9 Using spatial indicators to predict ventilation and energy performance

Correlation analysis for an apartment building in five Chinese cities[8]

ABSTRACT In the early design stages, architects are in constant search of a design direction that can determine the success or failure of the final design. However, in real design practice, most of the prediction methods for building performances, in this paper energy and thermal comfort, are utilised in the later design stages. Spatial configuration is one of the most important issues for architectural design in the early design stage. This study investigates the correlations between the spatial indicators connected with architectural design and the building physics indicators ventilation performance and energy performance. The main objective is to explore the potential

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of applying spatial indicators using space syntax to predict ventilation performance and energy performance in order to support architects for the evaluation of their concept and schemes in early design stage. The layout of a high-rise apartment in China in five different cities is chosen as a case study. The results show that the selected three indicators: connectivity value, air change rate and annual cooling saving ratio are linearly correlated, not just at building level but also at room level. R^2, the correlation coefficient of determination, is between 0.53 and 0.90 (except for the case of Chongqing at building level).

KEYWORDS Space syntax; air change rate; annual cooling saving ratio; connectivity; correlation analysis

9.1 Introduction

Various researchers have studied natural ventilation for thermal comfort and energy efficiency. Natural ventilation strategies can be applied without air conditioning and in mixed-mode ventilation, an operation in which both an air conditioning system and operable windows are available (Hiyama & Glicksman, 2015). Previous studies show that increasing the daytime air speed and high night ventilation rates can improve the thermal comfort and energy efficiency of buildings in summer because occupants prefer larger air movements so that thermal comfort ranges can be expanded with increased air movement and night ventilation rates can cool the thermal mass of the building (Mishra & Ramgopal, 2013; Schulze & Eicker, 2013; Zhang et al., 2007). However, designing a building for optimal natural ventilation in the early design stage is still a challenge.

9.1.1 Early design stages and performance simulation

Currently, the trend of aiming for a more comfortable and energy-efficient building design has increased the demand for building performance simulation in the early design stages before engineering systems are incorporated, i.e. the concept design and schematic design stages (Hiyama & Glicksman, 2015). The American Institute of Architects (AIA) identified the building performance simulation in the early design stages as Design Performance Modelling, a method to make design decisions by predicting a building’s performance (AIA, 2012). In the early design stages, architects are in constant search for a design direction to make an informed decision that can determine the success or failure of the final design (Attia et al., 2012). However, in real design practice, most of the prediction methods for building performances are utilised in the late design stages, such as the design development stage and contract documents stage because of their complexity and time-consuming nature. In the ideal case, architects and engineers cooperate but the engineer, with predictions and evaluations, is often in the lead. A method used for simulation in the early stage should be easy and fast, therefore a relatively rough simulation result is acceptable at this stage. In the early design stage, architects focus more on the general mass, layout, geometry and shape of buildings than details of components such as material features. To make a design decision in the early design stages, modelling a whole-building is required and tools should have the ability to predict the performance without too much detailed input of the building information. A detailed design of the building components can be left to the design development stage and the contract document stage using more accurate prediction approaches.

9.1.2 Existing methods for the prediction of ventilation performance and energy efficiency

A lot of research has been done on the prediction of ventilation performance in buildings. According to Chen (2009), the methods can be classified into analytical models, empirical models, experimental models, multi-zone models, zonal models and computational fluid dynamics (CFD) models. The analytical models and empirical models are simple to use and the requirements are small. But the model can only be applied to a simple room and the result is not very accurate. The experimental models can be applied to the entire building and the result can be accurate, but the cost is very high. The multi-zone model can be applied to the entire building and the zonal models can applied to large spaces. The result of the multi-zone model is accurate enough but the time consumption is considerable. The computational fluid dynamics (CFD) models can applied on an entire building. The result is visual. But the requirements (i.e. the computer capabilities and time consumption) of CFD models are high. The knowledge demand of users is high as well.

For energy performance prediction and evaluation, many tools were developed in the past decades. Some literature reviewed the methods (AIA, 2012; Attia et al., 2012; Foucquier, Robert, Suard, Stéphan, & Jay, 2013). The general method can be categorised into: physical models that are based on solving equations describing the physical behaviour of the heat transfer, statistical methods that use machine learning and hybrid models (Foucquier et al., 2013). However, most of the tools for both ventilation and energy performance prediction are difficult to use in the early design decision-making processes. Attia et al. (2012) studied the DOE website in 2011, and found that out of the 392 building performance simulation tools listed, less than 40 tools address architects directly in the early design stages. Most of the whole-building programs require detailed information about mechanical and electrical systems to attain accurate results. These tools also need professional training. There is a number of software tools designed for the early design stage, while many of the software programs have been developed as stand-alone programs that do not integrate seamlessly with existing CAD software platforms, which are broadly used for architectural design (AIA, 2012).

As mentioned in section 9.1.1, the whole building is the focus in the early design stage. Therefore, some researchers tried to find the relationship between the general building form, ventilation performance and energy consumption. Depecker et al. (2001) studied the relationship between the heating consumption of buildings and their shape. Wang et al. (2006) presented a methodology to optimise building plan shapes using the genetic algorithm. AlAnzi et al. (2009) provided a simplified analysis method to estimate the impact of building shape on energy efficiency of office buildings in Kuwait. Yi and Malkawi (2009) introduced a new method to control building forms by defining a hierarchical relationship between geometry points to allow the user to explore the building geometry without being restricted to a box or simple form. Liu et al. (2015) studied 8 cases of typical high-rise office building plans in northern China. The correlation between plan shape and energy consumption was studied based on the analysis of several key factors. However, no study was found that explored the relationship between the spatial configuration, ventilation performance and energy consumption even though spatial configuration is important for building form generation in the early design stage of architectural design.

9.1.3 Objective of this study

Spatial configuration is one of the most important issues for architectural design in the early design stage. Spatial analysis methods for architectural design should be considered when predicting ventilation and energy performance in the early design stage. This study investigates the correlations between spatial indicators, ventilation performance and energy performance. The main objective is to explore the potential of applying spatial indicators using space syntax (Hillier, 1999) to predict ventilation performance and energy performance in order to support architects for the evaluation of their concept and schemes in early design stages. The layout

TOC

of a typical high-rise apartment in five Chinese cities is chosen as a case study. The studied case was operated on natural ventilation (mixed-mode ventilation) for cooling in terms of ventilation for cooling load conservation in the hot and humid climate.

9.2 Inspiration from space syntax

9.2.1 The space syntax method in architectural design

A lot of research has focused on the spatial analysis of architecture to investigate the effect of spatial design on people's behaviour. This basically involves analysing the geometrical features such as shape, size and proportion of a spatial environment. In architectural theory, the compositional approach developed more or less formal language based on basic geometric primitives. The approach, however, did not lead to a quantitative description of all spatial features (Wiener & Franz, 2005).

Space syntax analysis turned attention away from the geometrical notions of spatial features in the study of buildings and cities, emphasising instead the spatial topological relationship (Hillier, 1999). "Space syntax is a set of techniques for the representation, quantification and interpretation of spatial configuration in buildings and settlements. The configuration is defined, in general, as the relationship between two spaces taking into account a third, or, at most, as the relationship among spaces in a complex, taking into account all other spaces in the complex" (Hillier, Hanson, & Graham, 1987). The parameters measured in the space syntax method can bring to light the accessibility, permeability and visibility characteristics of a spatial configuration in a particular spatial environment.

In the space syntax method, the spatial configuration and the social logic of a particular urban or building space can be visually represented by a topological network, a "justified graph", in which every space in a certain spatial configuration is represented as a "node". In the justified graph, a particular room of the spatial configuration is selected as the root node, and the spaces in the graph are then aligned in levels above, according to how many spaces one must pass to arrive at each space from the root (Hillier et al., 1987). From a justified graph, four major indices can be determined to evaluate the spatial configuration properties in terms of permeability or accessibility.

1 Connectivity: C_i is the total number of nodes which are directly connected to a given node i. The bigger C_i, the better the permeability of the space of the node.

