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A simulation of impact of micro-climate change and neighbourhood morphology on building energy demand

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Abstract

The aim of this study is to explore the impact of microclimate change, especially air temperature change, on the energy demand of buildings compared with other neighbourhood morphology parameters through simulation with tools-HTB2 and Virvil Plugin. The simulation is conducted with five models: a Standard Model, and four other models which consider one parameter for each model as follows: 1) building density; 2) building compactness; 3) building vertical layout; 4) air temperature change. The case is selected from a 250 m x 200 m site in Chengdu, which is a typical neighbourhood scale project in a city complex. The simulation result indicates a quantitative correlation between microclimate change and the energy performance of buildings at a neighbourhood scale. The study provides several perspectives for developers to reduce the energy demand at an early planning stage.

Keywords

Building energy demand, microclimate, urban morphology, urban neighbourhood scale projects.

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Introduction

Building energy consumption has been widely investigated, research has focused on energy efficiency and building materials (Liu et al., 2015), producing more efficient building services and thermal insulated building envelopes in practice (Li et al., 2014). However, energy consumption of buildings is closely related to the microclimate which is a local atmospheric zone in micrometeorological scale range that differs from the surrounding area. Microclimates exist almost everywhere we live. Water bodies such as pools, rivers and big fountains cool the local air temperature in a process called evaporative cooling. In most big cities concrete and asphalt are widely used and these built surface materials absorb short-wave solar radiation heating up the local atmosphere. In return, they emit long-wave radiation, heating up the surfaces that are not sunlit (Allegrini, Dorer and Carmeliet, 2012). This process leads to the well-known effect of the urban heat island effect.

The microclimate is an interaction of various physical parameters that include the airflow velocity, air temperature, relative humidity, solar radiation intensity, pollutant concentration, noise pollution and so on (Li et al., 2012). The parameters affect the microclimate in different ways while they interact with one another at the same time. Solar radiation heats up materials and other objects such as building façades and air when it hits them. The air is heated by solar radiation in two ways: in a direct way by solar radiation, and an indirect way by the transfer of heat from 'hot' surfaces absorbing solar radiation. The heating up of air causes temperature variations that lead to changes in air pressure and accelerate the movement of air, increasing wind velocity. The wind, in return, cools the ground and building surfaces, thereby rebalancing the local air temperature. The wind also brings air with different humidity, which alters the relative humidity in the local air. Therefore, the evaporative cooling process is effected by the wind effect which influences relative humidity. More specifically, the difference in wet bulb and dry bulb temperatures of the air decides the potential for evaporative cooling. Humid air with high relative humidity has limited capability to evaporate moisture, and the effectiveness of the cooling process will be decreased in comparison with a drier air with low relative humidity. So, the microclimate not only describes the average atmospheric condition but also indicates the recurring phenomena process.

The urban microclimate characterized as the urban heat island effect (UHIE), temperature and humidity effect (THE) and cumulative effect (CE) has significant influences on building energy consumption, especially on cooling loads (Li et al., 2014). UHIE increases the air-conditioning load by which more waste heat is produced and emitted into the urban area, and in turn, the extra heat accumulates, contributing to the UHIE. To some extent, at an urban scale as a more widely implemented proposal, mitigating the UHIE is an effective way to minimize the impact of extra energy consumption due to air temperature variation, while at the same time reducing the waste heat emitted, which contributes mitigating effects to UHIE (Li et al., 2014).

Ambient Temperature and Building Energy Consumption

As a topical point of public interest, the general effect of UHIE on increasing the summer cooling load and reducing the winter heating load is widely studied. In the Athens area, the summer cooling load of urban buildings in the city centre is recorded as double the amount of that in suburban areas due to the UHIE, while the winter heating load is reduced by up to 30-55% (Fung et al., 2006). When considering all characteristics of the microclimate (CE, UHIE, THE), which all affect the cooling load of urban buildings, a 1°C decrease in the average daily temperature of the urban district in

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the summer results in a 12.8% decrease in building energy consumption (Li et al., 2014).

Among all the parameters of microclimate, the outdoor ambient temperature is a primary factor governing urban energy consumption, some studies show it accounts for about 73% of the total variance among the parameters of microclimates (Fung et al., 2006). This is due to the internal temperature, which determines the heating and cooling energy demands, being driven by the external air temperature (Cox et al., 2015). A 1°C increase in monthly ambient temperature was observed with an annual electricity consumption increase of 9.2% in the domestic sector, 3% in the commercial sector and 2.4% in the industrial sector (Fung et al., 2006).

