. However, most of these existing studies and observations have been conducted for idealised environments without enough attention to their complex surroundings (Futcher and Mills, 2013). In the past several years, an increasing number of studies have been focusing on an interactive impact, generated by surrounding buildings, which may increase energy consumption of buildings. That is, energy demand reduction might be achieved by considering urban form and microclimate at a master planning stage.

Moreover, existing studies have mostly been performed in cities with single climate conditions, requiring either heating or cooling. Some researches were conducted in cities with tropical or subtropical climate (Cheng *et al.*, 2006; Jones *et al.*, 2009; Wong *et al.*, 2011; Lin, 2013; Huang *et al.*, 2017), some studies were carried out in cities with temperate marine climate (Salat, 2009; Strømann-Andersen and Sattrup, 2011; Futcher and Mills, 2013; Chatzipoulka et al., 2016), and some focused on Mediterranean climate cities

(Morganti *et al.*, 2017; Vartholomaios, 2017; Tsirigoti and Bikas, 2017). However, limited studies have been conducted to investigate the building energy performance in complex climates, requiring different operational conditions. For instance, a recent study was conducted in Nanjing with a typical hot-summer and cold-winter climate in which both heating and cooling are important (Zhang and Gao, 2021).

Overall, previous studies have demonstrated that urban form can play an important role in regulating energy performance of buildings at urban scale. However, there is a need to explore energy performance of blocks in a context with complex climatic conditions and to analyse the impact of the factors relating to urban form. Therefore, this study aims to explore the impact of urban morphology on energy performance of residential blocks in a hot summer and cold winter climate that has stricter requirements for energy use of heating and cooling.

Methodology

This study consisted of four parts: 1) Selecting sampling residential blocks and quantifying their block morphological characteristics by suitable indicators; 2) setting up unified boundary conditions for simulation, including construction parameters for single building, indoor conditions and operation dairy of building systems; 3) performing energy use intensity (EUI) simulation; 4) statistical analysis (Figure 1).

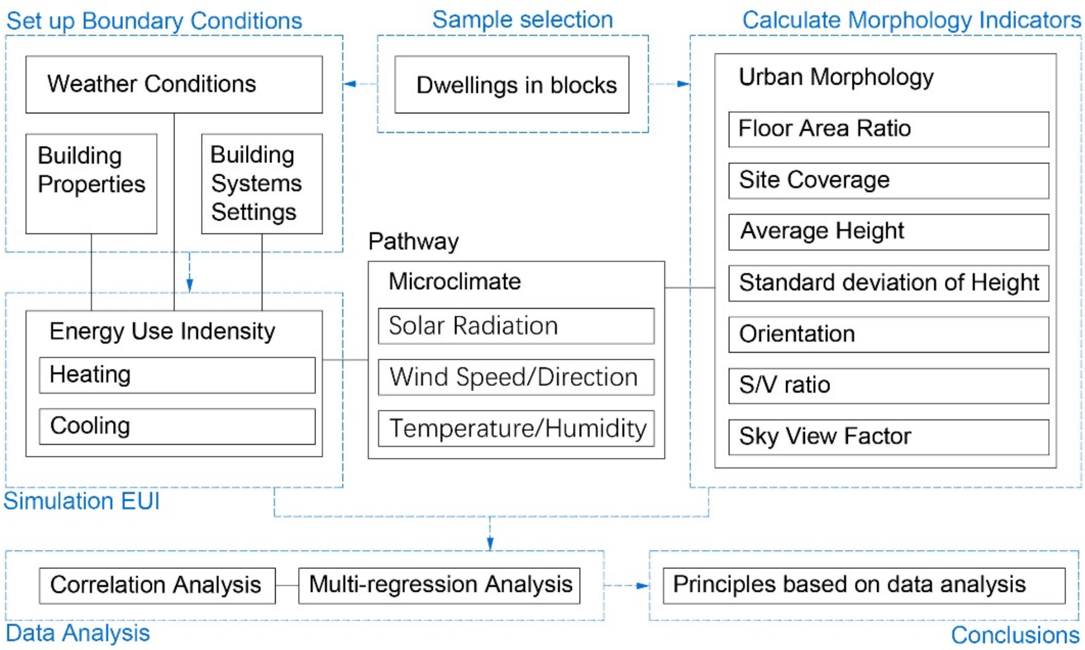

Figure 1. *Impact factors of buildings energy consumption in blocks and the structure of this research*.

