Simulating the Impact of Urban Morphology on Energy Demand - A Case Study of Yuehai, China

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1. Shortened Abstract

The aim of this study is to attempt to explore the impact of urban morphology on the energy demand of buildings, using simulation tools developed by the Welsh School of Architecture, Cardiff University, called VirVil Plugin and HTB2. The process of simulation is applied to one proposed project with four different scenarios, while the study considers one parameter for each scenario as follows: 1) building forms; 2) average building height; 3) orientation of building; and 4) community pattern. The project is chosen from an urban design scheme of Yuehai Eco-City in Yinchuan, China, designed by Architects& Engineers Ltd of Southeast University, China. The simulation results indicate a quantitative correlation between urban morphology features and the energy performance of buildings at urban scale. Furthermore, the results provide several perspectives for developing constructors to reduce the energy demand at the master planning stage. Moreover, the study also suggests that the method could spread globally.

2. Introduction

It is now widely accepted that enhancing energy efficiency of buildings is one of the primary approaches to achieve sustainable development. Most previous studies discussed this issue primarily from the perspective of individual buildings. A large number of reliable architectural design guides have been summarized, such as raising the thermal performance of fabric, improving energy efficiency of device systems, designing envelopes giving priority to climate and site, and even net zero energy buildings have been constructed. However, most of these researches and observations were conducted for a standard non-urban environment (Futcher et al., 2013). In this regard, it is important to recognize that if a cluster of buildings with good energy performance is assembled into a block in a non-optimal arrangement, the interactive influence generated by the surrounding buildings may increase the energy consumption of the buildings and the whole block. In contrast, greater reduction in energy consumption could be achieved in advance by considering urban form and micro climate at a master planning stage.

Only a few (but a growing number of) researches concerning building energy performance at urban scale have been addressed from the viewpoint of urban climatology, particularly with regard to the impact of urban morphology on the energy demand of buildings. Wong et al. (2011) simulated a three-storey office building located in a tropical climate city, Singapore, over one day. They employed 32 scenarios to represent different surrounding urban settings, accounting for three parameters: greenery, building height and building density. The simulation results showed that increasing the height and density of the surroundings (greenery and buildings) lowers the temperature of the external microclimate and reduces the cooling load of the building by around 5%. Strømann-Andersen and Sattrup (2011) found that the total energy consumption of low-energy buildings in the north-European setting may be affected by the geometry of urban canyons in the range of up to a 30% increase for offices and a 19% increase for housing, demonstrating that the geometry of urban canyons is a key factor in energy use of buildings. Adolphe (2001) developed a simplified spatial model based on a set of original morphological indicators of the environmental performance of urban patterns, to define urban morphology in terms of various parameters, such as density, rugosity, sinuosity, contiguity and solar admittance, anticipating the application of this approach to simplify the analysis of outdoor microclimate tendencies and the energy balance of urban patterns. Cheng et al. (2006) examined the relationships between built forms, density and solar potential based on a sky condition of low geographic latitude, by simulating 18 generic models with reference to three criteria: sky view factor at ground level, daylight availability on building facade and PV potential on building envelope, revealing that randomness in both horizontal and vertical layout and low site coverage with a higher building can provide helpful insights for planning solar cities. Futcher et al. (2013) examined the suitability of urban settings for buildings with a change-of-use function (from office to residential) in a typical city street and with the current and projected climate of London. By calculating the heating and cooling demands of buildings, they found that urban setting (and in particular street geometry) plays a significant role in regulating the solar access, and should be considered as a building and urban energy management parameter in the early design stages. Jones et al. (2009) simulated buildings in a proposed new city with hot and dry climates and considered four design parameters, including orientation, over-shading, construction type and internal heat gains. Salat (2009) observed a district of 96,000 existing buildings in Paris and compared some environmental metrics of urban forms. Their study revealed the impact of urban morphology and building typology on energy efficiency in the different zones of Paris. Finally, they emphasized the necessity of optimizing the parameters of urban form at the stage of urban planning and management.

The previous researches presented above demonstrated that urban form can play an important role in regulating energy performance of buildings at urban scale. Thus, considering the parameters of urban form (e.g. building shape, density, green ratio, orientation, street geometry, sky view factor) at the early design stage should help to minimize the energy demand of buildings. Therefore, there is considerable scope to explore the energy performance of blocks in environments with complicated climatic conditions and to establish the impacts of the parameters relating to urban form.