Other parameters show weaker correlations with building energy demand. In the study of Cox et al. (2015), a 10% change is applied in proposed parameters: solar radiation, air humidity, and wind velocity: the results show less than 6% corresponding change in the cooling load of the sampled building, and even less than 5% for relative humidity and wind velocity. Yan (1998) found that compared to the average temperature, the vapor pressure of air is further less correlated with residential electricity consumption. The United States Environmental Protect Agency (1992) reported 0.5% to 3% increases in peak cooling electricity loads in US cities due to 0.6°C increases in ambient temperature.

Urban Morphology and Building Energy Demand

Urban morphology impacts building energy demand in two ways: the choice of building geometry (building density, plot layout, building height), and potential effects to the UHIE (Lee and Lee, 2014) (Strømann-Andersen and Sattrup, 2011). The building shape significantly determines the daylight availability in terms of horizontal and vertical randomness (Cheng et al., 2006). The unit building density, as a better measure of building morphology (Galster et al., 2001; Lowry and Lowry, 2014), shows the highest correlations with building energy consumption in a site (Hachem, Athienitis and Fazio, 2012). Optimizing urban morphology is another strategy to mitigate UHIE, which provides more scope for reducing building energy demand. Building density and plot layout are initial factors of urban canyon geometry and orientation, which significantly impact the UHIE intensity (Oke and Cleugh, 1987). Urban morphology alters the thermal properties of urban surfaces, thereby affecting UHIE intensity (Lee and Lee, 2014).

Current Situation in China and Introduction of Study Site

In China, a series of actions on energy saving have been taken in the architecture industry. Considered as the pioneer of China's energy labelling programme, the first Management Method of Energy Efficiency Label in China was issued by the National Development and Reform Commission (NDRC) and the State Quality Supervision-Inspection-Quarantine Administration (SQSIQA) in 2005 (Zhang, 2011). This method promoted technical reform of energy-conserving and energy efficiency in building services, including domestic electric refrigerator and air-conditioning devices. Shortly after in 2006, China announced its first Evaluation Standards for Green Building (GB/T 50378-2006). The national policy of "The Twelfth Five-Year Plan" (Xinhua News Agency, 2011) was adopted in October

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2010 with the objective of reducing energy consumption and CO2 emissions per unit of GDP by16% and 17% respectively by 2015.

The study case is in the city of Chengdu which is the capital city of the Sichuan Provence and a major city in western China. It is located at 30°39'31"N, 104°03'53"E, with 2,174.6 km2 city areas hosting 7,415,590 citizens. The city is in a humid subtropical climate zone with four distinct seasons, with hot summers and cold winters. The 24-hour daily mean temperature is 5.6°C in January and around 25°C in July and August, with an annual mean temperature of 16.14°C. The highest average monthly precipitation totals are 225 mm in July, and the lowest rainfall value of 5.2 mm occurred in December. There have been some studies on microclimate in Chengdu, especially on UHIE. The phenomenon of UHIE in Chengdu was first documented by Yang (1988). He revealed the equation to calculate the UHIE intensity in Chengdu, taking into account cloudiness, wind speed, temperature and humidity. In recent years, studies using GIS statistical analysis methods (Xia, Dan and Chen, 2007; Zhang et al., 2007; Dan et al., 2009; Liu, Yang and Chen, 2009), investigate the cause of UHIE and mitigation strategies for UHIE considering the effects of vegetation and transportation in Chengdu.

Methodology

In this paper, the bottom-up approach is used to simulate energy performance at a neighbourhood scale. First, local statistical information on the weather, building occupancy, materials and plot layouts of buildings, as well as other microenvironments, are considered in the prototype creation stage. Then four experimental models considering a different parameter each are compared using the prototype as a basis. The parameters are: building density, compactness, vertical layout, and local air temperature change. All the simulation results are then analyzed to compare the impacts on building energy performance due to different design and microclimate parameters, thereby obtaining simple design principles to decrease building energy demand at neighbourhood design scale in Chengdu.

The simulation at neighbourhood scale is implemented by Google SketchUp 15 Pro, HTB2 v2.10 (WSA, 2008), and Virvil Plugins (WSA, 2010). As one of the most reliable simulation core engines in the prediction of energy use and internal temperature, the HTB2 is highly recognized (Alexander, 2003). The Virvil Plugins are used as a connection of HTB2 with SketchUp to extend the scope of implementation into the urban scale.

