Space Design for Thermal Comfort and Energy Efficiency in Summer

Passive cooling strategies for hot humid climates, inspired by Chinese vernacular architecture

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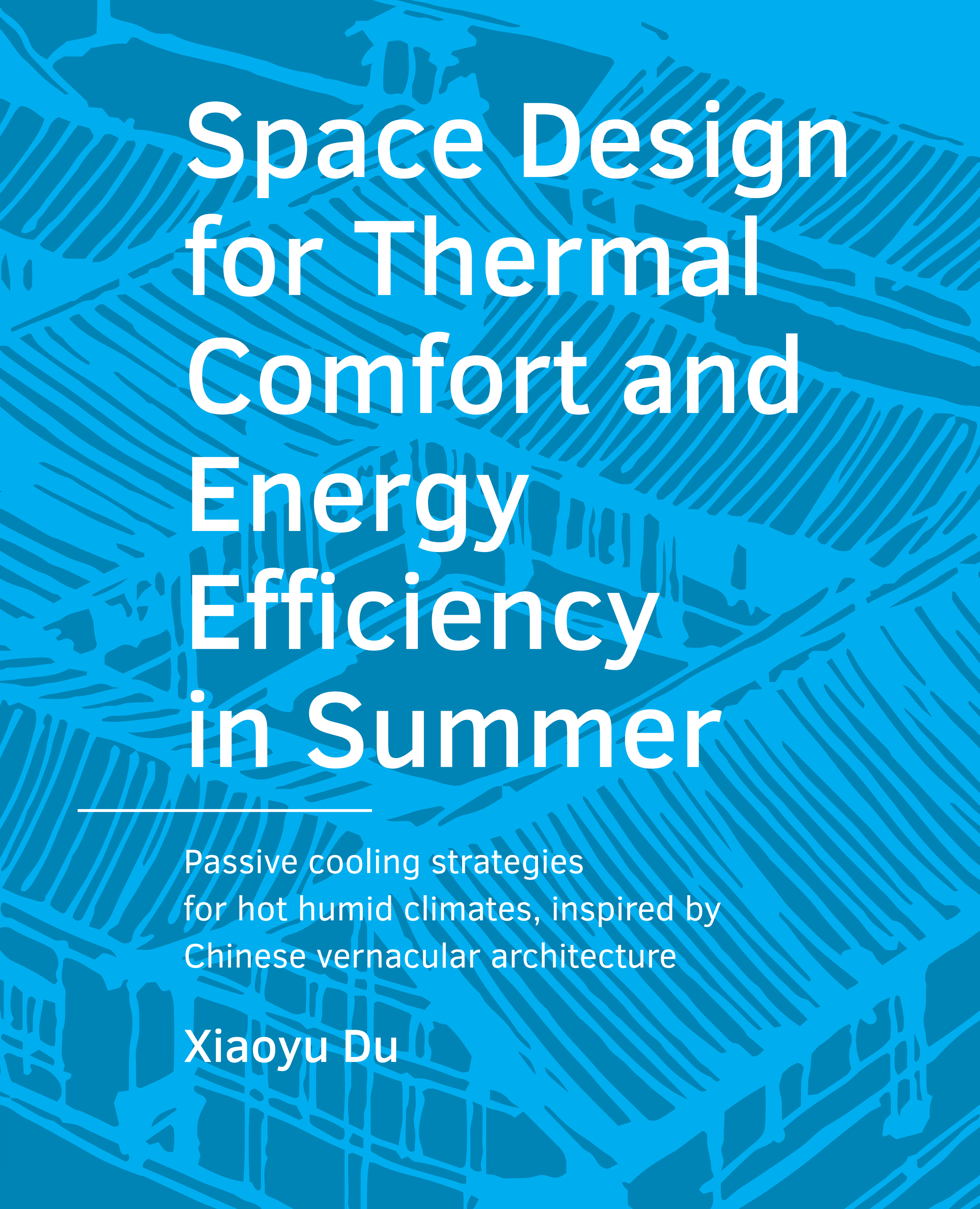
DOI
10.7480/abe.2019.10

Publication date
2019

Document Version
Final published version

Citation (APA)
Du, X. (2019). *Space Design for Thermal Comfort and Energy Efficiency in Summer: Passive cooling strategies for hot humid climates, inspired by Chinese vernacular architecture*. [Dissertation (TU Delft), Delft University of Technology]. A+BE | Architecture and the Built Environment. https://doi.org/10.7480/abe.2019.10



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A+BE | Architecture and the Built Environment | TU Delft BK

19#10

Design | Sirene Ontwerpers, Rotterdam

ISBN 978-94-6366-218-5
ISSN 2212-3202

Digital version freely available at **abe.tudelft.nl**

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Space Design for Thermal Comfort and Energy Efficiency in Summer

Passive cooling strategies for hot humid climates, inspired by Chinese vernacular architecture

Dissertation

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. T.H.J.J. van der Hagen
chair of the Board for Doctorates
to be defended publicly on
Monday 25 November 2019 at 10:00 o'clock

by

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This dissertation has been approved by the promotors.

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Prof. T. Zhou	Chongqing University, China

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Acknowledgements

I am very grateful to the TU Delft for giving me the opportunity to perform my PhD research at this excellent University.

I would like to thank the people who helped me. Their help, friendliness and enthusiasm eased my research and made me feel that I was not alone in this long journey.

I am very grateful to Prof.dr.Sevil Sariyildiz, Assoc.Prof.dr. Rudi Stouffs (NUS) and Dr. Michela Turrin. Their kindness and encouragement inspired me to start this research. They also guided me and gave many suggestions at the beginning of this research. I will never forget that.

I would like to express my gratitude to my promoter, Prof.dr.ir.Andy van den Dobbelsteen for his guidance and supervision on this research and many personal matters. His passion, confidence and diligence impressed and influenced me deeply. I am also very grateful to my co-promoter, Dr. Regina Bokel. Her kindness, friendship and confidence in me encouraged me to finish this research. She also gave me a lot of support on living in the Netherlands and how to understand Dutch culture. Their help with writing the research proposal, discussing the research methods, selecting the case studies, discussing the conclusions and writing papers, was constructive.

I would like to acknowledge the committee members: Prof.dr.ir. M.G.Elsinga, Prof.ir. N.A. de Vries, Prof.dr.K. Steemers, Prof. T. Zhou and Dr.ir.M.Y. Berghauser Pont, for reviewing this dissertation and giving me constructive suggestions and insightful questions. I would like to thank graphic designer Véro Crickx for helping me with the final layout and the publication of this work in time.

I would like to acknowledge my colleagues in Chongqing University as well. They let me have the time and helped me to finish this research. I particularly thank Prof. Zhou Tiejun for his advice and by promoting the collaboration between the two universities; Prof. Tang Mingfang, I thank for her help with the field measurements in the case studies in Chongqing.

I would like to thank my colleagues and PhD colleagues in the department, especially those in the climate design group and the design informatics group. They are always friendly and helpful in time. I thank them all for having shared their experiences with me. I really enjoyed working with them.

I would also like to thank my colleagues from the secretariat of AE&T. They were always there to help me, especially Bo Song.

Special thanks to my friends in the Netherlands. In particular, I thank Monya and Everhard for their friendship, kindness and support and for improving my English language. Their friendliness and warmth make me feel at home in Delft. I would like to thank Irem and Luc for their kindness and warmth. I also would like to thank Karen who checked the English of my papers.

Above all, I would like to thank my family for all their love and encouragement.

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Summary

Passive cooling for thermal comfort in summer is a big issue in low-energy building design. An important reason is global warming because global warming increases the number of cooling degree days. In addition, the energy demand of buildings has increased rapidly due to both the improvement of living standards and the globalisation of modern architecture. And finally, cooling a building is especially a challenge in countries where few resources are available. Passive cooling techniques, where solar and heating control systems are applied, largely depend on the design of the urban morphology and the building shape. The first research question is therefore: What is the relationship between spatial configuration, thermal environment and thermal summer comfort of occupants and how to apply spatial configuration as the passive cooling strategy in architectural design?

Space is the empty part of a building, but its volume is important for the activities of occupants. Architects define the general spatial structure of a building mainly in the early design stages. There they define the spatial properties of a building, i.e. how the spaces are connected and what are the boundary conditions between the spaces. The final research question of this research therefore is: What is the relationship between spatial configuration, thermal environment and thermal summer comfort and how to apply spatial configuration as passive cooling strategy in architectural design in the early stages?

In order to answer this research question, this dissertation is divided into two main parts.

Part I is the theoretical research phase. The goal is to clarify the relationship between spatial configuration of buildings, the thermal environment and thermal comfort of occupants in summer. In this part, a literature review of the fundamental theoretical background knowledge of thermal comfort and passive cooling technology is summarised. As the author got his inspiration from Chinese vernacular architecture, the second step was conducting surveys and performing analyses of the spatial design, thermal environment and thermal summer comfort in Chinese vernacular buildings. Contemporary residential buildings were also investigated. A challenge was to find examples of contemporary buildings with appropriate spatial designs and thermal comfort as well as contemporary buildings with less successful spatial designs and thermal comfort. The third step was to find correlations

between the occupants' spatial and thermal perception through questionnaires. Questionnaires were held among Chinese as well as Dutch architecture students.

The main research outcome of part I is the definition of "building microclimate". Building microclimate is defined as "a type of microclimate which involves indoor spaces and spaces surrounding the indoor spaces in a particular building".
It is not just the microclimate around the building; it also includes the indoor climate. A suitable building microclimate is important for the occupants' thermal comfort in summer. Another research outcome of part I is the revelation of the relationship between spatial perception and adaptive thermal comfort. Combining the relationship between spatial perception and adaptive thermal comfort with the new definition of building microclimate leads to the conclusion that the spatial configuration of a building plays an important role in creating a particular building microclimate.

Part II is a practical research phase. The goal is to explore the possibility of using a spatial design method as a passive cooling strategy for thermal summer comfort and to demonstrate how to apply this method in the early design stages.

As a first step, the potential of using a space analysis method for passive cooling and thermal comfort was investigated. A convex spatial analysis method was developed from the traditional space syntax method to analyse the natural ventilation potential. Both the logical relationship between the spaces and the boundary conditions between the spaces can influence the accessibility of a particular spatial configuration, and thus influence the potential for natural ventilation. The convex space analysis method is chosen for the preliminary analysis to show the logical relationships between spaces. It cannot completely predict natural ventilation, but it is a graphical method that is easy to use. Architects conceive design solutions generally through graphic methods, making the convex space analysis a good design tool. The extended visibility graph analysis (VGA) method is the best choice for the natural ventilation potential analysis for a spatial configuration. The isovist measure can be used for the natural ventilation potential of a single space.

Two case studies were performed to demonstrate the proposed method for architectural design in the early design stages. The main finding of part II is the potential of using spatial indicators to predict the airflow performance of buildings. New applications of the developed space syntax methods are proposed to help architects in designing a contemporary building that is thermally more comfortable and that has a lower energy demand for cooling.

This research is performed at the cross disciplines of architectural spatial design, passive cooling and thermal comfort. This research proposes several ideas for the first time. The term "building microclimate' is one. The application of a spatial design parameter for thermal comfort is another. This research can contribute to the sustainable development of buildings, Chinese ones in particular. It can help design residential buildings for occupants with low and medium incomes by decreasing the necessity of air conditioning and improving the living environment for thermal comfort as well. This research is also valuable for passive or zero-energy design of houses in the Netherlands and the Mediterranean area. This research will enrich the green building science by introducing enhanced space syntax methods for adaptive thermal comfort and for passive cooling by means of spatial design.

This thesis is mainly composed of a collection of the author's published papers.

Samenvatting

Passieve koeling voor zomercomfort is een belangrijk thema bij bijna energie neutrale gebouwen. Een belangrijke reden is de mondiale opwarming van de aarde omdat de mondiale opwarming er voor zorgt dat een hoger aantal graaddagen voor koeling nodig is. Daarnaast is het energiegebruik voor koeling snel gestegen door zowel de verhoging van de levenstandaard en de globalisering van de moderne architectuur. Technieken voor passieve koeling, zoals systemen die de zontoetreding en de verwarming beheersen, hangen voor een groot deel af van het ontwerp van de stedelijke morfologie en van de gebouwvorm. De eerste onderzoeksvraag is dan ook: Wat is de relatie tussen de ruimtelijke configuratie, de thermische omgeving en het zomercomfort en hoe kan de ruimtelijke configuratie toegepast worden als strategie voor passieve koeling in het architectonische ontwerp?

Ruimte is het lege deel van een gebouw, maar haar volume is belangrijk voor de activiteiten van de gebruikers. Architecten definiëren de algemene ruimtelijke structuur van een gebouw vooral in de eerste stadia van een ontwerp. Hier definiëren zij de ruimtelijke eigenschappen van een gebouw, hoe de ruimtes zijn verbonden en hoe de grenzen tussen de verschillende ruimen er uit zien. De uiteindelijke onderzoeksvraag is dan: Wat is de relatie tussen ruimtelijke configuratie, de thermische omgeving en zomercomfort en hoe kan de ruimtelijke configuratie toegepast worden als strategie voor passieve koeling in het ontwerpen van gebouwen in de eerste stadia van het ontwerp?

Om de onderzoeksvraag te beantwoorden is dit proefschrift in twee delen gesplitst: Deel I is het theoretische onderzoeksdeel. Het doel is om de relatie tussen de ruimtelijke configuratie van gebouwen, de thermische omgeving en het thermisch comfort van de gebruikers in de zomer te verduidelijken. In dit deel is de literatuurstudie naar de theoretische achtergrondkennis van thermisch comfort en van de theorie van passieve koeling samengevat. Omdat de auteur zijn inspiratie haalde uit de Chinese lokale architectuur, was de tweede stap het doen van metingen en analyses van het ruimtelijke ontwerp, het thermisch klimaat en het thermische zomercomfort van Chinese streekgebonden woningen. Eigentijdse, d.w.z. nieuwe, woningen zijn ook bestudeerd. Het was een uitdaging om zowel nieuwe gebouwen te vinden met een goed ruimtelijk ontwerp en goed thermisch comfort in de zomer als ook nieuwe gebouwen met een minder succesvol ruimtelijk ontwerp en thermisch comfort. De derde stap was het vinden van een correlatie tussen de ruimtelijke en

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thermische perceptie van bewoners door middel van een vragenlijst. De vragenlijsten werden afgenomen bij Chinese en Nederlandse studenten.

Het belangrijkste onderzoeksresultaat van deel I was de definitie van “gebouw microklimaat”. Een gebouw microklimaat is gedefinieerd als een type microklimaat van binnenruimtes en van de ruimtes die grenzen aan de binnenruimtes in een bepaald gebouw. Het gebouw microklimaat is niet alleen het microklimaat rondom het gebouw maar ook het microklimaat van de binnenruimtes. Een goed gebouw microklimaat is belangrijk voor het thermisch comfort van de gebruikers in de zomer. Een ander onderzoeksresultaat is het vinden van een relatie tussen ruimtelijke perceptie en adaptief thermisch comfort. Het combineren van de nieuwe definitie van gebouw microklimaat met de relatie tussen ruimtelijke perceptie en adaptief thermisch comfort leidt tot de conclusie dat de ruimtelijke configuratie van een gebouw een belangrijke rol speelt in het creëren van een gebouw microklimaat.

Deel II is het praktische onderzoeksdeel, Het doel is om de mogelijkheid te onderzoeken om een ruimtelijke ontwerpmethode te gebruiken als een passieve koeling strategie voor zomercomfort en te demonstreren hoe deze ruimtelijke ontwerpmethode toegepast kan worden in de voorlopige ontwerpfase.

Als eerste stap werd het potentieel van het gebruiken van de ruimtelijke ontwerp methode voor passieve koeling en thermisch comfort onderzocht. Een convex ruimtelijk ontwerp methode was ontwikkeld uit de traditionele space syntax methode om het potentieel van natuurlijke ventilatie te analyseren. Zowel de logische relatie tussen de ruimtes en de grenzen tussen de ruimten kan de toegankelijkheid van een specifieke ruimtelijke oriëntatie beïnvloeden en op die manier het potentieel voor natuurlijke ventilatie. De convex ruimtelijk ontwerp methode ia gekozen voor de voorbereidende analyse om de logische relatie te laten zien tussen de ruimten in het voorlopige ontwerp. De methode kan niet helemaal de natuurlijke ventilatie voorspellen, maar de methode is een eenvoudige grafische methode die gemakkelijk te gebruiken is. Architecten ontwikkelen ontwerp oplossingen in het algemeen met grafische methoden waardoor de grafische convex ruimtelijk ontwerp methode een goede ontwerp methode is. The uitgebreide VGA methode is de beste keuze voor het voorspellen van de natuurlijke ventilatie van een ruimtelijk ontwerp. De isovist maat kan gebruikt worden om het potentieel van natuurlijke ventilatie voor een enkele ruimte te bepalen.

Twee case studies zijn uitgevoerd om de voorgestelde methode voor architectonisch ontwerpen in de voorlopige ontwerpfase te demonstreren. De belangrijkste uitkomst van deel II is het potentieel van ruimtelijk ontwerp indicatoren om de prestatie van luchtstromingen in gebouwen te voorspellen. Nieuwe toepassingen van de ontwikkelde space syntax methoden zijn voorgesteld om architecten te helpen in het ontwerpen van hedendaagse gebouwen die thermisch meer comfortabel zijn en een lager energiegebruik voor koeling hebben.

Dit onderzoek is uitgevoerd op het grensvlak van de onderzoeksgebieden architectonisch ruimtelijk ontwerp, passieve koeling en thermisch comfort. Verschillende ideeën zijn in dit proefschrift voor het eerst naar voren gebracht. De term 'Gebouw microklimaat" is er een van. Het toepassen van ruimtelijk ontwerp parameters op thermisch comfort is een ander. Dit onderzoek kan bijdragen aan de duurzame ontwikkeling van woningen, in het bijzonder van Chinese woningen. Het onderzoek kan bijdragen aan het ontwerp van betere woningen voor bewoners met lage of gemiddelde inkomens door het verlagen van de noodzaak tot het gebruik van airconditiong en het verbeteren van het thermisch comfort. Dit onderzoek is ook waardevol voor het ontwerpen van passieve of nul-energie woningen in Nederland en in het Mediterrane Europese gebied. Dit onderzoek zal het onderzoek naar groene gebouwen verrijken door de introductie van verbeterde space syntax methoden voor adaptief thermisch comfort en passieve koeling bij het maken van een ruimtelijk ontwerp.

Dit proefschrift bestaat voor een groot deel uit de verzameling van gepubliceerde artikelen van de auteur.

1 Introduction

1.1 Research background

In our current age, sustainability is a key issue in the development of society, economy and environment. It is widely discussed that it is necessary to achieve a balance between the needs of people, business and nature. To maintain and possibly improve the built-up world in an ecological sense is a worldwide challenge for the current and next generation of architects, designers, technicians, public servants and decision-makers on every level (Kristinsson, 2012). Health nature and human delight are important factors in creating new manmade living environment-city, neighbourhood and building-but these form no common basis for design. The building sector plays a significant role in the overall energy consumption, consuming over one-third of the global final energy consumption. Most of the energy is for the provision of lighting, heating, cooling and air conditioning. As human society develops, the energy demand of buildings could continuously increase globally. Therefore, reducing the energy consumption in the building sector is an important research topic. After decades of effort, to improve the efficiency of energy systems and to develop clean and new energy, architects, engineers and researchers have also tried to develop passive ways to reduce the energy consumption of buildings and to provide a comfortable living environment for occupants. More attention is paid to vernacular buildings in order to get inspiration for passive cooling and heating techniques.

Passive cooling for thermal comfort in summer is a big issue for low-energy building design, and has received more attention from designers and researchers in recent years. An important reason is global and local climate change, which increases the ambient temperature and the corresponding number of cooling degree days. In addition, because of the developing economy, improvement of people’s living

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standards, and globalisation of modernist architecture[1], the energy needs of buildings have increased rapidly. In particular, cooling the building is challenge, especially in countries where few resources are available. Passive cooling techniques are based on the application of solar and heating control systems, dissipation of the excess heat into low-temperature natural sinks and the amortisation of the heat surplus through the use of additional thermal mass in the buildings (Santamouris & Asimakopoulos, 1996). The passive mode for cooling of buildings largely depends on the design of urban and building forms. Designers have proposed many passive design strategies to improve the thermal environment for summer comfort. Urban morphology, building form (shape) and building components are normally the focuses in these studies. However, the significance of building spatial configuration for passive cooling and occupants' thermal comfort in summer has not been studied sufficiently. Space is the empty part of the building, but its volume is important for the activities of occupants. It is the volume that people live in with various physical and psychological sensations. In his Taoist classics "Tao Te Ching", the great Chinese thinker, Lao Tzu (571 BC - 471 BC) described building space as: "By cutting out the doors and windows we built a house and on that which is non-existent (on the empty space within) depends the house's utility". An architect usually thinks and designs in squares and cubic metres, lines, areas, volumes, luminance differences (Kristinsson, 2012). Architects define the general spatial structures of buildings mainly in the early design stages, and the spatial properties, the connection of the spaces and the boundary conditions of them are significant for the building performance and thermal sensation of occupants. What is the contribution of spatial design for passive cooling? Can we achieve more a comfortable living environment through the adjustment of the spatial configuration? In this dissertation, the objects studied for passive cooling will be spatially configured instead of the urban morphology, building form (shape) and building component. The relationship between spatial configuration and thermal summer comfort will be clarified and a potential design method will be proposed for the spatial analysis for passive cooling.

1 In this thesis, the term modernist architecture refers specifically to the style in the modern architectural movement that emerged in the early-20th century, but the terms: modern architecture, modern building and modern house generally refer to all types of new buildings that use modern building materials, technologies and styles compared with traditional vernacular buildings.

1.2 The emergence of cooling buildings

1.2.1 Energy consumption of buildings

The building sector consumed over 30% of the global final energy consumption in 2014, or nearly 125 exajoules (EJ), and 55% of the final electricity demand (International Energy Agency [IEA], 2017). As human society develops, under the Reference Technology Scenario (RTS), the energy demand of buildings could increase globally to more than 160 EJ in 2060, if assertive action is not taken to improve the energy performance of buildings (IEA, 2017). Most of the energy for the building sector comes from fossil fuels, and the use of fossil fuels causes many environmental problems, such as environmental accidents, water pollution, maritime pollution, land pollution, radiation and radio activity, solid waste disposal, hazardous air pollutants, ambient air quality, acid rain, stratospheric ozone depletion and global warming (Omer, 2008). One of the significant impacts is the global warming, which is mainly related to CO_2 emissions and other GHGs (greenhouse gases). The building sector is responsible for almost 30% of energy-related CO_2 emissions, approximately two-thirds of halocarbon and 25-33% of black carbon emissions (Ürge-Vorsatz et al., 2015). Under the high pressure of serious environment problems and the rapid increase of energy demand, the concept of sustainability was widely accepted in the world and most of the countries put forward policies for the future targets of energy security and GHG emissions. Enabling rapid efficiency measures in the Beyond 2°C Scenario (B2DS), the final energy demand in the building sector could decrease to 114 EJ by 2060, or 30% below the Reference Technology Scenario (RTS) and 12% below the 2°C Scenario (2DS), while providing the same level of energy service as in the RTS and 2DS scenario (IEA, 2017).

1.2.2 Energy demand for cooling buildings

Because of the ambient temperature, solar radiation, internal heat gains and occupants, the indoor temperature changes seasonally and diurnally. When the indoor temperature goes beyond comfort levels, cooling is necessary for the occupants' comfort and health. Using passive cooling techniques to cool the building is good for sustainable development of the building sector because of its zero-energy demands. However, as people demands a more comfortable environment in buildings, active cooling has become broadly used in modern life. Active cooling means the application of mechanical ventilation systems and air conditioning devices, which cause an increase in energy consumption of buildings compared to passive solutions.

Santamouris (2016) reviewed the past, present and the future of cooling of buildings. Over viewing the world energy consumption, cooling represents approximately 2.9% and 6.7% of the total energy demand of residential and commercial buildings. Approximately 37% of the total cooling energy demand takes place in non-OECD countries (OECD is the organization for economic co-operation and development), 35% in the Americas, 17% in Europe and the remainder in the OECD Pacific countries. The global air conditioning market is expanding because of the increase of cooling demands. For example, in China, the ownership of air conditioning in the urban and rural area was consistently increasing from 2006-2012 (figure 1.1), and reached 126.8 units per 100 urban households and 25.4 units per 100 rural households in 2012.

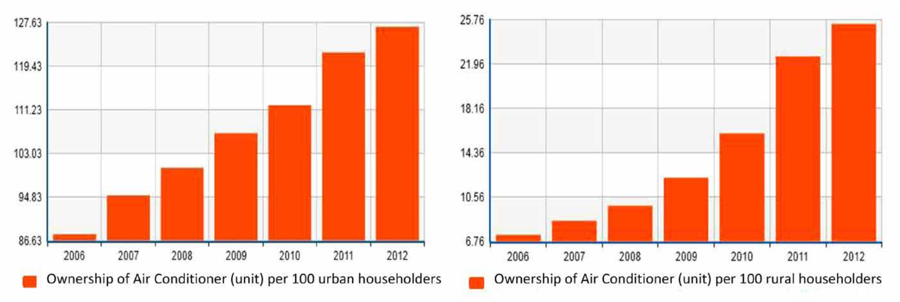

FIG. 1.1 Ownership of air conditioning per 100 households in the urban and rural area of China (2012-2016) (National Bureau of Statistics of China, 2017)

Climatic characteristics significantly influence the cooling of buildings. These are different for all geographical zones, but the building comfort demands for humans are almost at the same level. Therefore, buildings are responsible for providing comfort by adapting to the local climate. In summer, cooling is needed across the whole world. Some zones on earth demand cooling all year round. This includes the different climate types in the equatorial climate, hot arid climates and warm temperate climate zones. Global climate change increases the ambient temperature and the corresponding number of cooling degree days (CDD). According to Stocker et al. (2013), the global average land and ocean surface temperature has increased by 0.85 °C (0.65-1.06 °C) from 1880 to 2012. An increase of the ambient temperature from 0.0 to 1.0 K is expected to raise the number of global average cooling degree days by 13.7%, or 182 CDD (Mat Santamouris, 2016). For China, You et al. (2014) concluded that under the high emissions scenario (Representative Concentration Pathway), cooling degree days may increase following a trend close to 155 CDD/decade, presenting in 2100 an increase close to 240% compared to 2005, and an average value close to 2400 cooling degree days.

The future energy demands for cooling of buildings depends on the following parameters: local climatic conditions, global and local warming, increase of the earth's population, growth of the local income and GDP, electricity and equipment prices and efficiency and energy performance of the equipment (Santamouris, 2016). The predictions of the residential cooling energy demand for the major geographic zones and for the years 2030, 2050 and 2100 are shown in figure 1.2.

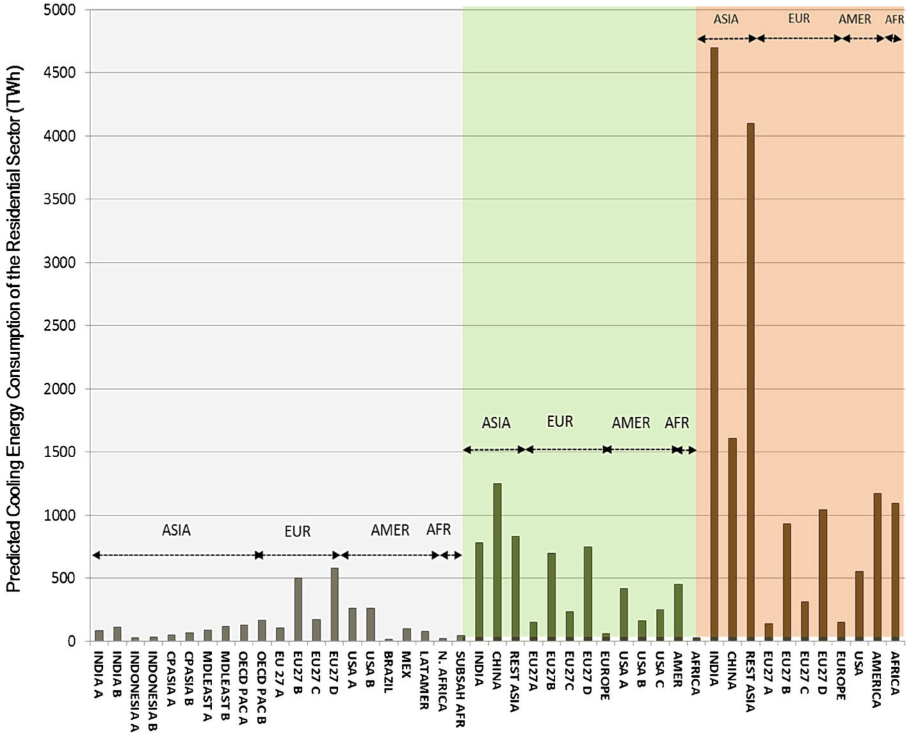

FIG. 1.2 Predicted Future Residential Cooling Energy Consumption by the various existing models. The blue Zone (left part of the figure) is for 2030, the green, (middle part of the figure) for 2050 and the red (right part), for 2100 (Santamouris, 2016).

1.3 Problem Definition

General problem statement:

There is a need to identify the key factors of spatial configuration in buildings that affects the thermal performance in summer, and to apply space design strategies in the early design stages as important passive cooling strategies for thermal summer comfort in which spatial configuration is the dominant factor. Consequently, architects need a new design method of using spatial configuration to evaluate and predict the building performance in the early design stages.

There is a shortage of research on spatial configuration for passive cooling in buildings.

Santamouris and Asimakopoulos (1996) identify passive cooling as the techniques based on the application of solar and heat control systems, dissipation of the excess heat into low-temperature natural sinks such as air, ground and water and the amortisation of the heat surplus through the use of additional thermal mass in buildings. Passive cooling techniques are broadly categorised by heat transfer in three categories: prevention of heat gains (reduce heat gains), modification of heat gains and heat dissipation (remove internal heat). Research has been conducted for all kinds of building types under different climate conditions, such as dry and hot climates, hot and humid climates, Mediterranean climates and warm climates around the world (Europe, China, India, Singapore, Vietnam, Malaysia, Indonesia, Thailand, Turkey, Iran and so on). Through literature review, it can be determined that most of the studies related to passive cooling technology in architectural design concerned building components and materials. Some of the research focused on building form generation, courtyards and atria. However, the effect of spatial configuration: the relationship between various spaces of a particular building in a complex, and their effect on passive cooling is not often studied.

The significance of the space design of Chinese vernacular buildings for passive cooling has not been fully explored.

Vernacular buildings are local buildings that have evolved overtime in one location to suit the local climate, culture and economy (Meir & Roaf, 2003). A vernacular building uses local resources to address local demands and evolves over time to reflect the environmental, cultural and historical context in which they exist (Coch, 1998). The knowledge obtained from vernacular buildings is always handed down by tradition and is thus based more on the knowledge achieved by trial and error and in this way handed down through generations (Singh, Mahapatra, & Atreya, 2009). China has a vast territory and diverse climate, and thus has rich and diverse vernacular architecture to inspire architects in their modern architectural design. The design strategies of Chinese vernacular buildings, in terms of passive ways to appreciate building performance, have been broadly investigated by researchers (Borong et al., 2004; Bouillot, 2008; Gou, Li, Zhao, Nik, & Scartezzini, 2015; Jiaping Liu, Wang, Yoshino, & Liu, 2011; Soflaei, Shokouhian, & Zhu, 2017). However, little to no research has been published that attempts to address the qualitative and quantitative aspects of passive cooling strategies based on the spatial configuration of traditional Chinese vernacular buildings and how to utilise these cooling strategies in contemporary building design.

There is a lack of space design methods for the prediction and evaluation of energy efficient performance and thermal comfort in early design stages.

A great success has been achieved for the green building movement in recent decades. But most of the green building achievements are related to engineering techniques, products and equipment. For example, in China, the top implemented green building techniques are: thermal insulation materials for the building envelope, water-saving appliances, and recyclable building materials. Unquestionably these engineering techniques are able to provide a significant and measurable contribution for green building performance. But what should architects do? As solvers of three-dimensional problems, architects are well suited to lead the change towards sustainability and to find the resolution of spatial problems because most professionals do not work in this way, and most people do not think spatially (Williams, 2007). Architects are the professionals to create man-made form and space, which lies in the natural environment and its inherent ability to provide comfort and security for the inhabitants. The relationships between man-made space, humans and environment are essential issues for architectural design. Environmental factors such as the climate deeply affect architectural form. In other words, traditional architecture had to be ingenious in providing comfort by integrating passive elements of the natural place into design solutions. These elements are the very foundation of the architectural and planning profession, grounded in sustainable principles before they were named like this (Williams, 2007). Space arrangement is one of the major considerations in the architectural design process.

Another problem is the traditional design process and practice; issues pertaining to green building performance are typically left to be dealt with until after the spaces are well articulated. Simulation programs for the evaluation with many aspects of building performance, including indoor comfort, airflow, daylight and energy consumption are most commonly used during mid to final design stages. Building simulation tools are used for analysis only, rather than for synthesis (Yi & Malkawi, 2012). Tools simulating performance and spatial configuration implemented separately in the different phases by different professionals. Spatial configuration and passive cooling should be considered together at the early design stages. Hiyama and Glicksman (2015) mentioned that, currently, the trend of more comfortable and more 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 conceptual design and schematic design stages. In the early design stages, the architects are in constant search for a design direction to make an informed decision which can determine the success or failure of the final design (Attia et al., 2012). After the early design stage, it is the design development phase. In this phase, different building professionals participate in the design and give professional advice to architects to modify the final building space and form concept. For building performance, some engineers implement simulation software to evaluate this. After the modification, it is the final design phase: construction documentation phase. In this phase, the building space and form cannot be changed at a large scale. But it is very common that some professionals find that the building form is not so good for a specific performance so that the problem emerges that changing the spatial configuration finds other solutions to solve the performance defect. Therefore, integrating different design targets in the early design phases is essential to create one appropriate space for optimal performance.

1.4 Research objective

The general research objective is:

To find the major factors of spatial configuration of buildings affecting the thermal summer environment and occupants' thermal comfort under the particular environment. Subsequently, the objective is to propose a space design method to support passive cooling strategies for thermal summer comfort.

1.5 Research questions

Main question:

What is the relationship between spatial configuration, thermal environment and thermal summer comfort of occupants and how to apply spatial configuration as the passive cooling strategy in architectural design in the early stages?

Sub-questions:

1. What are the major spatial design characteristics of a Chinese vernacular buildings for passive cooling in hot and humid climate?
2. What are the thermal summer environment features of Chinese vernacular buildings with a particular spatial configuration?
3. How can occupants achieve thermal comfort in a Chinese vernacular building?
4. Is it possible to convert the spatial design strategies found in Chinese vernacular buildings to the modern house design?
5. What is the relationship between the occupants' spatial and thermal perception?
6. Is there a potential to use spatial indicators to predict the ventilation performance for thermal comfort in the early design stages?
7. How can a spatial design method be used in the design practice?

1.6 Approach and methodology

The proposed research consists of two main parts:

Part I is the theoretical research phase. The goal is to clarify the relationship between spatial configuration of buildings, thermal environment and thermal comfort of occupants in summer.

In this part, the first step is summarizing the fundamental theoretical background knowledge of thermal comfort and passive cooling technology through literature review.

TOC

The second step is surveying and analysing the spatial design, thermal environment and thermal summer comfort of Chinese vernacular courtyard buildings and contemporary new residential buildings. The research scope is limited to hot and humid climate areas of China. Some cases were studied and field measurement and simulation methods were used. The research question 1,2,3 and 4 will be answered in this part.

The third step is to find the correlations between the occupants' spatial and thermal perception through questionnaires. The research question 5 will be answered in this study.

Part II is a practical research phase. The goal is to explore the possibility of using the spatial design method as the passive cooling strategy for thermal summer comfort and to demonstrate how to apply it in the early design stages.

The first step is to find the correlation and verify the potential of using a space analysis method for passive cooling and thermal comfort. Simulation and correlation analysis are the main research methods. The research question 6 will be answered in this study.

In the next step, an extended spatial analysis method was proposed for the evaluation of building spatial design for natural ventilation potential. And then, two case studies were performed to demonstrate how to use the proposed method for architectural space design in the early design stages. The research question 7 will be answered in this part.

The general research steps and methodology are shown in figure 1.3.