3. Methodology

Energy performance calculation at urban scale can be subdivided into two categories: top-down and bottom-up approaches. The top-down method focuses on long-term statistics and considers pertinent parameters and on-going changes in order to estimate the effect on energy consumption of buildings. The parameters commonly adopted are gross domestic product (GDP), employment rates, price indices, climatic conditions, housing construction and demolition rates, appliance ownership, and units (Swan and Ugursal 2009). On the other hand, the bottom-up method contains statistical and engineering aspects (ibid.). The statistical aspect uses similar historical data as the top-down method, but considers more information relating to the end-user. In contrast, the engineering aspect, which is strongly supported by technology and calculated in dynamic systems, accounts for the energy consumption with a massive amount of detailed information, such as diary and small power application. The advantage of the method is to allow researchers not only to simulate and analyze the energy performance of existing buildings, but also to predict the changes that will result from design strategies or technical improvements.

3.1 Framework of methods

The research method employed here is based on the concept of the engineering aspect in the bottom-up approach. In the first stage, detailed information relating to local weather, geometrical background, diary of occupancies, materials and layouts of buildings, and outdoor environmental information is considered in order to create a prototype. This prototype is then used as a basis in simulations for comparing with the results of experimental models. Within the simulations, four different experimental models are constructed, with each model considering a different parameter. The parameters considered are: form, average height, orientation and community pattern. Finally, through dedicated discussion and analysis of the simulation results, the principles required to save energy demand of buildings for the Yuehai Eco-City master planning are established (Figure 1).

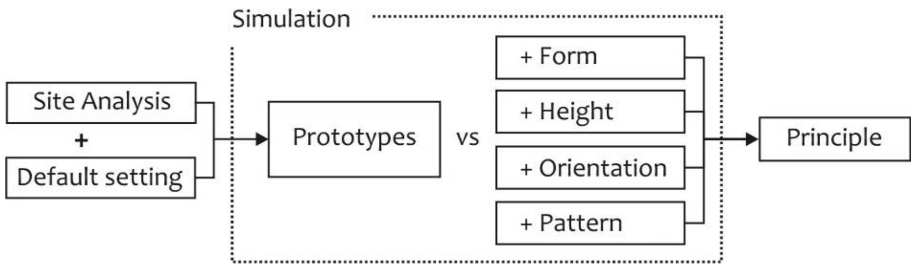

Figure 1 The framework of methods.

3.2 Technical tools

The proposed calculation engine was developed to simulate buildings at urban scale, and is integrated by SketchUp (@Last Software and Google), HTB2 v2.10 (WSA 2008), and Virvil Plugins (WSA, 2012). SketchUp is among the most popular software for 3D building used by architects and urban designers, while HTB2 is recognized as one of the most reliable calculation engines for energy use and internal temperature prediction (Alexander, 2003). Virvil Plugins are updated tools to connect both of them, helping to extend the limited scope of HTB2 to consider the relationship of buildings to the nearby surrounding areas (Lin, 2013). These tools were adopted in this research because of their high reliability, applicability and user-friendly interface.

4. Subject

This case is chosen from an urban design scheme of Yuehai Eco-City in Yinchuan, China, which is designed by Architects & Engineers Ltd. of Southeast University, China. Yinchuan is located in the northwest region of China, between 37°29′N~38°53′N and 105°49′E~106°53′E. The average elevation of Yinchuan is 1,010 to 1,150 metres. Yinchuan has a continental desert type of weather, with an annual average temperature of 9.4°C. Also, it is characterized by long hours of daily sunshine, intensive solar radiation, observable differences of diurnal temperature and four seasons.

The planned area of Yuehai Eco-City is 317.4 hectares, located at the north of Yinchuan city centre close to the Yuehai Wetland Park. In order to make a low carbon and ecological living environment and to meet the local government's requirements of energy performance for buildings, this planning aims to create a pleasant urban environment and to reduce the overall energy consumption of the eco-city.

The simulation prototype of this study is based on block numbers 6, 7 and 8 of the Yuehai Eco-City Planning Scheme. Building types are categorized as domestic, commercial, school and office (Figure 2). Building form has been simplified in order to reduce the simulation time, but without compromising the accuracy. The default settings for the construction, layout and materials of buildings are based on high standard building regulations. The parameter settings for different types of window-wall ratio and indoor conditions are given in Appendices A, B and C. The four simulated scenarios considered in this study are created by adjusting the building form, the average building height, the orientation of buildings, and the community pattern. The context of the proportion of building types, total floor area, and building construction are not changed, and are again set to satisfy the requirements of local planning regulations.