Morphological indicators

To indicate microscopic characteristics and more importantly to improve the feasibility of using potential morphological factors, there is a need to simplify morphological indicators. Accordingly, based on existing studies (Compagnon, 2004; Zhang *et al.*, 2012; Mohajeri *et al.*, 2016; Morganti *et al.*, 2017), seven indicators were chosen to reveal each block' s morphological features. They are: 1) Floor area ratio (FAR); 2) Site coverage; 3) Average building height; 4) Standard deviation of building height (StH); 5) Average orientation of the block; 6) Surface-to-volume ratio (S/V); 7) Sky view factor (SVF) (Table 1).

Table 1. Urban Morphological Indicators selected for parametric study.

Morphological Indicators	Formula or methods
1) Floor Area Ratio;	FAR= gross floor area/sample district area
2) Site coverage;	SC= footprint area/sample block area
3) Average building height;	Average H $=\sum(\text{footprint area x height})/\text{gross footprint area}$
4) Standard deviation of building height (StH);	StH= $\sqrt{\frac{\sum_{i=1}^{N}(H_i-\bar{H})^2}{N}}$, $\bar{H}$ is average building height, H_i is every single building height, N is the number of buildings in the block
5) Average orientation of the block	Orientation= $\Sigma\left(\frac{S_i}{S}\right)D_i$ S_i = floor area of single building, S = gross floor area of the block D_i = The angle at which the long axis of this building deviates from the south
6) Surface-to-volume ratio (S/V)	S/V = $\sum$external facades and roof areas [m^2]/ $\sum$ volume of building [m^3]
7) Sky view factor (SVF)	Average sky view factor, calculated by ENVI-met

Sampling blocks

This study aims to explore the impact of urban morphology on the energy performance of residential blocks in a city with a hot summer and cold winter climate that has both heating and cooling requirements. The location and climate conditions of Nanjing, China is perfectly suitable for this research aim. In Nanjing, therefore, 35 dwelling blocks were selected to perform this study. The 35 blocks were characterised by four types: point-type (A), line-type (B), courtyard-type (C) and hybrid-type (D). Hybrid-type refers to the other three types combine in pairs in accordance with literature (Martin and March, 1972; Steemers *et al.*, 1997; Adolphe, 2001; Rode *et al.*, 2014) (Figure 2).

Simulation settings

Setting up boundary conditions is the base of numerical simulation for subsequent parametric study. The boundary conditions were considered in aspects of construction parameters for single building, indoor conditions and operation dairy of building systems. Each value refers to: 1) Local construction standards of energy efficient buildings, and 2) Popular technical practice of energy efficient buildings in local market (Table 2, Table 3 and Table 4).