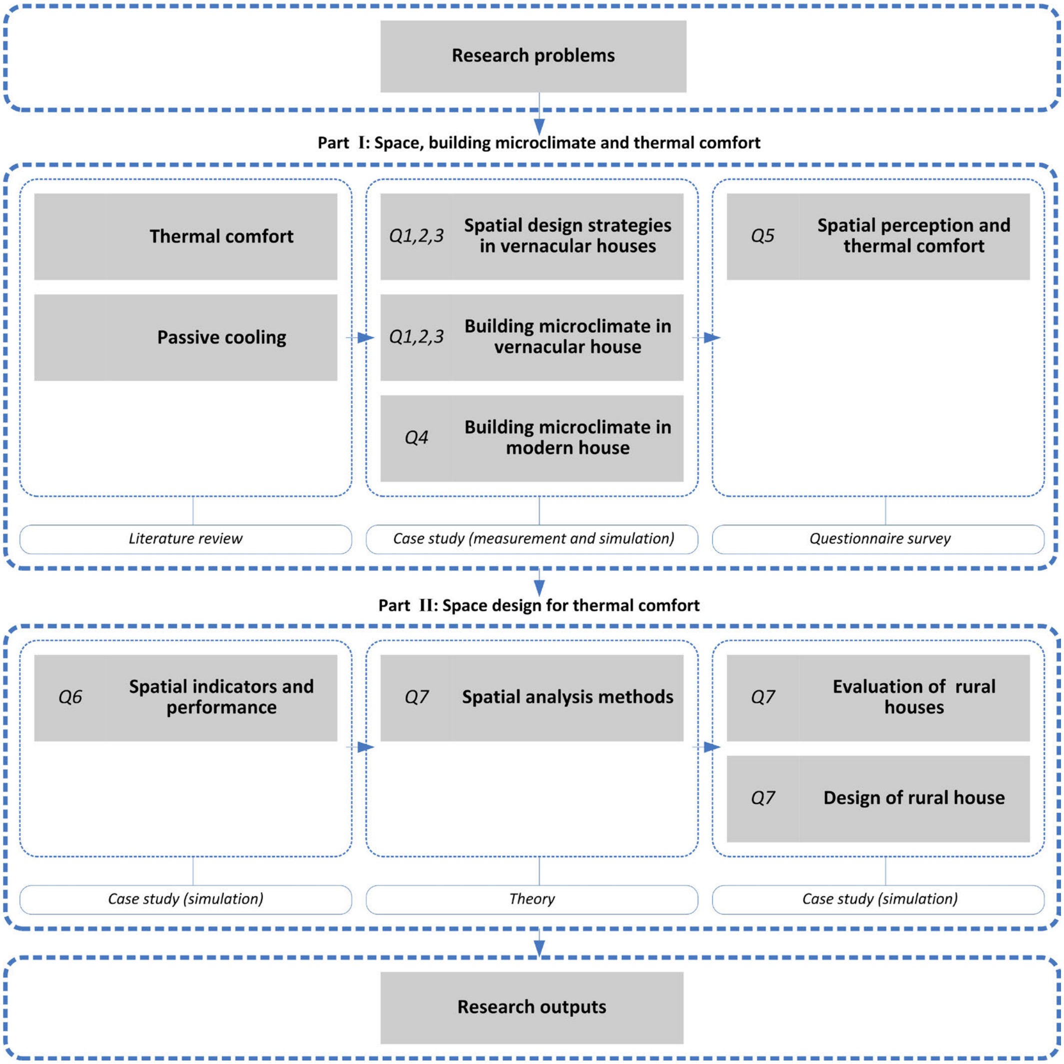

FIG. 1.3 The general research scheme (Q: research question)

1.7 Final Products

Guidelines for new Chinese residential building design for thermal comfort in the hot humid climate.

Creative spatial design method for passive cooling, which can be later adopted for other building designs.

1.8 Relevance

Societal relevance

The social relevance of this research lies in its contribution to sustainable solutions for Chinese development. Under the current circumstances, in China about half of the new residential buildings are built in rural areas, with the free-running model. Geographically, about half of the population lives in a hot summer area. Therefore, this research is significant for the improvement of the Chinese residential community especially in the rural area. The research can help the residential building design for occupants with low and medium income by decreasing the use of air conditioning and improving the living environment for thermal comfort.

Scientific innovation

This research will enrich the green building design science by introducing the theory and the applications for adaptive thermal comfort, principles of passive cooling by means of spatial design.

Project innovation

This research aims to create new design approaches for the passive cooling. It can be really practical for residential building projects with the free-running model.

1.9 Dissertation outline

Figure 1.4 shows the dissertation outline and the order of the chapters.

Chapter 1 is the introduction of this thesis.

Part I is the theoretical research to investigate the relationship between space, building microclimate and thermal comfort.

Chapter 2 and 3 contain a literature review on thermal comfort (chapter 2) and passive cooling (chapter 3).

Chapter 4, 5 and 6 investigate the spatial design of Chinese vernacular houses and modern houses through case studies. Chapters 4, 5 and 6 are published in the Journal of Asian Architecture and Building Engineering (Chapter 4), Building and Environment (Chapter5) and Energy and Buildings (chapter 6)

Chapter 7 is a questionnaire about occupants' spatial perception and thermal perception. It is published as a conference paper at PLEA 2017.

Chapter 8 is the conclusion of Part I. It is a bridge between Part I and Part II.

Part II is a practical research to explore the possibility of using the spatial design method as a passive cooling strategy for summer thermal comfort.

Chapter 9 investigates the correlation between spatial indicators and ventilation performance. This chapter is published in Frontiers of Architectural Research.

Chapter 10 proposes a theoretical method to extend the spatial analysis to predict the potential for natural ventilation.

Chapter 11 and 12 are two case studies that show how to use the proposed spatial analysis methods of chapter 10 to evaluate existing housing design (chapter 11) and new rural dwellings (chapter 12) for a better spatial configuration and better thermal comfort.

Chapter 13 is the conclusion.

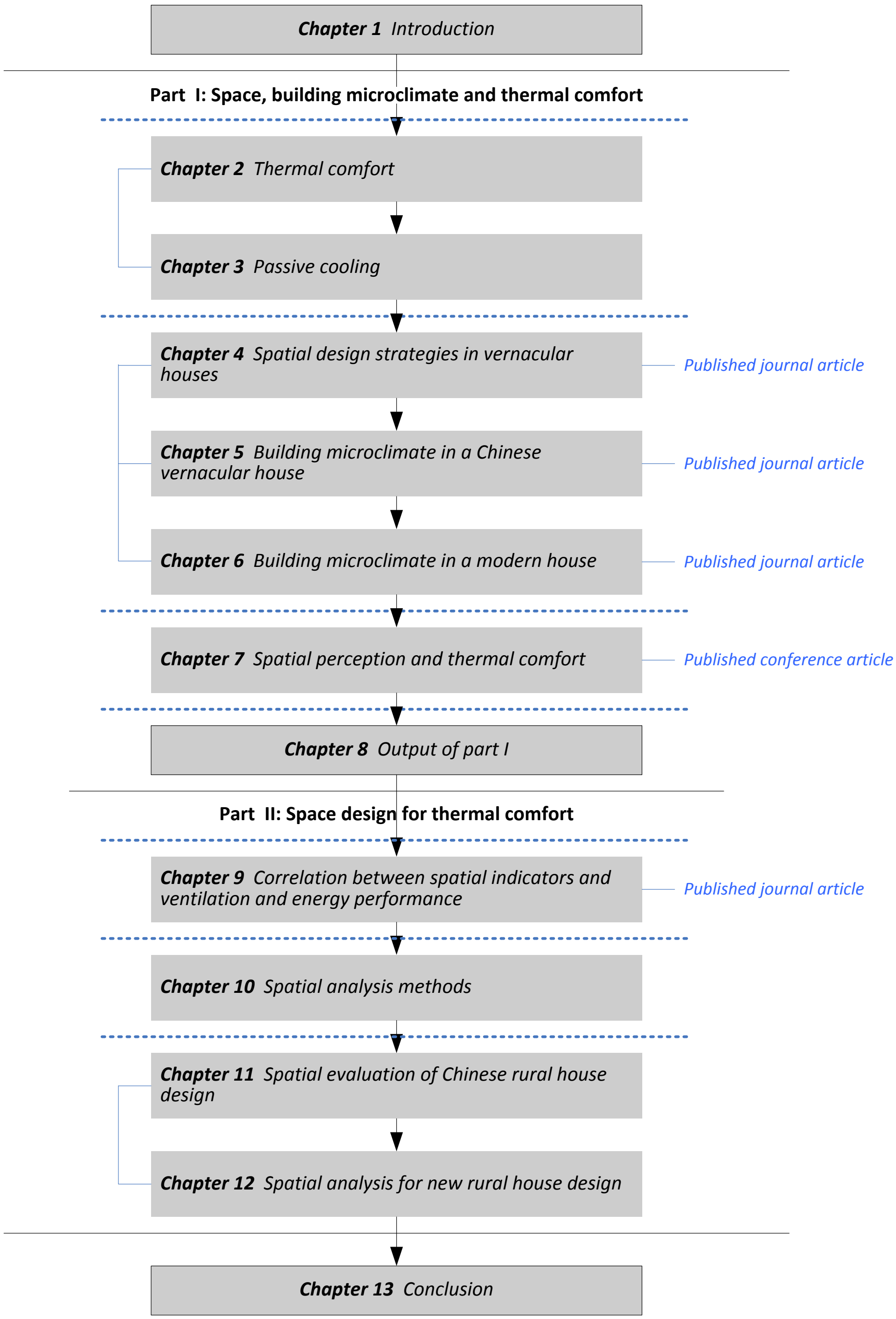

FIG. 1.4 Outline of this thesis

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PART 1

Space, Building Microclimate and Thermal Comfort

2 A review of thermal comfort

2.1 Human thermal comfort

Thermal comfort is defined as "that state of mind which expresses satisfaction with the thermal environment" (ANSI/ASHRAE, 2017). The definition of thermal comfort leaves open as to what is meant by condition of mind or satisfaction, but it correctly emphasizes that the judgment of comfort is a cognitive process involving many inputs related to physical, physiological, psychological, and other factors (Lin & Deng, 2008). People are always in an internal or external thermal environment. The human body produces heat and exchanges heat with the external environment. During normal activities these processes result in an average core body temperature of approximately 37 °C (Prek, 2005). This stable core body temperature is essential for our health and well-being. Our thermal interaction with the environment is directed towards maintaining this stability in a process called "thermoregulation" (Nicol, Humphreys, & Roaf, 2012).

Thermal comfort plays an important role in the energy consumption of buildings. So, researchers spent decades to find the appropriate approaches and models which evaluate and predict thermal comfort. A literature review of the current knowledge on thermal comfort shows two different approaches for thermal comfort, each one with its potentialities and limits: the heat-balance model and the adaptive model (Doherty & Arens, 1988). The heat-balance approach is based on analysis of the heat flows in and around the body and resulted in a model based on physics and physiology. Data from climate chamber studies was used to support this model. The best well-known heat-balance models are the predicted mean vote (PMV) (Fanger, 1970) and the standard effective temperature (SET) (Gagge, Fobelets, & Berglund, 1986). The PMV model is particularly important because it forms the basis for most national and international comfort standards. The adaptive approach is based on field surveys of people’s response to the environment, using statistical analysis and leads to an “empirical” model (Nicol et al., 2012).

2.2 The heat balance approach to thermal comfort

In 1962, Macpherson defined the following six factors which affect the thermal sensation. Air temperature, radiant temperature, humidity and air movement are the four basic environmental variables that effect the human response to thermal environments, and metabolic heat generated by human activity and clothing are the two personal variables (Lin & Deng, 2008). Fanger (1970) developed the theory of human body heat exchange and built the thermal balance equations. According to Fanger (1970), the requirements for steady-state thermal comfort are: (i) the body is in heat balance, (ii) mean skin temperature and sweat rate, influencing this heat balance, are within certain limits, and (iii) no local discomfort exists.

For practical applications, in which subjects do not feel neutral, an extension of the comfort equation was needed. By combining various experimental studies in the climate chambers involving 1396 subjects, Fanger (1970) expanded his comfort equation to the PMV index. The PMV index predicts the mean response of a large group of people according to the seven-point ASHRAE thermal sensation scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm and +3 hot). PMV is a function of the six factors mentioned above. PMV has been extended to predict the proportion of the group who would be dissatisfied with the environment in terms of PPD. The PPD predicts the percentage of the people who voted outside the central three points on the ASHRAE scale (votes -3, -2, +2, +3) which were counted as dissatisfied. The value of PPD is calculated from the value of the PMV.

The PMV (PPD) model of thermal comfort has been used more than 40 years worldwide to assess thermal comfort. Many studies have given support to the PMV model while others showed discrepancies (Howell & Kennedy, 1979; Humphreys & Nicol, 2002; van Hoof, 2008). The main debate focuses on two subjects: the PMV model’s validity and its application range. As the PMV model is derived from steady-state conditions in climate chambers and assumed clothing insulation and metabolic rate, the application range is limited. In practice, differences in the perception of the thermal environment were found among occupants of naturally ventilated (also referred to as free-running), fully air-conditioned and mixed mode or hybrid buildings (De Dear, Arens, Hui, & Oguro, 1997). It was found that for naturally ventilated buildings the indoor temperature in which is regarded as most comfortable increased significantly in warmer climatic contexts, and decreased in colder climate zones (De Dear, 2004). Conditions in passive buildings often cannot be controlled to the same extent as in buildings with mechanical air conditioning. Using natural phenomena such as wind, sun and outdoor temperature, such buildings cannot be closely regulated to a single temperature in the same way as those with fully mechanical systems. Therefore, the model based on heat balance approach is appropriate for mechanical heating or cooling buildings but not for free running passive buildings (Nicol & Roaf, 2007).

2.3 The adaptive approach to defining thermal comfort

The adaptive approach is based on field surveys of people's responses to the environment using statistical analysis and is called the "empirical" model (Nicol et al., 2012).

Field survey

A field survey is the basic tool of the adaptive approach (Humphreys, 1995). A field survey of thermal comfort is an in situ poll of comfort (7-point ASHRAE scale of thermal sensation) among a given population together with simultaneous measurements of the environmental conditions (Nicol et al., 2012). Compared to the climate chamber method, participants wear their normal clothing and go about their usual work. The researcher uses statistical methods to analyse the data, using the natural variability of thermal conditions. The aim is to find the temperature of combination of thermal variables (temperature, humidity, air velocity) which subjects consider "neutral" or "comfortable". This analysis is then used to predict the "comfort temperature" of "comfort conditions" which will be found acceptable in similar circumstances elsewhere (Nicol & Humphreys, 2002).

Indoor comfort and outdoor temperature from field survey

By collecting data from reports of field surveys from all over the world, Humphreys (1976) first found that the comfort temperature is closely correlated with the mean indoor temperature measured. After that, it was found that there was also a strong relationship between the indoor comfort temperature and the outdoor temperature. Humphreys (1978) produced the well-known graph to show the relationship between the indoor comfort temperature and the outdoor temperature based on the field survey data from the period during 1935-1975 (figure 2.1). The relationship for the free-running buildings was closely linear. For heated and cooled buildings, the relationship is more complex (Nicol & Humphreys, 2002). Michael Humphreys (1978) gave the linear relationship between comfort temperature and monthly mean outdoor air temperature as the following equation:

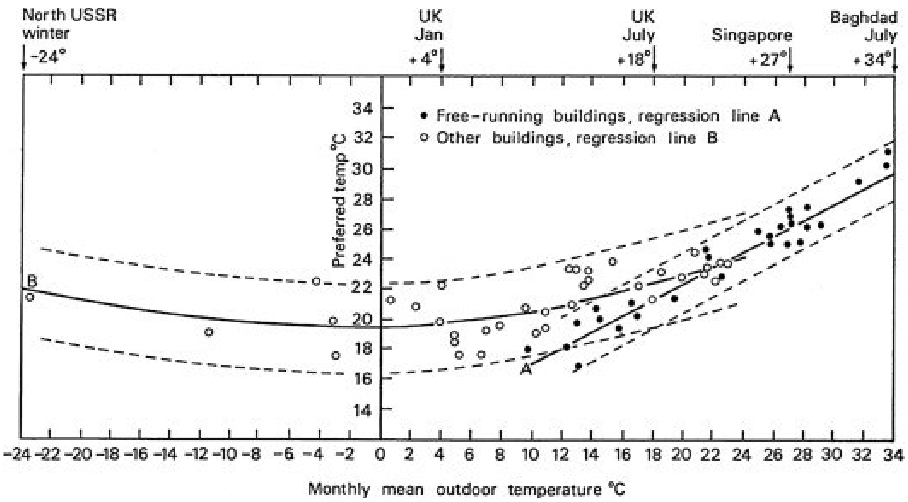

FIG. 2.1 Humphreys' graph for neutral/preferred temperature and the mean outdoor temperature (Humphreys, 1978)

T_n=11.9+0.534*T_o (coefficient of determination, R^2=0.97)

Where:

T_n= neutral or preferred indoor temperature (°C);

T_o = outdoor monthly mean air temperature (°C);

The linear relationship between comfort temperature and the corresponding mean outdoor air temperature was also found and developed by Auliciems (1981) and De Dear and Brager (1998) based on different databases. The general equation can be expressed as:

$$T_{comf}=A*T_{out,m}+B$$

where

T_{comf} = comfort temperature (°C);

$T_{out,m}$ = monthly mean out-door air temperature (°C);

A, B = constants.

Adaptive principle

The fundamental assumption of the adaptive approach is expressed by the adaptive principle: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Nicol et al., 2012).

People react in one of two principal ways corresponding to three categories: physiological adaptation, psychological adaptation and behavioural adaptation (Roaf, Nicol, Humphreys, Tuohy, & Boerstra, 2010). All of the three adaptations are related to the local climate, social and culture environment in where the subjects live. Behavioural adaptation is the most dominant factor in which people adjust their body heat balance to maintain thermal comfort through change “themselves” or the environment. People change “themselves” to avoid discomfort in the prevailing conditions: in many cases, this is through clothing adjustments, but also by other means - for instance, changes in posture (Raja & Nicol, 1997) or activity; people change the environment to keep thermal comfort, such as opening windows (to change temperature and air movement), drawing blinds (to reduce incoming radiation) or changing their location to a more comfortable spot in the room. The use of mechanical systems such as heating, cooling or fans can also be seen as examples of adaptive behaviour (Nicol & Humphreys, 2004). Nicol et al. (2012) categorized the adaptive actions as five basic types:

1. Regulating the rate of internal heat generation
2. Regulating the rate of body heat loss
3. Regulating the thermal environment

4 Selecting a different thermal environment

5 Modifying the body's physiological comfort conditions

Assuming that these responses are, on the whole, successful, the outcome of adaptive behaviours that subjects report themselves to be comfortable at a temperature which is typical of what they would expect to experience in their normal environment their 'customary' temperature, within a known behavioural lifestyle (Nicol & Roaf, 2007). The comfort temperature is a result of the interaction between the subjects and the building or other environment they occupy (Nicol & Humphreys, 2002). This comfort temperature is not static, it can change, for instance, season and the weather outside, or the location of a person's work.

Adaptive comfort model in design Standards

In different countries and regions, there are different standards for building design for thermal comfort specifically. But most of them are originated from the three well-known and widely used international standards: ISO Standard 7730, ANSI/ASHRAE Standard 55 and European standard EN 15251. At present, only two standards include adaptive comfort components:

1 ANSI/ASHRAE 55 adaptive thermal comfort standard

The ANSI/ASHRAE Standard 55 is the first international standard including adaptive comfort model to evaluate the indoor thermal comfort. This standard was put forward following the extensive work of De Dear and Brager (2002) and using data collected in ASHRAE project RP 884 (De Dear & Brager, 1998) for the "naturally conditioned" buildings. The standard used the equation, which resulted from more than 21,000 observations of thermal sensation from field study in 160 buildings from 9 countries to express the relationship between indoor thermal comfort temperature and outdoor temperature and defines zones within which 80 percent or 90 percent of building occupants might expect to find the conditions acceptable. Although ASHRAE 55 is an American national standard, because the field studies were sourced from different countries and regions, the adaptive model of ASHRAE 55 is regarded as a global implementation. The ANSI/ASHRAE 55 gave the optimal comfort temperature in occupant-controlled natural conditioned spaces as:

$$T_o = 0.31T_{out} + 17.8$$

Where:

T_o is the optimal temperature for comfort (°C);

T_{out} is the mean monthly outdoor air temperature for the survey in ANSI/ASHRAE 55 of 2004 and 2010, and the prevailing mean outdoor temperature ($t_{pma(out)}$) in ANSI/ASHRAE 55 of 2013 and 2017.

The prevailing mean outdoor temperature ($t_{pma(out)}$) was written as (ANSI/ASHRAE, 2017):

$$t_{pma(out)}=(1-\alpha).[t_{e(d-1)}+ \alpha\, t_{e(d-2)}+ \alpha^2\, t_{e(d-3)}+ \alpha^3\, t_{e(d-4)}+\ldots]$$

where α is a constant between 0 and 1 that controls the speed at which the running mean responds to changes in weather (outdoor temperature); $t_{e(d-1)}$ represents the mean daily outdoor temperature for the previous day, $t_{e(d-2)}$ is the mean daily outdoor temperature for the day before that, and so on. The prevailing mean outdoor temperature should be larger than 10 °C and lower than 33.5 °C.

The current version of ANSI/ASHRAE 55 of 2017 gives the acceptable operative temperature ranges in figure 2.2. The equation is:

$$T_o=0.31T_{out}+17.8\pm T_{lim}$$

Where T_o gives the limits of the acceptable zones and T_{lim} is the rang of acceptable temperature (for 80 percent or 90 percent of the occupants being satisfied). The given limits are $T_{lim}(80\%)=3.5$ °C and $T_{lim}(90\%)=2.5$ °C.

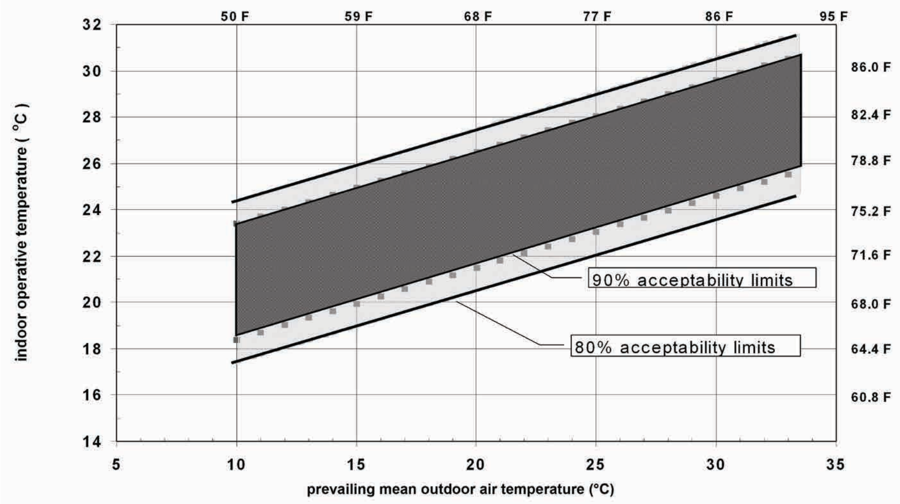

FIG. 2.2 Acceptable operative temperature ranges for naturally conditioned spaces (ANSI/ASHRAE, 2017)

2 EN 15251 adaptive thermal comfort standard

The adaptive standard in EN 15251 is similar to that in ASHRAE Standard 55, but using the database from the European SCATs project (Nicol & McCartney, 2001) that was collected from five European countries (France, Greece, Portugal, Sweden and UK) instead of the ASHRAE project RP 884 database. The optimal indoor comfort temperature in EN15251 (2007) is:

$$\theta_o = 0.33\ \theta_{rm} + 18.8$$

Where:

θ_o is the operative temperature (°C);

θ_{rm} is the running mean outdoor temperature. It was written as:

$$\theta_{rm(ed)} = (1-\alpha).[\ \theta_{ed-1} + \alpha\ \theta_{ed-2} + \alpha^2\ \theta_{ed-3} + \alpha^3\ \theta_{ed-4} + \ldots]$$

where α is a constant between 0 and 1, recommended 0.8; θ_{ed-n} represents the mean daily outdoor temperature for n-days prior the day in question. An approximate equation is provided when full records of daily running mean outdoor temperature are not available as:

$\theta_{rm(ed)} = (\theta_{ed-1} + 0.8\ \theta_{ed-2} + 0.6\ \theta_{ed-3} + 0.5\ \theta_{ed-4} + 0.4\ \theta_{ed-5} + 0.3\ \theta_{ed-6} + 0.2\ \theta_{ed-7})/3.8$

The acceptable indoor operative temperature ranges from the optimal temperature for comfort temperature mentioned above is divided into four categories (figure 2.3). The calculation of the upper and lower limits of the different categories shall be expressed as the following equation:

Upper limit of category III: $\theta_{omax}=0.33\ \theta_{rm}+18.8+4$

Upper limit of category II: $\theta_{omax}=0.33\ \theta_{rm}+18.8+3$

Upper limit of category I: $\theta_{omax}=0.33\ \theta_{rm}+18.8+2$

Lower limit of category I: $\theta_{omin}=0.33\ \theta_{rm}+18.8-2$

Lower limit of category II: $\theta_{omin}=0.33\ \theta_{rm}+18.8-3$

Lower limit of category III: $\theta_{omin}=0.33\ \theta_{rm}+18.8-4$

These limits apply when $10< \theta_{rm}<30°C$ for the upper limit and $15< \theta_{rm}<30°C$ for the lower limit.

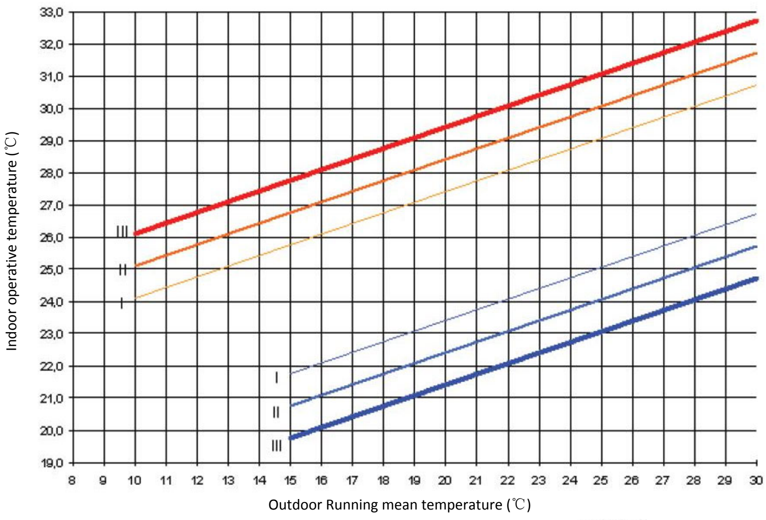

FIG. 2.3 Acceptable operative temperature ranges for naturally conditioned spaces (EN15251, 2007)

2.4 Thermal comfort in a hot climate

Selecting a thermal comfort model is important for saving cooling energy consumption and to evaluate occupants' thermal comfort correctly. Attia and Carlucci (2015) compared the different models used in the climates. It was found that the variation in the different comfort models is very large. The adaptive models (both ASHRAE 55 and EN 15251) predict a wider range of comfort temperatures than the Fanger's model. The adaptive comfort model is thought to be more appropriate for mixed-mode non air-conditioned buildings in hot climates (De Dear, 1999; Pfafferott, Herkel, Kalz, & Zeuschner, 2007; Rijal, Humphreys, & Nicol, 2008). The adaptive model is based on field surveys, including field surveys in a hot climate such as India, Iraq and Singapore. The field surveys indicated that the PMV model cannot predict the thermal comfort correctly in the hot climates, especially for free-running buildings. The subjects can be comfortable at temperatures up to or even exceeding 30°C (Nicol, 2004). The adaptive model has great energy saving and mitigation potential, especially in warmer climates, where the building cooling load is the major design consideration (Wan, Li, Pan, & Lam, 2012). The energy savings as a result of using an adaptive comfort model was estimated to be 10-18% of the overall cooling load (Attia & Carlucci, 2015).

For the application of the adaptive thermal comfort model in a hot and humid climate, the effect of air movement and humidity are considered. In hot climate regions, especially for free-running or naturally ventilated buildings, the influence of humidity and wind velocity on occupants' thermal comfort sensation is larger than in other climate regions and in conditioned buildings. The cooling effect of air movement depends on not only air velocity, but also the temperature, humidity and radiation balance, as well as on the activity (metabolic rate) and clothing of the individual (Szokolay, 2000). Studies done in different climates show that occupants prefer larger air movement and thermal comfort ranges can expand with the aid of air movement (Mishra & Ramgopal, 2013). In hot and humid climates, air movement can enhance convective heat transfer from the skin and increase the evaporation of sweat. Occupants appreciate air movement even when it is not necessary for cooling (Zhang et al., 2007). For air movement, Nicol (2004) proposes that there can be an allowance on the comfort temperature depending on the velocity of air movement that is felt by the occupants. Other researchers also proposed equations for the influence of the wind velocity on the thermal comfort in a hot climate (table 2.1).

TABLE 2.1 Effects of air movement on comfort temperature

Source	Comfort temperature Correction for enhanced air velocity	Conditions
ASHRAE Standard 55 (ANSI/ ASHRAE, 2017)	$\Delta T=1.2$ $\Delta T=1.8$ $\Delta T=2.2$	0.3m/s<Va<0.6m/s 0.6m/s<Va<0.9m/s 0.9m/s<Va<1.2m/s
EN15251-2007 (EN15251, 2007), Nicol (Nicol, 2004)	$\Delta T = 7 - \frac{50}{4 + 10V_a^{0.5}}$	0.1m/s<Va
Szokolay (Szokolay, 2000)	$\Delta T = 6V_e\text{-}1.6(V_e)^2, V_e = V\text{-}0.2\ \mathrm{m/s}$	V<2m/s
China (Su, Zhang, & Gao, 2009)	$\Delta T = -4(\varphi\text{-}70\%) + \frac{0.55V}{0.15}, \mathrm{T} > 28℃$ $\Delta T = \frac{0.55V}{0.15}, \mathrm{T} < 28℃$	V<0.8m/s

Here ΔT is the raise in comfort temperature (°C); T is the indoor air temperature (°C); Va is the air velocity (m/s); V is the air velocity at the body surface (m/s); ϕ is the relative humidity (if less than 70%, ϕ =70%)

The influence of humidity on thermal comfort is more difficult to determine. Humidity has been investigated in a number of field surveys in hot climates, and although the humidity is found to have a significant effect on the comfort temperature, the size of the effect is generally small, and further research is needed (Nicol, 2004).

2.5 Thermal comfort in outdoor and semi-outdoor spaces

To create a sustainable and comfortable outdoor built environment is one of the core issues in urban planning. At present, the outdoor thermal comfort in public spaces-pedestrian streets, public squares and gardens, is the common focus of urban planning. As cities expand and the population in the cities rises, many issues related to sustainable development extend to the urban scale. Consequently, the research of the urban microclimate and outdoor thermal comfort are becoming more and more important. However, compared to indoor thermal comfort for which the quantitatively analysis is reasonable well established, it is still a challenge to quantitatively describe the outdoor thermal comfort (Coccolo, Kämpf, Scartezzini, & Pearlmutter, 2016). This is due to the great complexity of the outdoor environment in terms of variability, temporally and spatially, and the large range of activities people are engaged in (Nikolopoulou, Baker, & Steemers, 2001). The variability in exposure time influences the human capacity to acclimatize, and underlines the need for non-steady state models to quantify outdoor human comfort (Höppe, 2002). In the outdoor environment, people are directly exposed to local microclimate conditions of solar radiation, shading and changes in wind direction and speed (Chen & Ng, 2012). People carry out various activities, and each person has a different thermal history, memory and expectations (Nikolopoulou et al., 2001).

For the evaluation and prediction of outdoor thermal comfort, Nagano and Horikoshi (2011), Chen and Ng (2012) and Coccolo et al. (2016) have done a review of outdoor thermal comfort models. The major outdoor thermal comfort models are steady-state models. These models are based on the assumption that people's exposure to an ambient climatic environment has, over time, enabled them to reach thermal equilibrium, and they provide numerical solutions to the energy balance equations governing thermoregulation (Chen & Ng, 2012). Even though the PMV-PPD index was originally developed for the evaluation of indoor thermal comfort, it is also commonly adopted in outdoor thermal comfort studies. The PET (Physiological Equivalent Temperature) (Mayer & Höppe, 1987) is another notable example of a steady-state model commonly used in outdoor thermal comfort research. PET is defined as the "air temperature at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed" (Höppe, 1999). The PET model is particularly suitable for the evaluation of the outdoor thermal comfort in that it translates the evaluation of a complex outdoor climatic environment to a simple indoor scenario on a physiologically equivalent basis that can be easily understood and interpreted (Chen & Ng, 2012). A further development of PET is mPET (modified PET) that improves the capacity of the model to react to the change of relative humidity and clothing insulation (Chen & Matzarakis, 2014). Some other steady-state models-thermal stress (ITS) (Givoni, 1976), the OUT-SET (Pickup & de Dear, 2000), the COMFA (Kenny, Warland, Brown, & Gillespie, 2009), and the UTCI (Jendritzky, de Dear, & Havenith, 2012) are also applied in the outdoor thermal comfort studies. However, the steady-state models cannot effectively account for the dynamic aspects of the course of human thermal adaption (Chen & Ng, 2012). Many researches are developing non-steady-state models for the evaluation of outdoor thermal comfort based on field studies.

Semi-outdoor spaces, which some researchers also call transitional spaces or buffer spaces, are spaces featuring a semi-enclosed wall or roof. Semi-outdoor spaces can flexibly connect the indoor spaces and outdoor spaces that make the spaces more diverse. The outside corridor, the terrace, the balcony and the veranda are the most common transitional spaces. Literature review revealed that only few studies focus on thermal comfort in these spaces. The field studies that were found were: a field study in Sydney Australia (Spagnolo & de Dear, 2003), two stadium case studies in Paris and Istanbul (Bouyer, Vinet, Delpech, & Carré, 2007), a space under a membrane in Japan (He & Hoyano, 2010), a field study in a workplace in Beirut (Ghaddar, Ghali, & Chehaitly, 2011), a field study in Taiwan (Hwang & Lin, 2007) and in Wuhan (Zhou, Chen, Deng, & Mochida, 2013). Nevertheless, there are no specific regulations and standards for the thermal comfort of such spaces, most of the studies use the outdoor thermal comfort models to evaluate the thermal comfort in semi-outdoor spaces.

2.6 The adaptive approach in China

2.6.1 Development of adaptive approach in China

Occupants' adaption in the thermal comfort study is investigated by Chinese researchers. Yang (2003) investigated the adaptive thermal comfort model of five typical cities in China and achieved a linear correlation between comfort temperature and outdoor temperature. A field study of a thermal environment was performed and an adaptive model was built in Shanghai (Ye et al., 2006). Han et al. (2007) discussed the inside thermal comfort of residences of three cities in the hot-humid climate of central southern China. It was found that only 48.2% of the measured variables are within the ASHRAE Standard 55-1992 summer comfort zone, but approximately 87.3% of the occupants perceived their thermal conditions acceptable, for subjects adapt to prevailing conditions. Han et al. (2009) investigated the occupants' thermal comfort and residential thermal environment conducted in an urban and a rural area in Hunan province and found the percentage of acceptable votes of rural occupants is higher than that of urban occupants at the same operative temperature. Wang, Zhang, Zhao, and He (2010) studied the thermal comfort for naturally ventilated residential buildings in Harbin. The acceptable air temperature range in winter and summer was identified. Thermal comfort in naturally ventilated buildings in the hot-humid area of China is investigated by Zhang, Wang, Chen, Zhang, and Meng (2010). The adaptive evidences were obtained for clothing adjustment, window opening and using fan, respectively, and a modified PMV model was validated to be applicable in NV buildings. Human thermal adaptive behaviour in naturally ventilated offices was studied in Changsha, China (Liu, Zheng, Deng, & Yang, 2012). Based on the survey, the characteristics of the thermal adaptive behaviour in the offices were revealed. A year-long field study of the thermal environment in university classrooms in Chongqing was done by Yao, Liu, and Li (2010). The adaptive thermal comfort zone for the naturally conditioned space for Chongqing has been proposed based on the field study results. Furthermore, Liu, Yao, Wang, and Li (2012) studied the occupants' adaptation in workplaces with non-central heating and cooling systems in Chongqing. They demonstrated that occupants are active players in environmental control and their adaptive responses are driven strongly by ambient thermal stimuli and vary from season to season and from time to time, even on the same day.

Some researchers found a linear correlation between the outdoor air temperature and comfort temperature corresponding to the local climate, culture and people's perception in different regions of China. Table 2.2 listed some of the major findings in terms of the linear relationship between the mean outdoor temperature T_{out} (°C) and the neutral or preferred indoor temperature T_n (°C).

TABLE 2.2 The major findings of the linear relationship between mean outdoor temperature and the neutral or preferred indoor temperature by different researchers in China

References	Equation	Location
Yang (2003)	$T_n = 0.30T_{out} + 19.7$	Five typical cities in China
Ye et al. (2006)	$T_n = 0.42T_{out} + 15.12$	Shanghai
Han (2007)	In city: $T_n = 0.67T_{out} + 10.32$ In rural: $T_n = 0.44T_{out} + 9.17$	"hot summer and cold winter" climate region
Wang et al. (2010)	$T_n = 0.468T_{out} + 11.80$	Harbin (summer)
Li (2008)	$T_n = 0.39T_{out} + 16.28$ (5.0°C-30.0°C.)	Chongqing

An interesting finding is by Su et al. (2009). He improved the study by Yang (2003) and proposed to add the effects of airflow velocity and relative humidity in the adaptive model. He considered that people will be more comfortable at the environment of temperatures over 26°C if they feel the wind. If the relative humidity exceeds 70%, the comfort temperature will ascend 0.4°C by a 10% increase of relative humidity on the premise that the indoor air temperature exceeds 28°C. The Comfort temperature will decrease 0.55 °C with a 0.15 m/s increase of airflow velocity. When the indoor air temperature is above and below 28°C, the thermal neutral temperature is thus improved to be as the following two equations respectively:

T_c=0.30T_o+19.7-4 (ϕ-70%)+0.55v/0.15

T_c=0.30T_o+19.7+0.55v/0.15

Where T_c is the neutral or preferred indoor temperature (°C), T_o is the monthly mean outdoor temperature (°C), ϕ is the relative humidity (if less than 70%, ϕ = 70%), v is the airflow velocity along the body surface. The velocity on body surface should not be over 0.8 m/s (Su et al., 2009).