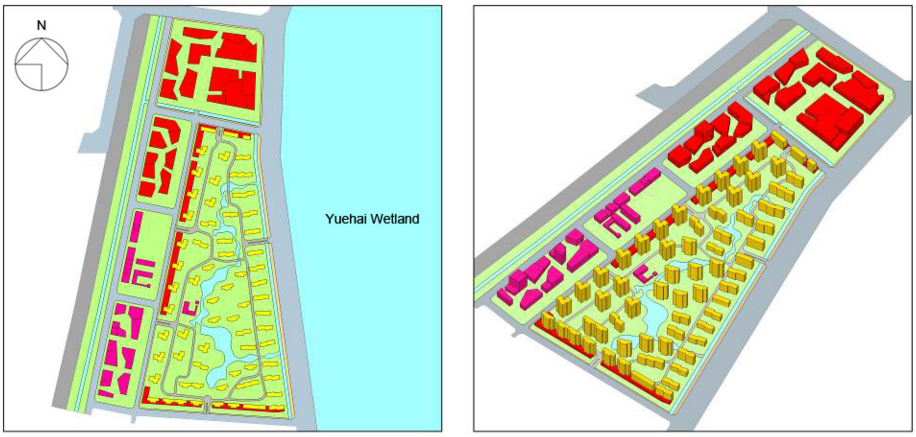

Figure 2 Images of the prototype used in this research: domestic (yellow), commercial (red), school and office (pink).

5. Discussion and Analysis

The simulation results of one prototype have been compared with four different experimental models based on consideration of the following four parameters: building form, average building height, orientation of buildings and community pattern (Figure 3). In the following sections, each of these parameters is analyzed and discussed.

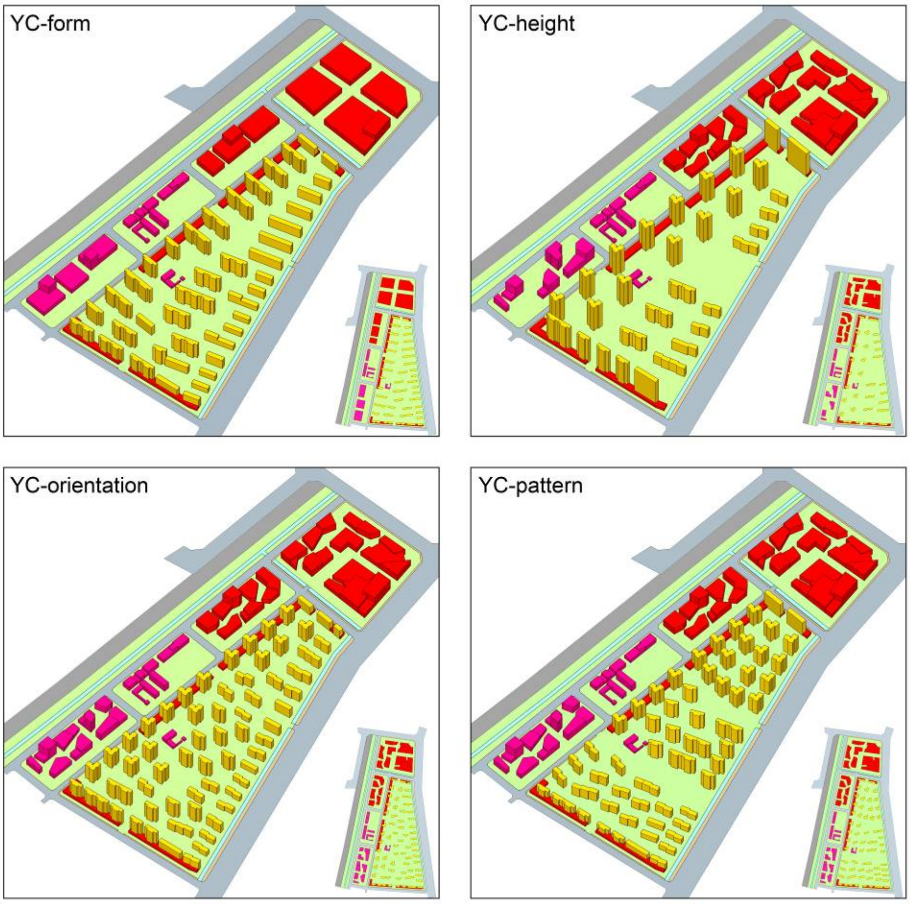

Figure 3 The four experimental models based on consideration of the following parameters: form (upper left) average building height (upper right), orientation (lower left) and community pattern (lower right).