The original model (shown in Figure 1) is created in a 220 m x 200 m site in Chengdu, China, where the neighbourhood scale projects in the form of a city complex are constructed (Le, 2010). The simulated buildings are simplified into 12 building boxes with two common building types –commercial and residential – in the neighbourhood scale project. In the standard model, the 12 buildings are created with 50 m in length, 40 m in width and 30 m height, and the floor area is 20,000 m2. No.1~No.6 buildings are defined to be commercial, No.7~No.12 buildings are residential ones, among which No.5 and No.8 buildings are located in the centre of this neighbourhood scale project surrounded by the other buildings. The basic construction settings, such as glazing ratio, indoor condition and building materials are used at default value in all four models,

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while all the settings satisfy the requirement of local planning regulations. The building density, building plot layout and air temperature change are adjusted in the four models. The Model-Density (shown in Figure 2) doubles the density of the standard model in terms of raising the height of buildings to 60 m. The more compact building settlement in the Model-Compactness is created (shown in Figure 3), wall-to-volume ratio in central buildings (No.5 and No.8) is 0.09, while the ratio in Building No.4, No.6, No.7 and No.9 is 0.13, the rest of the buildings (No.1, No.2, No.3, No.10, No.11 and No.12) are designed with a wall-to-volume ratio of 1.4. The randomness of the buildings in the vertical layout model (shown in Figure 4) is modified with two main 120 m high towers with 70,000 m2 in floor area and 15 m in height low surrounding buildings with a 10,000 floor area, while other parameters such as density and microclimate conditions remain with original values. In the air temperature model (shown in Figure 5), the physical structure of the simulated building is the same as that in the standard model, the only modification is on the weather file. A rise of 1°C is added on each value of meteorology data at each single collection time. Therefore, a new weather file is generated to simulate the variation of microclimate in terms of air ambient temperature.

Simulation result and analysis

The simulation results of the standard model have been compared with the other four models considering the parameters: building density, building compactness, vertical layout and air temperature change. Each parameter is analyzed in the following sections.

Building Density

In this simulation case, the building density is identified by floor area ratio, which directly affects the solar gain and energy demand of buildings (Robinson, 2006; Zhang et al., 2012). In local regulations, this parameter is strictly controlled by the city administration of urban planning, while the developers are keen to build projects with as high a density as possible to earn more economic interest. In the Model-Density, the floor area ratio is double that in the standard model, and simulates the high density building proposal in neighbourhood scale projects.

The results indicate that in both commercial and residential building types, the overall annual energy demands are higher in the higher density model (see Figure 6). For residential buildings, the cooling demand of buildings in the higher density model is 33.18 kWh/m^2/year, which is higher than that in the standard model, whereas the heating load is reduced by 9.95%. For commercial buildings, the cooling demand of buildings in the higher density model is 32.67 kWh/m^2/year with an 8.04% increase in comparison with the standard model's 30.24 kWh/m^2/year. The heating demand in commercial buildings with double density is reduced by 12.65% in comparison to that of the standard model. Due to the different indoor configuration (mechanical building services, services schedule, and building insulation conditions) the commercial buildings consume less energy in both heating and cooling compared to residential buildings in any single case. To sum up, in the Model-Density, denser buildings with greater building height increase the over-shading, where the shading effect significantly impacts the heating and cooling

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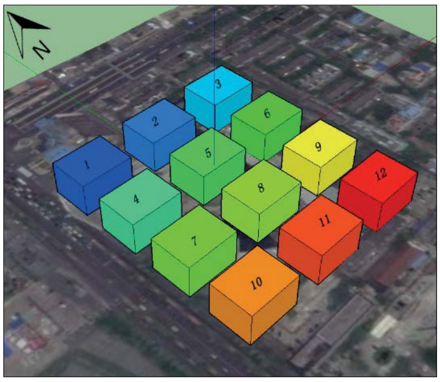

Figure 1. The standard model

Figure 2. Doubled density model

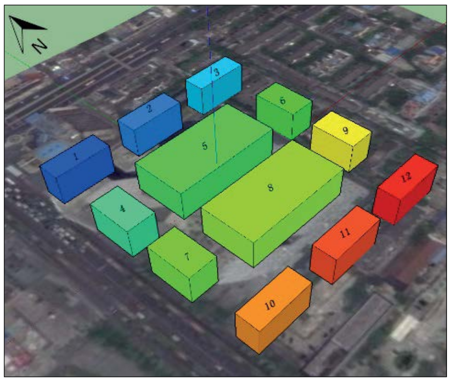

Figure 3. Compact building model

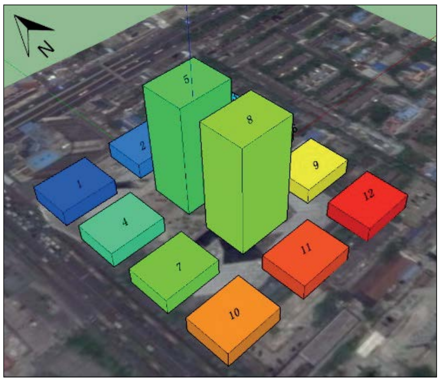

Figure 4. Vertical layout model

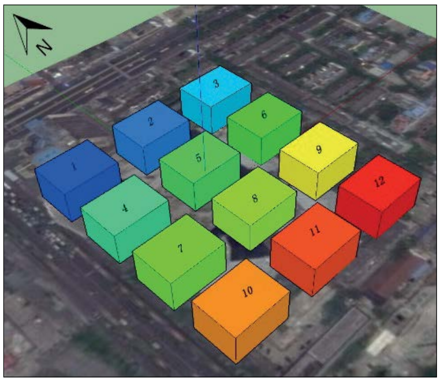

Figure 5. Changed air temperature model

Table 1.