2 Control: the control value of node i can be expressed as:

$$Ctrl_i = \sum_{j=1}^{k} \frac{1}{C_j}$$

where C_j is the connectivity value of node j, which is directly connected to node i, and k is the total number of connections associated with node i. The control value expresses the degree of dominance of node i allocated from its directly connected nodes. A bigger control value of a node means this node can control or influence a greater number of adjacent nodes.

3 Depth: this is measured in steps: the depth between one node to an adjacent node (it is directly accessible to it) is 1, and the shortest distance (minimum step) from node i to any other node, for example node j, is the depth, D_{ij}, of the two nodes. The total depth of node i is expressed as:

$$TD_i = \sum_{D=1}^{D_l} (D \times N_d)$$

where D is the depth from node i to any other node, ranging from 1 to Di (the longest depth); N_d is the number of traversed nodes corresponding to each D. The mean depth of node i can be presented as:

$$MD_i = TD_i/(n\text{-}1)$$

where TD_i is the total depth of node i; n is the total number of nodes in the spatial system. TD and MD indicate the accessibility of a node in the whole spatial system.

4 Integration: the total depth TD and mean depth MD value mentioned above are strongly influenced by the total number of nodes in a particular space configuration. To avoid node number interference in the spatial system, mean depth can be normalised into Relative Asymmetry,

$$RA_i = 2(MD_i\text{-}1)/(n\text{-}1)$$

where MDi is the mean depth of node i; n is the total number of nodes in the spatial system. In order to compare differently sized space systems, the equation can be further normalised into Real Relative Asymmetry,

$$RRA_{\mathrm{i}} = \frac{RA_i}{D_n}$$

where

$$D_n = \frac{2n\left[\log_2\left({}^{n+2}/_{3}\text{-}1\right)+1\right]}{(n\text{-}1)(n\text{-}2)}$$

is a RA value of a Diamond-shaped pattern (Hillier & Hanson, 1984). The integration value $I_i = 1/RRA_i I_i = 1/RRA_i$ was introduced to describe the positive correlation of the accessibility of a particular node in a space configuration. The bigger a node's integration value Ii, the better the relative permeability and accessibility of this node in the relevant spatial configuration. The integration value is one the most common and important indices used to evaluate spatial properties in spatial analysis.

Of the four indices identified above, connectivity and control describe the local spatial relationship in terms of one space to the adjacent spaces, while depth and integration trace the global relationships between one space and all other spaces involved in the whole system.

Over the past decades, space syntax and various related theories and methods, such as isovist (Benedikt, 1979) and Prospect-refuge (Appleton, 1975), have been applied in architectural design to investigate the relationship between spatial environment features and underlying social behaviour, for example the movement patterns, way-finding, security, living style at the urban scale (Choi, Kim, Oh, & Kim, 2006; Hillier, 2009; Hillier & Shinichi, 2005), and building scale (Choi, 2013; Dawes & Ostwald, 2014; Franz & Wiener, 2008; Hillier et al., 1987; Julienne, 1998). The theories and methods have undergone a great deal of development and have been verified through decades of research. Space syntax method provides the possibility for architects to explore their ideas, to understand the possible effects of their design and to show how their designs work (Dursun, 2007).

9.2.2 The potential of the space syntax method for the preliminary airflow performance analysis

Movement is a major factor underlying human behaviour influenced by the spatial characteristics analysed in space syntax. In a particular spatial configuration of a building or of urban morphology, people's movement patterns, way-finding behaviours and route choices can be predicted through space syntax analysis. In this study, however, the focus of the space syntax analysis is shifted towards air flows. The assumption is that there are common characteristics of people flows and air flows related to the spatial configuration. The space syntax method has proven that spatial accessibility and permeability are important for people's movement. In ventilation performance analysis, air movement patterns are the focus. The driving forces of the movement of air between the spaces, not only the outdoor spaces but also the indoor spaces, are pressure differences caused by buoyancy and wind. Ventilation rates are dependent on the magnitude and direction of these forces and the flow resistance of the flow path (Schulze & Eicker, 2013). Consequently, the spatial accessibility and permeability, important for people flows, are also important for the air movement between the spaces. The connectivity value, for example, describes the total number of spaces which are directly connected to a particular space. A larger connectivity value increases the permeability of the space. That means that the space with a bigger connectivity value has the potential to achieve more air flow from connected spaces, especially through cross ventilation.

9.3 Methodology

For this study, a typical high-rise apartment building in five Chinese cities was selected as a case study. The floor plan is identical for the majority of floors. A standard floor consists of six households, see figure 9.1. The floor area per household is 90 m^2 to 112 m^2. As the floor plan is axially symmetric, half of the plan (household 1,2 and 3) was analysed. The floor was performed in a spatial analysis (Depthmap10) to obtain the spatial indicators: connectivity and integration, and in a dynamic thermal simulation (DesignBuilder 4.0) to obtain the ventilation and energy performance indicators: air change rate and annual cooling load saving ratio (ACSR, see 9.3.3.4). To achieve more cases for the correlation analysis, the floor was taken into account by simulating the space syntax parameters for 16 different wind angles

TOC

(in step of 22.5 degrees). The dynamic thermal simulation in DesignBuilder was also simulated for 16 different building orientations (again in steps of 22.5 degrees).

The correlation analysis was performed at two levels (figure 9.2). For building level, the calculations were performed for the entire floor. Correlation between ACSR and the air change rate was expected. For room level, the calculations were performed for the individual rooms of the floor plan. Correlations between the ACSR, air change rate and the connectivity (integration) values of the rooms were expected.

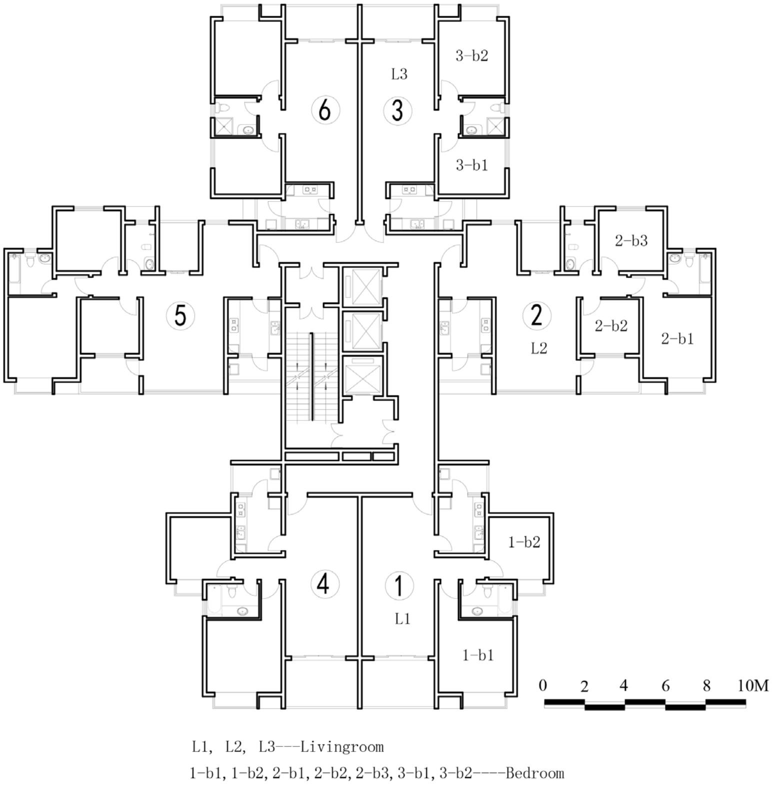

FIG. 9.1 The floor plan of the selected high-rise building (household 1,2 and 3 were analysed)