5.1 Building form

Building form, which refers to the geometrical characteristics of the buildings, affects the solar gain and energy demand of buildings in the urban environment by changing the wall-to-volume ratio and the corresponding effect of over-shading (Lin, 2013). In northern China, the two most popular forms of domestic buildings are point block and slab block. For commercial buildings, the most popular types are commercial blocks and shopping malls. The prototype, YC, adopts the point block form for domestic buildings and commercial blocks for commercial ones. On the other hand, the experimental model, YC-form, adopts slab block and shopping mall types.

The simulation results show that integration of the slab block form for domestic buildings and the shopping mall form for commercial buildings decreases the energy demand (Figure 4).

The heating demand of slab block domestic buildings is generally 2.3 kWh/m²/yr lower than that for domestic buildings with the point block form, whereas the cooling demand is nearly the same in each case. For commercial buildings, the shopping mall form consumes less energy both for heating and cooling. Although the dependence of energy demand on building form may be much less than the dependence of energy demand on other mechanical strategies, optimization of building form is nevertheless a passive design strategy that can improve the overall energy performance of buildings.

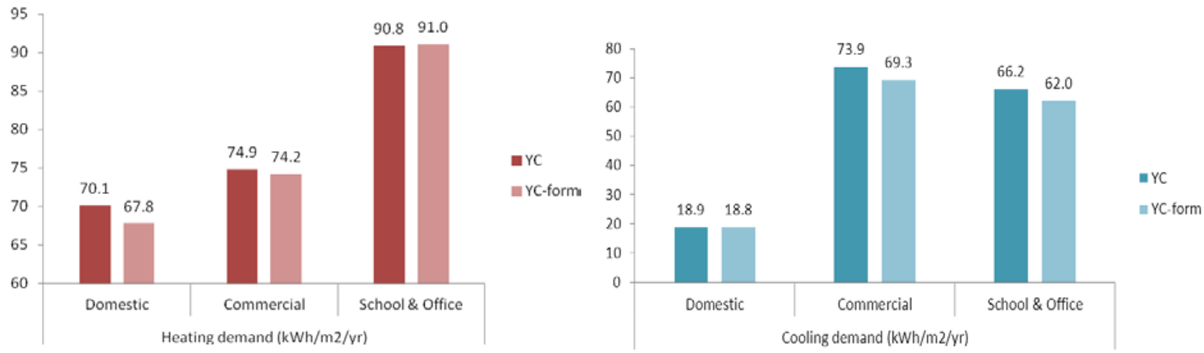

Figure 4 Comparison of energy demands between the prototype and the experimental models with different building forms.

5.2 Average building height

The impact of building height on the energy demand of buildings mainly arises from their role as practical obstacles in the urban environment. In particular, the building height not only shapes the skyline of a city and alters the amount of open space at ground level, but also affects the sunlight accessibility and solar gain. Based on the same building floor ratio of the site, an experimental model, YC-height, with higher average height of domestic buildings (78.3 metres) was created to explore the relationship between building height and energy demand (the average height of domestic buildings in the prototype model is 41.2 metres).

The simulation results indicate that the overall energy demands, considering all building types together, are higher as the building height increases. The annual heating demand of buildings in the YC-height model is higher for commercial and school/office buildings and slightly lower for domestic buildings compared to the prototype model (Figure 5). For commercial buildings, there is an increase in heating demand of 1.2 kWh/m²/yr for the YC-height model, whereas for school/office buildings, the increase in heating demand is 6.3 kWh/m²/yr. Furthermore, in the experimental model, over-shading brought about by higher buildings increases slightly, which is supposed to be the reason underlying the rising requirement of heating during the winter time in Yinchuan.