Simulation result of heating demand (upper) and cooling demand (below) for each single building considering the difference between each experimental model and the standard model.

(kWh/m2/year)

Heating Demand	Commercial						Residential					
Building ID	1	2	3	4	5	6	7	8	9	10	11	12
Mode-Standard	9.06	9.45	9.13	9.56	**10.06**	9.65	19.29	**20.01**	19.43	18.03	18.56	18.10
Model-Density	-1.36	-1.18	-1.31	-1.18	**-0.99**	-1.15	-1.72	**-1.42**	-1.66	-2.22	-2.07	-2.22
Model-Compactness	+2.48	+2.71	+2.58	+2.42	**-2.64**	+2.50	+4.21	**-4.92**	+4.42	+5.33	+5.46	+5.27
Model-Vertical Layout	+3.55	+4.20	+3.76	+3.52	**-3.60**	+3.68	+4.83	**-6.01**	+4.80	+5.19	+5.18	+5.19
Model-Air Temp.	-2.39	-2.43	-2.38	-2.43	**-2.50**	-2.44	-4.00	**-4.05**	-4.00	-3.93	-3.97	-3.94

(kWh/m2/year)

Cooling Demand	Commercial						Residential					
Building ID	1	2	3	4	5	6	7	8	9	10	11	12
Mode-Standard	31.68	30.34	31.51	29.94	**28.30**	29.68	30.89	**29.07**	30.60	32.95	31.38	32.65
Model-Density	+3.11	+2.41	+2.94	+2.31	**+1.58**	+2.23	+1.74	**+0.95**	+1.64	+2.66	+1.98	+2.56
Model-Compactness	+3.97	+3.60	+3.94	+3.59	**-0.51**	+3.39	+3.96	**-0.38**	+3.70	+4.27	+3.87	+4.29
Model-Vertical Layout	-7.52	-7.60	-7.49	-7.39	**+10.21**	-7.45	-6.56	**+10.29**	-6.64	-6.56	-6.10	-6.38
Model-Air Temp.	+4.77	+4.65	+4.68	+4.61	**+4.54**	+4.60	+5.72	**+5.61**	+5.69	+5.83	+5.74	+5.81

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demands. A previous study (Liu et al., 2015) shows similar results in an Energy-Plus simulation under a similar circumstance, as the building density is increased from 0.04 to 0.44, the corresponding cooling energy consumption is increased by 32%, and heating energy consumption is decreased by 24%.

Building Compactness

Generally, the building form can be defined in five dimensions: compactness, centrality, complexity, porosity and density (Huang, Lu and Sellers, 2007). In this study, the compactness is chosen to represent the patterns in the horizontal direction. The simulation results show that the compact buildings demand more energy for cooling compared to the model with standard buildings (see Figure 7). It is observed there is a 3.01% increase in residential buildings to 32.2 kWh/m^2/year and an increase by 2.71% to 31.06 kWh/m^2/year for commercial buildings, while there are only minor differences in heating demand between the two models, which is less than 0.5 kWh/m^2/year for all types of buildings.

On the other hand, for individual buildings, the central buildings (No.5 and No.8) are modelled with a lower wall-to-volume ratio (0.06) in Model-Compactness than that of all buildings in the other four models (0.09). They have a lower cooling demand (0.51 kWh/m^2/year less than that in No.5 Building in the standard model and 0.38 kWh/m^2/year less than that in No.8 Building in the standard model). Figure 8 indicates a significant linear correlation with a 0.47 R2 value between the cooling demands in each building in Model-Compactness with its wall-to-volume, where reduction of wall-to-volume ratio is shown to reduce the cooling demand at neighbourhood scale.

Building Vertical Layout

The vertical layout of buildings refers to the geometrical characteristics of the buildings in the vertical direction. In this research, 120 m high towers with surrounding low buildings with a height of 15 m are created to simulate patterns of buildings in extreme conditions with a more random vertical layout and rising height. The simulation results show that the more random vertical layout of buildings, together with rising height, increases the cooling demand in summer times and reduces the heating load in winter times (see Figure 9). The difference between the two models in heating demand is within 0.8 kWh/m^2/year, but that in cooling demand are more significant, being 2.07 kWh/m^2/year for residential buildings and 1.73 kWh/m^2/year for commercial buildings, respectively. The greater absolute value in the increase of cooling demand than that in the reduction of heating demand increases the total annual energy demand. This is mainly due to excessive solar gains in summer times due to huge exposed building surfaces.