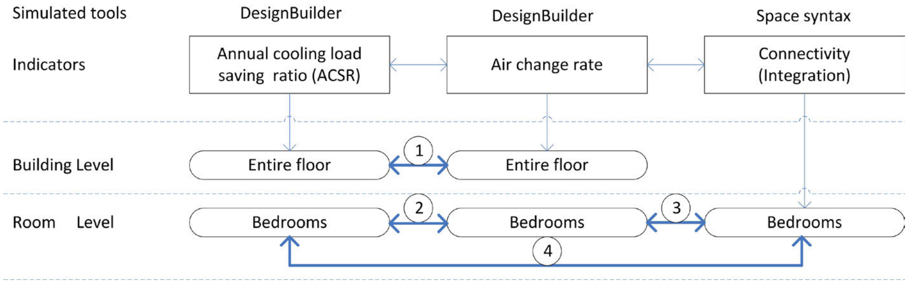

FIG. 9.2 The frame of the research method (1 / Correlation between ACSR and air change rate of the floor; 2 / Correlation between ACSR and air change rate of the rooms; 3/ Correlation between air change rate and connectivity of the rooms; 4 / Correlation between ACSR and connectivity of the rooms)

9.3.1 Climate conditions

In order to increase the universal significance of the study, five cities in China-Shanghai, Nanjing, Wuhan, Chongqing and Chengdu-were selected as weather locations of the dynamic thermal simulation to obtain the air change rates of the rooms and the yearly cooling loads. According to the national "Standard of Climatic Regionalisation for Architecture", all the five cities are located in the hot summer and cold winter zone of China. Common climate characteristics in this region are a hot and humid summer and a cold winter.

Figure 9.3 illustrates the average monthly temperatures and wind velocities in the five cities over an entire year, according to the Energyplus weather database, which was used in this thermal simulation. As we can see, in winter, the average temperature in Shanghai, Nanjing and Wuhan is lower than in Chongqing and Chengdu. The lowest average temperature is 2°C, in Nanjing in January; in summer, the average temperatures in all of the cities is high, except for Chengdu, where they are slightly lower. The highest average temperature of 29°Cis reached in Wuhan in July. For the monthly average wind velocities, the highest value is found in Shanghai, 2.5-3.5 m/s. Next to highest is Nanjing with wind speeds between 1.0-2.8 m/s, and Wuhan 1.0-2.8 m/s. The monthly average wind velocity in Chongqing and Chengdu is relatively low, i.e. 0.5-2.0 m/s.

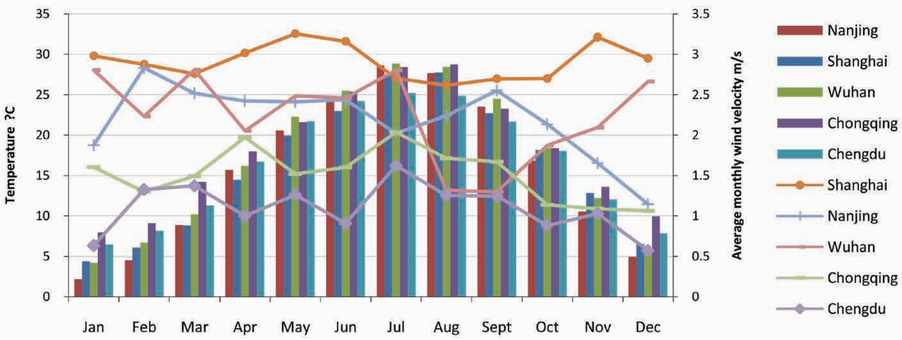

FIG. 9.3 The average monthly temperature and wind velocity of the five cities (the columns represent the average monthly temperatures and the lines represent the average monthly wind velocities)

Figure 9.4 shows the annual wind rose of the five cities, based on the annual frequency of the wind direction which comes from the Energyplus weather data base. The wind rose classifies incoming wind into 16 directions and expresses the frequency of wind in different directions. As we can see, for instance, during one typical year, in Shanghai, the highest frequency is in 90 degrees (east) and the annual prevailing wind direction is east to southeast.

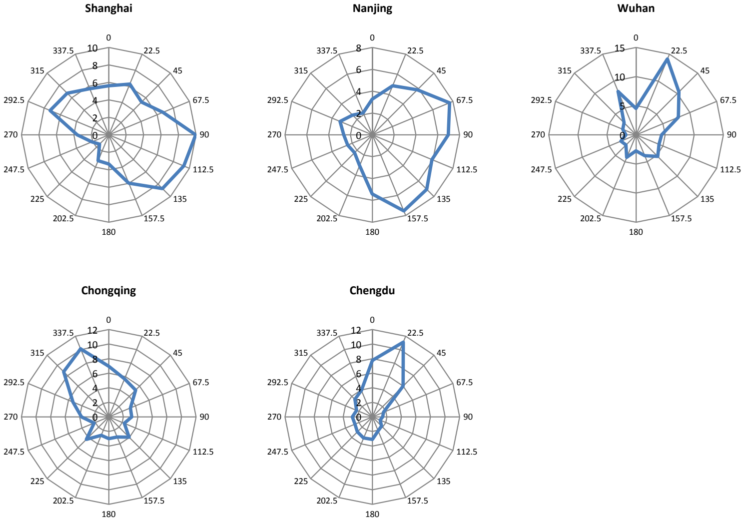

FIG. 9.4 The yearly wind rose of the five cities studied (based on the annual frequency of the wind direction) with 0 = north and 90 = east.

TOC

9.3.2 Space syntax analysis

The program Depthmap10 was used to perform the visibility graph analysis (VGA) in this study. In the VGA, the studied layout was divided into multiple rectangular convex spaces (squares) using a grid. The grid size determines the accuracy of the results. Here, the grid was set to 300x300mm. Each square (300x300mm) is a convex space to which a node was assigned, as described in section 9.2.1. The parameters related to the spatial features of each square were calculated and are shown in the VGA map. In this case, the local parameter-connectivity and the global parameter-integration were focused[9].

A special aspect of this study is that the outdoor environment was included in the VGA. In the usual space syntax analysis, the outdoor space is generally represented as only one node. This is because the space syntax analysis usually focuses on the spatial relationships between indoor spaces in buildings. In this case, we focused on the spatial visibility and permeability, not only of the indoor spaces but also of the outside spaces. The reason for this is that the permeability between indoor spaces and outdoor spaces is significant for the wind environment and air movement. A problem was how to include the outside wind environment in this VGA. The general idea is to extend the boundary of the building to a certain extent to represent the outside wind environment. The larger the boundary of the external wind environment, the greater the potential of natural ventilation in the indoor space. In order to simulate the influence of the wind direction, it was chosen to extend the outside boundary larger on the side respecting the wind direction than other sides. To find the suitable boundary of the outside wind environment, a test VGA was performed for the floor. Figure 9.5 (a) shows the boundary settings of the outside wind environment in the test. The outside environment was extended 1/10 of the width or length of each side of the layout. The wind direction was assumed above. The upper boundary of the outside environment was extended to 1.5L, 2.0L, 2.5L, 3.0L,3.5L and 4.0L where L is the length of the layout. The room of 3-b2 was selected as the test room. The connectivity values of the test room were obtained according to different boundary settings in VGA. Figure 9.5 (b) shows the correlation of the boundaries and the connectivity values. It was found that the boundary of the outside wind environment can influence the value of the connectivity in terms of larger external wind environment means high connectivity value, but the change of the value is linear. In this study, the absolute value of the spatial indicators is not the focus. The focus is the correlation between the spatial indicators and the ventilation and energy

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[9] These two factors are the basic indices which are common measured in space syntax analysis.

performance. Therefore, for time saving, the relatively small boundary of the outside wind environment, 1/2 of the length was extended as the boundary on the side of the wind direction and 1/10 of the width and length of the layout was extended on other three sides (figure 9.5 (c)).

As mentioned above, to obtain more cases, the floor plan was simulated in 16 situations by rotating the layout of the building 22.5 degrees counter-clockwise for each simulation (Figure 9.5 (c)). Because we did not change the outdoor wind environment settings, this means that the floor plan was simulated in 16 situations corresponding to 16 different directions of the outside wind relative to the floor plan.