2.6.2 Adaptive approach in Chinese standard

China is classified into five climate zones (very cold zone, cold zone, hot summer and cold winter zone, hot summer and warm winter zone, and temperate zone) for building design according to the national "Standard of Climatic Regionalisation for Architecture" (GB50178, 1993). Li, Yao, Wang, and Pan (2014) performed a detailed introduction in the development process of the Chinese standard of indoor thermal comfort. Before the newest code "Evaluation standard for indoor thermal environments in civil buildings GB/T50785-2012", which was published in May of 2012, the existing Chinese standards relevant to indoor environmental design and thermal comfort mainly adopted the international standards based on the PMV–PPD models. In the newest code of GB/T50785-2012, the thermal comfort for the heated and cooled spaces is based on the PMV-PPD models. However, for the free-running buildings, the code offers an adaptive comfort model for the evaluation of the indoor thermal environment. It includes two methods: a graphical method and a calculation method.

Graphical method

The graphical method is based on the adaptive thermal comfort model in ANSI/ASHRAE 55 (Li et al., 2014). In the graphical method, the operative temperature ranges were identified according to different climate zones (figure 2.4 (a)(b)). There are two categorizes for the acceptable operative temperature ranges: category I represents 90% occupant acceptability with the maximum temperature of 30°C and the minimum temperature of 18°C, and category II corresponds to 75-90% acceptability with the maximum temperature of 30°C and the minimum temperature of 16°C.

The running mean of outdoor temperature (t_{op}) was written as:

$t_{op}=(1-\alpha).(t_{ed-1}+ \alpha\ t_{ed-2}+ \alpha^2\ t_{ed-3}+ \alpha^3\ t_{ed-4}+ \alpha^4\ t_{ed-5}+ \alpha^5\ t_{ed-6}+ \alpha^6\ t_{ed-7})$

where α is a constant between 0 and 1, and is recommended as 0.8; t_{ed-n} represents the mean daily outdoor temperature for n-days prior the day in question.

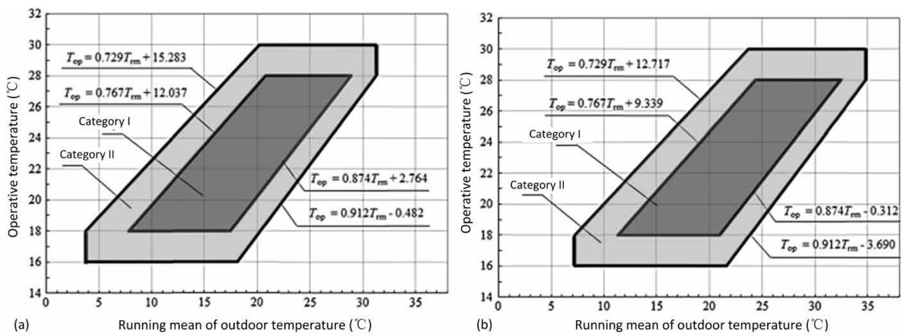

FIG. 2.4 (a) Acceptable operative temperature ranges of the thermal environment in free-running buildings in the very cold and cold zones (Top: operative temperature; Trm: running mean of outdoor temperature) (Li et al., 2014). (b) Acceptable operative temperature ranges of the thermal environment in free-running buildings in the hot summer and cold winter zone, the hot summer and warm winter zone and the mild zone (Top: operative temperature; Trm: running mean of outdoor temperature) (Li et al., 2014)

Calculation method

For the calculation method, the aPMV (adaptive prediction mean vote) was introduced. The aPMV (Yao, Li, & Liu, 2009) is the modification of the PMV model of the thermal comfort evaluation considering the adaption of occupants from field studies carried out in China between 2007 and 2011. The equation for aPMV is proposed as:

$$aPMV = \frac{PMV}{1+\lambda PMV}$$

where λ is the adaptive coefficient, which has a positive value when in warm conditions and a negative value when conditions are cool. Because the aPMV index is derived from Fanger's PMV, the input parameters (i.e. air temperature, mean radiation temperature, air speed, relative humidity, occupants' clothing insulation levels and metabolic rate) to PMV are also necessary for the calculation.

2.7 Conclusion

Summarizing the current evaluation approaches in scientific research and design standards for thermal environment of occupants, both the PMV/PPD model and the adaptive model are important related to different environmental conditions, even though there are still some discussion between the two models. The PMV/PPD model predicts thermal sensation well in buildings with HVAC systems, however, field studies in warm climates in buildings without air-conditioning have shown to predict a warmer thermal sensation than the occupants actually feel (Brager & de Dear, 1998). The adaptive model is suitable for the evaluation of the free-running buildings which have great potential for energy conservation. However, more field studies are needed to validate the linear correlation between the outdoor temperature and comfort temperature respecting to different climatic, social and culture environments. In this thesis, the summer thermal comfort and passive cooling are focused on the free-running buildings, therefore, the adaptive thermal comfort approach is applied for the thermal environmental evaluation. The adaptive thermal comfort in ANSI/ASHRAE 55 standards, the Chinese standards and the local equation (Chongqing) for adaptive thermal comfort are all considered in the following studies.

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3 Passive cooling techniques

3.1 Vernacular buildings

Vernacular buildings are local buildings that have evolved overtime in one location to suit the local climate, culture and economy (Meir & Roaf, 2003). The construction of vernacular buildings uses locally available resources to address local needs. These kinds of structures evolve over time to reflect the environmental, cultural and historical context in which they exist (Coch, 1998). The building knowledge of this type of architecture is always handed down traditions and is thus more based on the knowledge achieved by trial and error and in this way handed down through the generations (Singh et al., 2009). Vernacular buildings are most often residential buildings. People have traditional lifestyles in vernacular buildings in virtually every climate in the world, from the Arctic circle to the tropics, in temperatures from below zero to over 40°C, and historically without the benefit of gas or electrically driven mechanized heating and cooling systems (Meir & Roaf, 2003).

After the emergence of modernist architecture, aided by the industrial revolution, vernacular buildings are seen to be in a state of decline and are frequently looked down upon, abandoned, neglected or actively demolished. Associated, by many at least, with an out-dated past and poverty, they are steadily replaced by architectural models that favour more modern, inter-national technologies, materials and forms (Oliver, 1997). It is assumed, as in international standards such as CENASO 7730 or ASHRAE 55, that people suffer less discomfort in very closely controlled conditions, then such vernacular buildings, along with modern passive buildings, cannot provide their occupants with 'comfortable' indoor climates (Santamouris, 2007). But nowadays, by the more and more important issues of energy consumption in building construction sectors, the continuity of the vernacular traditions is emphasized in academic research and building practice because of its climate-response, passive model and low-energy consumption. The principles that were used in traditional buildings can very well be implemented in modern buildings so as to produce “energy saving” buildings. If these principles are sensibly adopted in modern buildings, it should be possible to build sustainable buildings for the future (Shanthi Priya, Sundarraja, Radhakrishnan, & Vijayalakshmi, 2012). We can learn a lesson from the approach of the builders who acknowledged the interdependence of human beings, buildings and physical environment (Coch, 1998). A “new vernacular” can be developed, harnessing the types of low-tech solutions that are familiar to most of us from the vernacular, together with modern passive and active renewable energy technologies and strategies to reflect the new cultural, climatic and economic realities of the 21st century (Meir & Roaf, 2003).

Vernacular buildings have to adapt to the environment through low-tech methods. Changing building form and material is the most important technique to adapt to the environment to obtain the best comfortable living space, in another words, the environment deeply influenced building form design and material use. Fathy (1986) described the climate effect on building form generation in vernacular building as: “For example, the proportion of window to wall area becomes less as one moves toward the equator. In warm areas, people shun the glare and heat of the sun, as demonstrated by the decreasing size of the windows. In the subtropical and tropical zones, more distinctive changes in architectural form occur to meet the problems caused by excessive heat. In Egypt, Iraq, India, and Pakijstan, deep loggias, projecting balconies, and overhangs casting long shadows on the walls of buildings are found. Wooden or marble lattices fill large openings to subdue the glare of the sun while permitting the breeze to pass through. Such arrangements characterize the architecture of hot zones, and evoke comfort as well as aesthetic satisfaction with the visible endeavour of man to protect himself against the excessive heat”.

In recent years, a significant amount of research has looked specifically at environmental performance issues of vernacular architecture, including its thermal properties, energy consumption and resources (Foruzanmehr & Vellinga, 2011). Both qualitative and quantitative such as field measurements, field surveys, statistical methods, comparative study and computer simulation methods are used in the investigation of the performance of vernacular buildings. Professor Paul Oliver of Oxford University compiled the book “Dwellings: Encyclopedia of Vernacular Architecture” and published in 1997 with 4000 pages collection of research by over 750 authors from 80 countries. With two volumes categorized by climate and the ‘‘vernacular responses’’ of a plethora of cultures and another volume focused on materials, resources and production, it is the world’s foremost source for research in the area (Zhai & Previtali, 2010). Zhai and Previtali (2010) introduced an approach to categorizing distinct vernacular regions and evaluate energy performance of ancient vernacular homes as well as identify optimal constructions using vernacular building techniques. Chandel, Sharma, and Marwah (2016) reviewed the vernacular architecture features affecting indoor thermal comfort conditions and energy efficiency for adaptation in modern architecture to suit present day lifestyles. Singh et al. (2009) carried out a qualitative analysis on the vernacular buildings in north-east India. And Shanthi Priya et al. (2012) have conducted the qualitative and quantitative analysis to investigate the indoor environmental condition of a vernacular residential building in coastal region of Nagapatinam, India. Cardinale, Rospi, and Stefanizzi (2013) performed one experimental research on two types of vernacular buildings which lie in Southern Italy. Nguyen, Tran, Tran, and Reiter (2011) carried out an investigation on climate responsive design strategies of vernacular housing in Vietnam by a new research methodology which is adapted to the natural and social context of Vietnam. Ng and Lin (2012) analysed the microclimate of two Minangkabau vernacular houses in villages of Balimbing of Bukittinggi, Sumatra, Indonesia. Ali-Toudert, Djenane, Bensalem, and Mayer (2005) addressed the issue of outdoor thermal comfort in a hot and dry climate in relation to urban geometry. Beccali, Strazzeri, Germanà, Melluso, and Galatioto (2017) reviewed some models evaluating thermal comfort in natural ventilated vernacular buildings, based on adaptive approaches.

Borong et al. (2004) concluded that sun shading and insulation are of great importance while natural ventilation is just considered as an auxiliary approach for the design principles of the traditional Chinese vernacular dwellings, based on the field measurements of the thermal environment parameters and a long-term auto-recorder of the indoor and outdoor temperature at four typical traditional vernacular dwellings at Wannan area in summer. Bouillot (2008) studied six Chinese vernacular houses in different provinces and found that the value and the diversity of the Chinese housing stock is due to the combination of the specific structure of the Chinese eastern climates, which creates the contrast of cold-dry winters and hot-humid summers, with the structure of the Ming t'ang, which contains the opposition of the yin and the yang. Liu et al. (2011)'s study interprets the characteristic of warm in winter and cool in summer in traditional Yaodong dwelling by measuring the indoor, outdoor and the wall's temperatures in winter and summer. The results show that the Yaodong thick wall effectively damps the external temperature wave and keeps a steady inner surface temperature, are the chief causes of warm in winter and cool in summer in Yaodong. Gou et al. (2015) focused on a qualitative analysis of ancient dwellings located in the village of Xinye, in the hot summer and cold winter region of China. According to the analysis, the climate responsive strategies of the dwellings are mainly focused on natural ventilation, sun-shading and thermal insulation, illustrated by different building aspects such as the building location, building group layout and orientation, internal space arrangement, opening design, among other variables. Soflaei, Shokouhian, and Zhu (2017) investigated the potential of traditional courtyard houses in Iran and China in responding to environmental challenges alongside social norms over a long period of time. The social and environmental dimensions of the sustainability as well as the main elements of traditional courtyard houses in Iran and China were identified.

Because of the advantage of vernacular building using passive ways to achieve thermal comfort and energy efficiency as mentioned above, this research will start with the investigation of a Chinese vernacular buildings in chapter 4. The next part of the literature review is an overview of passive cooling techniques.

3.2 Passive cooling techniques

Givoni (1994) identified “passive cooling systems” as the applications of various simple cooling techniques that enable the indoor temperatures of buildings to be lowered through the use of natural energy sources. Santamouris and Asimakopoulos (1996) identify passive cooling as the techniques which are based on the application of solar and heat control systems, dissipation of excess heat into low-temperature natural sinks, and the amortization of the heat surplus through the use of additional thermal mass in buildings. Passive cooling can broadly cover all the methods and processes that contribute to the control and reduction of the cooling needs of buildings.

Passive cooling techniques are broadly distinguished by their heat transfer in three categories: prevention of heat gains (reduce heat gains), modification of heat gains, and heat dissipation (removal of internal heat). The various techniques adopted for each of the three categories can be classified and are given in figure 3.1.

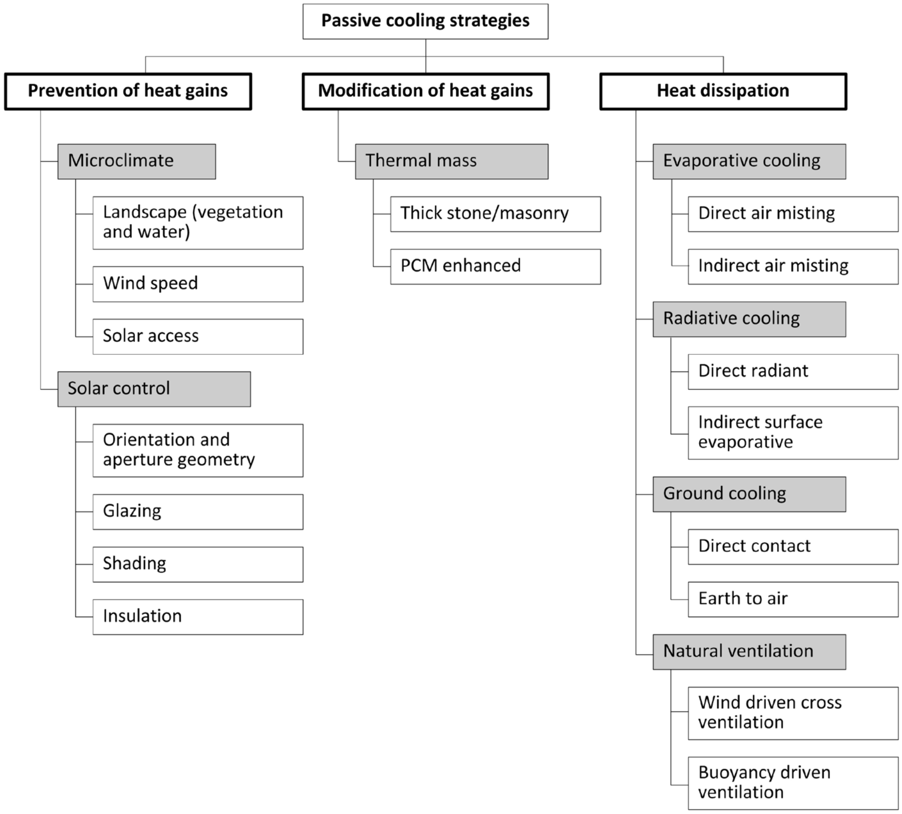

FIG. 3.1 Overview of passive cooling strategies (Geetha & Velraj, 2012; Valladares-Rendón, Schmid, & Lo, 2017)

3.2.1 prevention of heat gains

The first step to reduce the indoor heat gains is to prevent the heat load that comes from the sun and the outside thermal environment. The main approach to reduce the heat gain is solar control. Reducing the outside temperature is also an option, but this is described in section 3.3. where the passive cooling strategies at urban level are discussed.

Solar radiation reaches the external surfaces of a building in direct, diffuse and reflected form and penetrates to the interior through transparent elements. In general, the incident radiation varies with geographic latitude, the altitude above

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sea level, the general atmospheric conditions, the day of the year, and the time of the day. Solar radiation is the main factor that increases the building cooling load in summer, so controlling the solar radiation is important for a passive cooling strategy. Solar control denotes the complete or partial, permanent or temporary exclusion of solar radiation from building surfaces, interior or surrounding spaces (Geetha & Velraj, 2012). There are four major techniques for solar control.

1 Orientation

The orientation of an opening, combined with its size and tilt can change the solar gains passing through it (Santamouris & Asimakopoulos, 1996). Transparent components are essential to solar gains. The amount of heat that enters modern buildings by conduction via opaque areas of the envelope is usually small due to the small temperature differences in summer and the level of insulation that is already common in many countries (Santamouris, 2007).

Without the consideration of the wind direction for natural ventilation, Mazria (1979) defines the best orientation for the solar apertures of a building as one which receives the maximum amount of solar radiation in winter and the minimum amount in summer. Shaviv (1981) Studied the orientation of the glazing surface of a building and concluded that the main glazing surface should face south or southeast (northern hemisphere) to achieve the maximum energy saving of the building especially in countries with a hot and humid climate.

2 Aperture geometry

The size of the opening at each orientation should be defined according to the annual energy requirements of the specific building. This cannot be defined globally, but depends on the latitude of the place, the location, the functions and the architecture of the building. The concept of “window-to-wall-ratio” is commonly used to evaluate the opening area in the building envelop. It is identified as the percentage of the net gazing area to the gross wall area. For building’s energy performance, the optimal “window-to-wall-ratio” for hot and cold climates should be around 40% or less. A higher “window-to-wall-ratio” up to 90% can be accepted in cold climates, but only if the windows are well insulated, and in hot climates, only if the windows are well shaded (Valladares-Rendón et al., 2017). Tilt of the openings can also contribute to the shading effect since an outward tilt, facing the ground, restricts the direct solar gain (Santamouris & Asimakopoulos, 1996).

3 Glazing

The thermal properties of the glazing surface determine the amount of solar energy which penetrates into the interior of a building. Glazing with a low thermal transmittance can be achieved with specially treated glass such as: body-tinted glass with high absorptivity; surface coated glass with increased reflectivity; variable transmission glass; translucent glazing material; special sun-control membranes; temporary glazing coating; single-and double-glazed units with laminated glass incorporating blinds and louvers (Santamouris & Asimakopoulos, 1996). Research in the field of glazing systems received a boost, passing from a single pane to low-emittance window systems, and again to low thermal transmittance, vacuum glazing, electrochromic windows, thermotropic materials, silica aerogels and transparent insulation materials (TIM) (Geetha & Velraj, 2012).

4 Shading

Shading denotes the partial or complete obstruction of the sunbeam directed toward a surface especially the windows by an intervening object or surface. Shading on building façades controls the amount of solar radiation received by the building (Pacheco, Ordonez, & Martinez, 2012). The principal role of shading devices is to protect openings from direct solar radiation, while their second is to protect openings from diffuse and reflected radiation. Shading also can prevent visual discomfort. Solar gain through windows is a major component of the total heat gain of a building. Minimizing this heating source through the use of shading devices is therefore of primary importance in all types of hot climates (Givoni, 1994).

Shading devices can be classified as external shading devices and internal shading devices, or classified as fixed shading and adjustable shading. Fixed shading devices include horizontal overhangs, vertical fins, combination of horizontal and vertical elements closely spaced, balconies or internal elements like louvers and light-shelves. Adjustable shading devices are tents, awnings, blinds, pergolas, or internal elements like curtains, rollers and venetian blinds. In general, external shading devices have a higher performance than internal ones and fixed shading devices are economical solutions, as they do not require manual adjustments (Al-Tamimi & Fadzil, 2011; Freewan, 2014).

A suitable shading coefficient saves energy throughout the year (Yang, Li, & Hu, 2006). The shading coefficient is defined as the ratio of solar heat gain through a given fenestration system under a specific set of conditions to the solar heat gain through single glazing of standard 3 mm clear glass. One of the problems of establishing a fixed shading coefficient is that the angle of incidence of solar rays does not remain constant. Various research studies have been carried out to develop are liable method or system of calculating this shading coefficient (Pacheco, Ordonez, & Martinez, 2012). In hot climates, there are greater energy benefits with a high shading coefficient since heating gains are reduced.

Choice of the appropriate shading device from the wide range of fixed and adjustable elements depends on the latitude, sky conditions (the direct-diffuse-reflected solar radiation component), orientation, building type and overall design of the building. External shading devices are more effective as they obstruct the sun radiation before it reaches the interior of the building. In many cases fixed devices are preferred because of their simplicity, low maintenance cost and sometimes low construction cost. However, movable shading devices are more flexible as they respond better to the dynamic nature of the sun's movement, allow better control of the diffuse radiation and glare and, in most cases, causeless or negligible sun obstruction during winter (Santamouris & Asimakopoulos, 1996). The use of mobile shading systems is more beneficial in regards to natural illumination and to lower energy consumption.

5 Insulation

Insulation can efficiently prevent the building heat gains from the outside thermal condition. Belusko, Bruno, and Saman (2011) investigated the thermal resistance for the heat flow through a typical timber-framed pitched roofing system measured under outdoor conditions for heat flow up. However, with higher thermal resistance systems containing bulk insulation within the timber frame, the measured result for a typical installation was as low as 50% of the thermal resistance determined considering two-dimensional thermal bridging using the parallel path method. This result was attributed to three-dimensional heat flow and insulation installation defects, resulting from the design and construction method used. Translating these results to a typical house with a 200 m^2 floor area, the overall thermal resistance of the roof was at least 23% lower than the overall calculated thermal resistance including two-dimensional thermal bridging.

3.2.2 Modify heat gains

It is well-known that the thermal mass of a building (in the envelop, the inner wall, the floor, partition and other construction materials with a high heat capacity) is able to absorb heat and cold and store it for a period time before releasing it to the environment. Thermal mass, in summer, can regulate the size of indoor temperature swings, reduce peak cooling load and transfer a part of the absorbed heat to the ambient in the night hours. In addition, if there is a large enough temperature difference in the night, night ventilation enables the thermal mass to store the cold and release it in the early morning hours of the following day. The rate of heat transfer and the effectiveness of the thermal mass are determined by a number of parameters and conditions such as building material properties, building orientation, thermal insulation, ventilation, climatic conditions, use of auxiliary cooling systems and occupancy patterns (Balaras, 1996).

The thermal mass of a building can be achieved either through the construction materials or through phase change materials (PCM) in the building. Pasupathy, Velraj, and Seeniraj (2008) presented a detailed review on the PCM incorporation in buildings, and the various methods used to contain them for thermal management in residential and commercial establishments. Generally speaking, the PCM can be integrated with almost all kinds and components of building envelopes, but different application areas have their own unique configurations and characteristics (Geetha & Velraj, 2012).

3.2.3 Heat dissipation

Heat dissipation deals with the disposal of the excess heat of a building to a sink characterized by a lower temperature, such as the ambient air, the water, the ground and the sky. Effective dissipation of the excess heat depends on two main pre-conditions: (a) the availability of a proper environmental heat sink with a sufficient temperature difference for the transfer of heat and (b) the efficient thermal coupling between the building and the sink (Santamouris & Kolokotsa, 2013). There are four-well studied and developed techniques for heat dissipation: evaporative cooling, ground cooling, radiative cooling and natural ventilation cooling.

Evaporative cooling

Evaporative cooling is a process that uses the effect of evaporation as a natural heat sink. Sensible heat from the air is absorbed to be used as latent heat necessary to evaporate water. The amount of sensible heat absorbed depends on the amount of water that can be evaporated (Geetha & Velraj, 2012). There are two basic types of evaporative air cooling techniques (Santamouris & Kolokotsa, 2013): (a) the direct evaporative coolers commonly used for residential buildings. In this type of evaporative cooling the reduction of the temperature is followed by an increase in moisture content. Direct evaporative cooling is generally performed using a fan to draw hot outside air into the building by passing it over an evaporative pad. It is quite simple and cheap and is commonly used for residential applications. (b) the indirect systems where the evaporative cooling is delivered across a heat exchanger, which keeps the cool moist air separated from the room. This system does not cause an increase in air humidity. Indirect evaporative cooling usually incorporates an air to air heat exchanger to remove heat from the air without adding moisture. It is suitable for humid climate regions.

Ground cooling

It has long been known that the ground temperature changes more slowly than the temperature of the ambient air. The deeper one goes into the ground, the more the ambient temperature is attenuated, and at a certain depth the ground remains at an almost steady temperature level which is slightly higher than the yearly mean ambient air temperature (Santamouris, 2007). As a result, the ground can be used as a heat sink during the summer. Its cooling potential can be utilized directly when the building envelope is in contact with the ground (semi-buried buildings in hot summers), through horizontal earth-to-air heat exchangers or water-driven heat exchangers (Santamouris & Kolokotsa, 2013). The most common technique of ground cooling is the use of underground air tunnels, known as earth to air heat exchangers. Earth to air heat exchangers consist of pipes which are buried in the soil while an air circulation system forces the air through the pipes and eventually mixes it with the indoor air of the building or the agricultural greenhouse (Santamouris & Kolokotsa, 2013).

Radiative cooling

Radiative cooling is based on heat loss by long-wave radiation emission from one body towards another body of a lower temperature, which plays the role of heat sink. In the case of buildings, the cooled body is the building and the heat sink is the sky, since the sky temperature is lower than the temperatures of most of the objects on earth (Geetha & Velraj, 2012). Radiant cooling requires the roofs of building using heavy and highly conductive material (e.g. concrete) and insulation material. During the day, the external insulation on the roof minimizes the heat gain from solar radiation. The cooled roof mass can then act as a heat sink, and absorb, through the ceiling, the heat penetrating into and generated inside the building during the day-time hours (Pacheco, Ordonez, & Martinez, 2012).

Natural ventilation

Natural ventilation is achieved by infiltration (the term “infiltration” is used to describe the random flow of outdoor air through leakage paths in the building’s envelope) and or allowing air to flow in and out of a building by opening windows and doors (Santamouris & Asimakopoulos, 1996). In the process of passive cooling by natural ventilation, windows and doors, the large openings, are the main air flow paths as a result of the pressure differences due to wind and stack effect. There are basic functions of natural ventilation: maintain an acceptable indoor air quality and provide indoor thermal comfort. Provide indoor thermal comfort in buildings through natural ventilation is one important passive cooling strategy. For this objective, Givoni (1994) classified two types of natural ventilation: comfort ventilation and night ventilation. Comfort ventilation provides direct human comfort, mainly during the day. Night ventilation cools the structural mass of the building interior by ventilation during the night and closes the building during daytime, thus, lowering the indoor temperature during the day. The efficiency of night ventilation technique is mainly based on the relative difference between the outdoor and indoor temperatures during the night period. Various studies prove night ventilation effectiveness. Givoni (1998) carried out comprehensive experimental studies on night ventilation techniques in Israel and Pala, California. Based on the results in California, he argued that, if effective night ventilation can be ensured by the provision of exhaust fans, high mass buildings can be more comfortable, especially during the daytime hours than lightweight buildings, even in hot-humid regions. Kolokotroni and Aronis (1999) introduce some variables for the building such as building mass, glazing ratio, solar and internal gains, orientation and demonstrate that the optimization of the building design for night ventilation according to these parameters can cause an abatement of about 20-25% of the air conditioning energy consumption. Santamouris, Sfakianaki, and Pavlou (2010) pointed out that the application of night ventilation techniques to residential buildings may lead to a decrease of cooling loads almost 40 $kWh/m^2/y$ with an average contribution of 12 $kWh/m^2/y$. A comprehensive review of night ventilation strategies is presented in (Santamouris & Kolokotsa, 2013). However, there are still some limitations of night ventilation. Such as the moisture and condensation control, particularly in humid areas. The most important limitation of night ventilation techniques is associated with the specific climatic conditions of cities. Increased temperatures due to the heat island effect, as well as the decrease in wind speed in urban canyons, considerably reduces the cooling potential of night cooling techniques (Santamouris, 2007).

1 Wind driven cross ventilation

Wind driven cross ventilation caused by the wind-induced pressure differences. Positive pressure is created on the building sides that face the wind whereas suction regions are formed on the opposite sides and on the sidewalls. This results in a negative pressure inside the building, which is sufficient to introduce large flows through the building openings.

It should be noted, orientation is very important for cross natural ventilation. Appropriate orientation can obtain enough wind velocity and wind rate to achieve the successful comfortable ventilation and night ventilation. Orientation for ventilation does not imply that the building should be perpendicular to the prevailing wind direction. Givoni (1994) mentioned that oblique winds at angles between 30 and 120 degrees to the wall can provide effective cross ventilation if openings are provided in the windward and leeward walls (Assuming the building lies in the wide location without influence by other buildings). However, when the best building orientation for sunlight control is in conflict with the best orientation for natural ventilation, which is the primary factor? It is different in arid or humid regions. In hot and dry climates, shading is of great or importance than ventilation; in hot and humid climates, on the other hand, emphasis is given to cross ventilation as the high humidity of the air creates discomfort for human beings (Santamouris & Asimakopoulos, 1996).

2 Buoyancy driven stack ventilation

Buoyancy driven stack ventilation caused by the stack effect occurs when temperature differences between a zone and the environment adjacent to it, be it another zone or the exterior, cause light warm air to rise and flow out of the warm zone, while cooler air flows in. Buoyancy-driven stack ventilation relies on density differences to draw cool, outdoor air in at low ventilation openings and exhausts.

3.2.4 Conclusion

Passive cooling techniques are significant to save energy for cooling buildings. These techniques, which have been neglected for a period, are getting more and more attention by researchers and designers in the context of sustainable design for energy conservation and reduction of emission of greenhouse gases. However, it should be noted that choosing a suitable passive cooling strategy for a particular project is important in order to save energy and provide a comfortable environment. The suitable strategy is decided by the climate condition, urban environment, building type and style, material use and operation of the building. Additionally, the application of passive cooling strategies is strongly related to architectural design especially in the early design stages. The spatial design of urban morphology, building form and component can strongly influence the application. This will be discussed in the next section.

3.3 Passive cooling strategies related to urban spatial design

3.3.1 Urban morphology

In the field of urban planning and design, the study of urban morphology involves scrutiny and analysis of the urban fabric, and understanding and explanation of urban change in a wider sense. In its narrowest sense, urban morphology focuses on the study of the urban fabric of buildings, plots and street patterns (Marshall & Çalişkan, 2011). It refers to the organization of a group of buildings and the spaces between them in 3 dimensions. Urban planning focuses on the entire city, while, urban morphology focuses on the small scale of a city district. In a particular urban morphology, the position of neighbouring units and building form directly influence the accessibility to solar radiation from both the indoor and outdoor environment (Hachem, Athienitis, & Fazio, 2011; Kleerekoper, van Esch, & Salcedo, 2012; Taleghani, Tenpierik, van den Dobbelsteen, & de Dear, 2013). Orientation and neighbourhood patterns not only affect solar access but also airflow patterns and wind speed. Furthermore, the placements of buildings within the site and land use patterns strongly influence the outdoor air and radiant temperature of the microclimate created by city blocks (Taleghani et al., 2013). On the large scale, such as the city scale, it is hard to analyse the influence because of the enormous amount and complexity of the city buildings. But for the small scale such as the neighbourhood scale, through the development of computational simulations, it can be analysed and a lot of research has been done. Sanaieian, Tenpierik, Linden, Mehdizadeh Seraj, and Mofidi Shemrani (2014) reviewed the impact of urban block form on thermal performance, solar access and ventilation. Urban morphology relates to building block form, space between the building blocks and the arrangement of the two. The core problem is the arrangement. By the literature, most of the research of urban morphology which is related to outdoor thermal comfort and environment focuses on two aspects: street canyon and building group pattern (figure 3.2)

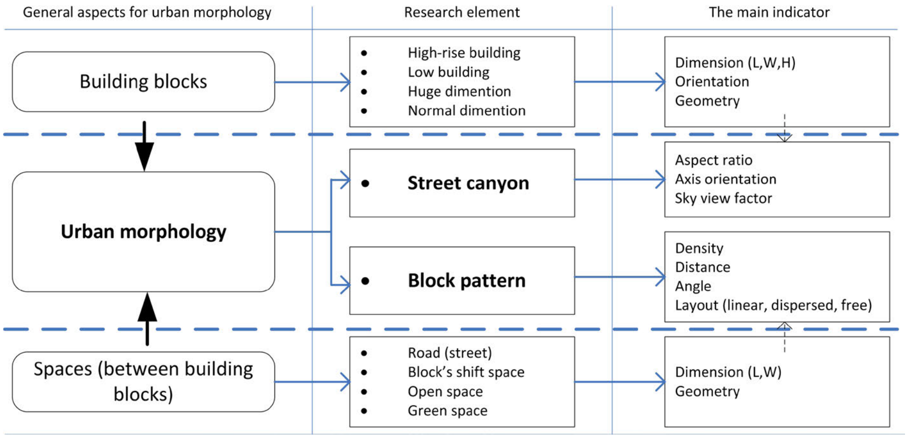

FIG. 3.2 Urban morphology related studies for outdoor thermal comfort and environment

Urban morphology to urban wind environment

The wind environment refers to the natural wind characteristics around buildings. The main indices to access the wind environment are the wind velocity, the wind direction, the wind pressure on the building (average pressure and pressure difference) and the wind field (the wind distribution in the vertical and horizontal direction which can be described by contours of air velocity magnitudes). The wind environment can be highly affected by building blocks especially in the urban region due to the variety of enormous building blocks. The main targets of the wind environment analysis are: outdoor comfort (such as the street, public space) and basic data for indoor comfort analysis.

In general, the higher the density of buildings in a given area, the poorer its ventilation conditions (Santamouris & Asimakopoulos, 1996). Kubota, Miura, Tominaga, and Mochida (2008) used a wind tunnel to test the relationship between building density and pedestrian-level wind velocity of several major Japanese cities. These results show that there is a strong relationship between the gross building coverage ratio and the mean wind velocity ratio. His wind environment evaluation for case study areas is performed using wind tunnel results. He proposed a method of guidelines for realizing an acceptable wind environment in residential neighbourhoods using the gross building coverage ratio (Kubota et al., 2008).

Urban or street canyon can influence the wind environment especially the wind velocity. Al-Sallal, Al-Rais, and Dalmouk (2013) simulated three cases in Al-Mankhool, Dubai, and concluded that in the modern urban pattern, the wind flow decreased when hitting the buildings, funnelled by the wider street canyons, then increased once again when the air flow is free stream. Wind velocities were more comfortable in wider street canyons. It was noticed that the wind speed increased substantially in open spaces such as parking areas and undeveloped plots. Fahmy and Sharples (2009) analysed urban canyons in a grid network, with three mid latitude orientations in Cairo. They found that although some very hot conditions were recorded, there were evident examples of more acceptable comfort levels and cooling potential for some orientations and degrees of urban compactness due to the clustered form with green cool islands and wind flow through the main canyons.

Building block patterns in the urban scale is also important for the urban wind environment. Zhang, Gao, and Zhang (2005) combined computational and experimental method to study the wind field around three different building block patterns. It was found that the wind environment for two improved arrangements with lower interval-height ratio is better than that for the reference layout with higher aspect ratios in terms of natural ventilation. The interference effect is more obvious for two improved arrangements than the reference one. The numerical results also show that changing the wind direction from perpendicular to the building facades to a 45 incidence angle has significant effect on the flow field for different configurations. Asfour (2010) used the CFD method to investigate the effect of the building grouping pattern on the resulting wind environment in the outdoor spaces and the resulting ventilation potential of these buildings. Several configurations of housing blocks exposed to different wind directions have been modelled and compared considering the hot climate of Gaza. It has been found that grouping pattern of buildings as well as their orientation with respect to wind has a dramatic effect on the resulting airflow behaviour and pressure fields. Configurations that contain a central space articulated by buildings and oriented towards the prevailing wind can offer better exposure to air currents and better containment of wind. Such configurations are recommended for better wind-driven ventilation, where the main design objective is passive cooling.

Urban morphology to solar control

The building blocks and neighbourhood morphology have the largest effect on the access of solar energy. A suitable design of the neighbourhood morphology can avoid the overheating of buildings. The major factors which affect solar access of buildings under a particular neighbourhood morphology are: urban density, orientation of building's façade and building outline and streets (ratio of building height to the street widths) (Sanaieian, Tenpierik, Linden, Mehdizadeh Seraj, & Mofidi Shemrani, 2014).

High-density urban neighbourhoods can minimize the building's solar exposure and provide outdoor shaded areas to avoid extra solar radiation through narrow streets and lanes. Many vernacular small towns proved that a narrow street is able to avoid the peak solar radiation in summer, especially in hot dry climate regions. Ali-Toudert et al. (2005) investigated the thermal environment of the old desert city of Beni-Isguen, Algeria. The results show that the vertical street profile is of prime importance in the resulting thermal sensation. Deep streets together with high thermal capacity materials mitigate the heat stress during the day. The high and heavy walls provide more shading and more heat storage, leading to lower surfaces temperatures. Andreou (2014) analysed the effect of parameters such as urban layout, street geometry and orientation on solar access and shading conditions in the Mediterranean, which strongly affect urban canyon microclimate through simulation and experimental measurements. It is demonstrated that the morphology of traditional settlements in the area examined, performs most positively and thus it can be claimed that lessons can be learned from vernacular architecture.