For each individual building due to higher randomness and greater height of the central buildings, the surrounding low buildings are observed to have different changes in heating and cooling demand for both two buildings types (see Table 1). During winter, the significant shading effect of Building No.5 on the surrounding low buildings and reduced building surface area decrease the accessibility of solar radiation to the surrounding buildings, therefore, more energy is needed due to the lower solar gains. The results from Table

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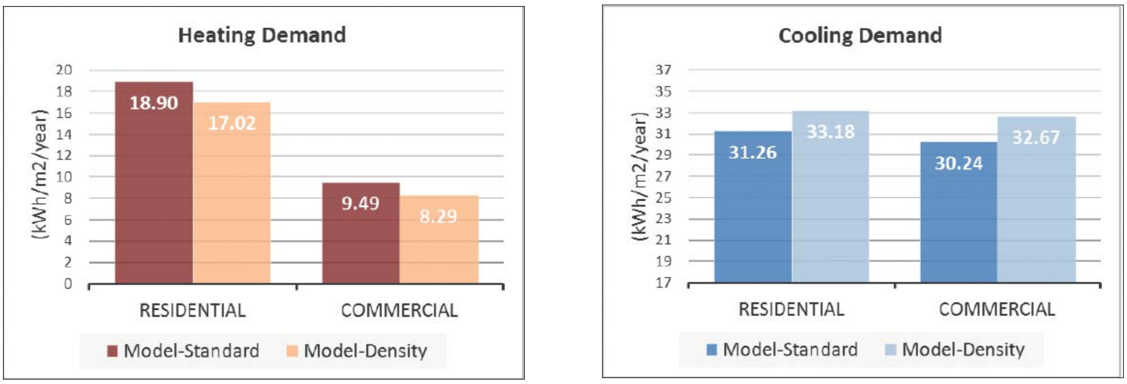

Figure 6. Comparison of energy demands between the standard model and the experimental model with different building density.

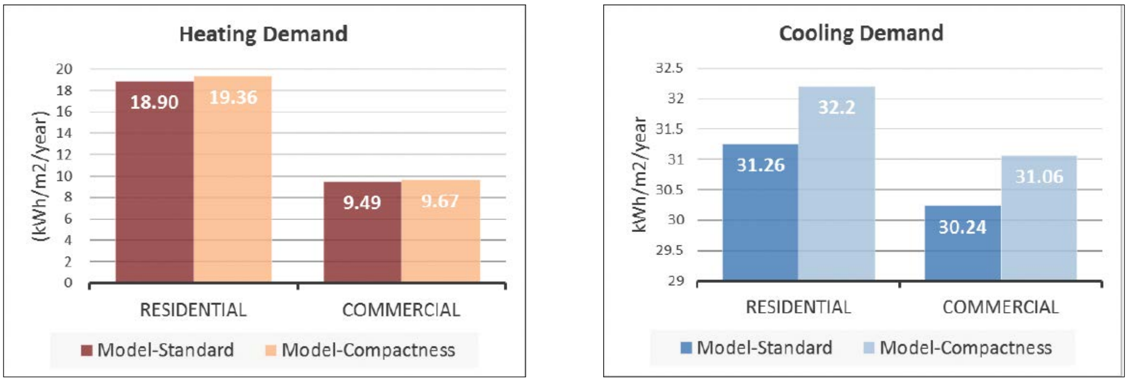

Figure 7. Comparison of energy demands between the standard model and the experimental model with different building compactness.