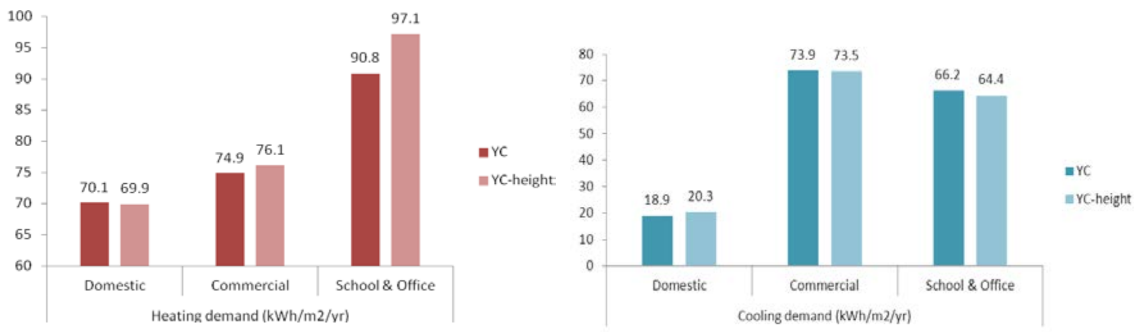

Figure 5 Comparison of energy demands between the prototype and the experimental models with different average building height.

5.3 Orientation of buildings

The orientation of a building is defined as the direction perpendicular to the main surface of the building. Clearly, the orientation of a building affects the solar gain and the energy demand by altering the incident angle and duration of sunlight. It is regarded as one of the most important parameters in housing design in northern China. In the prototype, YC, the direction of the domestic buildings is within plus or minus 15 degrees of a directly south-facing orientation. In the experimental scenario, YC-orientation, all domestic buildings have the orientation of facing south exactly.

The simulation result shows only minor differences in the energy performance of buildings between the two models, with differences of no more than 0.4 kWh/m²/yr for all types of building (Figure 6). Thus, the results suggest that the energy performance of buildings facing directly south and facing close to south in the community scale in Yinchuan are almost the same. The same situation is observed both for the heating demand in winter and the cooling demand in summer. In short, the orientation of buildings in the modelling situation has very limited impact on the energy demand of buildings.

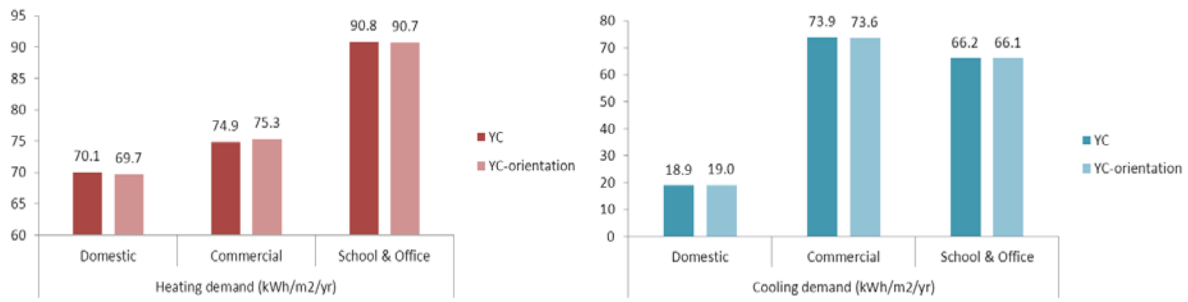

Figure 6 Comparison of energy demands between the prototype and the experimental models with different orientations of buildings.

5.4 Community pattern

Community pattern is another major issue, which has been analyzed by previous researchers with regard to the street geometry formed by buildings and the different horizontal and vertical layouts of buildings. It was demonstrated that the juxtaposition of buildings and the form of external spaces outside the envelops affect airflow below roof level, cause over-shadow, and change the reflected light, which consequently influence the entire energy consumption of the buildings.

In the experimental model, YC-pattern, the three different types of domestic building (multi-storied apartment group, point block group and slab block group) are arranged from north to south respectively. In contrast, in the prototype, YC, the different types of domestic building adopt a random layout.

The simulation results indicate that the differences in energy demand of buildings between the two models are within 0.5 kWh/m²/yr, with the exception of the heating demand for domestic buildings (Figure 7). Thus, for domestic buildings in YC-pattern model, the heating demand is approximately 2.3 kWh/m²/yr higher than the heating demand of the prototype. Furthermore, for each type of building, a negative correlation is observed between the heating demand and cooling demand in comparing the experimental model and the prototype model. In short, our results imply that over-shading arising from a relatively concentrated and unified community pattern should give rise to an increase in the heating demand of domestic buildings in winter and a decrease in the cooling demand in summer.