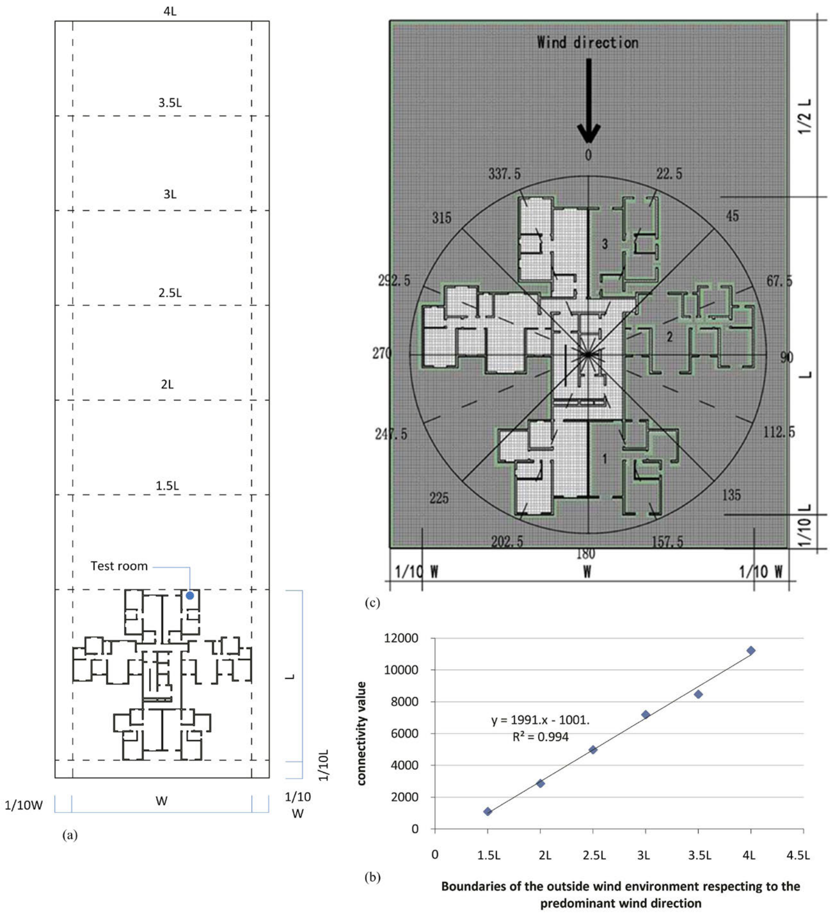

FIG. 9.5 The boundary setting of the floor plan for the VGA (a) the setting for the test VGA (b) the correlation between the boundaries and the connectivity value of the test room (c) the final setting of the outside wind environment boundary for the VGA (household 1,2 and 3 were analysed)

9.3.3 Dynamic thermal simulation

9.3.3.1 The simulation model

Figure 9.6 shows the building model used in the DesignBuilder simulation. The floor plan was also simulated with 16 cases in the dynamic thermal simulation. The floor plan was rotated 22.5 degrees clockwise from the north for each simulation, which means the floor plan was simulated in 16 orientations. It should be noted that here the rotation of the floor plan causes a different orientation of the building, whereas in the space syntax simulation, the rotation of the floor plan causes different wind directions relative to the coordinates of the floor plan.

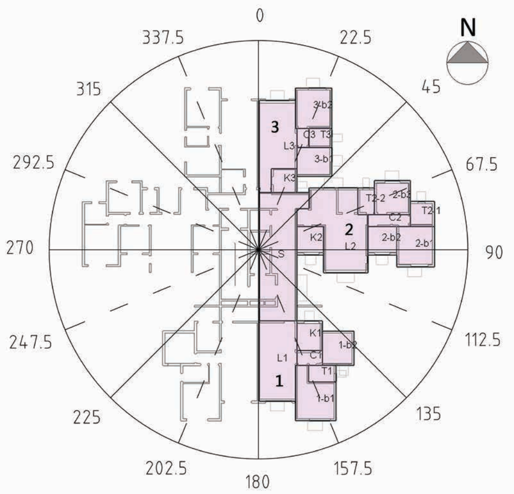

FIG. 9.6 The building model built in DesignBuilder (household 1,2 and 3 were analysed)

9.3.3.2 Building characteristics

The major building component features are listed in table 9.1. These features are commonly found in the design practice of the studied area determined from the Chinese national design standards for energy efficiency of residential buildings in hot summer and cold winter zones.

TABLE 9.1 Major building components features of the building studied

Construction	Material	Thickness (mm)	U-Value (W/m²K)
External wall	Cement	5	0.86
	Insulation mortar	25	
	Aerated brick	200	
	Cement	20	
Internal wall	Cement	20	1.02
	Aerated brick	200	
	Cement	20	
Internal ground	Sand Stone	500	1.5
	Reinforced concrete	100	
	Concrete	40	
Internal floor	Cement	20	2.7
	Reinforced concrete	120	
	Concrete	20	
Roof	Concrete- lightweight	40	0.44
	Cement	25	
	Insulation Expanded polystyrene extruded	100	
	Asphalt felt	3	
	Cement	20	
	Concrete- lightweight	40	
	Reinforced concrete	120	
	Cement	20	
Glazing			
Outdoor window	DblLoE (e2=.1) Clr	6/9Air/6	1.78
Outdoor door	DblLoE (e2=.1) Clr	6/9Air/6	1.78
Roof window	DblLoE (e2=.1) Clr	6/9Air/6	1.78

9.3.3.3 Ventilation strategy

In the dynamic thermal simulation, the building ventilation strategy was set as mixed mode. In mixed mode buildings, natural ventilation is used as the primary means of cooling and, when it is inadequate to provide comfort conditions, active cooling is introduced. Cooper (1998) formulated it as follows: “It is a building in which occupants can open windows, and which is designed with effective passive strategies for limiting the effects of the external climate. The passively designed building is utilised to provide acceptable conditions for the majority of the year, and is supplemented by a mechanical system, either on an ‘as and when required’ basis, or on a seasonal basis.”

In mixed mode, the operation of the air conditioning is controlled by the cooling set point temperature and the occupants’ schedule. In our case, the cooling set point temperature was set to 26°C. It means that when the indoor air temperature is higher than 26°C, the air conditioner starts to operate. Considering standard office hours in China (from 9:00 to 17:00 when people are not at home) and the habit of using the air conditioner in different types of rooms differently, the schedule is as follows, see table 9.2.

TABLE 9.2 Air conditioning schedule

		On	Off
weekday	bedroom	0:00-6:00 23:00-0:00	6:00-23:00
	Living room	17:00-23:00	0:00-17:00 23:00-0:00
weekend	bedroom	0:00-7:00 23:00-0:00	7:00-23:00
	Living room	14:00-23:00	0:00-14:00 23:00-0:00

In the façade, the opening is identified as the ratio of the effective opening area to the wall area. According to the design regulations in the area studied, the maximum window-to-wall ratio (WWR) is 30%. Generally, it is around 20% in the design practice. In this case, the WWR is set as 10% and 20%. The assumption of the window operation in our simulation was: when the air conditioning is on, or when the outdoor temperature is higher than the indoor temperature, the windows are closed; in other cases, the windows in the facades are half opened so that natural ventilation is possible.

9.3.3.4 Evaluation method for annual cooling load saving ratio

Since the focus of this study was the relationship between the cooling load and air exchange rate, the influence of solar radiation in different cases with different orientation should to be avoided. Therefore, the concept of the annual cooling load saving ratio (ACSR) was put forward (Li & Li, 2014; Zhang, 2010). The ACSR identifies the energy-saving potential of the annual cooling load induced by natural ventilation as: $ACSR=(1-Q_v/Q)*100\%$. Here ACSR is the annual cooling load saving ratio; Q_v is the annual cooling load of a building with natural ventilation (kWh/m^2); and Q is the annual cooling load of a building without natural ventilation (kWh/m^2). For the calculation of ACSR, the building was simulated twice in the same orientation, once with natural ventilation in terms of mixed mode, and another simulation without natural ventilation, where the air conditioning operates all the time according to schedule (when the indoor temperature is higher than 26°C and when windows are closed all the time).