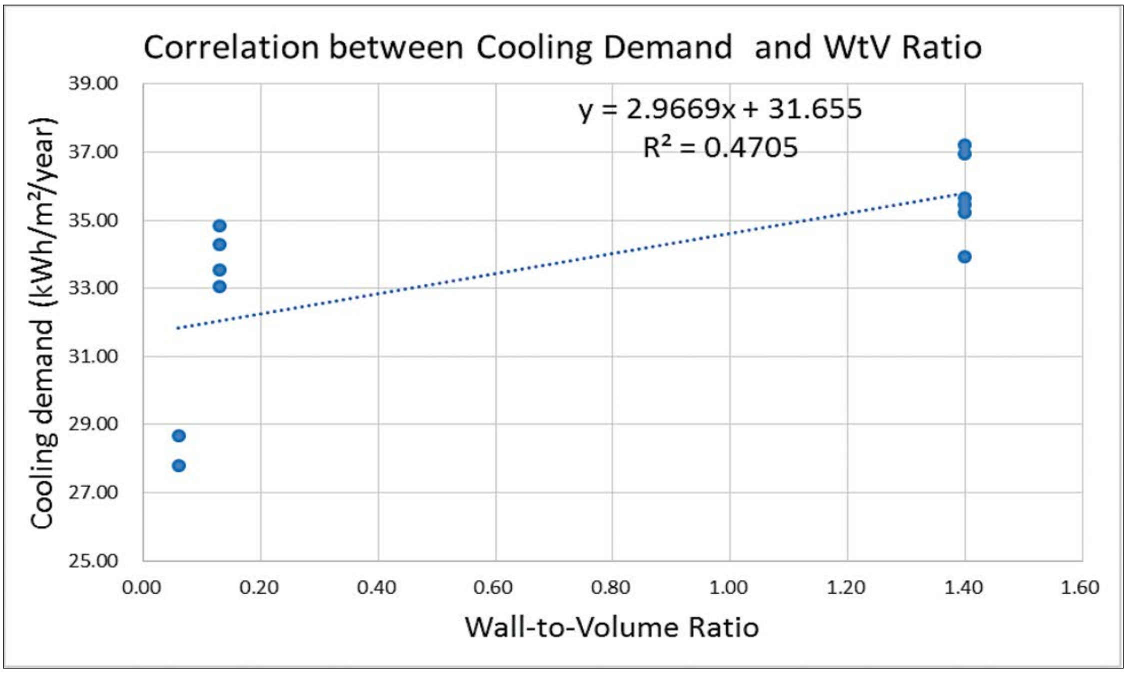

Figure 8. Comparison of energy demands between the standard model and the experimental model with different building compactness.

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1 indicate that compared to those buildings in the standard model, the heating demand in Building No.1, No.2, No.3, No.4 and No. 6 are shown with unusual increases of 3.51 kWh/m^2/year to 4.19 kWh/m^2/year for commercial, and 4.19 kWh/m^2/year to 5.79 kWh/m^2/year for residential. As the high central building enlarges the day-lighting area on building surfaces increasing the solar gain in this building, the heating demand is reduced by 3.49 kWh/m^2/year in No.5 Building, and 5.85 kWh/m^2/year in No.8 Building, respectively. During summer, the large solar exposure area in central buildings significantly increases the cooling demand, 9.95 kWh/m^2/year in No.5 Building and 10.03 kWh/m^2/year in No.8 Building. The lower solar gains mitigate the cooling demand in the surrounding buildings, and decreases ranging from 6.10 kWh/m^2/year to 7.76 kWh/m^2/year are achieved for the surrounding buildings.

Air Temperature Change

The parameter of air temperature change is another major issue which is chosen as a parameter representing the microclimate impaction on building energy demand. The previous researches on building energy demand change due to variations in air temperature are many (Fung et al., 2006; Hou et al., 2014; Li et al., 2014), but, none of them had studied the case in Chengdu. The results of this study illustrate the influence of the local air temperature on building demand. Figure 10 compares the energy demands between the standard model and the Model-Air Temp. In the Model-Air Temp., the temperature has risen by 1°C by modifying the loaded weather file.

Figure 10 indicates the overall heating and cooling demands, considering two air temperature conditions. In summer times, a rise of 1°C in air temperature leads to a significant increase in cooling demand by 18.33% for residential and by 15.34% for commercial. The annual heating demand for residential buildings in Model-Air Temp. is reduced by 3.98 kWh/m^2/year, whereas for commercial buildings, the decrease in heating demand is 2.43kWh/m^2/year.

Considering the shading effect of the surrounding buildings on the central buildings and the same geometry settlement in each individual building, the solar gain in central buildings is less than that of the surrounding buildings. Table 1 indicates that in No.5 Building for the commercial and No.8 Building for the residential, the heating demand in surrounding buildings is lower than the central building, whereas the cooling demand in these low buildings is higher than the central ones. The shading effect leads a similar trend in energy demand in Model-Air Temp.; the greatest reduction in heating demand and the smallest rise in cooling demand is observed in the two central buildings compared to the other five surrounding buildings of the same type due to the air temperature variation.

Summary

Firstly, in general, previous studies (Xu et al., 2013a; Xu et al., 2013b) on building energy consumption in hot summers and cold winters, which is the weather zone Chengdu is located in, show similar results in heating demand (34 kWh/m^2/year averaged by values in residential and commercial buildings) and average cooling demand (15 kWh/m^2/year