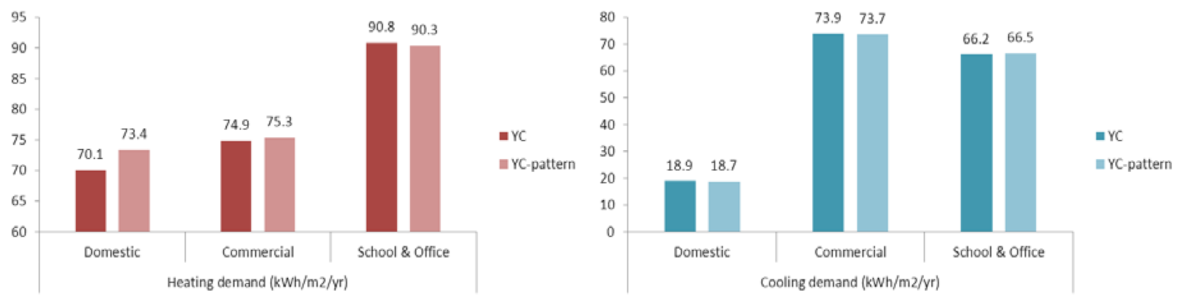

Figure 7 Comparison of energy demands between the prototype and the experimental models with different community patterns.

5.5 Summary

From detailed comparison of the simulation results for the prototype and the four experimental models, several significant conclusions emerge. Importantly, the total energy demand of YC-form is lower than the prototype by 1.6 kWh/m²/yr, the total energy demand of YC-orientation is nearly the same as the prototype, and the total energy demand of YC-height and YC-pattern are higher than the prototype by 2.5 and 3.2 kWh/m²/yr respectively (Figure 8). Consideration of the implications of our results in terms of building design strategies leads for the following conclusions: (1) compact building forms and horizontal and vertical random layouts are one of the most effective strategies for reducing the energy demand of buildings at urban scale, (2) when the average height of buildings is over 75 metres, the energy demand increases as the average height increases, and (3) moderate changes in the orientation of buildings do not have any significant effect on the energy demand at urban scale. Furthermore, the effect of altering the compactness of building forms may be interpreted in terms of changes in the wall-to-volume ratio of the buildings. Lower wall-to-volume ratios avoid massive heat exchange, leading to better energy performance of buildings.

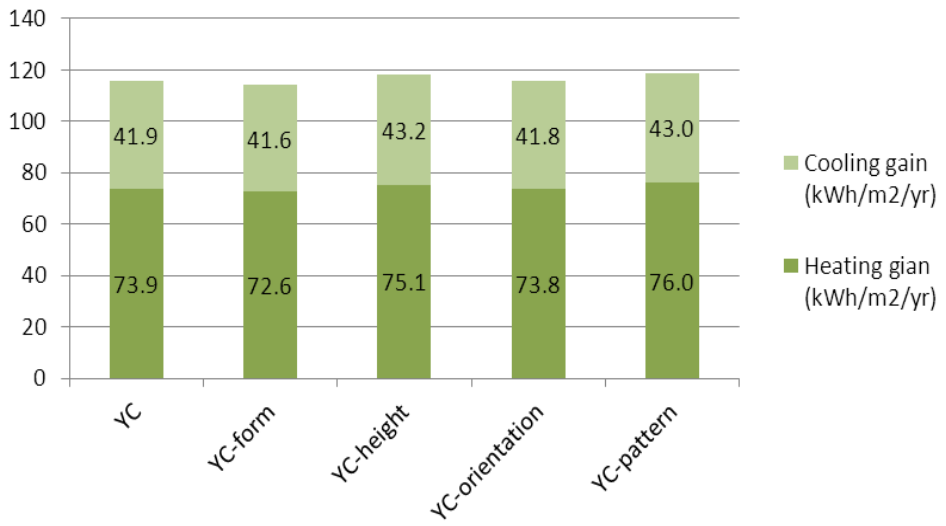

Figure 8 The comparison of annual energy demands between the prototype and experimental models

6. Conclusion

This paper simulates the energy performance of a community based on the urban design scheme of Yuehai Eco-City in Yinchuan, northern China. Four scenarios have been employed representing four different experimental models to investigate the effects of building form, average building height, orientation of buildings and community pattern on the energy demand of different types of building (domestic, commercial and school/office buildings). By comparison with the prototype model, the results of experimental simulations indicate that more compact building forms and horizontal and vertical random layouts of buildings can help to reduce the energy demand of buildings at urban scale. Additionally, when the average height of buildings is over 75 metres, increasing the average height has a detrimental effect on the energy demand. Moreover, moderate changes in the orientation of buildings only have a weak effect on the energy demand of buildings at urban scale.