9.4 Results

9.4.1 Results of the space syntax simulation

Figure 9.7 shows the distribution of the connectivity value (VGA map) in the Depthmap simulation corresponding to 16 different directions of the outside wind relative to the floor plan. From the VGA map, it is easy to see that the configuration of (outdoor and indoor) space changes with the wind direction. This causes a change in the accessibility and permeability of the rooms in the particular environment.

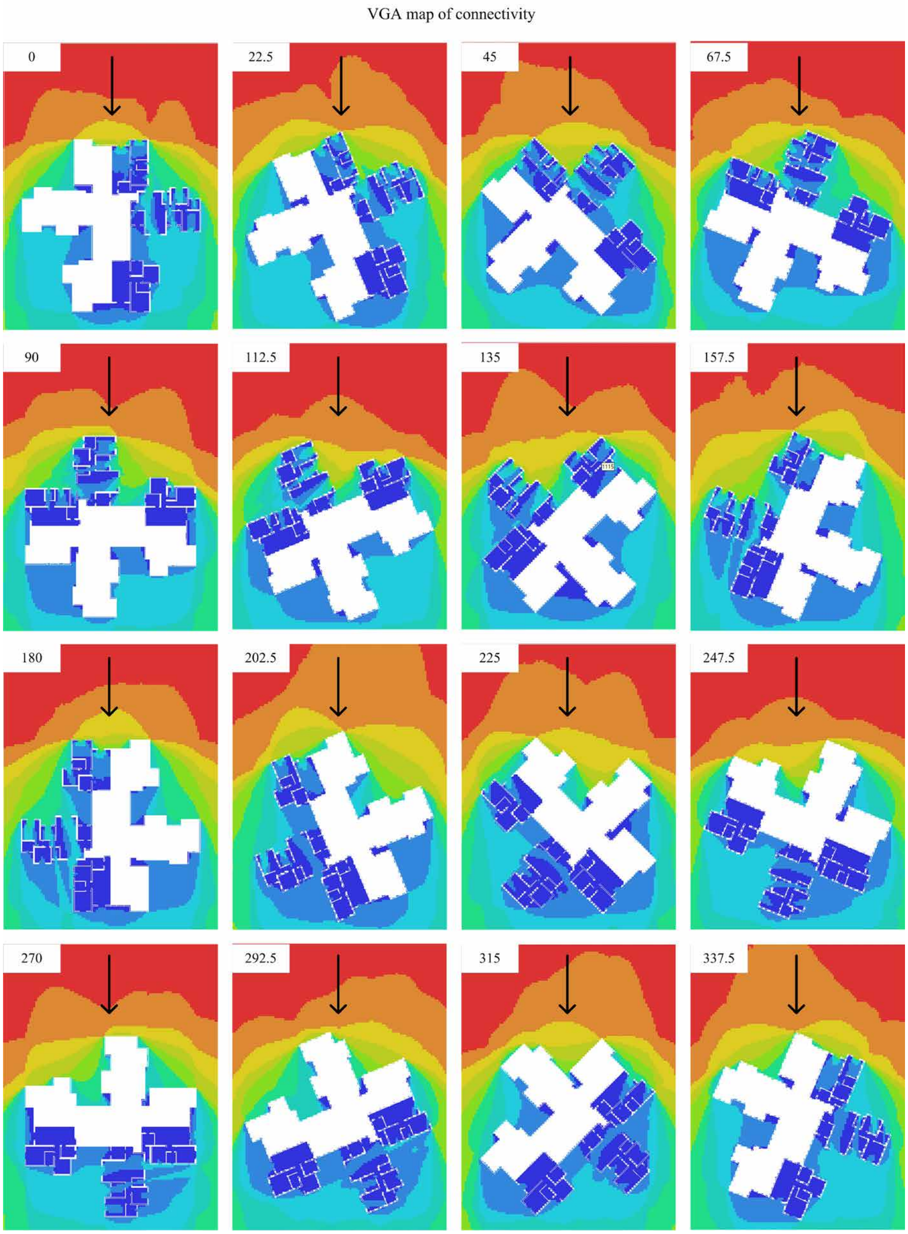

FIG. 9.7 The VGA map of the connectivity value corresponding to 16 different wind directions relative to the floor plan (0 = north and the arrow represents the wind direction; from red to deep blue, the connectivity is from big to small)

From the VGA map, the average connectivity and integration value in the different rooms (bedrooms) of households 1, 2 and 3could be obtained for different wind directions relative to the floor plan. It was found that there is a linear correlation between the connectivity and integration values (table 9.3) for all directions. Therefore, to simplify the analysis, only the relationship between the connectivity, the air change rate and ACSR is considered in the rest of this paper. Table 9.4 illustrates the connectivity value (average) of the major rooms in the VGA analysis.

TABLE 9.3 Linear correlation between the connectivity and integration value (R^2) of the major rooms for 16 different directions (with 0 = north and 90 = east)

	Wind direction related to the building (16 cases)															
	0	**22.5**	**45**	**67.5**	**90**	**112.5**	**135**	**157.5**	**180**	**202.5**	**225**	**247.5**	**270**	**292.5**	**315**	**337.5**
Correlation R^2	0.94	0.94	0.92	0.93	0.92	0.93	0.94	0.95	0.95	0.93	0.91	0.88	0.84	0.89	0.92	0.92

TABLE 9.4 The connectivity value (average) of the bedrooms in the VGA analysis for 16 different directions (with 0=north and 90 = east)

	Simulated wind direction relative to the building in the VGA analysis															
	0	**22.5**	**45**	**67.5**	**90**	**112.5**	**135**	**157.5**	**180**	**202.5**	**225**	**247.5**	**270**	**292.5**	**315**	**337.5**
1-b1	172	293	321	208	191	479	939	1147	1116	1016	544	252	190	322	295	185
1-b2	220	280	181	181	248	555	748	664	698	392	195	178	256	272	164	161
2-b1	664	655	553	633	934	1498	1711	1709	1516	1010	561	624	676	626	483	576
2-b2	856	811	699	720	872	1298	1580	1588	1399	911	573	674	764	643	518	735
2-b3	1361	1561	1473	1147	610	375	392	551	501	335	329	536	529	391	400	947
3-b1	536	868	1062	962	906	616	325	320	401	395	306	292	369	433	387	394
3-b2	1093	1113	944	445	194	192	334	300	181	170	297	323	187	257	537	1013

9.4.2 The results of the dynamic thermal simulation

Figure 9.8 shows the results of the annual cooling load with natural ventilation, the annual cooling load without natural ventilation, the annual cooling load saving ratio (ACSR) and air exchange rate of the five cities (when the window-to-wall ratio is 10%).Under natural ventilation conditions, the cooling load in Wuhan is the highest with a maximum of 24.4kWh/m^2; the second is Chongqing with a maximum cooling load of 21.2kWh/m^2; Nanjing reaches 17.7kWh/m^2; Shanghai 15.6kWh/m^2; and the lowest value is for Chengdu, 10.3kWh/m^2. The trend of the cooling loads in the five cities can be matched with the average monthly temperature, i.e. a higher monthly temperature of the city increases the cooling load.