Niachou, Livada, and Santamouris (2008) conducted a study that focused on the experimental investigation of thermal characteristics of a typical street canyon, under hot weather conditions. The results indicate that the air temperature distribution inside a street canyon is a function of canyon geometry and orientation, as well as of the optical and thermal properties of building and street materials and ambient weather conditions. Giannopoulou, Santamouris, Livada, Georgakis, and Caouris (2010) investigated the impact of canyon geometry on the temperature regime and nocturnal heat island development in the very dense urban area of Athens, Greece. A clear increase of the median, maximum and minimum values of the cooling rates has been observed for decreasing aspect ratios.

In Chinese traditional small towns, the streets usually are narrow and surrounded with high walls. This avoids direct solar radiation to reach the bottom of the wall and keeps the air temperature of the street in a low level. Some researchers think that is the cool source for natural ventilation. Lin et al. (2002) have done long-term field measurements of the indoor and outdoor thermal environment in several typical Chinese Wannan traditional residential buildings in the summer. The results show that the “cool entry way” (very narrow alley between the buildings) provides enough shading to avoid the solar radiation. Chen and Zhong (2011) carried out a field study of thermal comfort on narrow alleys of three residential buildings and found that the main strategies of passive cooling can be concluded as narrow alley sunshade and ventilation, the ground and wall of the alley as heat sink and night ventilation. Furthermore, to verify the cooling effect of cooling alley in traditional settlement, Chen, Zheng, and Fu (2013) measured some cooling alleys in Quanzhou Shoujin Liao, Wannan Hongcun and Xitang Shuixiang. The results show that a cooling alley in tradition folk houses has an obvious effect on cooling, on the thermal buffer and acclimation by the way of self-sun shading, thermal storage of ground and wall as well as night ventilation. Gou et al. (2015) did a qualitative analysis of ancient dwellings located in the village of Xinye, in the hot summer and cold winter region of China, and one of the findings is that the streets form a narrow urban canyon offering mutual shading to the dwelling during sunny hours and create a comfortable thermal environment in hot summer.

3.3.2 Urban microclimate

Because of the urban morphology strongly influences the wind and solar environment of the urban space, the particular urban microclimate is largely decided by the urban morphology which is significant for passive cooling of buildings and outdoor thermal comfort. The urban microclimate is defined as a small-scale climate pattern within a particular region that the deviations in the climate are experienced from place to place within a few kilometres distance. The microclimate is affected by the following parameters: topography, soil structure, ground cover and urban forms (Santamouris & Asimakopoulos, 1996). The principal elements that characterize climate and weather are the air temperature, the solar radiation, the amount of moisture and wind. The definition of microclimate indicates that the microclimate is different in rural regions and human designed urban regions, which deeply influence the local microclimate. Generally, the influence of human urban design is characterized by higher ambient temperatures (the heat island effect), reduced relative humidity, reduced wind speed and reduced received direct solar radiation (Geetha & Velraj, 2012). Therefore, in an urban region, changing the urban morphology can change the microclimate and thus change the thermal environment of buildings. The general influence of urban morphology on urban microclimate is characterized by Givoni (1989):

- High ambient temperatures even during evening hours
- Reduced relative humidity, due to high air temperature and lack of sources of humidity
- Disturbed wind patterns with a reduction of air speeds which contribute to an increase in air pollution
- Reduction of the received direct solar radiation and increase of diffused radiation, owing to pollution particles in the atmosphere

Consequently, design strategies for improvement of the microclimate to obtain thermal comfort conditions during summer should focus on (Santamouris & Asimakopoulos, 1996):

- Solar protection of buildings and pedestrians
- Reduction of outdoor air temperature
- Wind enhancement, for both pedestrians and the ventilation of buildings
- Improvement of humidity levels
- Design initiatives should aim to:
- Provide protected spaces for outdoor activities which both improve outdoor comfort conditions and promote indoor comfort (thermal comfort indoor and outdoor)
- Contribute to reduction of the cooling load and to a lesser dependence of buildings on air conditioning (energy conservation)

3.3.3 Urban morphology and space syntax

As mentioned above, urban morphology concerns the urban fabric, the urban form and the urban structure which is formed by the building blocks and the spaces between them. To analyse and understand the urban structure, the street network, and further finding the patterns of the city and the social meaning, some qualitative and quantitative methods are invented. Marshall (2005) developed the classification system for street morphologies analysis, and Berghauser Pont and Haupt (2009; 2010) developed the integrated density approach. Space syntax is one of the important theories and methods which was first proposed by Hillier (1999). Space syntax theory considers the city or architecture as a spatial system, thus the analysis turned attention away from the geometrical notions of spatial features, as described in figure 3.2, in the study of city or architecture, emphasising instead the topological relationship between the spaces. A set of techniques were proposed to analyse the spatial structure or the configuration of the city or architecture to foresee their functional outcomes, especially the human activities and their social meaning.

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 node (Hillier, Hanson, & Graham, 1987). Figure 3.3 shows a typical example to explain the logical relations between spaces in space syntax. In the first column, there are three layouts of buildings. They have the same shape and the same number of rooms. The only differences are the openings between the rooms. The corresponding pictures in the second column show the spaces as black colour as the focuses in space syntax. The third column shows the "justified graph" of the three layouts in terms of the topological relationships of the spatial configuration. As we can see, from the outside space (the root), layout (a) has a "deep tree" form; layout (b) has a "narrow tree" form; and layout (c) has a "ring" form. The spatial configuration of the three layouts is totally different even they have the same shape and numbers of rooms. Figure 3.4 shows another example of using "justified graph" to analyse the spatial structure. There is a layout with ten rooms. If we chose the different internal space as the root space in terms of room 1, 10, and 5, there is a large difference in the "justified graph". That means the topological relationship of the layout is different when the graph is justified from a different space.

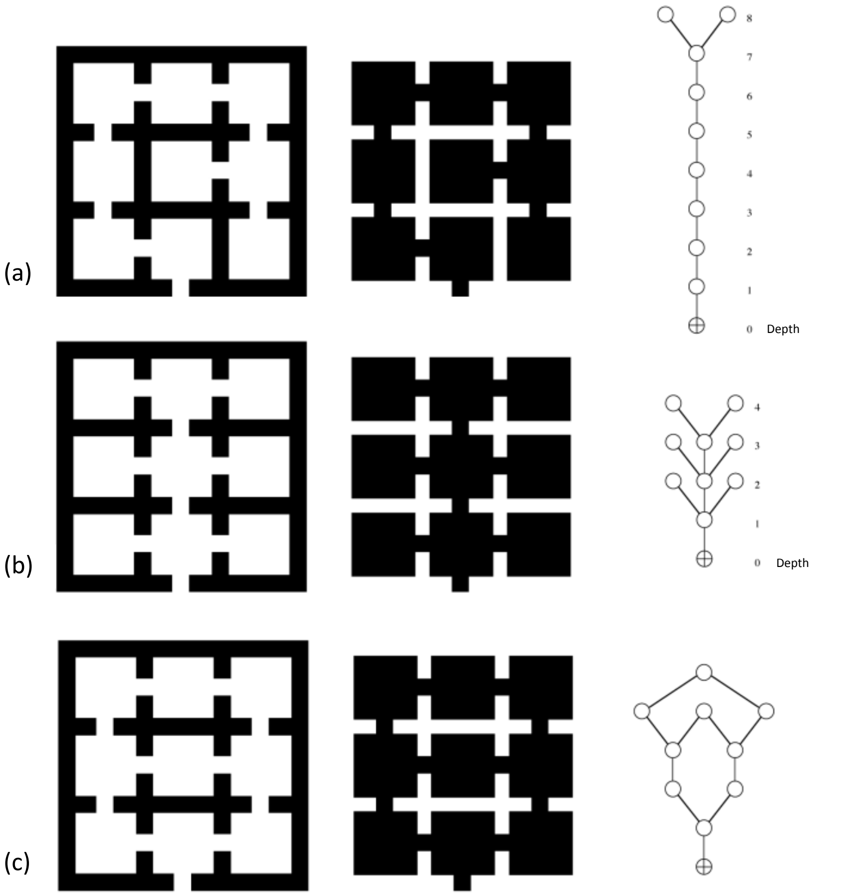

FIG. 3.3 A typical example to explain the logical relations between spaces in space syntax (Hillier, 1996)

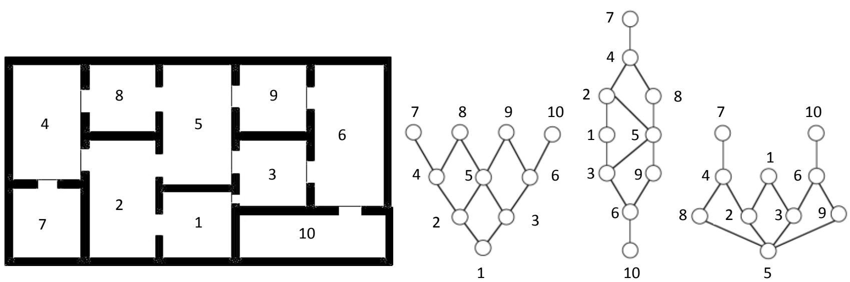

FIG. 3.4 The different “justified graph” from different root within a same layout (Hillier, 1996)

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From a justified graph, four major indices can be determined to evaluate the spatial configuration properties in terms of permeability or accessibility.

1 Connectivity value: the total number of nodes which connected to one chose node. The bigger the node's connectivity value, the better the permeability of the space in which the node is.

2 Control value: the control values are found by assigning each node's connection a value of 1. The control value of node "n" is the total connections received by node "n" during this operation. A bigger control value of a node means this node can control or influence more adjacent nodes.

3 Depth value: if it is 1 depth from one node to adjacent node (it is directly accessible to it), the shortest distances (minimum depth) from one node to another node is the depth of the two nodes. The total depth (TD) of node "n" is the total of the shortest distances from node "n" to all other nodes in the systems. The mean depth MD for a node "n" is the average depth from node "n" to all other nodes. If "k" is the total number of nodes in the spatial system, then MD=TD/(K-1).

4 Integration value: it is related to the "Relative asymmetry". The relative asymmetry (RA) describes the integration of a node with the value between 0 and 1. A low value describes a high integration. RA is calculated by the formula RA=2(MD-1)/(K-2). The integration value is 1/RA. The integration value is the most important index because some researchers indicate that it is closely related to human spatial behaviour. If a node's integration value is larger, the permeability and accessibility of this node is better.

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.

Based on the major parameters mentioned above, several computer programs have been development to implement these approaches to calculate the basic parameters and show them visually. The DepthmapX-one graph-based representations and measures program (Turner, 2001) is one of the most important platforms for space syntax analysis. Convex and axial analysis, isovist and VGA analysis, as well as segment analysis are the methods involved in this program (Al_Sayed, Turner, Hillier, Iida, & Penn, 2014). The axial and segment analysis are more suitable for the analysis at the urban scale. The convex analysis is suitable for the building scale and isovist and VGA analysis are suitable for both urban and building scale.

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 urban and architectural design to investigate the relationship between spatial features and underlying social behaviour, for example movement patterns, street network study, 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. The space syntax method provides the possibility for urban planners and architects to explore their ideas, to understand the possible effects of their design and to show how their designs work (Dursun, 2007).

3.4 Passive cooling strategies related building spatial design

The appropriate architecture form has significant potential for passive cooling of buildings via solar control and natural ventilation. The strategies of controlling building form and shape for passive cooling have been proved effective by the architectural practices of vernacular tradition buildings and contemporary buildings. Due to the close relationship with architectural innovation, it is the real strategy that architects can and should adopt in the early design stages. In the next sections, the building shape, building layout, building opening and building element are reviewed on passive cooling.

3.4.1 Building shape

The shape of a building influences the amount of solar energy that enters the building as well as the total energy consumption of the building (Tang, 2002). The optimal shape of a building is widely considered to be the one that loses the least heat in winter and gains the least amount of solar irradiation in summer. The building volume is approximately related to the thermal capacity, the ability to store heat. The exposed surface area is related to the rate at which the building gains or loses heat (Santamouris & Asimakopoulos, 1996).

The main variables related to building shape, which influence heating and cooling loads, are building form, compactness index and the shape factor. The compactness index is the ratio between the volume and the outer surface of the building facade. It is related to the building's capacity to store heat and avoid heat loss through its facade. A very compact building is one that has a high volume to surface ratio, where the surface exposed to possible heat losses or gains is as small as possible. The shape factor is the ratio of building length to building depth. Along with orientation, this factor defines the percentage of the facade exposed at each cardinal point (Pacheco et al., 2012).

In cold climate regions, high form compactness is preferable since it can reduce the heat loss in cold winter. In hot and warm climate regions, the situation is more complex. In hot arid climates, the building should be compact-the surface area of its external envelope should be as small as possible to minimize the heat flow into the building (Givoni, 1994). In a hot humid climate, ventilation is the most effective way to minimize the physiological effect of the high humidity. A spread-out building allows better natural cross-ventilation than a compact one by providing more wall area, and in more directions, for catching the winds. Buildings should maximize the area of the exposed surfaces in a hot humid climate (for free-running buildings without air conditioning). Evans (1980) presented a summary of requirements for conditions of optimal heat gain and heat loss for the case of a simple rectangular building form in different climates. Generally, for free-running building, volume-to-surface ratio is very important for the heating energy consumption in winter than cooling energy consumption in summer.

It is argued that restriction of the optimal shape could be relaxed by adopting several energy saving measures, for example extra insulation, allowing in this way architectural freedom in the choice of the building's form. Building's summer thermal performance could be improved by giving more importance to the materials used and to the architectural elements such as shading devices, wind walls and courtyards. To thermal characteristics, forms should be explored which enhance wind channelling into the building and permit ventilation throughout the occupied spaces (Santamouris & Asimakopoulos, 1996). Some researchers studied the relationship between building shape and thermal performance and energy efficiency (AlAnzi, Seo, & Krarti, 2009; Depecker, Menezo, Virgone, & Lepers, 2001; Liu, Lin, & Peng, 2015; Wang, Rivard, & Zmeureanu, 2006; Yi & Malkawi, 2009). Their objectives were to find the optimal building shape for energy efficient building design.

3.4.2 Building layout

The indoor space or layout determines the ventilation conditions. An open plan combined with a proper distribution of openings is preferable for undisturbed ventilation in the interior. As practical needs require separation of spaces, restriction of air-flow paths should be avoided and the positioning of partitions should help channelling the air through the occupied space (Santamouris & Asimakopoulos, 1996). In literature, the studies that focus on the building layout for cross ventilation is rare.

3.4.3 Building opening

A window is a very important component in the building envelope, providing enough sunlight, solar heating in winter, ventilation and visual contact with the outside. For sunlight, the window-to-floor ratio is the main index to consider in design. For solar gain and heat loss in winter, the window-to-wall ratio (the percentage of glazing area to the wall area of a building façade) is the most important index to evaluate suitable window size (obviously, material of glass and window frame are also important factors, but this is another issue). For visual needs, modern building prefers a window as large as possible as we see from the large amount of glass that is used in the façades of modern buildings. For passive cooling, ventilation and solar protection are the main issues of window.

In hot and humid regions, openings play a major role in determining the thermal comfort of the occupants as the location and size of the window determine the ventilation conditions of the building. In this respect, large openings in all walls can provide the design solution for effective cross ventilation. However, solar radiation can penetrate directly through un-shaded openings into the interior of the building and elevate the indoor temperature above the outdoor level. Therefore, utmost care should be taken in ensuring that all openings in the envelope of the building are effectively shaded (Givoni, 1994). In this case, window size, location and shape are the main factor to the efficiency of ventilation. Some research has focused on the optimization of window size for cross natural ventilation (Almeida, Maldonado, Santamouris, & Guarracino, 2005; Visagavel & Srinivasan, 2009; Yin, Zhang, Yang, & Wang, 2010). Another important issue is the summer thermal comfort and occupants' behaviour related to windows (Fabi, Andersen, Corgnati, & Olesen, 2012; Fabi, Andersen, Corgnati, & Olesen, 2013; Jeong, Jeong, & Park, 2016; Liu et al., 2012; Liu et al., 2012).

3.4.4 Building “elements”

Courtyard or patio

A courtyard is an old building element used in the vernacular traditional buildings around the world, especially in Asia, North Africa, South America, the Middle East and South Europe and which is still present in contemporary buildings. These significant outside spaces which are partly or completely surrounded by buildings or walls and are always combined with the landscape contribute to the architectural aesthetics and the building performance. The primary function of a courtyard is to provide light and ventilation for relatively large buildings which have a large depth and width. Traditionally, courtyards are used in both residential and public buildings. But now, as more families living in the apartments and small houses, courtyards are used more in public buildings. A courtyard can influence the building energy consumption and thermal comfort in two ways. Firstly, a courtyard provides sufficient shadow in summer, thus avoiding solar radiation and reducing the cooling loads. Secondly, a courtyard improves the natural ventilation and provides comfort ventilation and nocturnal ventilation. For low buildings with a courtyard, cross ventilation is the main type of natural ventilation and for high buildings, stack ventilation can also have a contribution. Plants and water (such as a ponds) in the courtyard also play a very important role in passive cooling.

A lot of research have investigated the orientation, geometry and use of vegetation and water of courtyard for thermal comfort and energy efficient which can be categorized into ventilation performance (Rajapaksha, Nagai, & Okumiya, 2003; Sharples & Bensalem, 2001) and solar performance (Aldawoud, 2008; Ghaffarianhoseini, Berardi, & Ghaffarianhoseini, 2015; Muhaisen, 2006; Muhaisen & Gadi, 2005, 2006; Safarzadeh & Bahadori, 2005; Soflaei, Shokouhian, Abraveshdar, & Alipour, 2017; Taleghani, Tenpierik, & van den Dobbelsteen, 2014a; Taleghani, Tenpierik, van den Dobbelsteen, & Sailor, 2014; Yang, Li, & Yang, 2012) in hot arid climate and hot humid climate through experiment or numerical analysis.

Atrium

An atrium is a relatively large space, usually with a glass roof, in the centre of a building. Its function in lighting and ventilation is similar to a courtyard, but unlike the courtyard, it is an indoor space. The glass roof of an atrium can lead to a high indoor temperature difference and enhances the stack ventilation in the building. Because of its huge volume, atria are usually applied in public buildings. A good atrium design will specifically bring natural lighting into the interior spaces of the building and therefore minimize the dependence on artificial lighting and reduce the energy demand for space conditioning.

Aldawoud (2013) put forward a study where the thermal performance of various shapes and geometries of atriums in buildings is examined under various conditions. The goal was to assess the impact of the atrium shape on the building total energy consumption and to identify the most energy-efficient atrium design. The results of this study indicate that in general, the total energy consumption of the narrow, elongated atrium or the rectangular atrium with high ratio of length to width is significantly greater than the square shaped atrium.

Transitional space (semi outdoor space, buffer zone)

The semi-outdoor space, which is also called transitional space or buffer space, is a space featuring a semi-enclosed wall or roof. It can connect the indoor spaces and outdoor spaces flexibly. The terrace, balcony, veranda and outside corridor are the main transitional spaces. For passive cooling purposes, the transitional space is generally regarded as one shading component for solar controlling of building. Therefore, the solar control function of semi-outdoor space was discussed in the shading part. The semi-outdoor space is also an important space for occupants' activities in the hot and humid climate regions in summer. In this space, occupants can enjoy more comfortable ventilation by catching the winds in various directions. And the thermal sensation is much better than in the compact indoor environment. The presence of transitional spaces provides the occupants with more choice in spaces with different thermal environments

3.4.5 Conclusion

Summarizing the passive cooling strategies related to building spatial design, some conclusions can be obtained:

1. Solar control and natural ventilation are the main passive cooling techniques used in the building spatial design.
2. The microclimate in building scale has not been paid enough attention.
3. Courtyard is broadly studied and building shape is focused in rising, however, translational space and building layout has not been paid enough attention.

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4 Architectural spatial design strategies for summer microclimate control in buildings

a comparative case study of Chinese vernacular and modern houses[2]

ABSTRACT The objective of this paper is to clarify the spatial design strategies used to control the microclimate of a Chinese vernacular house in summer by comparing the building with modern Chinese rural houses and presenting ideas for contemporary architectural design practice. For this goal the spatial configuration, the spatial boundary conditions, the vegetation in the space and the human activity in the space

2 This chapter is the original version which is published as: Du, X., Bokel, R., & van den Dobbelsteen, A. (2016). Architectural Spatial Design Strategies for Summer Microclimate Control in Buildings: A Comparative Case Study of Chinese Vernacular and Modern Houses. Journal of Asian Architecture and Building Engineering, 15(2), 327-334. doi: 10.3130/jaabe.15.327

were analysed for the vernacular house and for modern rural houses. Also, field measurements were conducted to evaluate the summer thermal environment in the vernacular and a modern house. The results show that the vernacular house has a diverse spatial design and a better building microclimate, making it easier to obtain thermal comfort than the modern houses. Therefore, spatial design strategies of Chinese vernacular houses are still of great value to modern house design, especially when the free-running thermal comfort theory is applied.

KEYWORDS spatial design strategies; building microclimate; Chinese vernacular house; adaptive thermal comfort

4.1 Introduction

It is broadly accepted that buildings worldwide account for 20-45% of the total energy consumption, and this number is still rising, especially in developing countries. This has caused designers to examine contemporary architectural design strategies and to reconsider and re-evaluate the passive design strategies used in vernacular buildings. The term vernacular architecture is used for architectural design that uses locally available resources to address local needs. Vernacular architecture has evolved over a long period of time in one location to suit the local climate, culture, economy and historical context of that period (Oliver, 1997). People have traditional lifestyles in vernacular buildings in virtually every climate in the world, from the arctic to the tropics, in temperatures from below zero to over 40 °C, and historically without the benefit of gas or electrically driven mechanized heating and cooling systems (Meir & Roaf, 2003). China, with a vast land area and a long history, has a rich heritage of various types of traditional vernacular houses in different climate regions. The importance of implementing passive design strategies used in Chinese vernacular buildings into modern architectural design can be seen by considering the rising Chinese energy use. China is already the largest energy consuming country in the world. In the year 2007 the Chinese building sector accounted for 23% of the total Chinese energy consumption (Liang, Li, Wu, & Yao, 2007). By the end of 2012, there were 169.9 air-conditioning units per 100 urban households and 28.9 units per 100 rural households in Chongqing (NBSC, 2018). To decrease the energy consumption for buildings, the authors investigated the passive design features for summer thermal comfort in a typical Chinese vernacular house from a new perspective, i.e. in terms of spatial design, to control the building microclimate. The objective of this paper is to clarify the spatial design strategies used to control the microclimate of the Chinese vernacular house in summer. These strategies are then compared with strategies in modern Chinese rural houses. Ideas for contemporary architectural design practice are presented as a result.

4.2 Methodology

The authors of this paper introduce the term building microclimate as "a type of microclimate which involves indoor spaces and spaces surrounding the indoor spaces in a particular building". It is not just the microclimate around the building; it also includes the indoor climate.

Santamouris and Asimakopoulos (1996) defined the microclimate as follows: "within a particular region, deviations in the climate are experienced from place to place within a few kilometres distance, forming a small-scale pattern of climate, called the microclimate". It is a flexible concept whose scale can be the region, city, neighbourhood or building. However, regardless of the scale, the author's literature review showed that previous definitions considered the microclimate to be the microclimate outside the building. This new definition of building microclimate is very useful in relating the thermal comfort in the building to the microclimate in the indoor, semi-indoor and outdoor spaces of the building. Passive design, especially spatial design, can modify the building microclimate (Du, Bokel, & van den Dobbelsteen, 2014). In a particular building microclimate, the spatial configuration and the spatial boundary conditions are the major elements of spatial design. These elements can control the building microclimate by influencing the physical parameters: air temperature, humidity, solar radiation and wind velocity.

General information on vernacular and modern houses is given in section 4.3. Spatial design aspects such as the area, size, height, spatial configuration, spatial boundary conditions, vegetation and occupants' activities of a vernacular house and of five modern rural houses are given in section 4.4. These spatial design aspects were obtained from a field survey and from interviews with the occupants.

In addition, field measurements were performed to evaluate the summer thermal environment in the vernacular house and in one of the investigated modern houses closest to the vernacular house. The measurements were performed in the summer period from 00:00 to 24:00 on August 28th 2012. In the vernacular house, the measured parameters were: air temperature, relative humidity, and wind velocity at key positions. The measurement points are shown in figure 4.1. In the modern house A, air temperature and relative humidity at different floors were measured. The measurement points are shown in figure 4.2. The measurement instruments were temperature loggers and temperature and humidity loggers recording data every five minutes. The accuracy of the temperature measurements is 0.2 °C, and the accuracy of the humidity measurements is 5%. The instruments were located at 1.2 m above the ground in the indoor and outdoor measuring points. The wind velocity was measured using a manual anemometer with a range of 0.1-30 m/s and an accuracy of 5% plus 0.05 m/s. During measurement periods, the vernacular house was free-running, i.e. without cooling and heating, the occupants of the modern house use fans for ventilation and cooling. The weather condition on the measured days was partly cloudy with occasional rain at night which is a typical summer weather condition in the Chongqing area. The measurement results, displayed in hourly averages are shown in section 5. Finally, lessons were learned from the vernacular house and discussed in section 6.

4.3 The studied houses and their local environment

The studied houses are located in the Shuangjiang town of Tonnan County, Chongqing, China. The vernacular house is a typical and traditional Chinese wall-enclosed courtyard house that is well preserved and therefore valuable as a case to study the Chinese traditional architectural design strategies. The symmetrical and axial wall-enclosed courtyard is the typical character of this type of dwelling. The whole building covers an area of 3,500 m^2 and the building area (S) is 1,768 m^2 (excluding gardens, courtyards and patios). Figure 4.1 shows the aerial view, the plan and the sections of the house. The vernacular house layout and spatial design are suitable for the traditional Chinese family that consisted of several subordinate families. Most of the rooms in Chinese courtyard dwellings, except the kitchen and the main hall, have flexible functions i.e. they could be bedroom, reading room or storeroom (Hu, 2008). Therefore, the vernacular house is neither a single building block nor a group of building blocks organized by the courtyards.

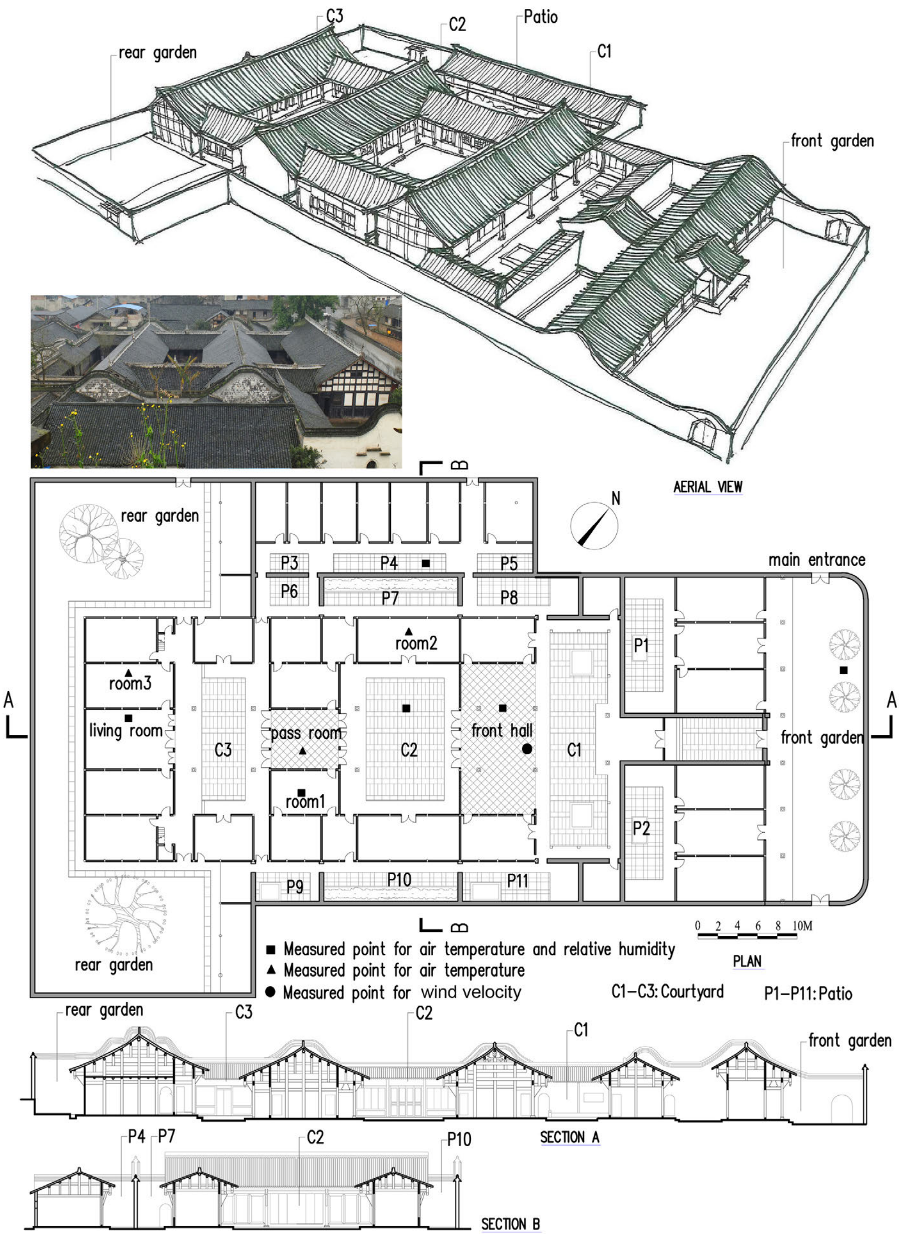

FIG. 4.1 The aerial view, plan and sections of the vernacular house and the measured points

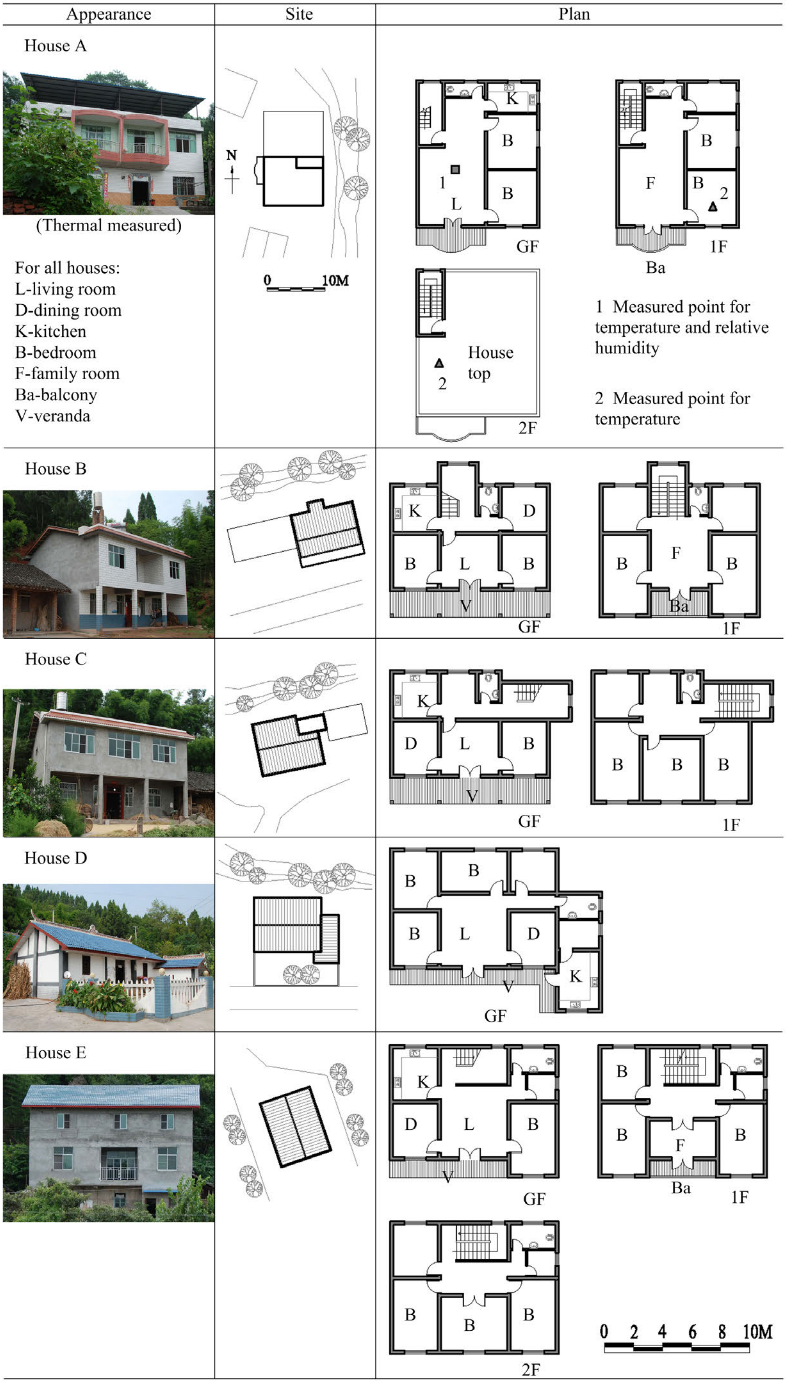

FIG. 4.2 The appearance, site and plan of the five investigated modern rural houses

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Five modern houses near the vernacular house were also investigated. These are typical local rural detached houses built between 2008 and 2011 by the famers themselves. The total area of the houses is 95 m^2 to 270 m^2. The appearance, site and plan of the five houses are shown in figure 4.2. The lifestyle in the rural house is close to a modern lifestyle although the inhabitants have retained some rural traditions. Normally, a family consists of three to six people. The rooms have clear functions with the living room, bedroom, kitchen and toilet as the basic elements. The thermal aspects in one of the houses (house A) were measured. House A is located approximately 480 m from the vernacular house. It is a typical rural two-story newly built residential building. The whole building is oriented east-west, covering an area of approximately 85 m^2, approximately 10 m long from east to west and 8 m wide from south to north.

The studied houses are located in the south-west of China, Chongqing and belong to the hot summer and cold winter climate zone (GB50176-93, 1993). The annual average temperature is 16 to 18 °C, and the annual relative humidity is 70% to 80%. The most extreme high temperature is 41.9 °C and the most extreme cold temperature is -1.7 °C. In summer, the maximum average temperature reaches 28.1 °C in July and the relative humidity is between 75 and 80%, the prevailing wind comes from the northwest and the average wind velocity is 1.6 m/s (National Meteorological Information Center of China Meteorological Administration & Department of Building Technology Tsinghua University, 2005). The summer here is extremely hot, humid and uncomfortable.

4.4 Spatial design of the studied houses

4.4.1 Spatial configuration

Indoor space

In the vernacular house, there are fifty-one rooms varying in size from 15 m^2 to 55 m^2, surrounded by courtyards or patios. The total area of the indoor spaces is 1,123 m^2, which is approximately 63.5% of the total area of the building (S). The rooms that surround courtyard 2 and courtyard 3 are the major rooms (living room, bedroom, dining room etc.) for the homeowner (figure 4.3). Other rooms are service rooms. The height of the rooms without attics or ceilings is 5 m to 7 m and the height of the rooms with attics or ceilings is 3 m to 4 m. In the modern house, six to twelve indoor spaces are present in each of the five objects. The areas of the rooms are 7 m^2 to 25 m^2 and the heights are 2.8 m to 3.3 m (figure 4.2).

Semi-outdoor space

The semi-outdoor space is a type of space with a semi-enclosed wall or roof. It is also called “grey” space or “buffer” space in architectural design. A Semi-outdoor space is an important component in architectural spatial design because it can provide diverse spaces and can flexibly connect the indoor spaces and the outdoor spaces. Two types of semi-outdoor spaces were designed in the vernacular house. One type is the transitional space between the indoor space and the outdoor space. The outside corridor and veranda are examples of the transitional space type. Another type is the semi-enclosed room with large openings. There are two semi-enclosed rooms in the vernacular building: the pass room and the front hall (figure 4.3). The total area of the outside corridor is approximately 484 m^2, 24.7% of the total area of the building (S), and the area of the semi-outdoor rooms is around 161 m^2, 9.1% of the total area of the building (S). The depth of the outside corridor is 1.5 m to 3.0 m. The height of the semi-outdoor spaces is equal to the adjacent indoor spaces.

For the modern house, two types of semi-outdoor spaces were designed. One is an outside veranda, which was set at the entrance; another is a balcony, which was set at the first floor. The depth varied from 1.2 m to 1.8 m (figure 4.2). The total area of the veranda and balcony is between 6%-8% of the total area of the houses.

Outdoor space

Outdoor space here refers to the space around the building, without a roof, that is directly exposed to the natural environment. Courtyards, patios and gardens are the main components. In this article, a courtyard is identified as having a small height to width ratio, and a patio is identified as having a large height to width ratio. Garden refers to a large green area space not completely surrounded by rooms. In this vernacular house an abundance of courtyards and patios were designed to provide natural light and ventilation for the numerous rooms. There are three main courtyards, eleven patios, one front garden and one rear garden in the house (figure 4.3). The three main courtyards are located in the centre and on the axis of the building. The total area of the outdoor spaces is 1,732 m², which is 49% of the total covered area of the building. The size, area, height and aspect ratio of all of the courtyards and patios are listed in table 4.1. The three courtyards are surrounded by the outside verandas and the patios are surrounded by verandas and enclosed walls. There are no courtyards or patios in the modern houses.