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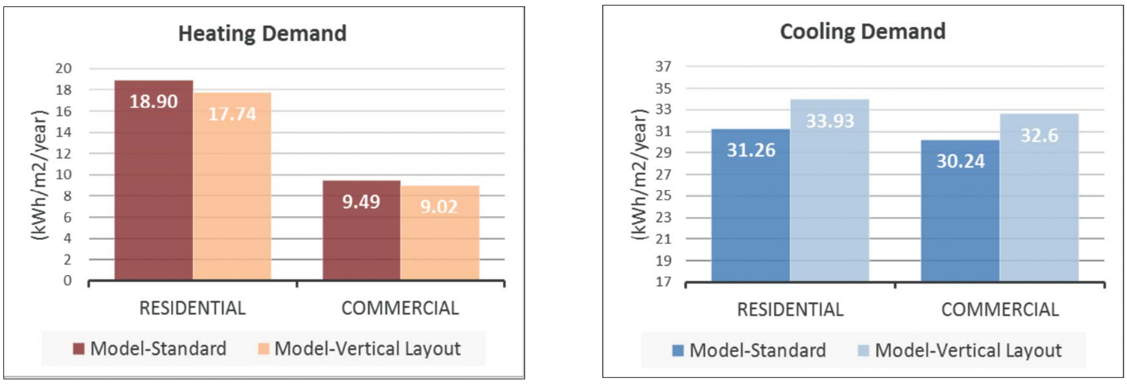

Figure 9. Comparison of energy demands between the standard model and the experimental models with different building vertical layout.

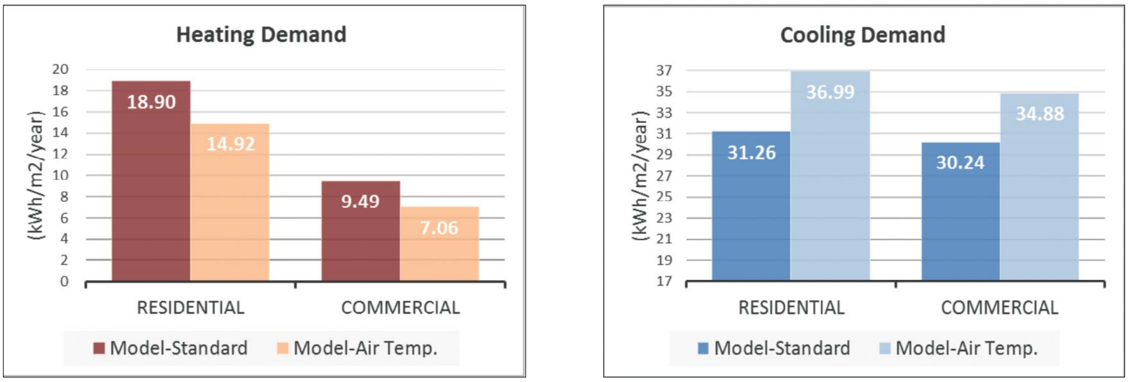

Figure 10. Comparison of energy demands between the standard model and the experimental model with different air temperature.

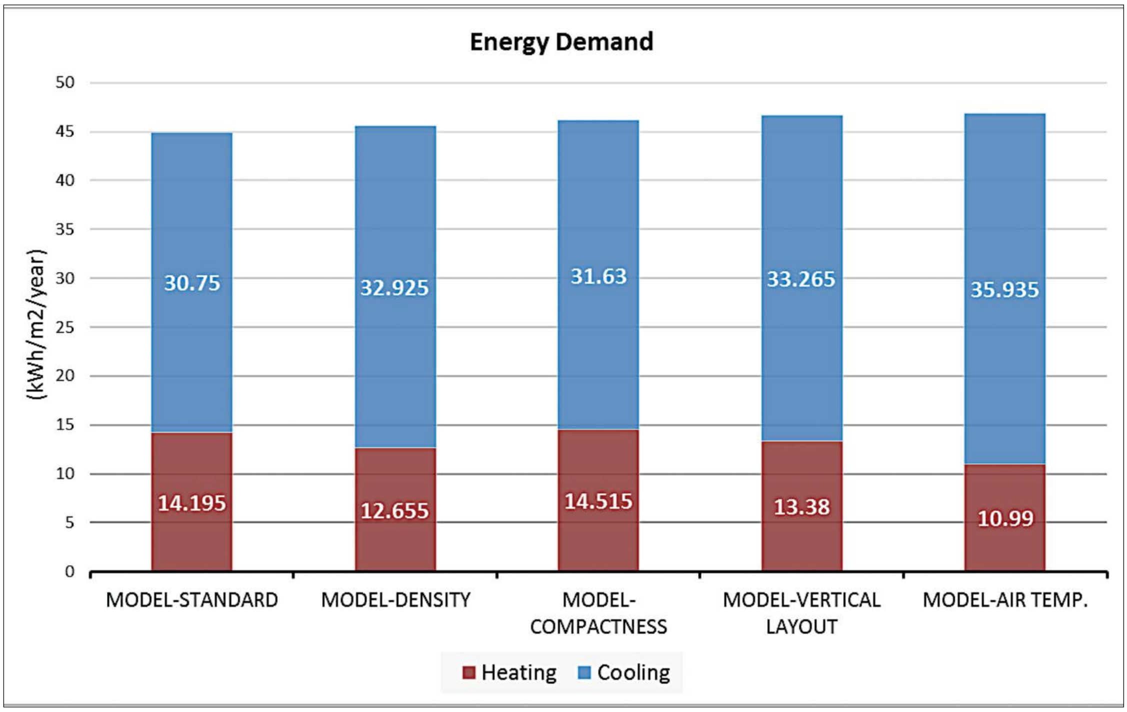

Figure 11. The comparison of annual energy demands between the prototype and experimental models.