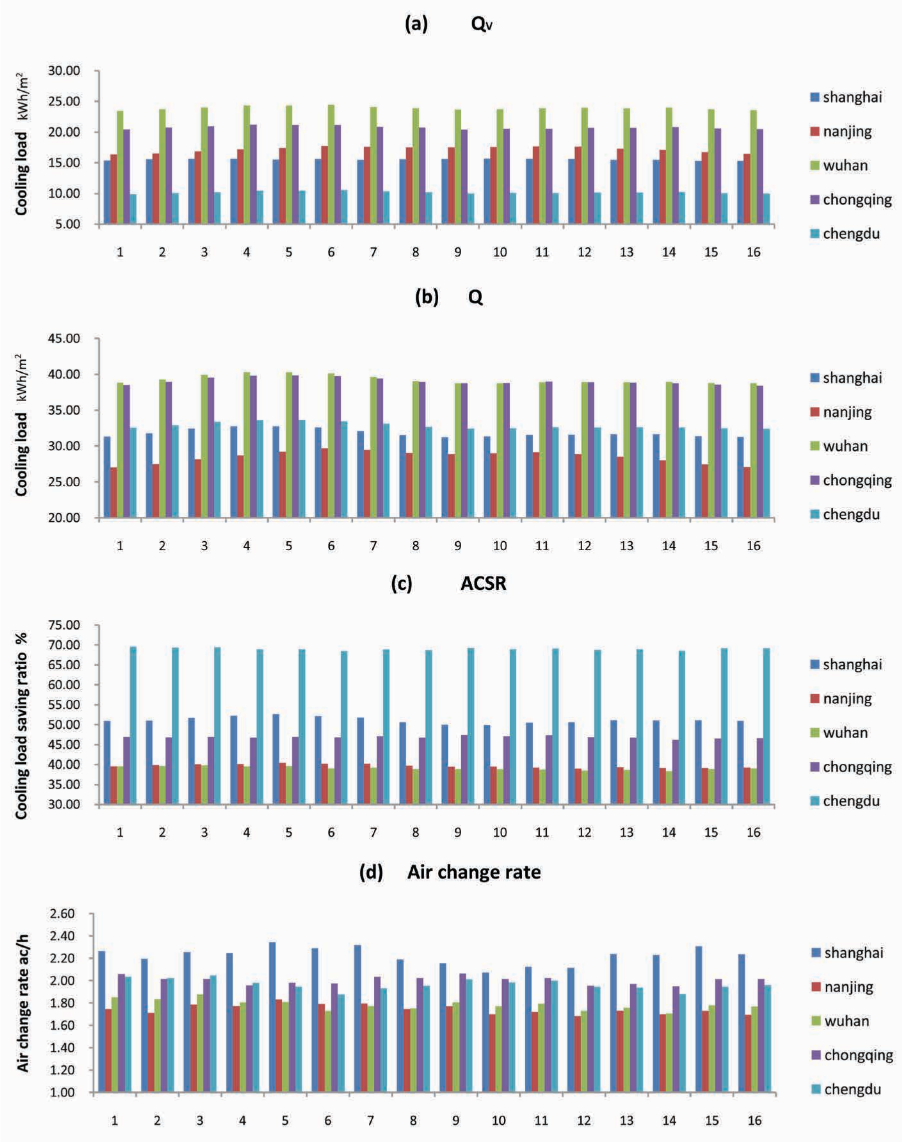

FIG. 9.8 The annual cooling load with natural ventilation, Qv (a), and without natural ventilation, Q (b), ACSR (c) and air change rate (d) of the five cities (when the window-to-wall ratio is 10%) for 16 building orientations (the orientation is from 0- 337.5 degree, see figure 9.7)

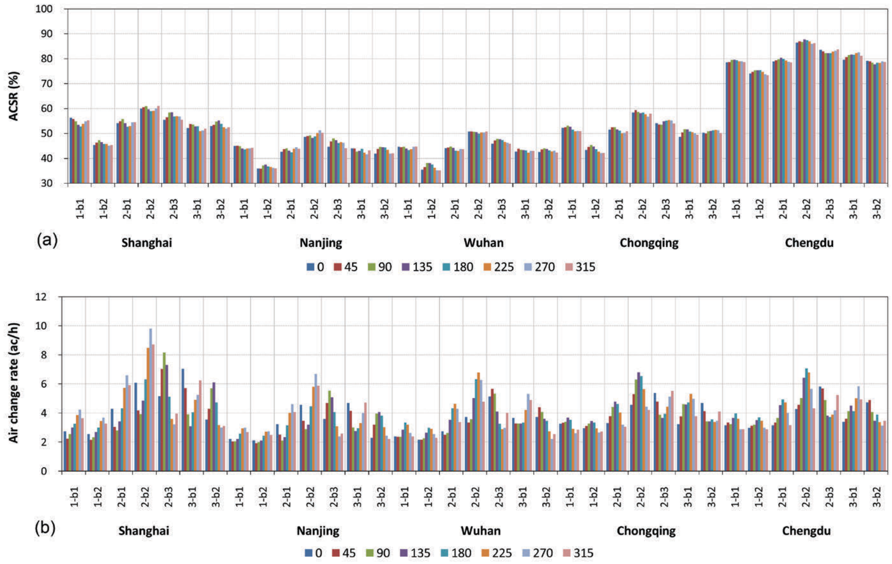

FIG. 9.9 The ACSR and air change rate per bedroom when the building orientation is 0,45, 90, 135, 180, 225, 270, 315 degrees with 0=north and 90=east in the five cities.

In the situation without natural ventilation, the order of the cooling load from highest to lowest is: Wuhan (maximum 40.3kWh/m^2), Chongqing(39.8kWh/m^2), Chengdu (33.6kWh/m^2), Shanghai (32.7kWh/m^2) and Nanjing (29.6kWh/m^2). For the ACSR, from highest to lowest, the order of the cities is: Chengdu (maximum 69.6%), Shanghai (52.7%), Chongqing (47%), Nanjing (40.4%) and Wuhan (39.8%). For the air change rate, from highest to lowest, the order of the cities is: Shanghai (maximum 2.3), Chongqing (2.1), Chengdu (2.0), Wuhan (1.9) and Nanjing (1.8). Under the condition of a 20% WWR, the general annual cooling load in the five cities is larger than with a WWR 10%, but the trend of the five cities is the same.

Figure 9.9 (a) and (b) shows the ACSR and air change rate of the major bedrooms according to eight simulated building orientations in the thermal simulation. It can be seen the variation of ACSR of the bedrooms is from 35-61% in the city of Shanghai, Nanjing, Wuhan and Chongqing. Nevertheless, the ACSR of the bedrooms in Chengdu is much higher which is from 73-88%. This is matched with the result of the ACSR of the whole building. The variation of the air change rate in different bedrooms is relative bigger than the ACSR which is from 1.9 to 9.8 (ac/h).

TOC

9.4.3 Correlation analysis

9.4.3.1 Annual cooling load saving ratio (ACSR) and air change rate (building level)

The linear regression analysis between ACSR and annual air change rate of the entire building (correlation 1) is illustrated in Figure 9.10 (with a WWR of 10% and 20%). A linear relationship between the ACSR and the annual air change rate for different orientations of the building can be seen. The coefficient of determination R^2 is between 0.67-0.76 for Shanghai, Nanjing, Wuhan and Chengdu when the WWR is 10% and is between 0.46-0.66 when the WWR is 20%. The correlation is significant. However, a linear relationship for Chongqing is not found. The relationship means that when the air change rate is bigger, the ACSR is larger. In order to reach a comfortable temperature for the occupants, increasing the natural ventilation can therefore reduce the air conditioning operation to cool the building. The linear relationship is stronger when the WWR is smaller. It means that the opening area of the façade influences the relationship between the ACSR and the air change rate. It is assumed that when the opening area is large, the stronger radiation and higher outside air temperature leads to too much air exchange between indoors and outdoors, thus increasing the cooling energy.