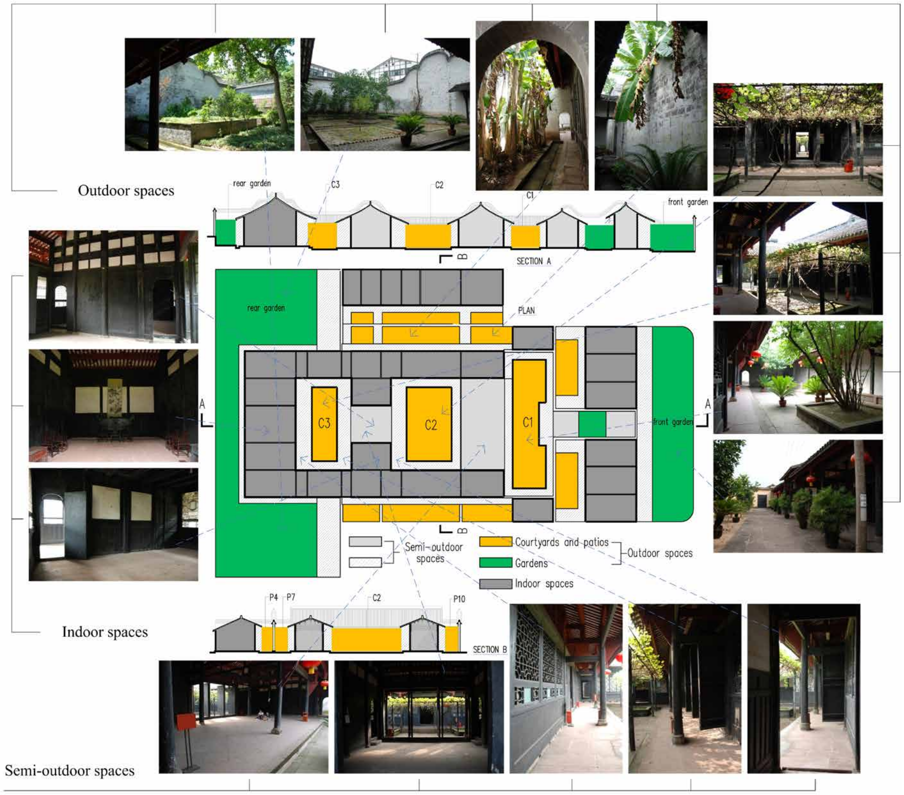

FIG. 4.3 The spatial configuration of the vernacular house

TABLE 4.1 Size of the courtyards and patios in the vernacular house

	Courtyards			Patios										
	C1	C2	C3	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11
Width (m)	21.5	12.4	12.4	9.5	9.5	3.9	11.5	5.7	3.9	13.5	7.3	6.4	13.6	8.9
Depth (m)	5.8	7.9	4.4	4	4	2	2	2	2.9	2.9	2.9	2.9	2.9	2.9
Height (m)	5	5	5	6	6	6	6	6	6	6	6	6	6	6
Ratio (H/D)	0.86	0.63	1.24	1.5	1.5	3	3	3	2	2	2	2	2	2
Area (m^2)	125	98	55	38	38	7.8	23	11.4	11.3	39.2	21.2	18.6	39.4	25.8

4.4.2 Spatial boundary conditions

Openings in the spatial boundary

1 Window

The traditional Chinese wood lattice window is used in the vernacular house. Windows are approximately 30 to 40% of the external walls. The traditional window is latticed into small cells by small wooden frames. There are a few cells with glass, other cells are empty but have translucent fabric shading. All of the windows in the modern houses, studied for this paper, had aluminium alloy frames with single glass. The window size in the major rooms is 1.5 m x 1.5 m to 1.8 m x 1.8 m. The modern windows are sliding windows, of which only half the area can be opened.

2 Door

In the vernacular house, the doors are wooden with a solid panel at the bottom. The construction of the upper half of the door is similar to the windows, with lattices. The doors in the external walls are large, especially in the walls of the living room, pass room and front hall, which are located on the axis of the building. The doors can be completely opened.

The doors in the indoor walls of the modern houses are wooden doors without any openings. Their size is 0.9 m x 2 m. The doors in the external walls are made of steel without an opening. Their size is approximately 1.2 m x 2.1 m.

3 Opening

In the external walls of the vernacular house, in addition to windows and doors, there are openings high in the external walls for ventilation. These are always latticed into cells with a wooden frame similar to the style of the windows. Doors and windows are the only openings in the modern houses.

Material use of the spatial boundary elements

Wood, brick, tile and stone are the main materials used in this vernacular house. The structure of the vernacular house is a traditional Chinese timber framework structure with logwood columns and beams. Most of the external and internal walls are constructed with a timber frame. Walls can be constructed using more than one material. The bamboo-mud wall uses woven bamboo as either the structure or the reinforcement of the wall and mud as the filling and finish. Brick was used for the enclosed wall around the building. Sandstone was used for the outside area and on parts of the indoor floor. Some indoor floors were made of wood. Wood is also used as a structural material for the roof. Black tile was used as the top layer of the roof.

In the modern house the main construction material was reinforced concrete and brick. Brick was used for the external and internal walls. Concrete was used for the ground floor and reinforced concrete slabs were used for the roof and floors.

4.4.3 Vegetation in the different spaces

The vernacular house has abundant room for vegetation in the outdoor spaces: front garden, rear garden, courtyards and patios. The vegetation consists of trees, bushes, herbs and climbing plants. Trees are mostly applied in the garden; bushes and climbing plants are applied in the courtyards and herbs are applied in the patios (figure 4.3). There is no vegetation in the modern houses. However, in the rural environment, there are trees and woods at the back of the rural houses as can be seen in figure 4.2.

4.4.4 Human activity in the spaces

The vernacular house is a free-running building, i.e. without any mechanical cooling or heating. Human activity in the building adapts to this situation. The occupants of the vernacular house adjust their activities to the thermal environment present in the house and obtain thermal comfort by moving to a different area and by changing the boundary conditions. In the morning the temperature is low so that occupants can undertake any activity in every space. It shows that in summer the morning is the best time for activities. In the afternoon, as the indoor temperature rises, occupants prefer to open all the doors of the semi-enclosed rooms (pass room and front hall) and remain there. In the evening, after sunset, occupants prefer to stay on the veranda, in the semi-enclosed rooms or in the courtyards. At night, the occupants remain in the indoor space where they open all the windows. During extremely hot days, even at night, the occupants prefer to stay in the semi-enclosed rooms.

The modern houses are free-running for most of the summer period. During extremely hot days, the occupants use mechanical cooling such as a fan. As in the vernacular house, occupants in the modern houses have no preferred room in the morning. In the afternoon, they prefer to stay on the ground floor, as there is no other kind of semi-outdoor space available. In the evening, occupants open the door on the ground floor and stay there or move outside. At night, the occupants go to the first floor or remain on the ground floor.

4.5 Comparison of the thermal environments

Figure 4.4(a) shows the comparison of the measured air temperature in the vernacular house and the modern house. It was found that in the vernacular house, in the living room, room 1, room 2 or room 3, the indoor temperature remained at approximately the same level during the day. In the modern house, the temperature in the bedroom was much higher than in the living room because the living room is on the ground floor and therefore has a better thermal buffer than the bedroom on the first floor. In the vernacular house, there is a remarkable temperature difference in the different types of spaces (indoor space, semi-outdoor space and outdoor space). This difference is not present in the modern house during the day in summer.

At night, the indoor temperature (living room, room 1, room 2 and room 3) in the vernacular house remained at approximately (within 1 °C) the same level as the outdoor temperature (front garden), whereas the indoor temperature (living room-M and bedroom-M) in the modern house was higher (3 to 4 °C for the living room and 4 to 5 °C for the bedroom) than the outdoor temperature (house top-M). This indicates that when the outdoor temperature decreases, the heat in the vernacular house dissipates more easily than in the modern house. The indoor thermal environment in the vernacular house was better than in the modern house at night. This can significantly influence the occupants' sleeping quality. Because an investigation showed that 60 to 90% of local people complained that they were sleepless on summer nights due to the sweltering and sultry weather (Fu, 2002).

During the day, the indoor temperature (living room, room 1, room 2 and room 3) in the vernacular house was higher than the temperature on the ground floor of the modern house (living room-M) as the environmental temperature of the vernacular house was higher than the modern house. Nonetheless, the indoor temperature in the vernacular house (except for room 2) was lower than the temperature on the first floor (bedroom-M) of the modern house with a maximum difference of 1.5 °C. The temperature in the bedroom of the modern house (bedroom-M) remained at a high level throughout the entire day. In the vernacular building, the outdoor temperature (front garden) peaked at 36.5 °C around 14:30, while the indoor temperature (living room) peaked at 31 °C at 16:30. There is an obvious time delay, which is around two hours, between the peak temperatures. This time delay is not present in the modern house. The time delay helps the vernacular building to obtain a better thermal environment during the entire day.

Figure 4.4(b) shows the comparison of the measured relative humidity in the vernacular house and the modern house. Generally, the relative humidity of the measurement points in the vernacular house was lower than in the modern house which can obviously influence the occupants' thermal sensation in the hot and humid climate (Zhang & Yoshino, 2010). The only exception is that the relative humidity in the living room of the vernacular house was approximate 8%-10% higher than in the living room (living room-M) of the modern house during the night.

The measured wind velocity in the vernacular house is shown in figure 4.5. In figure 4.5, it can be seen that there is a continuous airflow in the front hall of the vernacular house during the day. The average wind velocity was 0.74 m/s. The occupants in the vernacular house reported that they can always feel an air flow, while in the modern house, the occupants complained there is not enough wind in summer.

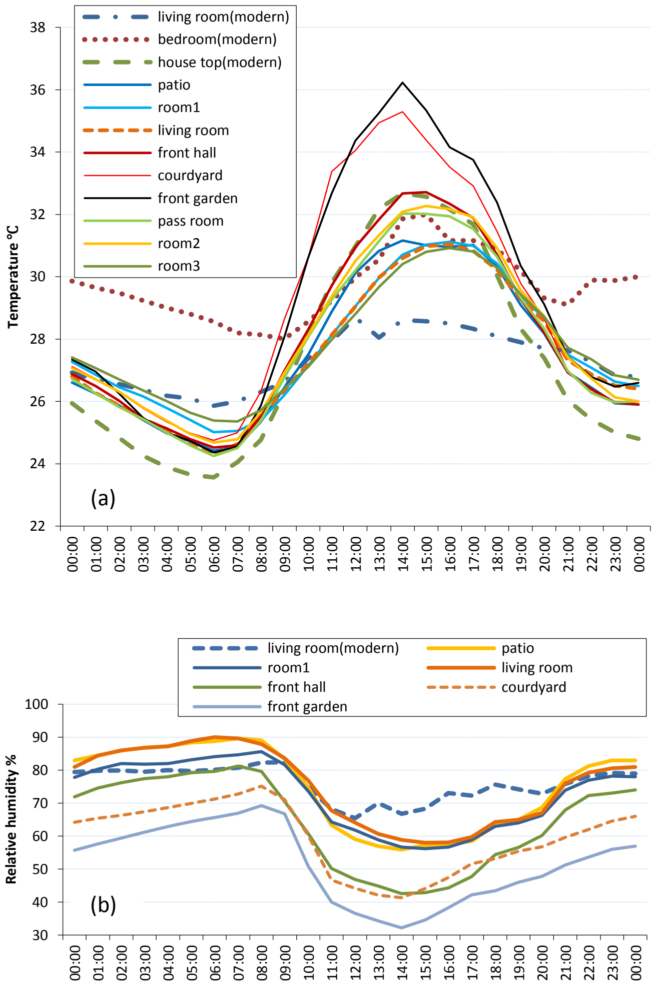

FIG. 4.4 (a) Measured air temperature in the vernacular and modern house (M) (b) Measured relative humidity in the vernacular and modern house. Hourly averages are displayed.

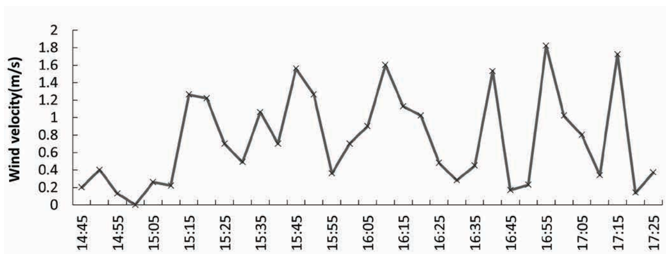

FIG. 4.5 Measured wind velocity in the front hall of the vernacular house

4.6 Strategies learned from the vernacular house

4.6.1 Diverse spaces

The biggest difference in spatial configuration between the vernacular house and the modern house is that the vernacular house is actually a combination of a group of houses, whereas the modern house is a single house. Therefore, the larger diversity in spatial design and spatial configuration of the vernacular house provides a good shading system and more natural ventilation. This potential can modify the building microclimate and adaptive spaces for occupants. As mentioned in section 4.1, in the vernacular building the total area of gardens, courtyards and patios is approximately 49% covered building area, and the area of semi-outdoor spaces is approximately 33.8% of the total area of the vernacular building, which is much larger than the percentage (6%-8%) of the modern houses. The high percentage of these spaces underlines the importance of these spaces for thermal comfort in summer.

Courtyards determine the arrangement of functional rooms, creating a good outdoor environment with vegetation and playing an important role in cross-ventilation and lighting. All the major rooms in the vernacular house are centred by three courtyards. Cross-ventilation is possible as the wind-assisted air can easily flow into the rooms through the one courtyard and flow out through the other courtyard. The wind velocity measured in the front hall proved that the average wind velocity was 0.74 m/s.

The patios are also indispensable for the vernacular house, as they have a major role in natural ventilation and solar control. A patio is clearly an important element in the architectural design because eleven patios were designed for this building. A patio is a tall, narrow and richly vegetated space with a height to depth ratio of 1.5 to 3, and its original purpose is to improve daylight access into the large and deep buildings. Such a narrow and richly vegetated space makes it difficult for the sunlight to reach the bottom of the patio and the adjacent indoor spaces. As a consequence, the measured peak temperature in the patio was 5 °C lower than the outdoor temperature (front garden) (figure 4.4(a)). The temperature difference between the top and bottom of the patio makes stack ventilation possible.

As mentioned in section 4.4.1, two types of semi-outdoor spaces were designed in the vernacular house: the one type being the verandas and the outside corridors and another type the semi-enclosed rooms. The outside verandas surrounding the courtyards and patios are a buffer space between indoor and outdoor spaces. With their great depth, the verandas shade the envelope of the indoor spaces well. Thus, they can create a transitional area with a lower air temperature. Due to their openness, the, occupants in the semi-outdoor spaces can catch the wind from various directions and the thermal sensation of the occupants is therefore much better than in the enclosed indoor environment (Szokolay, 2000). The lower relative humidity in the semi-enclosed spaces also contributes to a more comfortable thermal sensation. Having semi-outdoor spaces provides a wider choice of living spaces for the occupants, so that the occupants can choose their preferred thermal environment in summer.

According to the adaptive thermal comfort theory, “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort” (Humphreys & Nicol, 1998). Moving to a thermally more comfortable location in the house, including the semi-outdoor spaces is one of the possible adaptive reactions of the occupants.

The indoor spaces of the vernacular building are relatively simple, but they have a remarkable characteristic: the sloping roof as the principal form, with a large height. As mentioned in section 4.4.1, the height of the rooms in the vernacular house is much higher than the height of the rooms in the modern house. The rooms in the vernacular house also have a larger volume. In the large space, air can move more easily and remain fresher and occupants will feel more comfortable.

The spatial configuration in the modern house is relatively simple; most of the spaces are single indoor spaces. An independent microclimate cannot be created in the modern building because of its simple spatial design. Thus, the modern house cannot create enough shading to prevent heat gains and cannot obtain enough natural ventilation. Occupants have few choices to move to a different space to adapt to the thermal environment in the modern building due to the limited availability of semi-outdoor spaces.

4.6.2 Adaptive boundary conditions

The total area of openings (window, door and opening) took a large percentage of the envelope of the vernacular house, as mentioned in section 4.4.1. The most important design characteristic of the windows and the openings are that they consist of empty lattices without glass. This ensures that the heat in the indoor spaces can easily dissipate at night. It is one of the reasons why the temperature in the indoor spaces is close to the outdoor temperature at night. In the modern houses, the aluminium window is completely covered with glass and cannot open completely (maximum 50 %). Therefore, the indoor temperature remained at a high level at night.

The large door area in the envelope of the vernacular house, especially in the semi-enclosed rooms (pass room and front hall), can be completely opened. This adaptive design ensures that the doors can be closed in winter to limit the heat loss and can be opened in summer to dissipate heat at night and obtain more cross-ventilation during the day.

4.6.3 Heavy and light materials

Both lightweight and heavyweight materials are used in the vernacular house. As mentioned in section 4.4.2, lightweight material (timber) was used in the main external walls and partitions, with a U-value of around 3.2-3.6 (W/m^2K). In contrast, heavyweight material (sandstone, tile and hollow brick) was used in the floors, roofs, enclosed walls and part of the gable walls, with the U-value of 1.2-1.5 (W/m^2K). A major benefit of using lightweight materials in the walls is that the indoor spaces can be cooled down quickly after sunset, i.e., the indoor heat can dissipate quickly at night. The measured indoor temperature was close to the outdoor temperature at night, which proves the benefit of using lightweight materials. The heavyweight materials can store the heat at night and delay the peak temperature in daytime. The heavy roof has a very good insulating function. In the modern building, brick and concrete slab are used, which is common in this area of China. The insulation of the modern walls and roofs (U-values of 1.5-2.0 W/m^2K) is better than the timber wall used in the vernacular house. However, better insulation is not good for heat dissipation at night. This difference in insulation can explain why at night the indoor temperature was much higher than the outdoor temperature in the modern building. The indoor thermal environment of the modern house at night in summer is therefore not as good as in the vernacular house.

4.6.4 Vegetation

As mentioned in section 4.3, the vernacular house has a lot of vegetation whereas there is hardly any vegetation in the modern house. Various plants are planted in the outdoor spaces, i.e., courtyards, patios and gardens, of the vernacular house. The lush vegetation in the courtyards and patios provide enough shading to prevent direct solar radiation on both the envelope and the floor of the building. The measurements show that the air temperature in the courtyards and patios is lower than the temperature in the outdoor space (front garden). Especially in one of the patios (measured), the temperature was close to the indoor temperature, with a maximum temperature difference with the outdoor temperature (front garden) of 5 °C (figure 4.4(a)). Vegetation seems a very effective strategy in modifying the microclimate of the vernacular building in this study.

Santamouris and Asimakopoulos (1996) also stated that apart from the decorative function of vegetation, the vegetation also modifies the microclimate and the energy use of buildings by lowering the temperature of the air and of the surfaces. Vegetation increases the relative humidity of the air, functioning as shading devices and channelling the wind flow.

4.7 Conclusions

Various passive cooling strategies have been adopted in the vernacular house to cool the space in summer. The spatial design improved the microclimate in the house. An optimum solar control system and a good natural ventilation system have achieved a good building microclimate in the vernacular house. The diversity in spatial configuration also provided different spaces for the occupants from which to choose their preferred thermal environment. The adaptive boundary design (doors and windows) between the spaces makes it possible to transform the spaces easily from an indoor to a semi-outdoor space.

The modern rural houses have a “modern” spatial design which is adapted to “modern” life, and “modern” materials are used in the construction. However, the measurements showed that the modern design does not achieve a satisfactory summer thermal environment for occupants under free-running conditions. The modern house has lost the local bioclimatic technologies, i.e. the low-tech and energy saving measures but, at the same time, high-tech technologies are not utilized to obtain thermal comfort because of the poor financial situation of the rural occupants[3].

This study shows that the spatial design strategies of Chinese vernacular houses are still of great value to modern house design, especially for free-running building design. Obviously, the occupants' life style in the vernacular house and modern houses is different, which influences the architectural spatial design. Design issues such as privacy, safety and finances also influenced the spatial design of the modern house to achieve diverse spaces. However, without using the vernacular spatial design strategies, a good thermal comfort without mechanical cooling cannot be obtained in a modern house.

3 It should be noted that some of designs in the modern rural house have their advantages. For example, the two floors design made the living room in the ground floor of the modern house is cooler than other rooms because the shading and insulation through the first floor.

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5 Building micro-climate and summer thermal comfort in free-running buildings with diverse spaces

a Chinese vernacular house case[4]

ABSTRACT

In this paper, the authors first clarify the definition of building microclimate in free-running buildings and the relationship with summer thermal comfort. Next, field measurements were conducted to investigate the microclimate in a Chinese traditional vernacular house. Subsequently, the results of measurements were compared with a dynamic thermal and a CFD simulation in order to determine the

4 This chapter is the original version which is published as: Du, X., Bokel, R., & van den Dobbelsteen, A. (2014). Building microclimate and summer thermal comfort in free-running buildings with diverse spaces: A Chinese vernacular house case. Building and Environment, 82, 215-227. doi: 10.1016/j.buildenv.2014.08.022

building microclimate and thermal comfort of the present vernacular house over the period of an entire summer. The field measurements show the present Chinese vernacular house has its own independent building microclimate in summer, which is in accordance with the main character of microclimate in terms of different distributions of solar gain, air temperature and wind velocity in different spaces. The simulation results of the vernacular house could be matched well with the field measurements. According to the simulations, at night, a comfortable temperature could be obtained throughout most of the summer period whereas in the daytime the operative temperature was higher than the comfortable temperature for one-third of the summer period. Wind velocity in the semi-outdoor and outdoor spaces however, improves the thermal comfort significantly. The thermal comfort environment can thus not only change in time but also in space. This example of the vernacular building shows that it is possible to create comfortable conditions for the inhabitants when not only the indoor climate is taken into account but the whole building microclimate as defined in this paper. This paper also shows that the simulations can predict the building microclimate.

KEYWORDS Building microclimate, Summer thermal comfort, Adaptive thermal comfort, Free-running building, Diverse spaces, Chinese vernacular house

5.1 Introduction

In recent years, researchers, environmentalists and architects have become increasingly interested in the thermal performance of buildings in summer. This interest is mainly directed at the two main aspects, energy consumption and thermal comfort. Rising standards of living, the globalization of modern architecture, urban heat islands and global climate change, together with the affordability of air conditioning, have caused the energy demand for cooling to increase dramatically. Studies have shown that refrigeration and air conditioning are responsible for about 15% of the total electricity consumption in the world (Santamouris & Kolokotsa, 2013). On the other hand, the thermal comfort in modern buildings, whether free-running or air-conditioned, tends to be poor. Inferior architectural design can make it impossible to utilize passive cooling approaches for thermal comfort in summer, while the constant use of air conditioning leads to uncomfortable conditions due to the bad indoor environmental quality.

Climatic features can significantly influence the performance of the built environment in terms of thermal comfort and energy consumption. When spatial scale is considered, the climate can be subdivided into macro-scale, meso-scale, local scale and micro-scale (Oke, 1987). There is no strict boundary between the different scales. For urban planning and architectural design, local climate and microclimate are the main focus.

Bioclimatic design is an approach based on local climate. These methods result in buildings that respond to the climatic conditions of their environment, are able to modify them and thus contribute to resource conservation with maximum comfort (Zuhairy & Sayigh, 1993). The design of the built environment can modify the climate on different scales, especially the microclimate scale. Hence, in bioclimatic building design in which passive approaches are applied, it is crucial to first analyse the local climate and microclimate to which the building is exposed and to explore how the microclimate can be modified and improved to ensure a good building performance.

Neither the horizontal extent nor the vertical thickness of the air layer of the microclimate is rigidly defined, although several millimetres to 1 kilometre is often employed (Oke, 1987). Within a particular region, deviations in the climate are experienced from place to place within a few kilometres distance, forming a small-scale pattern of climate, called the microclimate (M. Santamouris & Asimakopoulos, 1996). With respect to urban and building design, neighbourhood, urban canyon, building block, building and indoor space are all part of the microclimate spatial scale. In the microclimate, the distribution of air temperature, relative humidity, solar radiation and wind characteristics are the principal elements determining the physical character of the microclimate.

A literature review revealed that the majority of previous studies have focused on the urban microclimate in relation to the urban scale, i.e., neighbourhoods, urban canyons and building blocks. Some researchers have conducted field studies on the thermal environment, assessing aspects such as air temperature distribution and wind characteristics in the urban microclimate (urban canyon and streets) (Dimoudi, Kantzioura, Zoras, Pallas, & Kosmopoulos, 2013; Gaitani et al., 2011; Niachou et al., 2008). Others have examined the effect of geometry and orientation on urban and street canyon (Andreou, 2014; Giannopoulou et al., 2010; Shashua-Bar & Hoffman, 2003; Zhen, & Jiasong, 2006). Still other researchers have studied the thermal comfort of outdoor and semi-outdoor environments in the urban microclimate (Andreou, 2013; Ali-Toudert et al., 2005; Spagnolo & de Dear, 2003; Taleghani, Kleerekoper, Tenpierik, & van den Dobbelsteen, 2014). Studies have also been carried out to investigate how to use passive approaches to improve the thermal comfort of outdoor spaces (Al-Sallal & Al-Rais, 2012; Gaitani, Mihalakakou,

& Santamouris, 2007; Santamouris et al., 2012; Shashua-Bar, Tsiros, & Hoffman, 2012). On the other hand, large number of studies focused on indoor climate. Few studies focused on the microclimate at the single building scale.

In this paper, the authors first clarify the definition of building microclimate in free-running buildings and define the building microclimate in terms of building spatial features, thermo-physical features and the relationship with summer thermal comfort. Next, the authors discuss the field measurements conducted to investigate the microclimate in a Chinese traditional vernacular house. This house is free-running, comprises of a number of different spaces and is situated in a hot and humid summer climate region of China. Subsequently, the results of measurements were compared with a dynamic thermal and a CFD simulation in order to determine the microclimate and thermal comfort of the typical Chinese vernacular house over the period of an entire summer. The authors expect their findings to contribute to more comfortable and more energy-efficient buildings using bioclimatic design in hot and humid summer climates.

5.2 Building microclimate and thermal comfort

In this section, the authors clarify the definition of building microclimate, as used in this paper. The authors also attempt to clarify the relationship between building microclimate and summer thermal comfort in the free-running buildings.

5.2.1 Building microclimate

As mentioned above, the term microclimate in urban planning and urban design always refers to the climate connected with a group of buildings in the urban fabric or to the climate around a single building. But, within a particular building, a small-scale pattern of “building microclimate” is found, which is different from the microclimate related to the urban fabric scale. In this paper, “building microclimate” refers to one type of microclimate, involving the indoor space and the spaces around the indoor spaces of a particular building. It is the extension of the indoor climate. The building microclimate is mainly defined by the spatial and the thermo-physical properties.

The spatial characteristics of a building microclimate regard the following aspects (Figure 5.1):

The spatial scale is smaller than the urban fabric. It rarely covers an area more than several hundred meters wide, but is bigger than an indoor space alone. It is limited to one particular building, whether a small house or a big stadium.

The spaces in a building microclimate are connected for particular building functions in one building. The spaces are connected either directly or by building components such as walls, roofs and beams. Sometimes, the area of an urban canyon or building block is similar in size to one big single building. However, urban canyons and building blocks lack continuous spaces for particular building functions. Architectural decisions are typically made at the building scale, thus effect the building microclimate.

The existence of diverse types of spaces is another important feature of the building microclimate, distinguishing it from a single indoor climate. Indoor space, semi-outdoor space and outdoor space are the main spatial types in a building microclimate. Hence corridors, semi-outdoor rooms, courtyards, patios and atria play a very important role in the spatial design to obtain a good building microclimate.

The boundary between the different spaces should be adaptive and switchable. For example, the openable windows and doors in the boundaries always are adaptive. This applies especially to the boundary between the indoor space and the semi-outdoor space and outdoor space. As a result, the spaces can be mutually adjusted as needed.

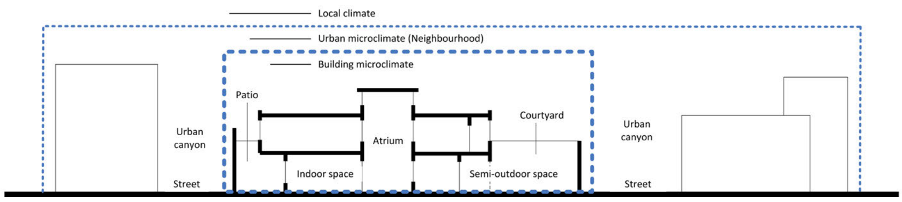

FIG. 5.1 The spatial features of building microclimate

At the building microclimate scale, the thermo-physical properties are as follows:

The average air temperature and humidity in the building microclimate are influenced by the local climate. However, air temperature and humidity distribution vary in the different spatial types. In summer, normally, the indoor temperature of the free-running buildings is lower than the semi-outdoor and outdoor temperature during the daytime; at night, the situation is reversed. The humidity follows the air temperature changes.

The influence of the local climate on the solar radiation in the microclimate is relatively small, but is significantly influenced by the design of the building components.

The wind velocity distribution is significantly different tin different spaces. Generally, the wind velocity in the semi-outdoor and outdoor space is higher than in indoor spaces. The wind velocity and direction are influenced by the local wind environment, the organization of building spaces and the envelope design.

5.2.2 Thermal comfort in a building microclimate

In the building microclimate identified above, the spatial features and thermal properties of the building microclimate are interactive, just as in the urban space, where urban form, landscape and used material influence the urban microclimate. Similarly, the building microclimate is significantly influenced by building form, spatial organization, vegetation and landscape in building and construction materials. The essence of architectural bioclimatic design is to understand the local climate and utilize appropriate design strategies for building form generation and material selection, in order to create or modify the building microclimate required for a comfortable living environment. Building form, solar control and natural ventilation are the main bioclimatic design strategies to control the building microclimate. In this paper, the authors will explain the relationship between building microclimate and summer thermal comfort using adaptive thermal comfort theory. Architectural bioclimatic design strategies for modifying the building microclimate will be in the authors' next paper.

Adaptive thermal comfort and building microclimate

Adaptive thermal comfort theory may be used to explain the comfort in a free-running building, since the relationship between indoor comfort temperature and outdoor monthly mean temperature for free-running buildings was found to be closely linear in Humphreys's field survey (Nicol & Humphreys, 2002). According to Humphreys's opinion, it is in principle possible to design and operate buildings that provide comfort in the free-running mode, at least within a range of prevailing mean outdoor temperatures from 10 to 30°C(Humphreys, Rijal, & Nicol, 2013).However, when talking about thermal comfort, a distinction is always made between indoor thermal comfort and outdoor thermal comfort. In this paper, the authors put forward the idea that thermal comfort should be considered at the building microclimate scale in terms of combining the indoor and outdoor thermal comfort to evaluate the thermal comfort in free-running buildings with diverse spaces during the summer, especially in the hot and humid climate area. This is based on adaptive thermal comfort theory.

Adaptive comfort is based on the concept that thermal comfort is highly influenced by personal preference and contextual factors that are commonly found in naturally ventilated buildings (Nicol & Humphreys, 2002). The fundamental assumption of the adaptive approach is expressed by the adaptive principle: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort". There are five basic types of adaptive actions: 1) regulating the rate of internal heat generation 2) regulating the rate of body heat loss 3) regulating the thermal environment 4) selecting a different thermal environment 5) modifying the body's physiological comfort conditions (Nicol et al., 2012).

One of the most important adaptive behaviours related to building components is the opening of windows and doors. Opening windows is one of the most favoured adaptive measure across countries (Mishra & Ramgopal, 2013). In a field survey conducted in Changsha, China, the opening of windows and doors was found to be the most frequently used adaptive action (Liu et al., 2012). The main goal of opening windows or doors is to obtain more air movement and fresh air. In this respect, a large opening in all the walls can provide the design solution for effective cross ventilation in the hot and humid climate areas, especially for free-running buildings (Givoni, 1994). Examples can be found in many vernacular buildings in tropic or sub-tropic climate areas such as Australia, India, Indonesia, Malaysia, Singapore, Thailand, Vietnam and China. If the windows or doors are big enough, the point at which the indoor space stops and the semi-outdoor or outdoor space begin will blur (figure 5.1). The indoor space can thus be changed to a semi-outdoor space.

Another important adaptive behaviour is movement. When people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like (Humphreys, 1997). Occupants can change their location for different activities. Movement is possible between buildings, between rooms, around rooms, out of the sun and into the breeze, and so on (Nicol et al., 2012). Buildings with diverse spaces provide opportunities for movement. Indoor space, semi-outdoor space and outdoor space are the three typical kinds of space. These types of spaces are also emphasised in architectural spatial design. Atria, corridor, porch, patio and courtyard are commonly utilized elements to provide diversity in the types of space in the building. In hot and humid climates, occupants prefer to move from indoor spaces to semi-outdoor spaces. Occupants can expand their comfort from this adaption in two ways: physiologically as more air movement can influence the comfort sensation, and psychologically as people prefer an open environment in summer. The field survey about occupants' adaptive movement in the building is limited. Part of the reason is that in modern buildings the opportunities for movement on the part of occupants are restricted. If opportunities for movement are not available to the building occupants, only the indoor thermal comfort is considered, which does not reflect the true comfort situation, as the semi-outdoor and outdoor thermal comfort are also should be evaluated. The diversity in spaces and thermal environment in the building microclimate provides a range of choices for human's action which produces a different thermal environment.

According to Nicol et al. (2012), "The key to mastering the skill of producing comfortable, low-carbon building is to look at the 'whole system' when designing. The adaptive comfort approach helps us here because it works with many attributes of the system. The outside climate, the building's context, its form, services and occupants as well as the seasons and times of day are all part of this complex package of attributes that determine our comfort in a system". The building microclimate in a building is such a system and can be characterized as: dynamic and interactive, changing, customary and seasonally adjusted.

Evaluation of thermal comfort in the building microclimate using the adaptive approach

One of the main outcomes of the adaptive approach is the thermal comfort evaluation method based on field studies, in which the indoor thermal comfort temperature is shown to be a function of the outdoor temperature. The equation is:

$$T_n=A+BT_o$$

Where T_n is the neutral or comfort temperature (°C); T_o is the mean outdoor air temperature (°C); A, B are the constants. The constants A and B are different in different climate regions and cultural contexts. They can be confirmed by field survey in different regions. Some of the equations, especially applied to China for free-running buildings, are listed in table 5.1.

TABLE 5.1 Adaptive comfort equations

Location (source)	Equation
Humphreys (Humphreys & Nicol, 1998)	$T_n = 11.90+0.534T_o$
ASHRAE Standard 55-2010 (ANSI/ASHRAE, 2017)	$T_n = 17.80+0.31T_{ref}$
China (general) (Yang, 2003)	$T_n= 19.70+0.30T_o$
Shanghai, China (Ye et al., 2006)	$T_n = 15.12+0.42T_o$
Chongqing, China (Li, 2008)	$T_n = 16.28+0.39T_o$
Harbin, China (in summer) (Wang et al., 2010)	$T_n = 11.802+0.468T_o$

Here T_n is the neutral comfort temperature (°C); T_o is outdoor monthly mean temperature (°C); T_{ref} is the prevailing mean outdoor air temperature (°C) (for a time period between last 7 and 30 days before the day in question)

Another important issue relating to adaptive comfort is the influence of humidity and wind velocity. In free-running or naturally ventilated buildings, the influence of humidity and wind velocity on occupants' thermal comfort sensation in hot and humid climate regions is greater than in other climate regions and in conditioned buildings. The cooling effect of air movement depends on, not only air velocity, but also temperature, humidity and radiation balance, as well as on the activity (metabolic rate) and clothing of the individual (Szokolay, 2000). Studies done in different climates show occupants prefer greater air movement and comfort ranges can expand with the aid of air movement (Mishra & Ramgopal, 2013). In hot and humid climate areas, air movement can promote convective heat transfer from the skin and increase the evaporation of sweat. Occupants appreciate air movement, even when it is not necessary for cooling action (Zhang et al., 2007).

In order to approximate the potential cooling effect of an elevated air velocity to compensate for a room's high operative temperature, Nicol (2004) proposed the raise in comfort temperature caused by the air movement as:

$$\Delta T = 7 - \frac{50}{4 + 10V_a^{0.5}}$$

TOC

Where ΔT (°C) is the raise in comfort temperature and V_a (m/s) is the air velocity and the equation is applicable when V_a consistently remains above 0.1m/s. This equation is also included in EN15251. Szokolay (Szokolay, 2000) proposed the function as follows, based on the analysis of other 11equations adopted by other researches.

$$\Delta T = 6V_e\text{-}1.6(V_e)^2$$

Where ΔT (°C) is the cooling effect compensated for by the elevated air velocity, V_e is the effective velocity (V_e = V–0.2 m/s); where V is the air velocity at the body surface); the equation is valid up to 2m/s (Szokolay, 2000). Su et al. (2009) derived two equations for the influence of wind velocity and relative humidity on thermal comfort in China based on other researcher's studies:

1) If the relative humidity exceeds 70%, the thermal temperature will ascend 0.4°C per 10% increase in relative humidity on the premise that the indoor air temperature exceeds 28°C.

2) The thermal temperature will decrease 0.55°C with a 0.15m/s increase of airflow velocity.

When indoor air temperature is over 28°C:

$$\Delta T = -4(\varphi\text{-}70\%) + \frac{0.55V}{0.15}$$

When indoor air temperature is below 28°C:

$$\Delta T = \frac{0.55V}{0.15}$$

Where ΔT (°C) is the cooling effect compensated for thermal neutral temperature by relative humidity and elevated air velocity, Φ is the relative humidity (if less than 70%, Φ =70%) and V is the air velocity at the body surface. The equation is valid up to 0.8m/s. This equation will be adopted in the section 5.4.2.2 for the evaluation of thermal comfort in the vernacular house as it obtained from Chinese climate condition.