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averaged by values in residential and commercial buildings), compared to the results as shown in Figure 8 in this study.

Most importantly, total energy demands in Model-Density, Model-Compactness, Model-Vertical Layout and Model-Air Temp. are higher than that in the standard model by 0.64 kWh/m^2/year, 1.7 kWh/m^2/year and 1.98 kWh/m^2/year, respectively. When considering the living habits in Chengdu where people seldom use heating services in winter times, the significant increases in the total cooling demand in each experimental model (2.18 kWh/m^2/year for Model-Density, 0.88 kWh/m^2/year for Model-Compactness, 2.52 kWh/m^2/year for Model-Vertical Layout and 5.19 kWh/m^2/year for Model-Air Temp., respectively) are of much practical meaning.

Lastly, based on the comparison of the study results for the standard model and the four experimental models, the following conclusions emerged: (1) Increase in building compactness is one of the most effective strategies for reducing the cooling demand at a building scale and achieving the least increase in cooling demand at a neighbourhood scale (see Figure 11), (2) reducing the outdoor air temperature is the most effective strategy to reduce building energy demand (especially in reducing the cooling demand) at neighbourhood scale, where a rise in air temperature of 1°C increases the cooling demand to the highest level and reduces the heating demand to the lowest level, (3) denser buildings with a larger floor area ratio and greater height are more effective strategies to achieve better energy performance, compared to compact building forms and more random vertical layouts with greater height. Furthermore, the exterior surface of the building significantly influences the building energy consumption due to convective heat transfer, and a lower wall-to-volume ratio leads to less heat transfer surface through which energy may be lost (Caldas, 2002; Liu et al., 2015). Considering this fact, in this study, the ratio of surface-to-volume of all buildings is the same in all experimental models and also in the standard model.

Conclusions

In this study, the energy performance of a neighbourhood scale project in Chengdu, southwest China, is simulated. The effects of building density, building compactness, vertical layout and air temperature change are investigated in four models and compared with the standard model. The results of comparison between each of the four target models and standard model indicate that denser buildings and more compact building plot layout increase the energy demand of buildings. Additionally, changing the outdoor air temperature has a detrimental effect on total building energy demand. Moreover, moderation in building density only achieves a weak effect on total energy demands for heating and cooling at a neighbourhood scale.

The study provides valuable design principles for achieving energy-efficient neighbourhoods at the urban planning stage and architectural scheme stage in cities within the weather zone of hot summers and cold winters. The initial recommendation based on results of this study is to mitigate temperature variation in the urban microclimate; thus, strategies such as choosing more reflective material for roofs and streets, more open spaces for water bodies and vegetation planting to increase the extent of water evap-

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oration and plants evapotranspiration, promoting energy efficiency in building services to reduce anthropogenic heat and lesser use of motorcars, are effective to reduce the building energy demand indirectly by mitigating the outdoor air temperature (Okeil, 2010). Furthermore, among all the urban morphology parameters selected in this study, building density is found to be the most effective one to directly optimize energy performance at neighbourhood scale; it impacts the outdoor air temperature in terms of Urban Heat Island effect by affecting the amount of stored heat in surfaces (Radhi, Fikry and Sharples, 2013), which is more effective than planting additional trees in outdoor spaces (Wong et al., 2011); therefore, optimization of urban morphology in terms of setting an appropriate density for a neighbourhood scale project is an effective strategy to improve energy performance in both direct and indirect ways. Finally, compacting of buildings by reducing the wall-to-volume ratio is shown to reduce the summer cooling demand of buildings.

Lastly, there are some limitations as follows. First, the simulation configuration in each of the experimental models is set with one condition, which hardly describes global configurations of each parameter; therefore, if other configuration conditions were considered, the suspected outcomes might be different. Second, the interactions among the selected parameters that affect the building energy demand are not discussed in this paper: the accumulative effect due to these parameters still needs to be investigated. Further studies should also consider other factors that influence building energy demand, with more comprehensive comparisons between these factors. Third, the weather condition and geo-location are based on the reality of Chengdu, China, and the findings might be inapplicable in other locations.

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