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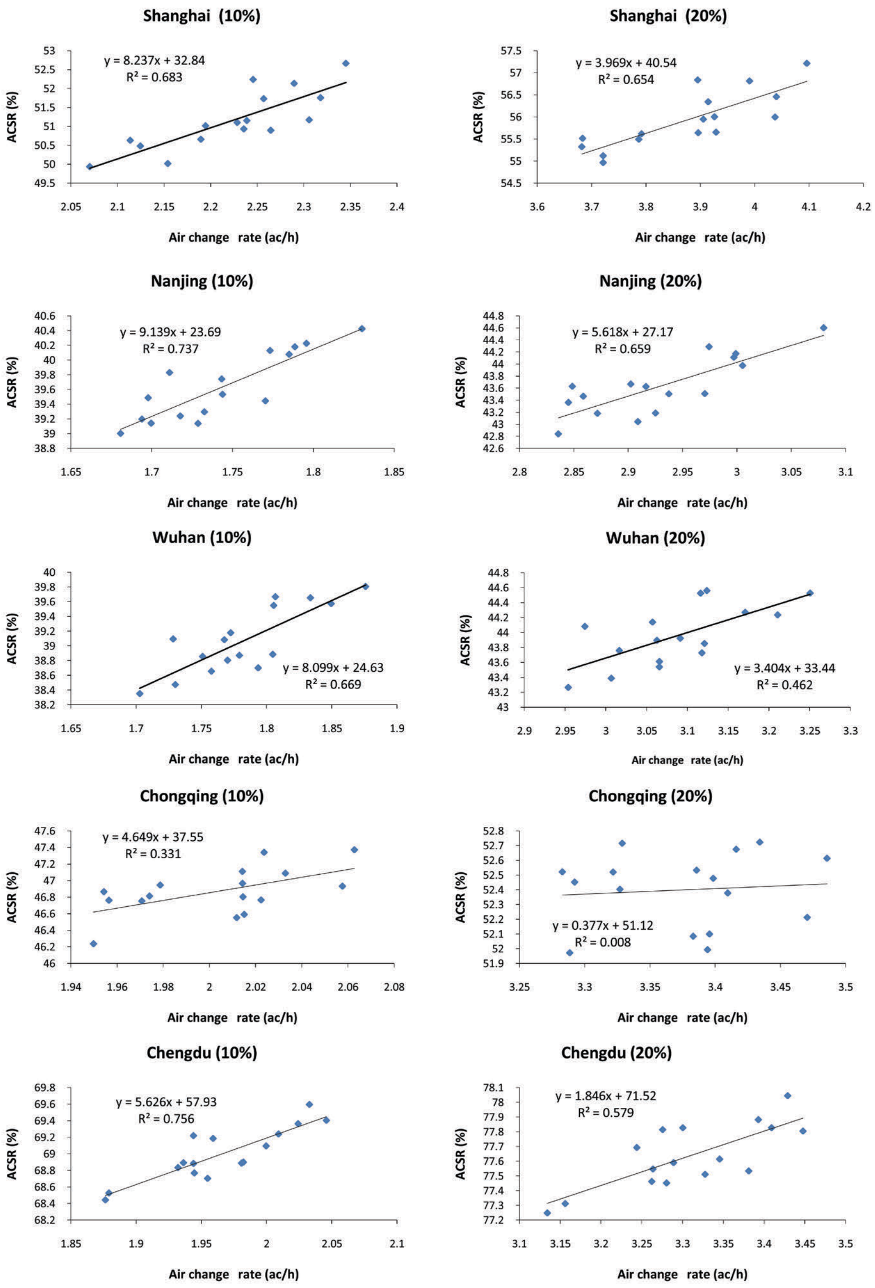

FIG. 9.10 The linear correlation between ACSR and annual air change rate of an entire floor for 16 different orientations and 2 different window-to-wall ratios.

9.4.3.2 Correlations of ACSR, air change rate and connectivity (room level)

The correlations between the ACSR, air change rate and connectivity (correlation 2, 3 and 4) were investigated for seven bedrooms (1-b1, 1-b2, 2-b1, 2-b2, 2-b3, 3-b1 and 3-b2). For the convenience of the correlation analysis, the mean connectivity, the mean ACSR and the mean air change rate of the seven bedrooms for eight building orientations were calculated and listed in table 9.5-9.7.

TABLE 9.5 Mean connectivity

	Rooms						
Mean weighted connectivity	1-b1	1-b2	2-b1	2-b2	2-b3	3-b1	3-b2
Shanghai	480	337	902	915	715	536	474
Nanjing							
Wuhan							
Chongqing							
Chengdu							

TABLE 9.6 Mean ACSR

	Rooms						
Mean ACSR (%)	1-b1	1-b2	2-b1	2-b2	2-b3	3-b1	3-b2
Shanghai	54.7	46.0	54.2	60.1	56.9	52.4	53.4
Nanjing	44.3	36.5	43.5	49.4	46.2	43.1	43.3
Wuhan	44.3	36.6	43.9	50.5	46.8	43.1	43.2
Chongqing	51.9	43.6	51.3	58.2	54.5	50.4	50.8
Chengdu	79.0	74.6	79.3	86.8	82.8	81.3	78.6

TABLE 9.7 Mean air change rate

	Rooms						
Mean air change rate (ac/h)	1-b1	1-b2	2-b1	2-b2	2-b3	3-b1	3-b2
Shanghai	3.19	2.89	4.51	6.54	5.44	5.03	4.20
Nanjing	2.46	2.31	3.25	4.62	3.88	3.70	3.12
Wuhan	2.69	2.50	3.50	4.98	4.17	3.90	3.34
Chongqing	3.19	3.05	3.90	5.47	4.59	4.37	3.77
Chengdu	3.34	3.23	3.94	5.51	4.65	4.44	3.87

Figure 9.11 shows the regression curve and linear correlations between the mean connectivity value, ACSR and air change rate of the seven bedrooms in the five cities and table 8 shows the summary of the coefficient of determination, R^2 and the equations.

It was found that there is a positive linear correlation between the mean ACSR and the mean air change rate (correlation 2) of the seven bedrooms in the five cities (figure 9.11 (a)). The coefficient of determination, R^2 is from 0.64 to 0.90. The result matches the general correlation of the ACSR and air change rate of the building (correlation 1) in section 9.4.3.1. The expected correlation in Chongqing is also found at room level although it is not found at building level. The existing correlation 2, i.e. that increasing the air change rate can save the annual cooling load under certain climate conditions is further confirmed.

The correlation between the mean air change rate and the mean connectivity (correlation 3) is also linear, as shown in figure 9.11 (b)). As we can see, the coefficient of determination, R^2 is between 0.53 and 0.60. The air change rate matches the connectivity value in the seven bedrooms.

The positive linear correlation between the mean ACSR and the mean connectivity value (correlation 4) of the bedrooms was found in all of the five cities as well (figure 9.11 (c)). The coefficient of determination, R^2 is between 0.55 and 0.59. The correlation indicates that when the room has a higher connectivity value, the energy saving rate is higher and the performance of natural ventilation to cool the room is better.