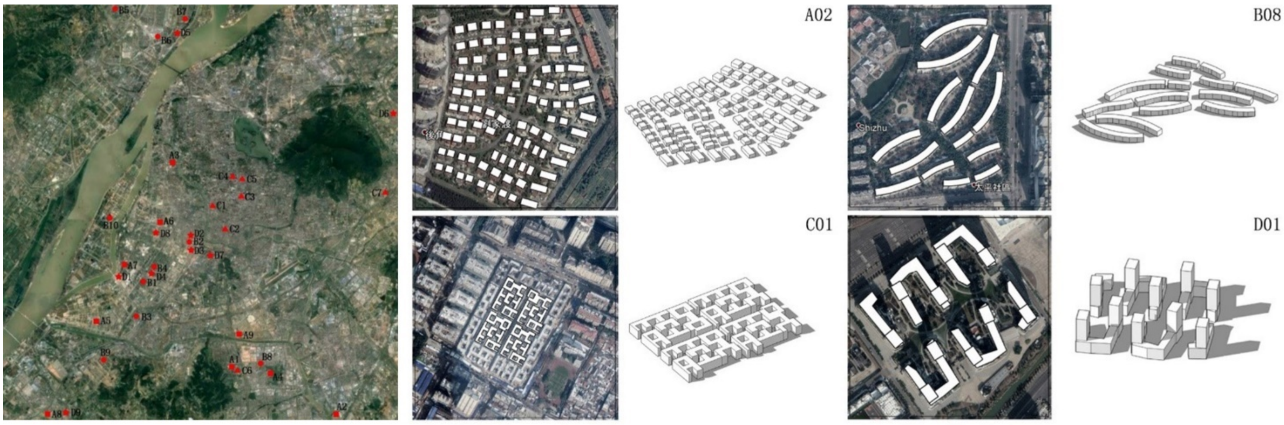

Figure 2. *Location of 35 dwelling blocks selected in Nanjing and an example of each type*.

Table 2. Simulation conditions of building construction and materials.

Construction	U value (W/m²·C)	Required U value	Materials	Thickness(mm)
External wall	0.45	0.55	Cement Mortar	10
			RFT Plate	35
			Aerated Concrete Block	200
			Cement Mortar	20
Roof	0.43	0.45	High Polymer Waterproof Sheet	3
			Fine Aggregate Concrete 2300	30
			RFT Plate	60
			Reinforced Concrete	120
			Cement Mortar	20
Ground	0.4	1.5	Reinforced Concrete	60
			Autoclaved Aerated Concrete Block	140
			SBS Modified Asphalt Rolling Material	3
			RFT Plate	30
			Fine Aggregate Concrete 2300	60
			Earth	600
Window	2	2.4	Glass	6
			Cavity	12
			Glass	6

Table 3. Simulation conditions of indoor environments.

Heating/cooling	Design temperature	18-26°C
	Operation schedule	Monday to Friday: 00:00-08:00 &18:00-24:00
		Saturday to Sunday: 00:00-24:00
Internal gains (from lighting, small power and occupancy)	Output power	15W/m²
	Operation schedule	Monday to Friday: 00:00-08:00 &18:00-24:00
		Saturday to Sunday: 00:00-24:00
Ventilation	Weekday	0.5,1.0,1.0, 26°C
		On during 08:00-18:00 &18:00-24:00
	Weekend	On during 00:00-24:00

Table 4. Simulation conditions of other building settings.

Type of Building	Window-wall ratio	Floor height
Commercial	60%	4.0 m
Domestic	40%	3.0 m

Energy use intensity simulation

A proposed calculation engine was developed to simulate buildings at urban scale, through integrating SketchUp (@Last Software and Google), HTB2 (HTB210, WSA, 2018), and VirVil SketchUp extension (WSA, 2017). SketchUp is among the most popular software for 3D buildings used by architects and urban designers, while HTB2 is recognised as one of the most reliable calculation engines for energy use and internal temperature prediction (Alexander, 2003). VirVil SketchUp extension is an updated tool to connect SketchUp and HTB2, helping to extend the scope of HTB2 in consider the relationship of buildings to their surrounding areas (Lin, 2013). Moreover, these tools have the advantages of their high reliability, applicability and user-friendly interface. The simulation mimicked the energy performance of residential blocks in a whole year, including every single day in different seasons. Therefore, the energy use intensity (EUI) value by simulation can be much closer to the reality than simulation only focusing on a typical time period.