5.3 Methodology

Vernacular architecture, built by people whose design decisions were influenced by local climate and culture, has been gleaned through a long period of trial and error and the ingenuity of local builders who possess specific knowledge about their location, and thus are valuable in promoting the bioclimatic design approach to modern buildings (Zhai & Previtali, 2010). In many traditional buildings, bioclimatic design strategies are utilized to achieve an appropriate building microclimate for thermal comfort. In the present study, in order to investigate the building microclimate and evaluate the thermal comfort in a single building, a typical Chinese vernacular house, situated in Chongqing, in the hot and humid climate area of China, was studied. First, measurements were taken on site on two typical summer days. Air temperature and the relative humidity were measured at measured points distributed across various spaces. Wind velocity was also gauged in the key spaces. Thermal and CFD simulations were also performed because of the limited measurement equipment to predict the distribution of air temperature, relative humidity and wind velocity as well as to analyse the thermal comfort in the vernacular house in summer. The simulation results are validated with the field measurements.

5.3.1 The Chinese vernacular house

The house that formed the object of the study is located in Shuangjiang Town of Tongnan County, Chongqing China, located in the Sichuan Basin in the western part of the hot summer and cold winter climate zone (eastern longitude 105°17’–110°11’ and northern latitude 28°10’–32°13’). Table 5.2 (National Meteorological Information Center of China Meteorological Administration & Department of Building Technology Tsinghua University, 2005) shows the monthly climate data in the typical meteorological year of Chongqing. In the typical meteorological year, the annual average temperature there is 18.4°C; the average temperature in the hottest month is 28.1°C and in the coldest month is 8.1°C;the highest temperature is 37.7°C in August and the lowest temperature is 2.8°C; the annual relative humidity is around 70%-80%.The average wind velocity in summer is 1.6 m/s and the prevailing wind comes from the north-west.

TABLE 5.2 Monthly climate data of Chongqing in the typical meteorological year

Month	1	2	3	4	5	6	7	8	9	10	11	12
Average air temperature (°C)	8.1	10.3	13.7	18.7	23.0	25.2	28.1	27.6	24.1	18.4	14.6	9.2
Max air temperature (°C)	13.6	19.5	25.1	29.7	34.9	35.4	36.6	37.7	34.5	27.9	23.1	15.2
Min air temperature (°C)	3.4	2.8	8.2	10.8	15.3	18.2	22.2	19.9	18.5	12.1	7.0	2.8
Average relative humidity (%)	85	82	77	81	74	81	77	76	81	83	85	86
Average wind velocity (m/s)	1.3	1.4	1.6	1.5	1.6	1.5	1.6	1.7	1.4	1.1	1.4	1.1

The summer here is extremely hot, humid and uncomfortable. A survey showed that 60–90% of the local population complained of sleeplessness on summer nights due to the sweltering heat and sultry weather. Air conditioning is used on a wide scale in the urban area. According to a survey carried out in 1997, average daily electricity consumption could rise to 20 kWh per household in Chongqing during a summer season (Fu, 2002).

The object of this study is Yang's house, built in the Qing Dynasty and representing more than 120 years of history. Figure 5.2 shows the location and bird's-eye view of the house. The building is well-preserved, except for minor building maintenance and repairs, and it completely retains the original architectural form and spatial distribution. In addition, its shape and structure are that of a typical Chinese vernacular building with quadrangle courtyards (the enclosed courtyard is surrounded by building groups or walls). The whole building covers an area of about 3500 m^2 with the maximum depth of 85 m and the maximum width of 53 m, and the building area is about 1768 m^2. There are 3 main courtyards, 10 patios and 51 rooms in different sizes. Most of the building has one floor and there are only a few attics. The spatial distribution and images of the house are shown in figure 5.3. The main construction is formed by the traditional timber-framed structure. The building is composed of lightweight walls, windows and doors. Primary construction materials are wood (for the main structure, enclosure structure, bedroom ground etc.), grey tiles (for roofs), stone material (for enclosing walls and ground floor) and brick (for enclosing walls).

FIG. 5.2 Location and bird's-eye view of "Yang's house" in Shuangjiang town of Tongnan, Chongqing

5.3.2 Field measurements

A period of continuous measurements took place in 2012, from 12:00 on August 28th to 12:00 on August 30th. Measurements were taken of the temperature, relative humidity, and the wind velocity in key positions at the measured points. The position of the measured points for temperature and relative humidity is shown in figure 5.3. Use was made of an automatic temperature logger and temperature and humidity logger, which recorded data every five minutes. Temperature accuracy was 0.2°C; the accuracy of relative humidity was 5%. The equipment was placed above the ground at a height of 1.2 m at the measured points both indoors and outdoors. The position of the measured wind velocity on August 28th was in the middle of the multifunctional room (m-room). The wind velocity was recorded every five minutes in the measured period. The position of the measured wind velocity in the afternoon of August 29th is shown in figure 5.3. The wind velocity was measured five minutes at every point and the average wind velocity was recorded. The accuracy of the readings of the manual anemometer was5% reading add 0.05 m/s. Weather conditions on the test days of August 28th and 29th were partly cloudy with occasional rain at night, which is typical summer weather in the Chongqing area. Since it rained during the day on August 30th, the following analysis will focus on August 28th and 29th.

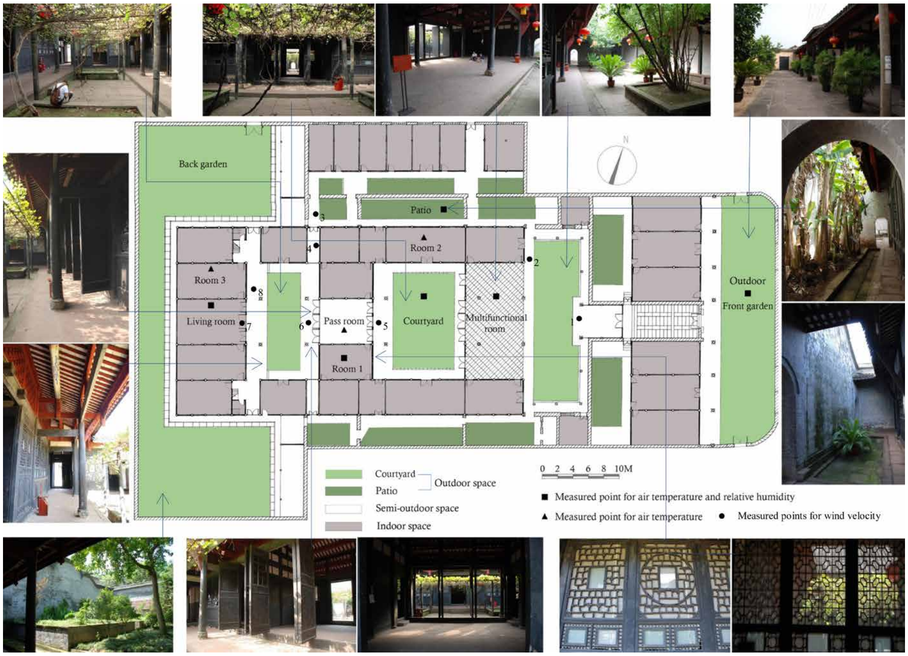

FIG. 5.3 The plan, measured points, spatial distribution and images of the vernacular house

5.3.3 Thermal and CFD simulation

Because of the limited number of measurement points, a thermal simulation was performed to obtain the temperature and humidity distribution in the building over a large time period and a CFD simulation was performed to predict the airflow distribution in the building.

Thermal simulation

The thermal simulation was performed with DesignBuilder(DB) software. DB is one of the most comprehensive user interfaces for the EnergyPlus dynamic thermal simulation engine. Figure 5.4(a) (b) shows the 3D model of the vernacular building in DB. Because of the limitation of the software, i.e. it cannot simulate the outside temperature, the courtyards and patios were modelled as atria. In the model, roof windows of the atria are constantly open and some shading was simulated as well, to simulate the presence of trees in the courtyards and patios (figure 5.4 (c)). This

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model's simulation of the courtyards and patios will impact the accuracy of the thermal and CFD simulation, as the model's roof windows and shading is not exactly the same as the vegetation in the courtyards and patios. However, it is assumed that the accuracy is enough for the analysis in the present research which is comparing the measurements to the simulations and predicting the temperature over a large time period and in all the rooms.

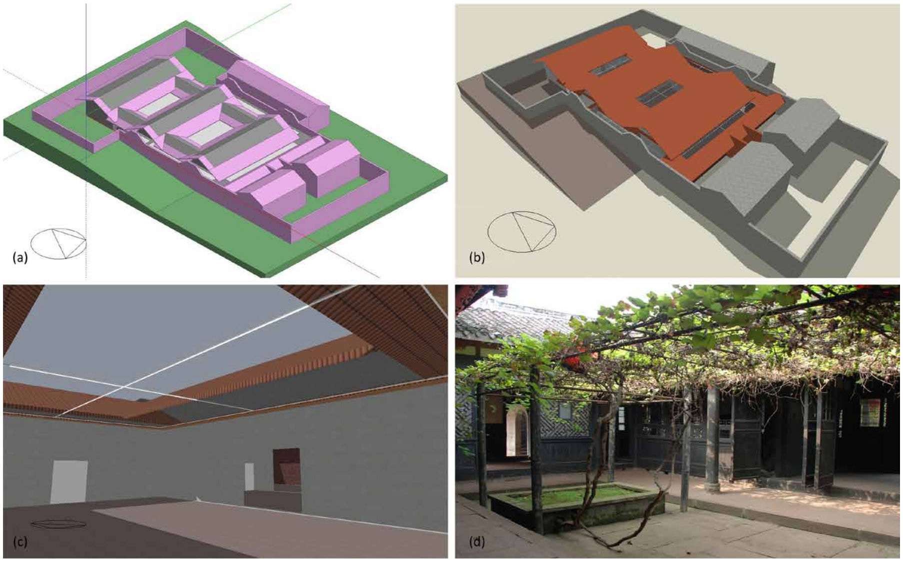

FIG. 5.4 The simulation model (top) The model of the studied vernacular house (bottom left) The rendered model (bottom right) The comparison of model and real courtyards

The entire building energy simulation was performed using the Chinese typical meteorological year weather (CTYW) data from Energyplus weather data sources. The hourly weather data in Chongqing, which is the nearest weather station to the measured subject, was utilized. The thermal simulation was performed during the whole summer time from June 1st to August 31st. Figure 5.5 shows the input weather data in the simulated period. Based on the weather data, the temperature was relative mild from June to the middle of July. The temperature changed quickly and was unstable in this period. From the middle of July to the first ten-days of August, the temperature was at a stable high level. These 20 to 25 days were the hottest days in summer. After that, the average temperature decreased and some days were relative warm. The mentioned summer climatic characteristics above are in agreement with the local summer climate and local occupants' experiences in summer. According to the utilized weather data, it was found that the solar radiation in the summer in the studied area remained at a high level, especially in July and August. This is agreement with the fact that there is strong solar radiation in summer and that the maximum value is beyond 500MJ/m^2 and the total solar radiation in July and August accounts for 31% of yearly radiation (National Meteorological Information Center of China Meteorological Administration & Department of Building Technology Tsinghua University, 2005).

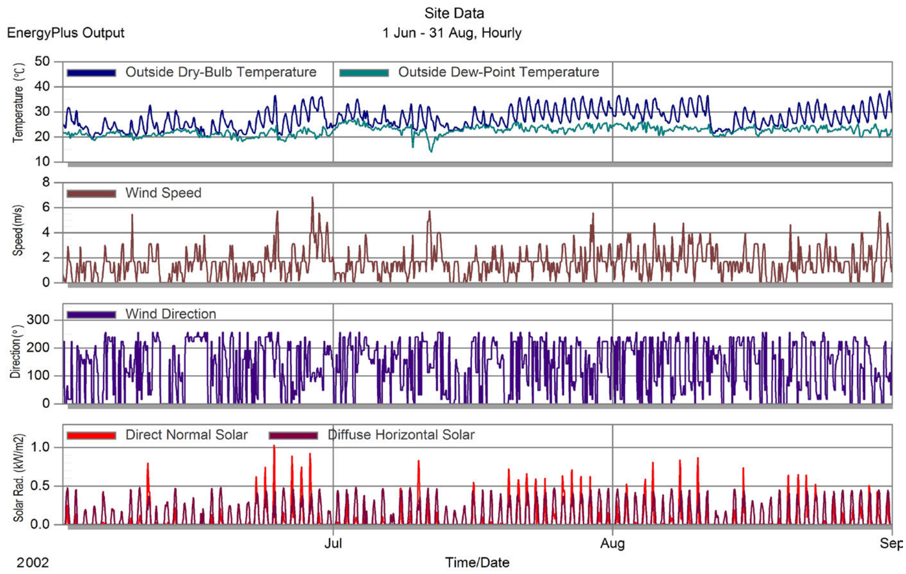

FIG. 5.5 The used weather data for the thermal simulation

The characteristics of the simulated house and the characteristics of building components are shown in table 5.3. The building performed as a free-running building with natural ventilation without any heating or cooling, corresponding to the real situation of the building. Thus, the windows on the outside walls were assumed 70% opened, internal windows were assumed 60% opened and roof windows were completed opened; all of the doors were assumed 90% opened in the simulation period. The infiltration was switched off since infiltration heat flows through the cracks are only a very small part of summertime air flow with the windows of the outside wall 70% opened. For validation, the simulation results will be compared with the field measurements taken on the test day.

TABLE 5.3 Characteristics of the simulated house and the building components

Characteristics /component	Description
Location	Chongqing
Running model	Free-running
Activity	Without occupant and equipment
Natural ventilation	Natural ventilation-no heating/cooling, calculated, constant
Construction	
External wall	Wood, dry, 20mm, U-Value=3.476(w/m^2-k)
Internal wall	Wood, dry, 20mm, U-Value=3.476(w/m^2-k)
Internal floor	Stone, sand stone, 500mm, U-Value=1.71(w/m^2-k)
Roof	Tile, 40mm; air gap, 20mm; woods, 50mm; U-Value=1.507(w/m^2-k)
Glazing	
Outdoor	Uninsulated, clear 6mm, U-Value=5.778(w/m^2-k), 70% opened
Indoor	Uninsulated, clear 6mm, U-Value=5.778(w/m^2-k), 60% opened
Roof window	Uninsulated, clear 6mm, U-Value=5.778(w/m^2-k), 100% opened, with shading

CFD simulation

For air velocity assessment, a validated CFD model is necessary since other methods are not able to provide detailed information on the performance of a natural ventilation strategy (Chen, 2009). In the present study, the CFD code from the DB software wa s used. The numerical method used by DBCFD is known as the primitive variable method, and comprises the solution of a set of equations that describe the conservation of heat, mass and momentum. The equation set includes the three velocity component momentum equations (known as the Navier-Stokes equations), the temperature equation and where the k-e turbulence model is used, equations for turbulence kinetic energy and the dissipation rate of turbulence kinetic energy. The equations comprise a set of coupled non-linear second-order partial differential equations having the following general form, in which Φ represents the dependent variables:

$$\frac{\partial}{\partial t}(\rho\phi) + div(\rho u\phi) = div(\Gamma grad\phi) + S$$

Where the $\frac{\partial}{\partial t}(\rho\phi)$ term is the rate of change, the $div(\rho u\phi)$ term is convection, the $div(\Gamma grad\phi)$ term is diffusion and S is source term.

The boundary conditions for DB's CFD simulations, such as the input weather data, building's constructional components, opening sizes and operation schedule were established from previously calculated values using the thermal modelling software EnergyPlus, which was also run from within the DB environment. Thus, an accurately built model and correct input parameters were ensured to give accurate CFD results. In DB CFD package, there are two general approaches to natural ventilation modelling: scheduled and calculated natural ventilation. In this case, the calculated natural ventilation model was used where the ventilation rates between the zones are calculated using wind and buoyancy-driven pressure, opening size and operation. DB uses the Energyplus Airflow Network method to calculate air flow rates which can be descried as following equation:

$$Q = C_d A \sqrt{\frac{2\Delta P}{\rho}}$$

Where Q is the air flow rate (m^3/s); C_d is the opening's discharge coefficient; A is the opening's area (m^2); ΔP is the pressure difference across the opening or crack (Pa); ρ is the density of air (kg/m^3). The default value of opening's discharge coefficient 0.65 was utilized in this case. For wind-driven ventilation situation, the pressure on any point on the surface of the building façade can be represented by:

$$P = 0.5\rho C_p V^2$$

Where P is the surface pressure due to wind (Pa); ρ is the density of air (kg/m^3); C_p is the wind pressure coefficient; V is the wind velocity (m/s). The wind pressure coefficient C_p is a function of wind direction, position on the building surface and side exposure. DB provides default wind pressure coefficients suitable for use in basic design calculations for buildings having no more than three stories. In this case, the building is only one storey, thus the default settings of wind pressure coefficients were utilized.

The grid used by DBCFD is a non-uniform rectilinear Cartesian grid, which means that the grid lines are parallel with the major axes and that the spacing between the grid lines enables non-uniformity. In this case, the grid spacing was adopted that is generated with 0.2 m with a 0.025 m grid line merge tolerance. The details related to the CFD simulation set up in the present case are summarized in table 5.4.

TABLE 5.4 Summary of CFD cell setting and time steps

Total cells	530469
Cell size	0.2 m
Max aspect ratio	6.045
Iterations	15000
False time step	0.10

5.4 Results and analysis

5.4.1 The results of the field measurement

Temperature and relative humidity

Figure 5.6 shows the air temperature and relative humidity of the measured vernacular house in the period from 12:00on August 28th to 24:00 on August 29th 2012. The analysis will mainly focus on August 29th, as measurements were taken throughout the entire day. The positions of the test points were shown in figure 5.3.

On August 29th, the lowest measured outdoor temperature was 24.3°C. The outdoor temperature then started to rise at 7:00, peaked at 36.6°C at 14:00, after which it went back down.

Figure 5.6 (a) shows the comparison of the outdoor air temperature and indoor air temperature (room1, room2, room3 and living room). From 00:00 to 07:00 on August 29th, the measured indoor air temperatures remained at almost the same level as the outdoor temperature. As can be seen, the difference was small. The indoor air temperatures then began rising at 07:00 (with a small time delay in room1 and room3). The temperature in room1, room3 and the living room peaked at 31.0°C-31.3°C at around 16:40. The temperature in room2 reached a peak of 32.5°C at 15:00. An obvious time delay was seen in the max temperature between the air temperature outdoors and indoors. The results showed that an indoor air temperature was around five degree lower than the outdoor air temperature during the day and a time delay of the peak temperature of around two and half hours. At night, the heat in the building quickly dissipated and the indoor temperature then approached the outdoor temperature, resulting in thermal comfort.

Figure 5.6 (b) shows the comparison of the outdoor, courtyard and patio air temperature and semi-outdoor air temperature (pass room and multifunctional room). From 00:00 to 07:00 on August 29th, all of the semi-outdoor air temperatures remained at almost the same level as the outdoor temperature. As can be seen, the difference was small. The semi-outdoor air temperatures then began rising at 07:00. The temperature in the courtyard reached a peak of 35.3°C at 14:30; the temperature in the multifunctional room peaked at 33.0°C at 15:00; in the pass room the temperature peaked at 32.6°C at 15:00; and in the patio at 31.5°C at 15:00. During the day, the courtyard air temperature was one degree lower than the outdoor temperature due to the vegetation in the courtyard. The semi-outdoor air temperature was some 3-4°C lower than the outdoor temperature and the time delay of the peak temperature was about 1 hour. The patio temperature was five degree lower than the outdoor temperature, as the patio receives no direct solar radiation due to the lush vegetation and narrow opening.

In Figure 5.6 (c), the outdoor and patio air temperature, the semi-outdoor air temperature (multifunctional room) and the typical indoor air temperature (living room) are compared. From 00:00 to 07:00 on August 29th, both the semi-outdoor air temperatures and the indoor air temperature remained at almost the same level as the outdoor temperature. At 07:00, these temperatures reached their lowest point around 24.3°C. The semi-outdoor peak temperature was higher than the indoor temperature, but much lower than the outdoor temperature. The patio temperature in particular was lower than the outdoor temperature, with a maximum difference of around 5°C which was almost equal to the indoor temperature.

Figure 5.6 (d) shows the distribution of the air temperature in the different spaces at different times. The graphs clearly indicate that there is a remarkable difference in air temperature in the different spaces of the building during the day-time. It was found that as the outside air temperature rises, the temperature difference also increases. In other words, the outdoor temperature was higher than the semi-outdoor temperature and the semi-outdoor temperature was higher than the indoor temperature. In contrast, at night, the air temperature returned to the same level in the different spaces.

In general, the relative humidity followed the air temperature during the day. At night, humidity levels mostly exceeded 70%. Indoor relative humidity was higher than semi-outdoor relative humidity, which in turn was higher than the outdoor levels measured, whether at night or in the daytime; see figure 5.6 (e).

Air velocity

Figure 5.7 shows the air velocity measurements taken every five minutes in the multifunctional room of the vernacular house from 14:00 to 17:00 on August 28th. The air velocity was between 0-1.8m/s and can be characterized as an unstable gust with fluctuations. The average air velocity was 0.74m/s, which is higher than the average air velocity of 0.26 m/s measured outdoors.

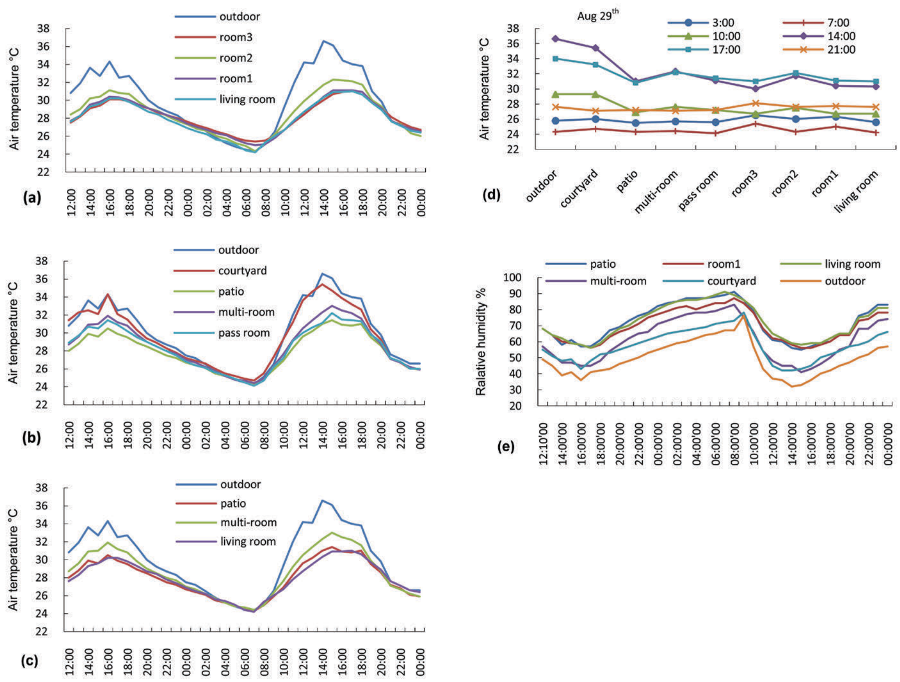

FIG. 5.6 Measured hourly results of temperature and relative humidity in the vernacular house on 28/29 Aug 2012

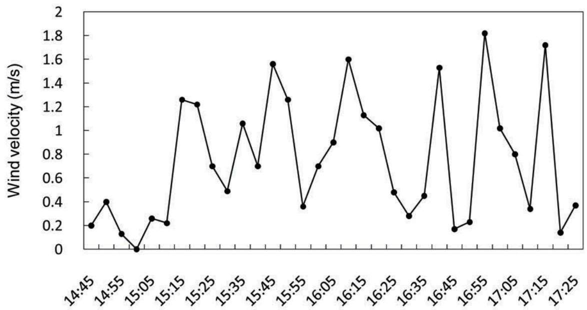

FIG. 5.7 Measured results of wind velocity on Aug 28th

5.4.2 Simulation results

5.4.2.1 Thermal simulation results

Comparisons with measurements

The hourly temperatures of the house during the summer time were obtained from the simulation. In figure 5.8, the simulated outdoor air temperature and air temperature in the different spaces, from 12:00 on August 28th to 24:00 on August 29th, is compared with the field-measurements. Figure 5.9 shows the T_m/T_s (T_m is the measured air temperature and T_s is the simulated air temperature) of all the measured points. The simulated results were found to fit well with the test results except for the time period after 18:00 on August 29th. The air temperature changes from the simulated results were matched with the measured results. On August 29th, differences between the measured temperature trends and the simulated trends were only seen after 18:00. These were caused by the accuracy of the weather data used in DB. Generally, the simulated temperature was higher than the measured temperature, especially at night. Nonetheless, all of the test data fell within a 15% range of the simulated data and the average difference was within 5% (figure 5.9). Hence, the same conclusion can be drawn from the simulations as from the field measurements: the temperature difference in the different spaces and rooms can be measured and simulated for this building using dynamic hourly temperature calculations.

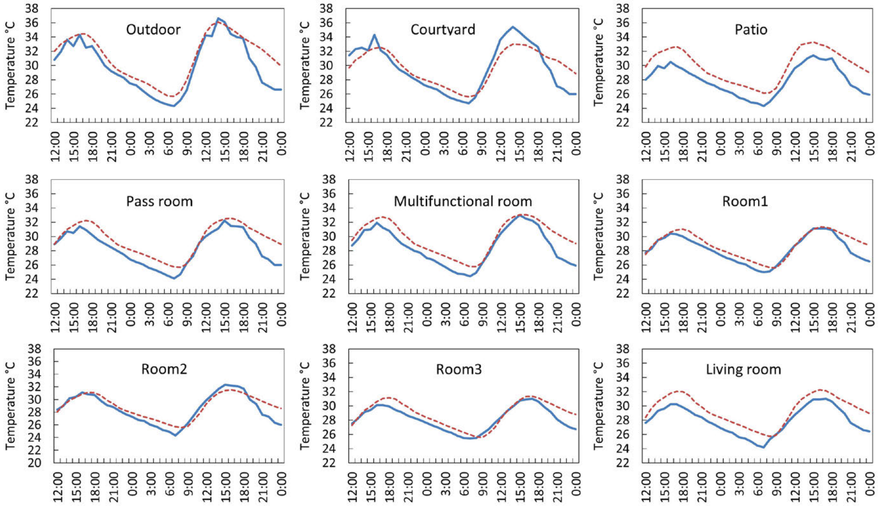

FIG. 5.8 Comparison of simulated and measured results in temperature on 28/29 Aug 2012

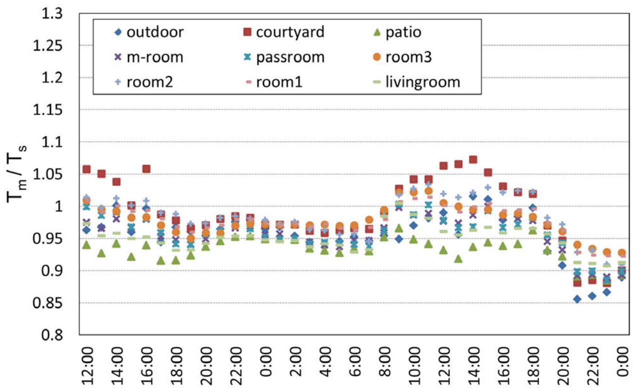

FIG. 5.9 The Tm/Ts of measured points on 28/29 Aug 2012 (Tm is the measured temperature and Ts is the simulated temperature)

Comfort

The adaptive comfort model is used to evaluate the thermal comfort in this vernacular house. For the present location, the proposed relationship between thermal comfort temperature and monthly mean outdoor temperature in the Chongqing area is:

$$T_n = 16.28 + 0.39T_o$$

Where T_n is the comfort temperature (°C) and T_o is the monthly mean outdoor temperature (°C); the range is 5.0°C-30.0 °C (Li, 2008). According to this equation, the comfort temperatures in June, July and August are: 25.7°C, 26.6°C and 26.9°C. According to ASHRAE Standard 55, a comfort zone band of ± 2.5°C corresponds with 90% acceptability, and ± 3.5°C corresponds with 80% acceptability. So, the comfort zone, which in this case corresponds to 90% acceptability, ranges from 23.2°C-28.2°C in June, 24.1°C-29.1°C in July to 24.3°C-29.3°C in August. Figure 5.10 shows the simulated results of the operative temperature in the living room, which had the lowest measured temperature during the day, in June-August and the comfort temperature zone based on the local climate in this period. The comfort temperature zone based on ASHRAE Standard 55-2010 is also shown in figure 5.10 as the reference to the equation for comfort temperature calculation used in Chongqing area. According to the local summer climatic features analysis in section 5.3.3, in the relative mild days in terms from June to the middle of July, the operative temperature was lower than the comfort upper temperature limit in most of the days. The building can provide a comfortable thermal environment for the occupants without mechanical cooling. In the hottest days, during the middle of July to the first ten-days of August, almost all of the operative temperatures in the daytime exceed the comfort upper temperature limit. The comfort thermal environment cannot be achieved in the building with the free-running model, even if the building has a very good passive cooling design. In the relative warm days, during the middle and last ten days, the uncomfortable time was limited and the thermal environment in the building could be accepted most of the time. Generally, during the entire summer, it was found that a comfortable temperature could be achieved most of the time in the building. However, around 1/3 of the daytime, the temperature exceeded the upper temperature limit of the comfort zone. In other words, in summer time, a comfortable indoor thermal environment could be achieved in the vernacular house around 2/3 of the daytime, and the operative temperature was lower than the upper limit comfort temperature at night. However, as shown in section 5.2.2, an increased air movement can increase the comfortable temperature. In the following section, the air velocity for thermal comfort in the different spaces will be analysed.

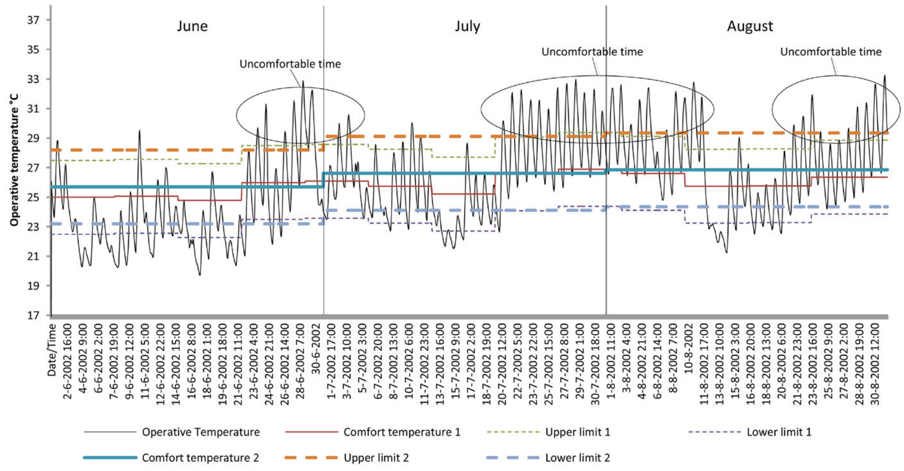

FIG. 5.10 The simulated operative temperature of living room and comfort temperature zone for 90% acceptability (1-Based on ASHRAE Standard 55-2010, 2-Based on the equation for Chongqing area)

5.4.2.2 CFD simulation results

As mentioned before, the boundary conditions of the CFD simulation in DB derive from the thermal simulation. This has been done in DB in order to achieve more accurate results in CFD. The validation of the thermal simulations compared with the field measurements was described in the previous section. One way to validate the CFD is to compare the results with the measured wind velocity. Figure 5.11 (a) shows the simulated wind velocity distribution in the whole building at 14:00 on the 29th of August and the measured points 1-8 for validation. Table 5.5 shows the measured and simulated wind velocity at the 8 points which were distributed in the different position of the vernacular house. Figure 5.12(a) shows the comparison of measured and simulated wind velocity and figure 5.12 (b) shows the ratio of measured and simulated wind velocity (V_m/V_s). It was found that point 1, 2, 4 and 7displayeda relatively large difference between the measured and simulated results and the measured and simulated wind velocity at point 3, 5, 6 and 8 were matched well. General say, the trend of the measured and simulated wind velocity distribution matches well. It may therefore be assumed that the calculated wind velocities in other areas of the vernacular house are accurate enough to predict the trend.

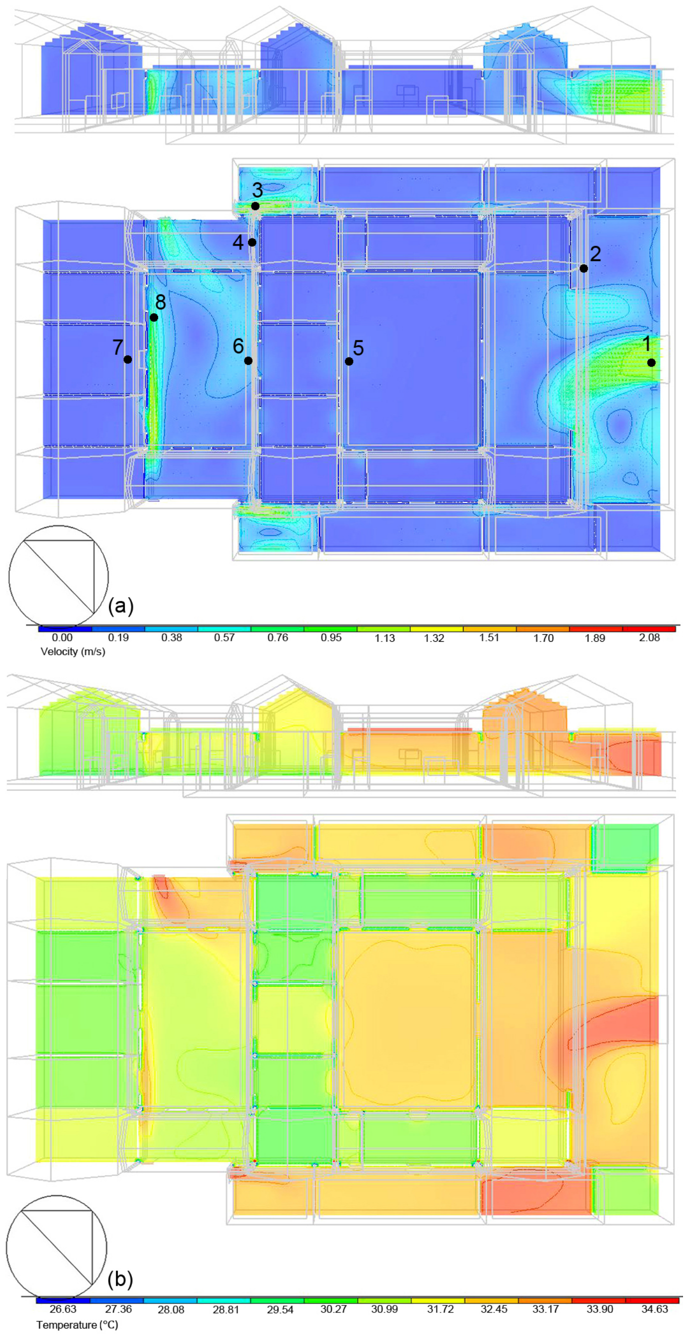

FIG. 5.11 The wind and temperature distribution at 14:00 Aug 29th (a) Wind distribution (b) Temperature distribution

TABLE 5.5 The measured and simulated wind velocity at different position of the vernacular house

Measured points	1	2	3	4	5	6	7	8
Measured wind velocity (m/s)	0.60	0.35	0.97	0.48	0.28	0.53	0.05	0.80
Simulated wind velocity (m/s)	0.95	0.25	0.95	0.30	0.25	0.57	0.20	0.80

The simulated wind velocity showed a clear difference in wind velocity in the various spaces in the building. The indoor wind velocity is low, below 0.2m/s. This is due to the fact that the window does not easily allow the passage of wind. The wind velocity in the centred courtyard and in some of the patios without openings was low that almost kept the same speed as the indoor wind velocity, as there was no opening for cross ventilation and neither the height nor the temperature difference between the bottom and top of the courtyard and patio was large enough for stack ventilation. The wind velocity in the courtyards and in some of the patios with openings was high between 0.6-1.1 m/s. In the semi-outdoor spaces, a wind velocity of 0.6m/s can be obtained in some areas of the multifunctional room. The wind velocity in the pass room was around 0.3m/s, which is not remarkably higher than the indoor wind speed. In the indoor spaces, there is no clear difference in vertical direction. However, in the courtyards and patios with openings, the wind velocity at the bottom was higher than at the top.