TOC

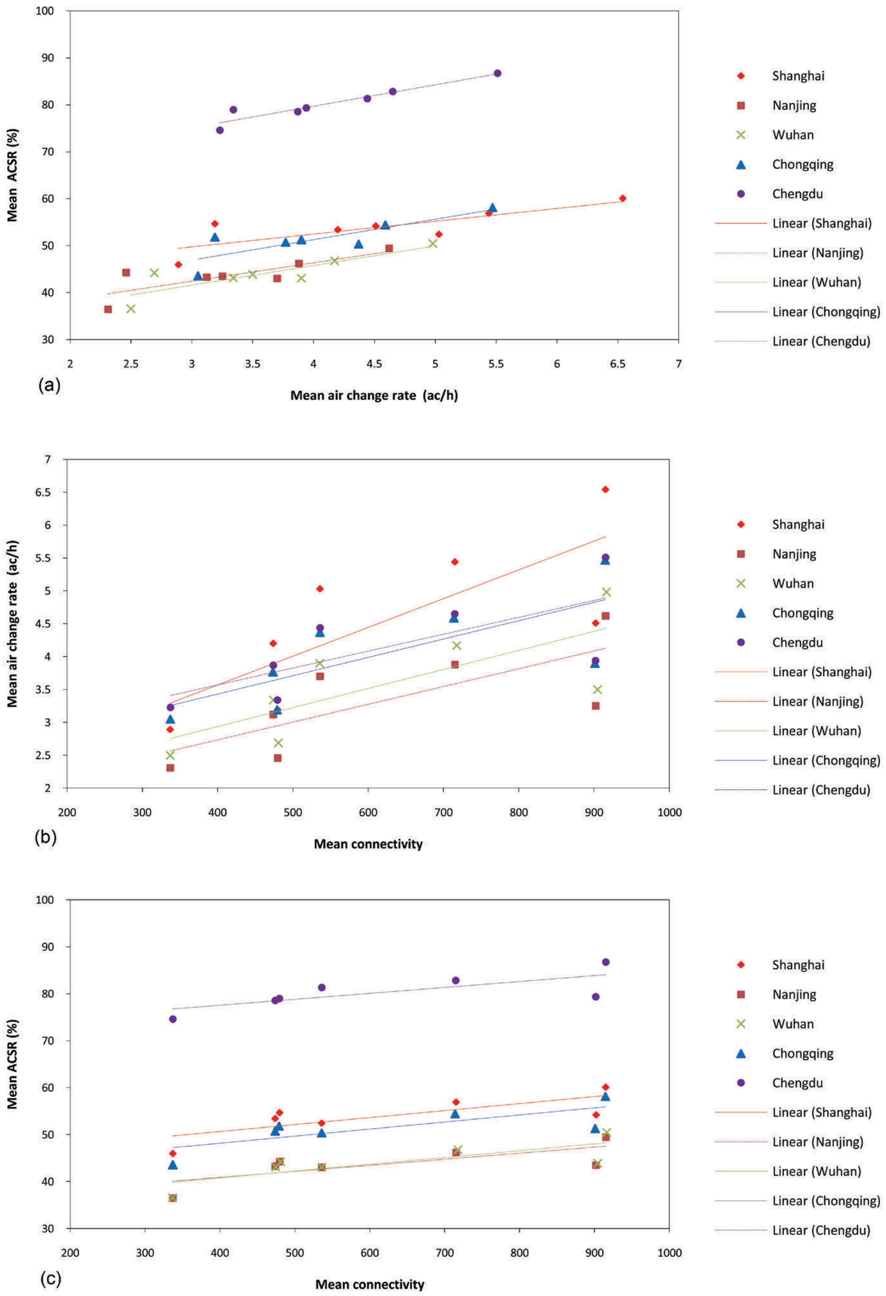

FIG. 9.11 The correlations between the average weighted connectivity value, ACSR and air change rate of the selected seven bedrooms in the five cities

TABLE 9.8 Summary of the linear equations and coefficient of determination R^2 of the correlations

Correlations	Mean ACSR (%) & mean air change rate (ac/h), correlation 2		Mean air change rate (ac/h) & mean connectivity, correlation 3		Mean ACSR (%) & mean connectivity, correlation 4	
	Equation	R^2	Equation	R^2	Equation	R^2
Shanghai	y = 2.73x + 41.5	0.64	y = 0.004x + 1.81	0.60	y = 0.015x + 42.1	0.59
Nanjing	y = 3.92x + 30.7	0.66	y = 0.002x + 1.65	0.56	y = 0.012x + 72.5	0.55
Wuhan	y = 4.17x + 29.1	0.72	y = 0.002x + 1.77	0.58	y = 0.014x + 35.0	0.60
Chongqing	y = 4.35x + 33.9	0.69	y = 0.002x + 2.31	0.55	y = 0.014x + 44.7	0.59
Chengdu	y = 4.56x + 61.5	0.90	y = 0.002x + 2.54	0.53	y = 0.013x + 35.7	0.56

9.5 Discussion

Based on the results of the spatial analysis and thermal simulation, in the five cities studied, the positive linear correlations were found between the annual cooling load saving ratio, air change rate and spatial indicator (connectivity) even some of the correlation value are not so high. However, because this is the first study that combines spatial analysis with ventilation and energy performance, some limitations should be noted.

First is the limitation of the research methodology. In the thermal simulation, the opening area on the wall was only assumed to be 10% and 20% of the wall area. The influence of the opening area on energy saving and air change rate was not investigated in this paper. It can however affect the correlation between the cooling loads and air change rate. In the VGA, the outside wind environment and wind direction are taken into account by extending the boundary of the studied layout to a certain extent. Although the results support the fact that this is an available way to take the wind environment into account, this might not be the optimal way to represent the wind environment and wind direction. The connectivity value of the rooms cannot be achieved directly in the software of Depthmap. Therefore, there is a certain amount of error of the calculation of the average connectivity value. These settings and limitations of the software and the methodology may be the cause that some of the linear correlations are not perfect and always clear. For example, in the city of Chongqing, a correlation between the general air change rate and the ACSR was not found.

The second limitation is the application of the spatial analysis method for the evaluation of the ventilation and energy performance. Ventilation behaviour in buildings is so complex that many factors are related. In this study, a lot of simplification have done for the analysis. The space syntax method cannot predict the actual wind velocity, air flow rate, wind pressure and the air temperature. The method only can show the potential of a particular spatial configuration to achieve the natural ventilation.

Although there are many limitations as mentioned above, this study reveals the potential to use the spatial indicator to predict the air flow performance and even the energy performance in the early design stage. Even though the prediction maybe rough, it is meaningful for the early design stage of the architectural design because some advantages can be achieved: saving time, ease of use, a visual result and a multi-objective prediction. Table 9.9 is the comparing of the different models for the prediction of ventilation performance. For example, when we use the space syntax method to predict the air flow and energy performance in a particular spatial configuration, the occupants' movement behaviour can also be predicted, which is significant to evaluate the thermal comfort of the built environment. At present, space syntax is the only method that can quantitatively analyse building spaces and urban spaces. The program can easily transfer the documents from other CAD software platforms. For the design practice is valuable to extend the use of this spatial analysis method to building ventilation and energy performance analysis.

TOC

TABLE 9.9 Comparing of the different models for the prediction of ventilation performance

	Analytics and Empirical models	Experimental models	Multi-zone models	Zonal models	CFD models	Space syntax model
Methods	Conservation equations calculation	Measurement	Conservation equations calculation	Conservation equations calculation	Conservation equations calculation	Topology connection analysis
Predicted indexes	Temperature/ Flow rate	Temperature/ Wind velocity	Temperature/ flow rate	Temperature/ flow rate	Field distribution of pressure/ temperature/ air velocity	Distribution of air flow potential
Scale of building	Simple room	Entire Building	Entire Building	Entire Building	Room or rooms	Entire Building
Accuracy	Qualitative/ coarse	Quantitative/ accurate	Quantitative/ accurate	Quantitative/ accurate	Quantitative/ accurate	Qualitative/ coarse
Time consuming	Fast	Normal	Normal	Normal	Slow	Fast
Cost	Small	Big	Normal	Normal	Big	Small
Needed computing resources	Small	Small	Normal	Big	Big	Small
Easy or difficult to use	Easy	Relatively easy	Relatively easy	Relatively easy	Difficult	Easy
Visual or not	No	Yes	No	No	Yes	Yes
Other functional predictions	No	No	No	No	No	Yes (occupant's movement)

9.6 Conclusion

In this study, a standard floor of a high-rise apartment building was selected as a case study to reveal the correlations between a spatial indicator, an air flow indicator and an energy indicator under hot summer and cold winter climate conditions in five cities of China. The results show that the selected three indicators: connectivity value, air change rate and annual cooling saving ratio are linearly correlated, not just at the building level but also at the room level. The correlation coefficient of determination R^2 is between 0.53 and 0.90 (except for the case of Chongqing at building level).

TOC

It was found that increasing the airflow of the building can reduce the cooling load under certain conditions. Increasing the natural ventilation has a significant energy saving potential in the hot summer and cold winter climate of China. There is a potential to using spatial indicator of connectivity to predict the air flow performance and the energy performance can be predicted with the air change rate and also with connectivity in the early design stage. This new application of the space syntax method is proposed to help architects and designers in designing a modern dwelling that is thermally more comfortable and that has a lower annual cooling demand. However, more case studies and more future research should be done to validate the method so that it can be applied in the design practice.

TOC

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