The findings of this study provide some valuable principles for energy-efficient community design at the master planning stage for cities with continental desert weather type. The primary recommendation from this study is to choose compact building forms; thus, given the same amount of floor area, a decrease in the average wall-volume ratio of buildings should reduce the total energy demand. Furthermore, random layouts in both horizontal and vertical levels are shown to be advantageous over regular layouts. Finally, a lower average height of buildings is found to give rise to better energy performance, in contradiction to the widely held view that increasing the compactness of cities, in particular by increasing the average height of buildings, should be advantageous for reducing energy consumption.

Lastly, it is relevant to highlight some limitations of this study. Firstly, the prototype model was selected from a proposed design scheme which already incorporated consideration of energy efficiency through the experience of the designer. Thus, there is only limited scope for the experimental models considered in the present study to achieve improvements in energy efficiency relative to the prototype model. However, the accumulative effect of all relevant parameters that influence energy demand at urban scale still requires to be investigated, and such studies should lead to the development of better passive design approaches. Thus, further studies should focus on understanding the effects of groups of parameters and their individual impacts on energy performance in more aggressive situations.

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Appendix A

Simulation conditions of building construction and materials

Building type	**Construction**	**U value (W/m².C)**	**Required U value**	**Materials**	**Thickness (mm)**
Domestic & School	External wall	0.45	0.52	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	0.52	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	2.00	2.8	Glass	6
				Cavity	12
				Glass	6

Building type	**Construction**	**U value (W/m².C)**	**Required U value**	**Materials**	**Thickness (mm)**
Commercial & Office	External wall	0.44	0.6	Cement Mortar	10
				XPS Plate	30
				Aerated Concrete Block	200
				Cement Mortar	20
	Roof	0.43	0.55	SBS Modified Asphalt Rolling Material	4
				Fine Aggregate Concrete 2300	30
				XPS Plate	60
				Reinforced Concrete	120
				Cement Mortar	20
	Ground	0.28	0.3	Reinforced Concrete	60
				Autoclaved Aerated Concrete Block	140
				SBS Modified Asphalt Rolling Material	3
				RFT Plate	60
				Fine Aggregate Concrete 2300	60
				Earth	600
	Window	2.00	3.5	Glass	6
				Cavity	12
				Glass	6

Appendix B
Simulation conditions of building indoor

<table>
<tr><th colspan="2"></th><th>Domestic</th><th>Commercial</th><th>School & Office</th></tr>
<tr><td rowspan="3">Heating/cooling</td><td>Design temperature</td><td>18-26°C</td><td>18-23°C</td><td>18-23°C</td></tr>
<tr><td rowspan="2">Operation schedule</td><td>Monday to Friday: 00:00-08:00&18:00-24:00</td><td rowspan="2">Monday to Friday: 08:00-18:00</td><td rowspan="2">Monday to Friday: 08:00-18:00</td></tr>
<tr><td>Saturday to Sunday: 00:00-24:00</td></tr>
<tr><td rowspan="3">Internal gains (from lighting, small power and occupancy)</td><td>Output power</td><td>15W/m²</td><td>35W/m²</td><td>40W/m²</td></tr>
<tr><td rowspan="2">Operation schedule</td><td>Monday to Friday: 00:00-08:00&18:00-24:00</td><td rowspan="2">Monday to Friday: 08:00-18:00</td><td rowspan="2">Monday to Friday: 08:00-18:00</td></tr>
<tr><td>Saturday to Sunday: 00:00-24:00</td></tr>
<tr><td rowspan="3">Ventilation</td><td rowspan="2">Weekday</td><td>0.5,1.0,1.0,26°C</td><td>0.5,2.0,2.0,26°C</td><td>0.5,2.0,2.0,26°C</td></tr>
<tr><td>On during 08:00-18:00&18:00-24:00</td><td>On during 08:00-18:00</td><td>On during 08:00-18:00</td></tr>
<tr><td>Weekend</td><td>On during 00:00-24:00</td><td>Off all the day</td><td>Off all the day</td></tr>
</table>

Appendix C
Simulation conditions of other building settings

	Domestic	Commercial	School & Office
Window-wall ratio	30%	60%	50%
Floor height	3.0 m	4.0 m	4.0 m