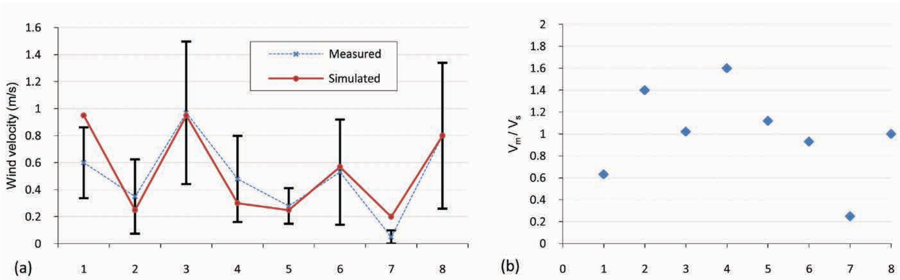

FIG. 5.12 (a) Comparison of measured and simulated wind velocity in different position (b) The ratio of measured and simulated wind velocity (Vm is the measured and Vs is the simulated wind velocity)

Combining the equation for thermal comfort calculation to Chongqing area and the equation for thermal comfort, taking into account relative humidity and wind velocity which mentioned in section 5.2.2, the equations for thermal comfort calculation here can be:

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When indoor air temperature is over 28°C:

$$T_n = 16.28 + 0.39T_o\text{-}4(\varphi\text{-}70\%) + \frac{0.55V}{0.15}$$

When indoor air temperature is below 28°C:

$$T_n = 16.28 + 0.39T_o + \frac{0.55V}{0.15}$$

Where T_n is the comfort temperature(°C), T_0 is the monthly average of outdoor air temperature(°C), ϕ is the relative humidity (%) (if less than 70%, ϕ =70%) and v is the wind velocity(m/s). This shows that wind and humidity impact on thermal comfort to a major extent.

At the time of simulation, relative humidity was lower than 70%, and the temperature was higher than 28°C. The comfort temperature at the points of the semi-outdoor and outdoor spaces can be calculated taking wind velocity into account (table 5.6). This shows that the occupants will feel more comfortable with 90% accept ability if they remain at points2, 3, 6, 7, 8 and with 80% acceptability if they remain at points 1-8. During daytime, occupants could move to semi-outdoor or outdoor spaces to perform their activities.

TABLE 5.6 The influence of wind velocity for adaptive thermal comfort at point 1-8

Location (points)	1	2	3	4	5	6	7	8
Simulated wind velocity (m/s)	0.95	0.25	0.95	0.30	0.25	0.57	0.20	0.80
Simulated air temperature (°C)	33.90	31.00	32.00	31.00	31.00	30.10	29.00	30.10
Δ T (°C) (Raise in comfort temperature)	3.48	0.92	3.48	1.10	0.92	2.09	0.73	2.94
T_n (°C) Comfort temperature	30.52	27.96	30.52	28.14	27.96	29.13	27.77	29.98
Upper limit temperature for 90% acceptability (°C)	33.02	30.46	33.02	30.64	30.46	31.63	30.27	32.48
Upper limit temperature for 80% acceptability (°C)	34.02	31.46	34.02	31.64	31.46	32.63	31.27	33.48

Figure 5.11 (b) shows the air temperature distribution according to the CFD simulation. It again shows that different temperatures occur in the indoor space, semi-outdoor space and outdoor space.

5.5 Conclusion

In this paper the authors have clarified the definition of building microclimate in free-running buildings. It is a type of microclimate, involving the indoor space as well as the spaces around the indoor spaces (semi-outdoor space and outdoor space) of one particular building. It is the extension of the indoor climate belonging to one single building. The spatial and the thermo-physical properties of the building microclimate were examined.

Building microclimate can help to create comfortable conditions for the occupants in summer, especially in the hot and humid climate areas. The essence of architectural bioclimatic design is to understand the local climate and utilize appropriate design strategies for building form generation and material selection, in order to create or modify the building microclimate required for a comfortable living environment. The adaptive thermal comfort model is suitable to evaluate the summer thermal comfort in the building microclimate, as its core assumption is that "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol, 2002) and building microclimate provides this opportunities by taking all spaces (indoor, semi-outdoor and outdoor) of a single building into account.

A case study was conducted in a Chinese traditional vernacular house with quadrangle courtyards in the hot and humid climate area of China. The aim was to determine the summer building microclimate in the building and to assess its function with respect to thermal comfort based on the adaptive comfort approach.

The field measurements show that the present Chinese vernacular house has its own independent building microclimate in summer, which is in accordance with the main character of microclimate in terms of different distributions of solar gain, air temperature and wind velocity in different spaces. Firstly, even at night, the air temperatures in different spaces close to the outdoor temperature, with only slight differences between the different spaces. However, during the daytime a remarkable temperature difference developed between the spaces, with the maximum temperature varying from 31°C to 35°C. Secondly, the relative humidity differed in the various spaces. The relative humidity was higher at night than during daytime and the indoor humidity was higher than outdoors, both day and night. Thirdly, the wind velocity differed strikingly in the building especially during the daytime. The wind velocity was low in the indoor spaces, but rose considerably in some of the courtyards and patios.

The simulation results of the vernacular house could be matched well with the field measurements, hence have sufficient accuracy for the research objective. The building microclimate and thermal comfort can be predicted by simulation. According to the simulation, at night, a comfortable temperature could be obtained throughout most of the summer time while in the daytime the operative temperature was higher than comfortable temperature for one-third of the summer period when only looking at the operative temperature. Wind velocity in the semi-outdoor and outdoor spaces could improve the thermal comfort significantly. The thermal comfort environment would thus not only change in time but also in space.

It is possible to create comfortable conditions when not only the indoor climate is taken into account but the whole building microclimate, as the example of the Chinese traditional vernacular house shows. Obtaining an appropriate organisation of spaces in terms of outdoor space, semi-outdoor space and indoor space for solar control and natural ventilation was the main bioclimatic design strategy for thermal comfort in the vernacular house studied for this research. Utilising suitable material and vegetation also contributed to the good building microclimate. Based on the appropriate bioclimatic design, the microclimate in the building could be modified for more comfortable living environment. This yielded comfortable temperatures throughout most of the summer, especially at night and provided enough air flow to promote thermal comfort during the day time. Finally, different spaces were available to the occupants enabling them to adapt to the thermal conditions.

New buildings can be made more comfortable when taking the combination of adaptive thermal comfort and building microclimate into account. Inspiration can be drawn from this study summer microclimate in a Chinese vernacular house for a modern building's bioclimatic design. Creating an appropriate building microclimate in a building is important for the thermal comfort in summer in a hot and humid climate zone. A key issue in this respect is the fact that building form generation significantly influences the microclimate in a building. Therefore, in architectural design, appropriate building form and space are not only important in terms of aesthetics, function and landscape, but also in terms of building performance, and, especially thermal performance in summer. Building performance simulation can help the bioclimatic design to predict and achieve a good building microclimate.

The present study, however, is not without limitations. The field data were collected for a period of two days only and the wind velocity measurements demonstrate shortcomings due to the limited equipment; the climate data used for thermal simulation was based on the year 2002 and the distance the nearest weather station is not so close; the house studied had a large building volume, and it is unclear whether the building microclimate features discussed above might apply equally in a small-volume building. Additional research is required in the future to investigate these problems. Further work is to investigate the building microclimate in a new modern house with diverse spaces and use the bioclimatic design principles to create a comfortable building microclimate in design practice. A Chinese rural house is planned as the case for an example of a free-running building.

Acknowledgments

The authors gratefully acknowledge professor Tang Mingfang and Zhou Tiejun from Chongqing University for the help of the field measurements.

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6 Spatial configuration, building micro-climate and thermal comfort

a modern house case[5]

ABSTRACT In this paper, the authors attempt to clarify the relationship between spatial configuration, building microclimate and thermal comfort through the investigation of a modern house in hot and humid climate with spatial diversity. First, the spatial configuration of the house was analysed in detail. The spatial geometric features, spatial boundary conditions, and human activities in the building were categorised. Secondly, field measurements were conducted to investigate the microclimate of the house. The air temperature, relative humidity and wind velocity were monitored on typical summer days. Thirdly, a dynamic thermal simulation was performed to predict the thermal comfort performance of the building over the period of an entire summer. The simulated results were compared with the measurements, and the adaptive thermal comfort approach was used to evaluate the thermal comfort. The modern house studied was found to have a varied spatial configuration, similar to local vernacular buildings, which produces diverse thermal environments in

5 This chapter is the original version which is published as: Du, X., Bokel, R., & van den Dobbelsteen, A. (2019). Spatial configuration, building microclimate and thermal comfort: A modern house case. *Energy and Buildings, 193*, 185-200. doi: 10.1016/j.enbuild.2019.03.038

the building. The microclimate of this specific building could provide considerable thermal comfort for the occupants in summer under the local climate conditions, although thermal comfort cannot be achieved through free-running model in the hottest days, mechanical cooling or mixed model are needed.

KEYWORDS Spatial configuration; Spatial diversity; Building microclimate; Summer thermal environment; Adaptive thermal comfort

6.1 Introduction

Space is a major aspect in contemporary architectural design that influences building functions and aesthetics as well as the physical and psychological sensations of a building's occupant. As the basic volume for human activities, the space of a building also constitutes the basic element of a living environment. A particular space can provide both a special environment and a microclimate significant to the occupants' living quality, which is determined by physical and psychological demands. This applies regardless of scale, whether at the regional, urban or neighbourhood level, or at the level of building block, building and room. At building scale, a building that has diverse spatial configurations can provide a rich and varied environment and can influence the way in which we use the rooms (movement, sequence and activities) and how we feel in them (related to temperature, light, sound and air velocity).

Spatial diversity in and around a building can therefore lead to variations in comfort over the various spaces. With free movement between the spaces, spatial and comfort diversity can lead to a better comfort for the inhabitants as they are able to choose the spatial environment that fits their activities and their comfort needs. A few studies were directed at spatial diversity and its environment (Andreou, 2013; Merghani, 2004; Niu et al., 2015; Spagnolo & de Dear, 2003; Steane, 2004; Steemers, Ramos, & Sinou, 2004; Tsiros & Hoffman, 2013). Du et al. (2014) studied the building microclimate at building scale for a Chinese vernacular house. The building microclimate was defined as the type of micro-climate that involves the indoor space as well as the spaces surrounding the indoor space (i.e. semi-outdoor space and outdoor space). The paper showed that the building microclimate of the vernacular building was different for different spaces. This vernacular building, therefore, was able to offer a different comfort in different spaces leading to an increased comfort over the entire day by moving from space to space over the day.

However, the house then studied was large and built in a traditional architectural spatial style. Sadly, modern residential buildings are currently losing their spatial diversity (Du, Bokel, & Dobbelsteen, 2016). There are a number of reasons for this, namely: 1) the number of people living in the city has risen, limiting the living area per household; 2) the wide application of mechanical ventilation, heating and cooling; and 3) the occupants' higher demands with regards to comfort 4) the high building construction speed and the low building cost of the modern houses.

This loss of spatial diversity is causing a poorer quality of the building microclimate; especially with regards to thermal comfort. Not only is the thermal comfort of the occupants becoming increasingly difficult to achieve in a free-running (non-air conditioned) modern house without spatial diversity, but the energy consumption of these buildings also continues to rise. In this study, the authors focus on the effects of building spatial design on the building microclimate, and then on the residents' thermal comfort. They want to answer the question if a good building microclimate be achieved in a modern house through an appropriate spatial configuration, providing thermal comfort through the use of an all passive system.

After a broad survey of modern houses in the hot and humid region of China, the authors found a modern house with a design offering a diversity of spaces. The studied house is situated in Chongqing located in the southwest of China. The selected object of this study is an untenanted house with no interior decoration, making it ideal for the purpose of this research, as the intrinsic thermal environment could be studied without any disturbances of the occupants.

The spatial configuration, the building microclimate and the thermal comfort of the house were studied. First, the spatial configuration of the house was analysed in detail. The spatial geometric features, spatial boundary conditions, and human activities in the spaces were categorised. Secondly, field measurements were conducted on typical summer days to investigate the building microclimate of the house. Air temperature, and relative humidity were monitored in the various spaces of the house. The air velocity was measured in detail at key points throughout the ground floor area. Thirdly, a dynamic thermal simulation was performed to determine the thermal comfort performance of the building over the period of an entire summer. The simulated results were compared with the measurements and the adaptive thermal comfort approach was used to evaluate thermal comfort. The relationship between the spatial configuration, the building microclimate and the thermal comfort was discussed in the end.

6.2 Theory

6.2.1 Spatial configuration

6.2.1.1 Outdoor, indoor and semi-outdoor spaces

When we talk about different kinds of spaces on the building scale, conventionally these are divided into indoor space, outdoor space and semi-outdoor space, reflecting their architectural functional design. Indoor space refers to space that is surrounded by walls, windows or doors and covered with ceilings, roofs or roof windows. It is the most common and important space for the occupants' daily life. It might be a closed space that is separated from the outdoor environment. The outdoor space is defined as the space included in the building, but lacking a ceiling, roof or roof window; hence a space that is directly exposed to the natural environment. Courtyards, patios and gardens are the main components of this category. In this context, a courtyard is identified as having a small height-to-width ratio and a patio is identified as having a large height-to-width radio. A garden is a big green space that is not completely surrounded by rooms. The semi-outdoor space, which is also known "grey" space or "buffer" space in architectural design, is a space featuring a semi-enclosed wall or roof. The semi-outdoor space is an important component in architectural spatial design. It can create various spaces and can connect the indoor spaces and outdoor spaces flexibly. The outside corridor, terrace, balcony and veranda are the main components used as transitional space. It should be noted that the three kinds of spaces can be transformed into each other through changing the spatial boundary conditions.

6.2.1.2 Spatial geometric features and spatial boundary conditions

Spatial geometric features convey the basic information about a space: size, height, area, horizontal location, vertical location and orientation. These parameters define the volume of the space and the relationship with the local environment: sun, earth, wind, and other buildings. Spatial boundary conditions refer to the floor, wall and roof which cover the space. Opening ratio (the ratio of the area that can be opened to relevant floor area), material use and adjacent conditions are the main boundary conditions. It should be noted that the definitions of indoor space, semi-outdoor space and outdoor space are determined by the opening ratio in the horizontal and vertical direction of the building space. If the horizontal opening is big enough, for example, if the roof is completely open, such as in the case of a courtyard or patio (the opening ratio is 1), the space is always considered an outdoor space. If the vertical opening is big enough, for example, one or two facades are completely open, the space is always considered a semi-outdoor space; examples are balconies, corridors, porches or vestibules. The opening conditions can be controlled in some spaces by opening or closing the windows or doors. An indoor space can thus be changed into a semi-outdoor space or an outdoor space. Such a space is known as an adaptive space.

6.2.1.3 Spatial design and adaptive comfort opportunities

As mentioned before, another function of spatial design is to provide different spaces that offer occupants opportunities to adapt their thermal comfort. The living style in this paper is separated into three different styles: daily life, sleep and study. According to adaptive thermal comfort theory, one kind of important adaptive behaviour is movement. If people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like (Humphreys, 1997). Occupants can change their location for different activities. Movement is possible between buildings, between rooms, around rooms, out of the sun and into the breeze, and so on (Nicol et al., 2012). Buildings with diverse spaces provide opportunities for movement. Indoor space, semi-outdoor space and outdoor space are the three typical kinds of spaces. Atria, corridors, porches, patios and courtyards are commonly utilized elements to provide diversity in the types of space in the building. In hot and humid climates, occupants prefer to move from indoor spaces to semi-outdoor spaces. Occupants derive additional comfort from this adaption in two ways: physiologically, as more air movement can influence the comfort sensation, and psychologically, as people prefer an open environment in summer. Heidari (2000) spent a week studying how six subjects used different parts of their house in Llam (Iran) and concluded that the subjects tended to actively seek out the most thermally comfortable spaces in the house over the course of the day; also, Merghani (2004) conducted fieldwork in Khartoum, Sudan, where the climate is hot and dry. The results show that, if given the chance, people will make the best of the spatial diversity available.

6.2.2 The local climate

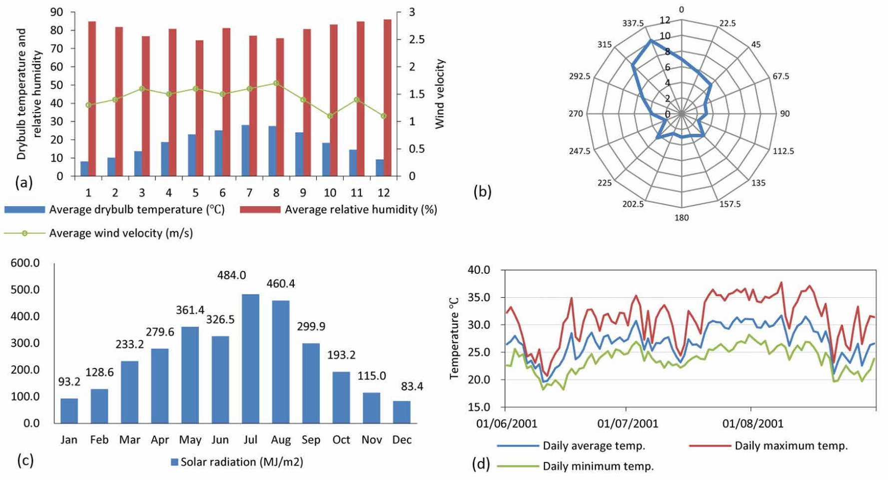

FIG. 6.1 Local climate features in the studied area. (a) Dry-bulb temperature, relative humidity and wind velocity (b) Wind rose (c) Monthly solar radiation (d) Dry-bulb temperature in summer

The studied house is situated in Chongqing, China. Chongqing is located in the southwest of China (longitude 105°11’–110°11’ and latitude 28°10’–32°13’) and belongs to the hot summer and cold winter zone according to the national “Standard of Climatic Regionalisation for Architecture”. The hot summer and cold winter zone is the transient climate region between the cold and the hot zones of China, well-known for its hot and humid summer. Figure 6.1 (National Meteorological Information Center of China Meteorological Administration & Department of Building Technology Tsinghua University, 2005) (a) (b) (c) illustrates the weather features over an entire year. The annual average temperature is 16 to18°C, and the annual relative humidity is 70% to 80%; the extreme maximum temperature is 41.9°C and the extreme minimum temperature is -1.7°C. The levels of yearly solar radiation are high, especially in July and August with a maximum value approaching 500MJ/m^2, while the total solar radiation in July and August accounts for 31% of the yearly radiation. The yearly prevailing wind comes from the northwest and the average wind velocity is 1.6 m/s. Figure 6.1 (d) shows the temperature features in a typical summer. According to the weather data, the temperature is relatively mild from June to the middle of July. The temperature changes quickly and is unstable in this period. From the middle of July to the middle of August, the temperature remains at a stable high level. These 30 to 40 days are the hottest days in summer. After this period, the average temperature decreases, with some days that are nonetheless relatively warm.

6.2.3 Thermal comfort

The adaptive thermal comfort theory can be used to determine the comfort in a free-running building, since the relationship between indoor comfort temperature and outdoor monthly mean temperature for free-running buildings was found to be closely linear in Humphreys's field survey (Nicol & Humphreys, 2002). One of the main outcomes of the adaptive approach is the thermal comfort evaluation method based on field studies, in which the indoor thermal comfort temperature is shown to be a function of the outdoor temperature. The equation is: T_n=A+BT_o, where T_n is the neutral or comfort temperature (°C); T_o is the outdoor monthly mean air temperature (°C); and A, B are constants. The constants A and B are different in different climate regions and cultural contexts. They can be confirmed by field surveys in different regions. Some of the equations, especially applied to China for free-running buildings, are listed in table 6.1.

TABLE 6.1 Adaptive comfort equations (free-running model)

Location (source)	Equation
Humphreys (Humphreys & Nicol, 1998)	T_n = 11.90+0.534T_o
SHRAE Standard 55-2010 (ANSI/ASHRAE, 2017)	T_n = 17.80+0.31T_{ref}
EN15251-2007(EN15251, 2007)	T_n = 18.80+0.33T_{rm}
China (general) (Yang, 2003)	T_n= 19.70+0.30T_o
Shanghai, China (Ye et al., 2006)	T_n = 15.12+0.42T_o
Chongqing, China (Li, 2008)	T_n = 16.28+0.39T_o
Harbin, China (in summer) (Wang et al., 2010)	T_n = 11.802+0.468T_o

Here T_n is the neutral comfort temperature (°C); T_o is outdoor monthly mean temperature (°C); T_{ref} is the prevailing mean outdoor air temperature (°C) (for a time period between last 7 and 30 days before the day in question); T_{rm} is the exponentially weighted running mean of the daily outdoor temperature of the previous seven days.

Another important issue relating to adaptive comfort is the influence of humidity and wind velocity. In free-running or naturally ventilated buildings, the influence of humidity and wind velocity on the thermal comfort sensation of the occupants in hot and humid climate regions is greater than in other climate regions and in conditioned buildings. The cooling effect of air movement depends on not only air velocity but also temperature, humidity and radiation balance, as well as on the activity (metabolic rate) and clothing of the individual (Szokolay, 2000). Studies done in different climates show that occupants prefer greater air movement and that comfort ranges can expand with the aid of air movement (Mishra & Ramgopal, 2013). In hot and humid climate areas, air movement can promote convective heat transfer from the skin and increase the evaporation of sweat. Occupants appreciate air movement, even when it is not necessary for direct cooling (Zhang et al., 2007). In order to approximate the potential cooling effect of elevated air velocity and how this can compensate for a room's high operative temperature, some functions were proposed by ASHRAE Standard 55, EN15251 and functions by other researchers are listed in table 6.2.

TABLE 6.2 Effects of air movement on comfort temperature

Source	Comfort temperature Correction for enhanced air velocity	Conditions
ASHRAE Standard 55-2010 (ANSI/ASHRAE, 2017)	ΔT=1.2, 0.3m/s<V_a<0.6m/s ΔT=1.8, 0.6m/s<V_a<0.9m/s ΔT=2.2, 0.9m/s<V_a<1.2m/s	
EN15251-2007 (EN15251, 2007) Nicol (Nicol, 2004)	$\Delta T = 7 - \frac{50}{4 + 10V_a^{0.5}}$	0.1m/s<Va
Szokolay (Szokolay, 2000)	$\Delta T = 6V_e\text{-}1.6(V_e)^2, V_e = V\text{-}0.2 \text{ m/s}$	V<2m/s
China (Su et al., 2009)	$\Delta T = -4(\varphi\text{-}70\%) + \frac{0.55\text{V}}{0.15}, \text{T} > 28℃$ $\Delta T = \frac{0.55V}{0.15}, \text{T} < 28℃$	V<0.8m/s

Here ΔT is the raise in comfort temperature (°C); T is the indoor air temperature (°C); V_a is the air velocity (m/s); V is the air velocity at the body surface (m/s); ϕ is the relative humidity (if less than 70%,ϕ =70%)

6.2.4 Spatial configuration, building microclimate and thermal comfort

Spatial design is an important passive cooling strategy, see figure 6.2. It can cool down the microclimate in two important ways: via solar control and natural ventilation. Solar radiation is the main factor that increases the building cooling load in summer. It denotes the complete or partial, permanent or temporary exclusion of solar radiation from building surfaces or interior or surrounding spaces (Geetha & Velraj, 2012). Orientation and shading (self-shading) are the major methods for solar control related to building spatial configuration. Natural ventilation is achieved by infiltration and allowing air to flow in and out of a building by opening windows and doors (Santamouris & Asimakopoulos, 1996). Wind driven and stack driven natural ventilation are the main styles. Therefore, architectural spatial design has a significant effect on thermal environment, and especially on thermal comfort. The influence of the spatial configuration is two folds: in the first place, spatial design can influence the building microclimate directly. An appropriate spatial design can, for example, cool down the building microclimate in summer. In the second place, it can provide adaptive comfort opportunities for the occupants, which is significant for summer thermal comfort.

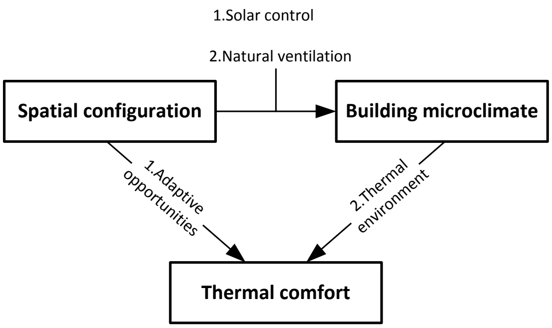

FIG. 6.2 The relationship between spatial configuration, building microclimate and thermal comfort

6.3 Method

6.3.1 Profile of the studied house

The selected house is a town house located in a suburban district of Chongqing constructed in 2010. The house is situated in a residential community with mixed building types. It is located on a cliff and faces 12 degrees off south-east (Figure 6.3). To the east of the house is a golf course with a huge green area. To the west of the house are three high-rise apartment blocks that are approximately 100 m high. The adjacent houses are built to the south and the north of the house. Figure 6.3 shows the location and overview of the environment of the house.

The total habitable floor area of the house is around 325 m^2. The house is around 8 m wide, with a depth of around 15 m. Figure 6.4 shows the plans, elevations and sections. There are four floors in the building. The basement floor (-1F) is a semi-basement with three of the walls underground because of the mountainous terrain. One of the walls on the ground floor (0F) is also under-ground, while the first floor (1F) and second floor (2F) are completely above ground. There are nine main rooms, three patios, two courtyards, one balcony and two terraces. A play-room and a garage are situated on the semi-basement. Patio 1 and patio 3 are on the semi-basement and the ground floor. The ground floor boasts a living room on the east-southeast side; a kitchen and dining room are located on the west-northwest side of the house. Patio 1, 2 and 3 were designed to surround the dining room. On the north-northwest side of the house is a courtyard with grass and trees. The first floor features two bedrooms facing east-southeast and a family room on the west-northwest part of the plan. Bedroom 1 has a balcony on the east-southeast; a grassy rear courtyard is located to the west-northwest of the house. On the second floor, the master bedroom and the study room are on the east-southeast side; one terrace faces towards at the west-northwest; another is near the study room.

FIG. 6.3 Location of the studied object and its environment

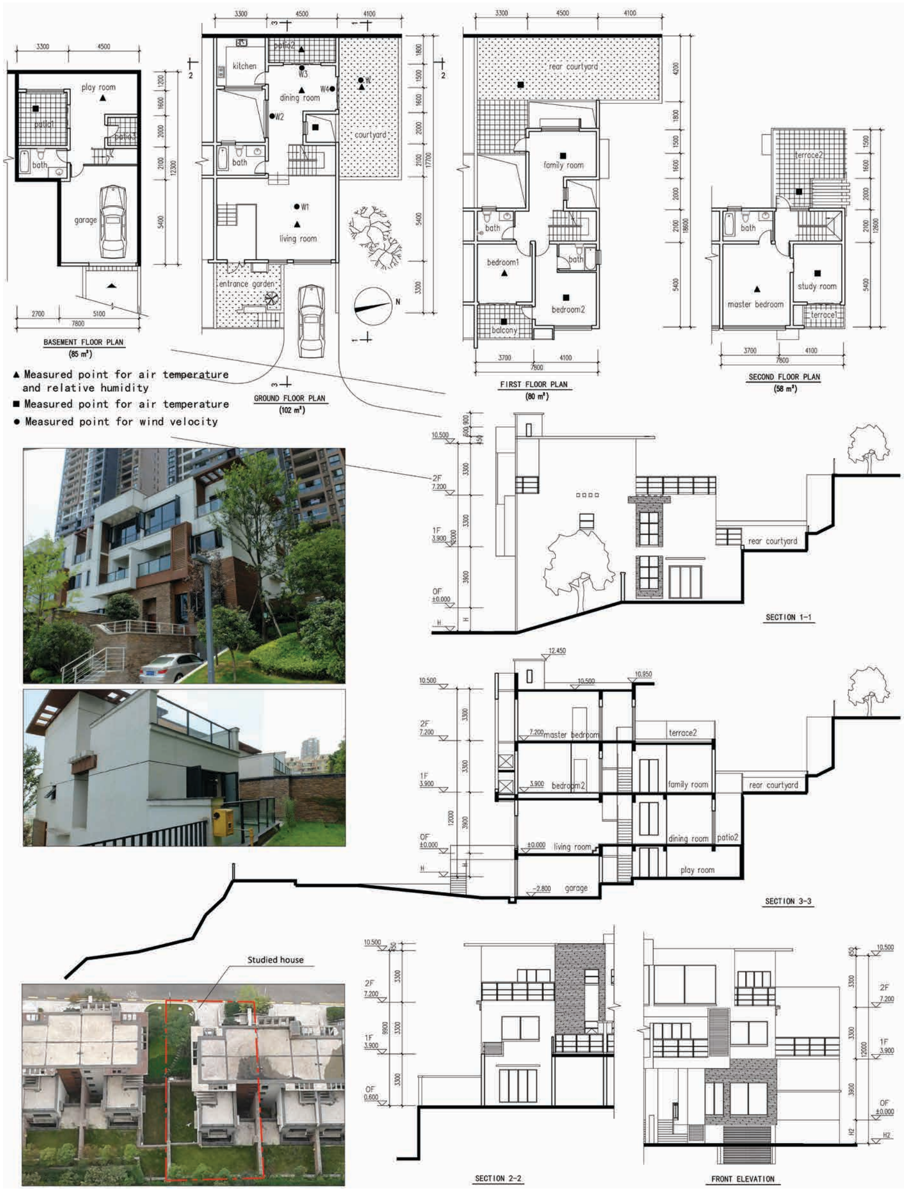

FIG. 6.4 Plans, elevation, sections, appearance and measurement points of the studied house in Chongqing, China

6.3.2 Building Microclimate Measurements

In this study, the authors focus on the affects of building spatial design to the building microclimate, and then for the residents' thermal comfort. There are some literatures about the physical environment measurements (Silva & Henriques, 2014; Wang, Long, & Deng, 2017) and simulation (Cardinale et al., 2013; Chen & Yang, 2015; Taleghani, Tenpierik, & van den Dobbelsteen, 2014b; Taleghani et al., 2013) for thermal comfort prediction. Therefore, the selected object of this study was an untenanted house with no interior decoration, making it ideal for the purpose of this research, as the intrinsic thermal environment could be studied without disturbance. For the investigation of the thermal environment, measurements were carried out in the house on typical summer days. The air temperature and relative humidity were measured in the various spaces of the house. The air velocity was measured in detail at key points throughout the ground floor space.

Building Microclimate measurements were performed in the summer period from August 18 to August 22 2014. The measurement points are shown in figure 6.4, and the measurement setup is shown in figure 6.5. Temperature and relative humidity were measured at 7 different points in the building, and the temperature was measured at an additional 8 points. The measurement instruments employed were automatic temperature loggers and temperature and humidity loggers recording data every ten minutes. The temperature measurement had an accuracy of 0.2°C; the humidity measurement had an accuracy of 5%. The instruments were located at a height of 1.2 m above the ground at the indoor and outdoor measuring points. The sensors measuring the air temperature and relative humidity at the outdoor points were protected by a white shield to minimise the radiation effect. Wind velocity was measured with the help of a manual anemometer with an accuracy of 5% of the value plus 0.05 m/s. During measurement periods, the house was free-running, in this case without occupants and mechanical ventilation. The house had no interior decoration and there were no doors in the interior rooms. The rooms could therefore be considered to be connected through holes in the wall. The windows and doors in the facades were semi-opened, which, because of the construction of the window, was the maximum open area. Before the measurements started on August 18, the weather was rainy. During the first three days of measurements (August 18-21), it was sunny and partly cloudy. On the last day, August 22, it was rainy again.

FIG. 6.5 The measurement setup in the studied house

6.3.3 Thermal comfort calculation

To evaluate the thermal comfort of the house, a dynamic thermal simulation was performed using DesignBuilder software, which is a comprehensive user interface for the EnergyPlus dynamic thermal simulation engine. Two simulations were performed. Firstly, the thermal environment of the house was simulated for the measured days (August 18-22) using actual outdoor weather data from the nearest weather station as the input weather data for the simulation. The simulated air temperatures in different spaces were compared with the measured data to validate the 3D model and simulation settings. Then, a dynamic thermal simulation of the house was performed during the entire summer (June 1 to August 31) using the typical meteorological year data from the EnergyPlus weather data for Chongqing to evaluate the summer thermal performance of the house.

Figure 6.6 shows the 3D model of the house in DesignBuilder. It should be noted that the patios were modelled as indoor spaces with roof windows because of the constraints of the software. This setting will influence the accuracy of the simulated thermal environment in the patios. However, the accuracy is assumed to be sufficient for the purpose of the present analysis, which aimed to compare the measurements with the simulations in order to be able to predict the temperature over a large time period and in all the rooms.

The characteristics of the simulated house and the characteristics of the building components are shown in table 6.3. The building performed as a free-running building with natural ventilation without any heating or cooling. In the case of validation, there was no activity setting that the house was operated without occupants and equipment corresponding to the actual situation. For the simulation of the entire summer, activity was set in terms of occupants and equipment were considered, and the internal heat loads were produced. The windows on the outside walls were assumed to be half opened and the roof windows in the patios completely opened, reflecting the actual situation. The infiltration was switched off, since infiltration heat that flows through the cracks is only a very small part of the summertime air flow, if the windows in the outside wall are half opened.

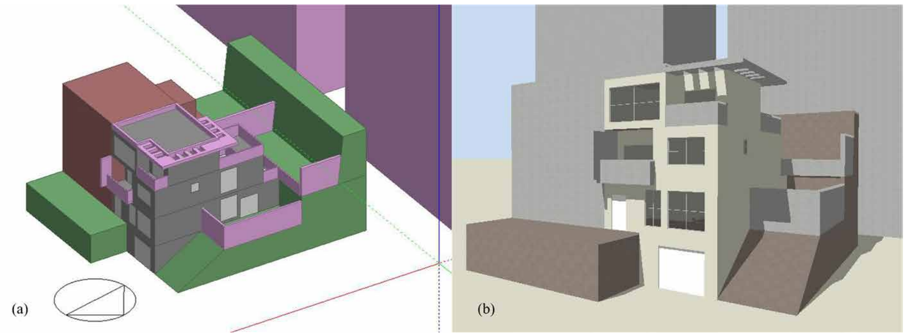

FIG. 6.6 Simulation model (a) 3D model (b) rendered model

TABLE 6.3 Input parameters of the simulation

Characteristics /component	Description		
Location	Chongqing		
Running model	Free-running		
Activity	Without occupants and equipment (for validation) With occupants and equipment (for entire summer)		
Natural ventilation	Natural ventilation-no heating/cooling, calculated, constant		
Construction	**Material**	**Thickness (mm)**	**U-Value (w/m²-k)**
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

6.3.4 Validation of the simulation with measurements

The hourly temperatures of the house during summer were obtained from the simulation. In figure 6.7, the simulated air temperature on the different floors was compared with the measured data obtained from the measured five days. The simulated results were found to fit well with the measured results: the simulated temperature variation showed the same trend as the measured results. The simulated temperature fluctuation was bigger than the measured one, indicating that the simulated minimum and maximum peak temperature were higher than the measured temperatures. Nonetheless, while a very small portion of the measured data fell within a 15% range of the simulated data, most fell within a 10% range of the simulated data. Therefore, the accuracy of the simulation was considered to be sufficient to obtain the thermal environment data of the house for the thermal performance evaluation.

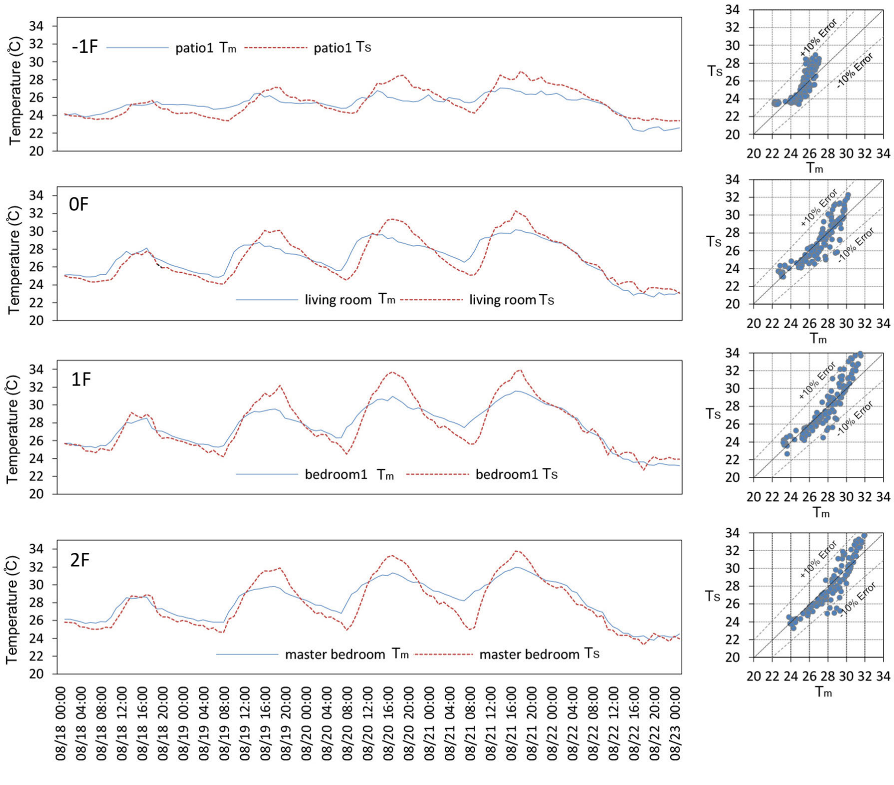

FIG. 6.7 Comparison of simulation results and measurement results.
Ts: simulated temperature, Tm: Measured temperature

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6.4 Results

6.4.1 Spatial configuration

The different spaces in the house are characterised according to their spatial configuration. This spatial configuration consists of the spatial geometric features (height, size, horizontal and vertical location and orientation), the spatial boundary conditions (horizontal and vertical opening area, major materials and adjacent spaces), and the occupants' activities (daily life, sleep or study and the time periods that the spaces are used), as shown in table 6.4. The profile of the house shows that it was designed to create different types of spaces, not only in the horizontal but also in the vertical direction. Based on the spatial configuration the spaces were divided into indoor space, semi-outdoor space or outdoor space. The analysis of the different spaces in the building shows that a lot of different spatial configurations can be found in this building. The horizontal openings and the vertical openings have a large range, from 1.8 to 56 m^2 and 4 to 50 m^2 for the horizontal and vertical openings, respectively. The floor areas also differ a lot in size, from 4.2 m^2 to 42.1 m^2. The orientation of the vertical openings is only E-SE or W-NW, thus avoiding the South and South-West orientation.