Statistical Analysis

Statistical analysis was conducted in two aspects: 1) Performing Pearson correlation analysis, on SPSS Statistics 22.0 platform, of dependent variables (total EUI, heating EUI, cooling EUI) and independent variables (urban morphological indicators), in which correlation coefficient r was used to measure the strength of the statistical correlation relationship. The indicators with strongest and significant correlation were selected for 2) Multiple linear regression analysis for further quantitatively analysis. For the significance test, a significance level of 0.05 was chosen, where the indicator variable was statistically significant if $p<0.05$. Every value of the independent variable (urban morphological indicators which p-value is <0.05) could be associated with a value of the dependent variable (EUI). At last, an equation was developed to explain how much each significant independent variable (morphological indicator) affected the dependent variable (EUI). From the perspective of the sampling size, the statistical analysis was divided into holistic analysis (all 35 blocks together) and stratified analysis (each type of block separately).

Results and Discussions

The results of Pearson correlation test and multiple linear regression analysis in holistic way are shown in Table 5 and the scatterplot diagram is shown in Figure 3.

Table 5. Correlation Analysis and Regression analysis of overall cases between form indicators and EUI.

Form indicators	Total EUI			
	Correlation analysis	Regression analysis		
	r		coefficient	Sig(p)
FAR	0.009	R^2=0.117 p=0.044	-	-
Site coverage	-0.179		-	-
Average height	0.211		-	-
StH	0.051		-	-
Orientation	-0.069		-	-
S/V ratio	0.342*		26.855	0.044
SVF factor	-0.137		-	-

Form indicators	Heating EUI				Cooling EUI			
	Correlation analysis	Regression analysis			Correlation analysis	Regression analysis		
	r		coefficient	Sig(p)	r		coefficient	Sig(p)
FAR	-0.592**	R^2=0.980 p<0.001	0.132	0.763	0.622**	R^2=0.810 p<0.001	1.397	0.29
Site coverage	0.560**		9.452	0.009	-0.721**		-24.347	0.022
Average height	-0.606**		0.112	0.035	0.793**		0.042	0.781
StH	-0.371*		-0.011	0.578	0.425**		0.069	0.228
Orientation	0.005		-	-	-0.059		-	-
S/V ratio	0.979**		107.519	0.001	-0.754**		-21.786	0.139
SVF factor	-0.272		-	-	0.177		-	-

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).

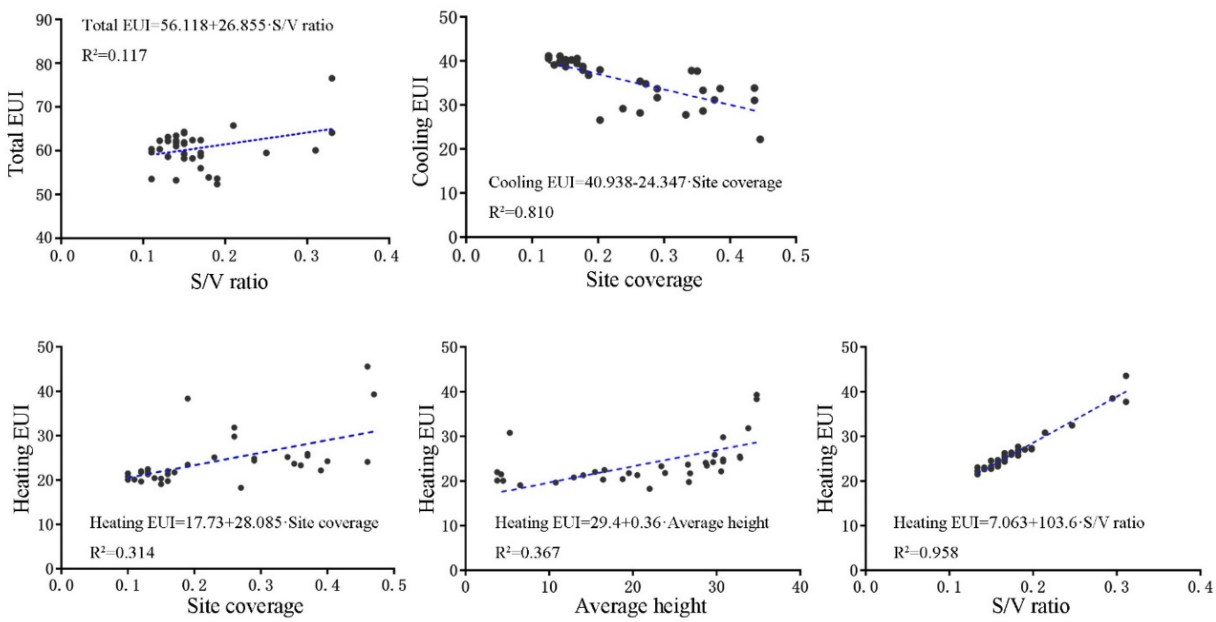

Figure 3. *Relations between EUI (kWh/m2/y) and form indicators based on correlation and regression analysis of overall cases.*

From the correlation analysis (Table 5), at the significance level of 0.05, the total EUI was significantly related to the S/V ratio (|r|>0.3), so that S/V ratio would be used to conduct the regression analysis. From the linear regression analysis, the determination coefficient $R^2=0.117$ (the closer R^2 is to 1, the better the fitting degree of the model is to the dependent variable) was relatively not very high and it indicates that the independent variable (S/V ratio) only accounted for 11.7% of the change in the dependent variable (total EUI), and 88.3% of the changes were caused by random variables. The result of significant value (Sig.) $p=0.044<0.05$ suggested that the developed model had statistical significance and reliability. Finally, the regression equation was:

Total EUI= 56.118+26.855 x S/V ratio.

Moreover, from the results in Table 5, the heating EUI was significantly related to FAR, Site coverage, Average height, StH and S/V ratio ($|r|>0.3$). Accordingly, these five variables would be used to conduct the regression analysis. The linear regression analysis indicated that the determination coefficient $R^2=0.98$ had a high fitting degree of the equation. This result indicates those five independent variables accounted for 98% of the change in the dependent variable (total EUI). However, the significant value (Sig.) $p_{FAR}=0.763>0.05$ and $p_{StH}=0.578>0.05$ meant FAR and StH could not affect heat EUI significantly. The results of significant value (Sig.) of Site coverage, Average H and S/V ratio were 0.009, 0.035, $0.001<0.05$, with coefficient 9.452, 0.112, 107.519. Finally, the regression equation was:

Heating EUI=2.387+9.452 x FAR +0.112 x Average H+107.519 x S/V ratio.

Similar conclusions could be drawn respectively from the result of statistical analysis in a stratified way.

Table 6. Summary of results of significant morphology indicators in holistic and stratified statistical analysis

	Total EUI	Heating EUI	Cooling EUI
Overall	S/V ratio	S/V ratio	Site coverage
		Site coverage	
		Average height	
Point-type	Site coverage	S/V ratio	S/V ratio
			Site coverage
Line-type	Site coverage	S/V ratio	Site coverage
Courtyard-type	-	S/V ratio	Average height
Hybrid-type	Orientation	S/V ratio	Orientation

Conclusions

Table 6 summarized the results of significant morphological indicators in holistic and stratified statistical analysis. Site coverage and S/V ratio were the most important indicators that could significantly affect dwelling block EUI in Nanjing. Especially, S/V ratio was the only significant morphology indicator for Total EUI of overall types of blocks and S/V ratio was the only significant indicator for Heating EUI of any morphological types of blocks. For point-type and line-type blocks, Site coverage was the only significant indicator for Total EUI and Cooling EUI. On the contrary, there was no significant indicator for Total EUI of courtyard-type blocks.

Whist the final conclusion might be sensitive to sample size, this research is still a positive attempt to explore the impact of urban morphology on the energy consumption of dwelling in blocks under complex climate conditions. Furthermore, the results provide a reference for urban planners and designers to reduce building energy demand at the master planning stage.

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