6.4.2 Temperature measurements

Figure 8 illustrates the hourly air temperature and relative humidity curves in different rooms of the basement floor, ground floor, first floor and second floor over the entire measured period of five days. The average temperature measured rose from day one through day four, but decreased suddenly on the final day due to heavy rainfall. This short-term climatic shift is a characteristic weather feature of the local climate conditions: rainy weather can turn to sunny as the temperature rises, and back to rainy within a short period of time. Because of the rain, the last day was not included in the analysis. The trends of the curves were similar on the four days on which the measurements were taken, which means there was a similar variation in temperature over theses four days. During this period, the lowest reference outside temperature, T_{wst}, was around 24°C and the highest was 30- 35°C. The weather was relatively mild in this period, under the local summer weather conditions. The relative humidity followed the temperature trends, i.e. when the temperature increased, the humidity decreased. The humidity varied from 30% to 90%, which matches the highly humid summers of the local climate. Since the humidity followed the temperature trend, the further analysis focused on the temperatures; and because the temperature trends were similar over the four days on which the measurements were taken, the following analysis focused on one entire day, i.e., August 20.

Figure 6.9 shows the hourly average temperature curves and the temperature variations in different spaces on August 20, separated in indoor spaces (a) and outdoor space (b) and semi-outdoor spaces (c). The indoor temperatures were higher than the outdoor temperature in the period between 00:00-10:00 and 21:00 and 24:00. On the other hand, the indoor temperatures were lower than the reference outside T_{wst} in the period between 10:00-21:00. The trend of the indoor temperatures is very similar except for the playroom (in the basement) which has a constant 25°C. The difference in temperatures between the different spaces, except for the playroom, can be up to 2°C.

Comparing the outside temperatures, immediately noticeable is the sudden temperature change in the curves of patio2 and the rear courtyard. The temperature was found to soar swiftly to an extremely high level in a short period. The temperature in patio 2 rose suddenly at 12:00 from 30.5oC to peak at 38.8°C at 13:00, after which it quickly dropped to 32.2°C at 14:00. The reason is that patio2 is a very narrow space with a height-to-width ratio of 3; direct solar radiation was only able to reach the logger at the bottom of the patio during the period between 12:00-14:00. The temperature measured was influenced by the radiation, although radiation-shield instrument boxes were used to minimise this effect. Therefore, the actual curve (dashed curve) could be modified as the solid curve in this period based on the average increase rate before 12:00. Similar situations occurred at the measurement point in the rear courtyard. However, the rear courtyard was a relatively broader space than patio2, so the period during which it was heated up by direct solar radiation was longer on patio2. The curve of the rear courtyard was modified for the period between10:00-15:00. The measured temperature at the bottom of Patio1 remained very low and relatively stable, with a temperature fluctuation of only 2°C during the entire day. At night, all the measured temperatures in the outdoor spaces were almost at the same level as the reference outside T_{wst}. After the temperature increased at 7:00, patio1 peaked at 27°C (13:00), patio2 peaked at 32°C (corrected temperature) (14:00), patio3 peaked at 30°C (15:00), the courtyard peaked at 31.5°C (14:00) and the rear courtyard peaked at 35°C (corrected temperature) (13:00). As can be seen, the temperatures in the outdoor spaces were much lower than the weather station temperature (except for the rear courtyard), and there was a huge temperature variation in the outdoor spaces.

TABLE 6.4 Spatial design features in three aspects of the studied house

Space type	Space name	Spatial features in four aspects													
		1.Spatial geometric features						2.Spatial boundary conditions						3.Activities	
		Size (plan)(m)	Height (m)	Area (m²) S	Horizontal Location (from the centre of the house)	vertical Location (in floor)	Orientation (main windows)	Vertical opening area (m²) S_v	Vertical opening ratio S_v/S	Horizontal opening area (m²) S_h	Horizontal opening ratio S_h/S	Major materials 1. Roof or ground 2. wall	Adjacent spaces (major spaces)	Periods in use	Activities
1.Indoor space	Play room	4.5x2.8	2.2	12.6	-	-1	-	0	0	0	0	1.Concrete 2.cavity brick	Patio1,3	M,A, E,N	Daily life
	Living room	7.8x5.4	3.6	42.1	-	1	E-SE	2.2	0.05	0	0	1.Concrete 2.cavity brick	Dining room	M,A,E	Daily life
	Dining room	4.5x3.1	3.3	17.2	-	1	W-NW	22.3	1.30	0	0	1.Concrete 2.cavity brick	Patio 1,2,3, court-yard, living room	M,A,E	Daily life
	Bedroom 1	3.7x3.9	3.3	14.4	-	2	E-SE	2.2	0.15	0	0	1.Concrete 2.cavity brick	Bed-room2, balcony	N	Sleep
	Bedroom 2	4.1x3.6	3.3	14.8	-	2	E-SE	1.8	0.12	0	0	1.Concrete 2.cavity brick	Bed-room1, balcony	N	Sleep
	Family room	4.5x3.1	3.3	14	-	2	W-NW	2.5	0.18	0	0	1.Concrete 2.cavity brick	Pa-tio1,2,3, rear courtyard	M,A, E,N	Daily life
	Master bedroom	4.5x5.2	3.3	23.4	-	3	E-SE	3.0	0.13	0	0	1.Concrete 2.cavity brick	Study room, terrace1	N	Sleep
	Study room	3.3x3.9	3.3	13	-	3	E-SE	1.8	0.14	0	0	1.Concrete 2.cavity brick	Master bedroom, terrace1	M,A, E,N	Study

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TABLE 6.4 Spatial design features in three aspects of the studied house

Space type	Space name	Spatial features in four aspects													
		1.Spatial geometric features						2.Spatial boundary conditions						3.Activities	
		Size (plan)(m)	Height (m)	Area (m^2) S	Horizontal Location (from the centre of the house)	vertical Location (in floor)	Orientation (main windows)	Vertical opening area (m^2) S_v	Vertical opening ratio S_v/S	Horizontal opening area (m^2) S_h	Horizontal opening ratio S_h/S	Major materials 1. Roof or ground 2. wall	Adjacent spaces (major spaces)	Periods in use	Activities
2.Outdoor space	Patio 1	3.3x3.6	5.8	12	W-NW	-1, 1	-	-	-	12	1	1.Concrete 2.cavity brick	Play room, Dining room, rear courtyard	M,A,E	Daily life
	Patio 2	4.5x1.8	3.6	8.1	W-NW	1	-	-	-	8.1	1	1.Concrete 2.cavity brick	Dining room, rear courtyard	M,A,E	Daily life
	Patio 3	2.1x2.0	5.8	4.2	N-NW	-1, 1	-	-	-	4.2	1	1.Concrete 2.cavity brick	Play room, Dining room, courtyard	M,A,E	Daily life
	Courtyard	4.1x9.1	-	37.3	N-NW	1	-	-	-	37.3	1	1.Soil 2.cavity brick	Dining room, patio3	M,A,E	Daily life
	Rear courtyard	12x4.2	-	50	W-NW	2	-	-	-	50	1	1.Soil 2.cavity brick	Patio1.2, courtyard	M,E	Daily life
3.Semi-outdoor space	Terrace 1	3.3x1.5	-	5	E-NE	3	-	13.3	2.68	4	0.8	1.Concrete 2.cavity brick	Study room, Master bedroom	A,E	Daily life
	Terrace 2	4.7x3.1	-	14.6	W-NW	3	-	56.1	3.85	13	0.9	1.Concrete 2.cavity brick	Study room, Master bedroom	M,E	Daily life
	Balcony	3.7x2.1	3.3	7.8	W-NW	2	-	11.6	1.49	12	0	1.Concrete 2.cavity brick	Bed-room1,2	A,E	Daily life

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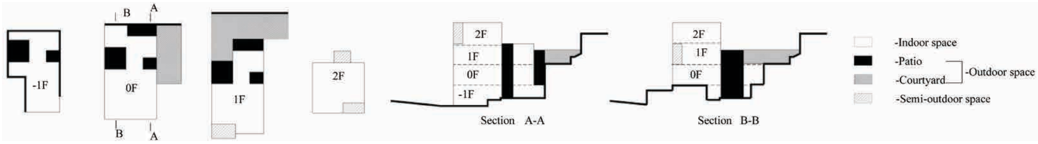
TABLE 6.4 Spatial design features in three aspects of the studied house

The diverse space of the house in horizontal and vertical direction



The images of three kinds of spaces

1. Indoor space:
1(a) living room (b) dining room (c) bedroom1,2 (d) master bedroom

2. Outdoor space:
2(a)(e) patio1 (b) patio2 (d) patio3 (c) (g) courtyard (f) rear courtyard

3. Semi-outdoor space:
3(a) balcony (b) terrace2 (c) terrace3

**N-north; S-south; E-east; W-west; SE-south east; NW-north west*
**M-morning; A-afternoon; E- evening; N-night*

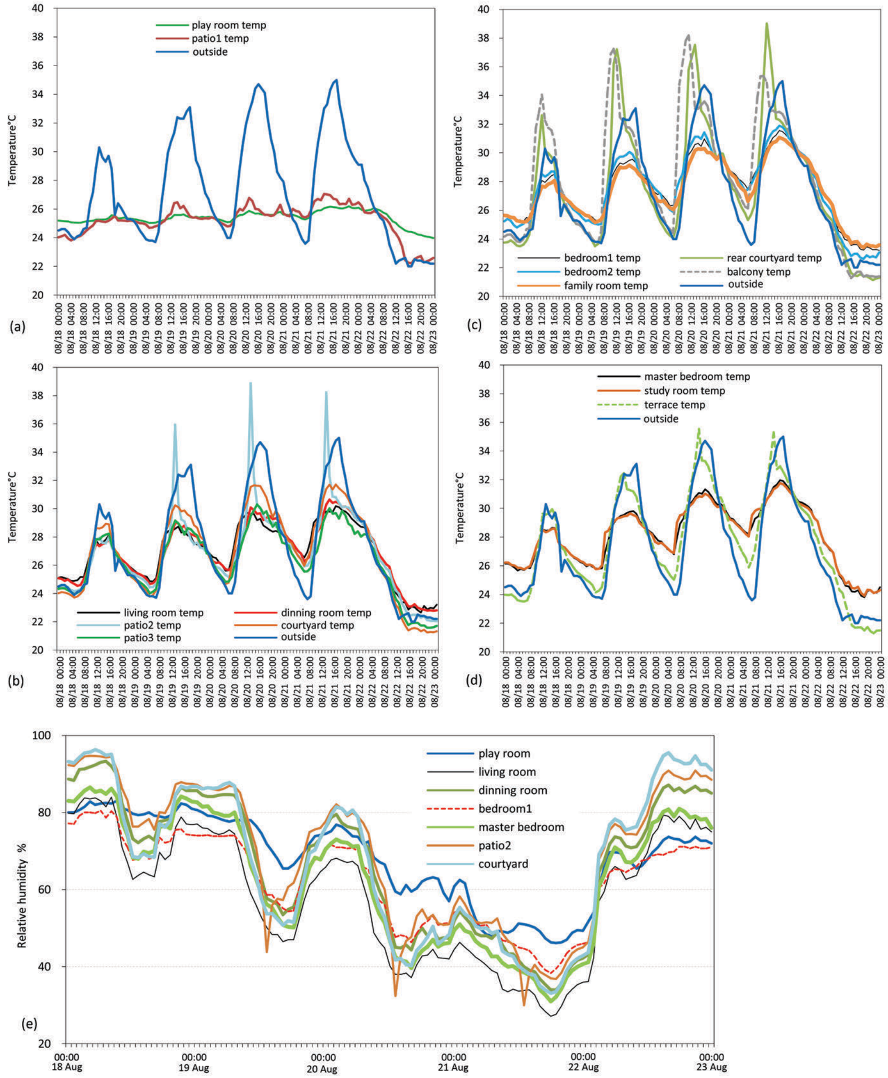


FIG. 6.8 Temperature and relative humidity curve of the measured points (hourly).
(a) temperature of the rooms in the basement floor (b) temperature of the rooms in the ground floor (c) temperature of the rooms in the first floor (d) temperature of the rooms in the second floor (e) relative humidity of the measured points

Figure 6.9(c) shows the temperatures in the semi-outdoor spaces compared with the reference outside T_{wst}. The semi-outdoor temperature curves were also modified during the period with direct solar radiation based on the same reason mentioned above. At night, the temperatures on the balcony and the terrace remained at the level of reference outside T_{wst}. The balcony temperature peaked at 34°C at 10:00 and the terrace temperature reached its peak at 33.5°C at 13:30 which is close to the weather station temperature.

Figure 6.9(d) shows the temperature variation in different spaces at different times. The temperatures in the play-room and patio1 were similar and much lower (4-7°C) than the temperatures in other spaces: outdoor, semi-outdoor or indoor spaces throughout the entire day. Except for these two spaces in the semi-basement, the night-time peak temperature in the indoor space was higher than the temperature in the outdoor and semi-outdoor spaces. This was reversed during the day, with the maximum difference of 4°C. The biggest difference in temperature variation was around 8°C in all of the compared spaces.

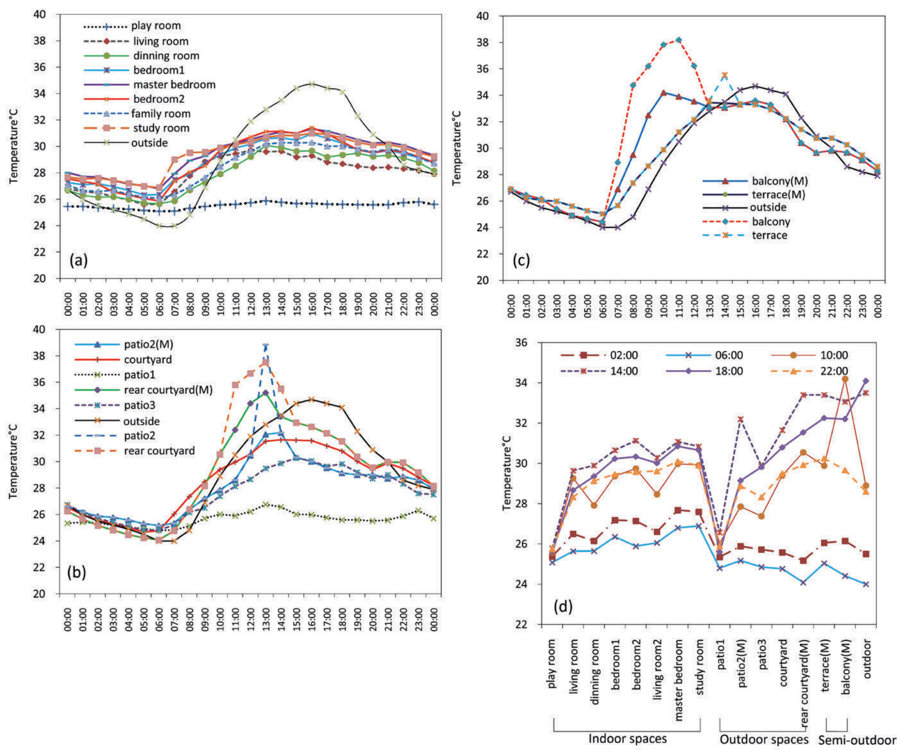


FIG. 6.9 Hourly temperature variation curve of the measured points on August 20 (M stands for modified) (a) Indoor spaces (b) Outdoor spaces (c) Semi-outdoor spaces (d) Temperatures in different spaces for different times over the day

6.4.3 Air velocity

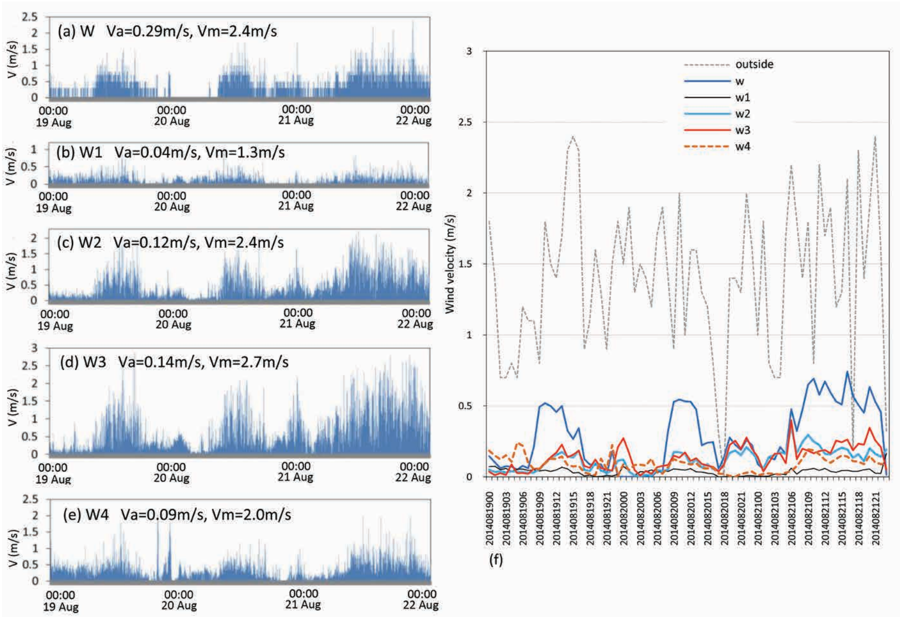


FIG. 6.10 (a)-(f) Wind velocity measured in different spaces
(a) Wind velocity in the courtyard (b) Wind velocity in the living room (c) Wind velocity near patio1 (d) Wind velocity near patio2 (e) Wind velocity near courtyard; Va: average wind velocity Vm: maximum wind velocity
(f) Hourly wind velocity measured in different spaces and outside wind velocity at the weather station

Figure 6.10(a)-(e) shows the wind velocity per second in the period spanning August 19-21 at the measured points shown in figure 3. The wind velocity was found to follow the general trend of the observed temperature change for all of the measured points. The average wind velocity on August 21 was higher than on August 20, and higher on August 20 than on August 19. The results were matched with the temperature changes occurring over these three days. On one of the days, the wind velocity increased concurrently with the temperature and peaked at almost the same time as the temperature. The wind velocity was low at night. This indicated that the difference in temperature indoors and outdoors significantly influenced the air flow in this particular building environment. The graph also shows that the air flow was unstable and fluctuated from 0 to 2.7 m/s.

Comparing the average wind velocity (V_a) over these three days, it can be seen that the wind velocity in the courtyard (0.29 m/s) was higher than at a point near patio2 (0.14 m/s), followed by the point near patio1 (0.12 m/s), the point near the courtyard (0.09 m/s) and the point in the living room (0.04 m/s). Figure 6.10(f) shows the hourly average wind velocity at the measured points and the wind velocity recorded by the nearest weather station. The weather station wind velocity was much higher than the measured wind velocity in this specific building microclimate, owning to the location of the weather station in the open field, where it catches more wind. Another finding was that the outdoor wind velocity was irregular compared to the measured points in the building, which followed the temperature trends. Most of the time, the wind velocity in the courtyard was the highest in the building environment due to the fact that it is an outdoor space that easily catches the wind from all directions. The measured wind velocity at the points near patio1 and patio2 was higher than at the point in the living room, indicating both a low level of cross ventilation on the ground floor and that the stack ventilation in the patio contributed to the process of natural ventilation. In other words, the spatial diversity enhanced the natural ventilation. The results show that the wind velocity distribution is varied in the building.

6.4.4 Thermal comfort in summer

Figure 6.11 shows the simulated operative temperature of the house in the period of June-August and the comfort temperature zone. The comfort temperature zone is determined using the adaptive comfort approach for the Chongqing area as given in table 6.1 (Li, 2008). The relationship between the thermal comfort temperature and the monthly mean outdoor temperature then is: $T_n = 16.28+0.39T_o$, where T_n is the comfort temperature (°C) and T_o is the monthly mean outdoor temperature (°C); the range is 5.0-30.0°C (Li, 2008). According to this equation, the comfort temperatures in June, July and August are: 26.1°C, 27.2°C and 27.1°C. According to ASHRAE Standard 55, a comfort zone band of ±2.5°C corresponds with 90% acceptability, and ±3.5°C corresponds with 80% acceptability. So, the comfort zone, which in this case corresponds to 90% acceptability, ranges from 23.6-28.6°C in June, 24.7-29.7°C in July to 24.6-29.6°C in August.

On the relative mild days from June to the middle of July, the operative temperature was lower than the upper temperature limit of the comfort zone on most days. The building has the ability to provide a comfortable thermal environment for the occupants without mechanical cooling most of the time. During the hottest days, from mid-July to mid-August, almost all of the operative temperatures in the daytime exceeded the upper temperature limit of the comfort zone. Hence, a comfortable thermal environment could not be achieved in the building using the free-running model. On the relatively warm days at the end of August, the amount of time during which thermal comfort could not be achieved was limited, which means that the thermal environment of the building was acceptable most of the time. Table 6.5 shows the percentage of hours above the upper limit, in comfort range and below the lower limit in different spaces for the three periods mentioned above.

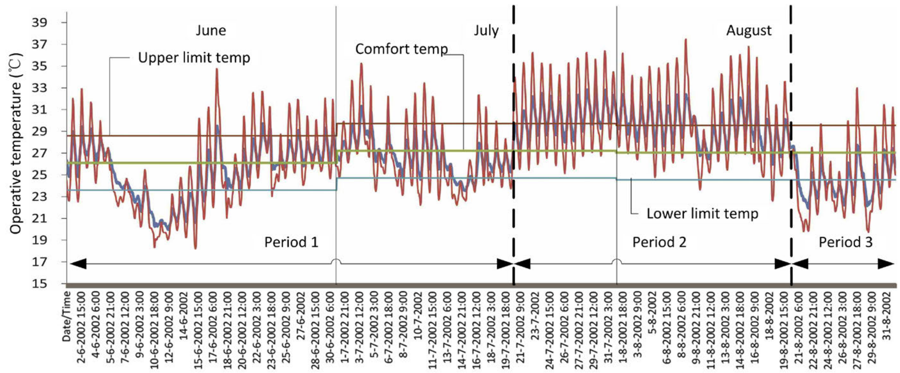


FIG. 6.11 Simulated operative temperature of the house during the entire summer (the red curve is the outside Dry-Bulb temperature and the blue curve is the operative temperature)

TABLE 6.5 Percentage of hours (24h per day) above the upper limit, in comfort rang, and below the lower limit in different spaces according to the different thermal periods (slightly warm, hot and warm) of figure 11

		Period 1(6/1-7/20) outside temperatures slightly warm			Period 2(7/21-8/20) outside temperatures hot			Period 3(8/21-8/31) outside temperatures warm		
		> (%)	=(%)	< (%)	>(%)	=(%)	<(%)	>(%)	=(%)	<(%)
B1	Patio 1	11.2	70.7	18.1	63.2	36.8	0	0	48.3	51.7
	Play room	2.8	77.6	19.6	47.4	52.6	0	0	43	57
GF	Living room	13.7	69.1	17.2	70.1	29.9	0	0.3	56	43.7
	Dining room	13.1	68.5	18.4	64.7	35.3	0	0.3	53.5	46.2
1F	Bedroom1	16.8	66.2	17	75.9	24.1	0	1.7	59.1	39.2
	Bedroom2	16.9	65.9	17.2	75.5	24.5	0	1.4	59.4	39.2
	Family room	15.6	67.4	17	71.2	28.8	0	1.4	59.1	39.5
2F	Master bedroom	20.6	64.3	15.1	79.8	20.2	0	2.4	66.4	31.2
	Study room	17.4	66.1	16.5	78.3	21.7	0	1	60.5	38.5

“>”-percentage hours above upper limit; “=”-percentage hours in comfort rang; “<”-percentage hours below lower limit

Figure 6.12(a) illustrates the total percentage of comfort hours, percentage of discomfort hours (temperature exceeded upper limit) and discomfort hours (temperature dropped below lower limit) in the different spaces for the entire summer. The percentage of comfort hours ranged from 49-65%, with the lowest percentage measured in the master bedroom and the highest in the play-room. It should be noted that the percentage of discomfort hours includes the hours when the operative temperature is below the lower limit. However, when the operative temperature drops below the lower limit of comfort temperature, in the studied area in summer, cold is relatively easy to solve, for example by wearing more clothes. If we disregard the discomfort hours when the temperature was lower than the lower limit of the comfort zone, the percentage of comfort hours stretches remarkable, see figure 6.12(b)). As we can see, the percentage of comfort hours varies considerably from one space to another. In the basement (play-room), the percentage that the temperature does not exceed the upper comfort limits was 83% and in the second floor (master bedroom), the percentage of hours that the upper comfort was not exceeded was only 62%.

Increased air movement can increase the number of comfort hours even more. According to the measured wind velocity in the living room and dining room, the average wind velocity was 0.04 m/s in the living room, which is too low to increase the comfort level. In the dining room, however, the average wind speed reached 0.14 m/s, which was high enough to influence the comfort temperature. Assuming the average wind velocity remains at 0.14 m/s in the dining room, according to Nicol's proposed equation, the comfort temperatures in June, July and August may be increased to 26.6, 27.8 and 27.6°C, respectively. The percentage of comfortable hours would then rise by 3% in June, 7% in July and 8% in August (figure 6.12(c)). Actually, the influence of the wind velocity in the dining room is even greater as the assumed wind velocity of 0.14 m/s represents the average over the three days on which the measurements were taken. The wind velocity was around 0.2 m/s during the daytime (9:00am-6:00pm), which is higher than it was at night. Calculated on the basis of the average wind velocity during the daytime, the percentage of comfortable hours would increase by 6% in June, 11.2% in July and 9.2% in August. Hence, during the daytime, the influence of wind velocity for comfort temperature is bigger than at night.

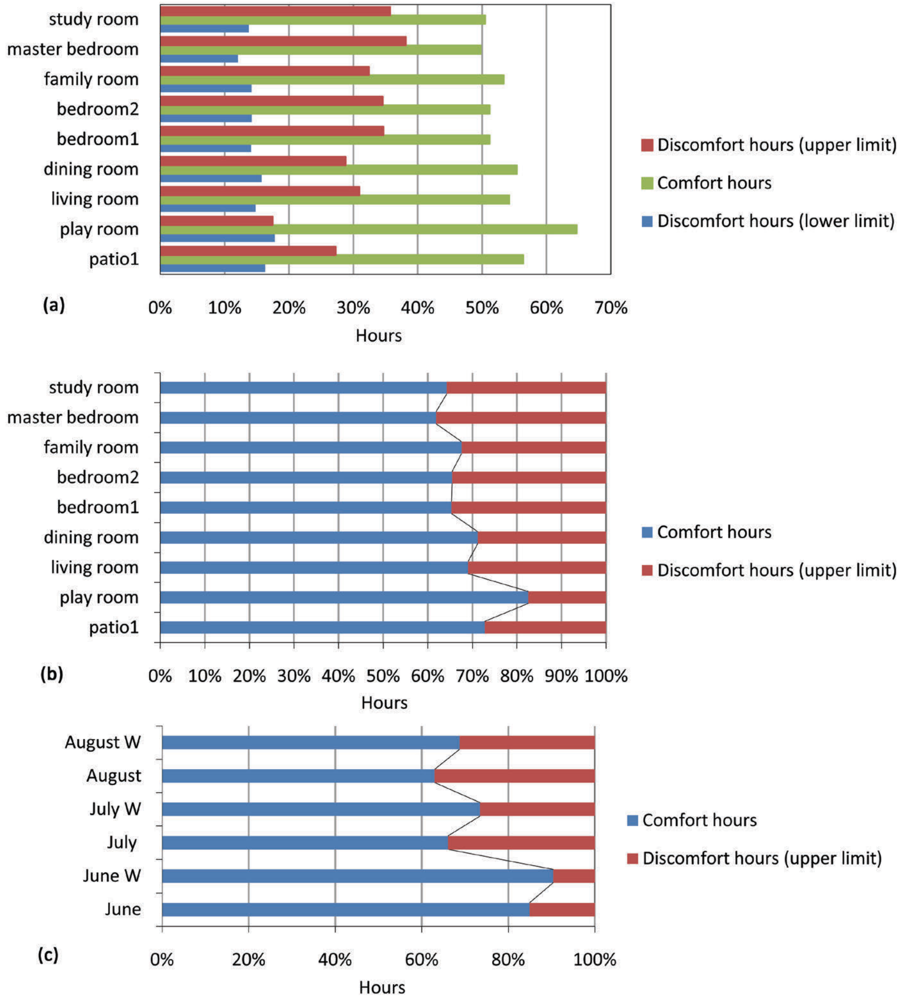


FIG. 6.12 (a) Comparison of the comfort hours and discomfort hours in different spaces (b) Comparison of the comfort hours (hours below lower limit are involved) and discomfort hours (upper limit) in different spaces (c) Comfort hours (hours below lower limit are involved) increasing caused by the wind velocity in the dining room (June, July, August –without wind velocity; June W, July W, August W –with wind velocity)

6.5 Conclusions

In this study, the spatial configuration, building microclimate and thermal comfort of a modern town house were analysed with the help of a field survey, measurements and simulation. The first finding is that the studied house has a varied spatial design, which creates diverse thermal environments in this modern building.

- The general temperature of the building and the peak temperatures in most of the spaces were much lower than the outside weather station reference temperature T_{wst}, during the daytime, especially in the indoor spaces. The maximum difference between reference outside T_{wst} and the temperature in the building was around 9°C.
- There is a diverse temperature distribution in the different spaces of the studied house. The biggest temperature difference was around 8°C. The measured temperature was higher with a higher vertical location. The temperature variation in the outdoor spaces was bigger than in the indoor spaces.
- The temperature in the spaces in the semi-basement remained very low and stable, both in the indoor space and in the outdoor space. For example, the temperature measured on patio1 and patio2 were shown to remain very low during the hottest period of one day.
- The temperature in the outdoor and semi-outdoor spaces was influenced by the orientation and shape of these spaces. Without direct solar radiation, the temperature was maintained at a low level, that was also lower than the reference outside T_{wst} throughout the whole day.
- Significant wind velocity can constantly be obtained in this building. The temperature difference between the bottom and top of Patio1 and patio2 illustrates the potential of stack ventilation. The measured average wind velocity also differs at the various measured points by a maximum of 0.14 m/s.

The second finding is that the microclimate of this particular building can provide considerable thermal comfort for the occupants in summer under local climate conditions. The diverse spatial design also provided the opportunity for occupants to maintain their thermal comfort by means of movement. There are at least 16 different thermal environments in the building. According to adaptive thermal comfort model, thermal comfort is relatively easy to achieve in most of the spaces of this modern house for most of the summer time, in the free-running model. The percentage of discomfort hours during which the temperature exceeds the upper limit of the comfort zone can be limited to 17% in the semi-basement room over the whole summer. Sufficient wind velocity can be achieved, especially in the dining room, by opening the windows and doors to regulate the thermal environment.

However, in the hottest days, thermal comfort cannot be achieved through free-running model so that mechanical cooling or mixed model are needed. In addition, when we consider the adaptive behaviour (for example movement and opening window) of occupants, their living habits should be taken into account.

Comparing this modern house case and our previous study-the vernacular house (Du et al., 2014), some similarities and differences can be found between them. Both of them have diverse spatial design with courtyards, patios, semi-outdoor spaces and indoor spaces. But the volume of the vernacular house is much larger than the modern house. The vernacular house only has one floor, so that the diverse spaces are spread horizontally. However, the modern house has four floors and the diversity extends vertically. The diversity of the thermal environment has the same characters with the spatial diversity. The spaces in the vernacular house are more diverse than the modern house because the size and volume is much larger. The vernacular house is also easier to obtain the cross natural ventilation. The modern house also has its advantages in space. For example, the basement is significant for the diversity of the thermal environment. It can be concluded that we cannot copy the spatial design of the vernacular house, but spatial diversity could be achieved in the modern house design.

There are still some limitations to the present study. The occupants' activities and satisfaction with the thermal environment are absented, as our focus in this case was on the physical thermal environment. Because of the limitations of our measurement instruments, the solar radiation was not measured and the wind velocity could not be obtained in every room. For the thermal simulation, the thermal comfort in the outdoor spaces could not be calculated because of the limitations of the software. Future research will look at the occupants' perception in a particular spatial and thermal environment. How to apply spatial configuration as the design strategy for passive cooling is also the focus.

Acknowledgments

The authors gratefully acknowledge professor Tang Mingfang from Chongqing University for the help of the field measurements.

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7 Can thermal perception in a building be predicted by the perceived spatial openness of a building in a hot and humid climate?[6]

ABSTRACT The authors wanted to prove that there is a large correlation between the concepts spatial openness and comfort (visual, wind speed and thermal) perception in people's minds in a hot and humid climate in summer in order to be able to use

6 This chapter is originally published as: Du, X., Bokel, R., & van den Dobbelsteen, A. (2017). *Can thermal perception in a building be predicted by the perceived spatial openness of a building in a hot and humid climate?* Paper presented at the PLEA 2017 Design to Thrive, Edinburgh. Part of the content is slightly modified in this thesis.

spatial configuration parameters such as openness, connectivity and depth as a design tool for a comfortable an energy efficient building in the early design stages. 513 local Chinese college architecture students in 2015 were questioned about the relationship between spatial openness and comfort perception. The main findings for a hot and humid climate are: a. spatial openness of a particular space significantly effects occupants' visual perception, wind speed perception and thermal perception in a particular space ($p < .05$). b. There is a strong effect size between spatial openness and visual and wind perception ($w = .50$ and $.54$); the effect size of the thermal perception is weaker ($w = .14$). c. The comfort perception is strongly influenced by the time of day, therefore visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort.

KEYWORDS Spatial openness, thermal environmental perception, adaptive thermal comfort

7.1 Introduction

Architecture as a shelter protects people from the natural environment through various architectural elements: floors, walls, columns, windows, doors and roofs. These elements can be identified as architectural boundaries, which distinguish the outdoor from the indoor environment and the various indoor spaces from each other. The outdoor and indoor architectural boundaries determine a spatial environment. In a particular spatial environment, next to the basic functional requirements for occupants' activities, the perceptions of the occupants such as aesthetics, delight and comfort, are also very important for the quality of a built environment. Studying the relationship between the spatial environment and the way the spatial environment is perceived can yield important insights into the way architectural design can create more comfortable living environments.

Comfort (especially thermal comfort) is heavily related to building energy consumption; therefore, comfort is one of the most important considerations in modern architectural design within the scope of sustainable development. A wealth of thermal environment studies have investigated the relationship between building shape, geometry and envelop, and thermal environment (AlAnzi et al., 2009; Hirano, Kato, Murakami, Ikaga, & Shiraishi, 2006; Naraghi & Harant, 2013; Ratti, Raydan, & Steemers, 2003; Yi & Malkawi, 2009), yet less research has been carried out on the influence of the spatial configuration, i.e. the relative arrangement of parts or elements in a three-dimensional space, inside a building on the thermal environment and occupants' thermal perception.

Common sense tells us that in summer in a hot and humid climate there is a correlation between the concept spatial openness and comfort perception in people's minds. The authors' hypothesis is that there is a large correlation between the concept spatial openness and comfort perception in people's minds. If this hypothesis is confirmed, using spatial configuration is a good design tool for (thermal) comfort in the early design stages.

This hypothesis is tested by questioning around 500 Chinese architecture students about their comfort perception in several spatial environments in summer in a hot and humid climate. Five different spatial environments with different spatial openness were described in writing as indoor space, semi-outdoor space, outdoor space, a room with a large operable area and a room with a small operable area. The three perceptions were visual perception, thermal perception and wind perception. The comfort perception over the day for the different spatial environments was also investigated. A similar questionnaire was given to Dutch architecture students, but the results were inconclusive due to the low number of responses.

7.2 Study method

In 2015, a written questionnaire was administered to 513 Chongqing University bachelor students[7] of architecture during one of their courses within one week. It was estimated that the questionnaire would take about 10 minutes to complete. The filled-out questionnaire had to be handed in when the class was finished.

The written questionnaire was obligatory, anonymous and in Chinese and English, see appendix A. The questionnaire was developed by one of the authors. The questionnaire included 10 questions of four parts. The first part consisted of questions requesting demographic information, such as gender (male, female) and

7 Due to the limitation of financial and human resources, only students were selected as subjects for the questionnaire. This may lead some deviations of the conclusion in this investigation. However, the students have lived there at least more than 2 years, therefore, they are representative we believe.

age (between 17 and 25 years old or not). The second part included questions relating to the general perception of the local climate in summer. This included thermal sensation (slightly cool, neutral, slightly warm, warm and hot), air velocity preference (not noticeable air velocity, low air velocity, high air velocity and very high air velocity) and preferred changes to the student's living room (air movement, operable window size, openness of the living room, presence of balcony or terrace, presence of courtyard or patio). The questions in the third part were related to the visual perception (good, neutral, not so good), wind speed perception (too low, low, neutral, high, too high) and thermal perception (cold, cool, neutral, warm, hot) in the different types of spatial environments: indoor space (a space with small openings), semi-outdoor space (a space with large openings), and outdoor space. The fourth part included questions about occupants' spatial preferences for different spatial environments (indoor space, semi-outdoor space, outdoor space, no preference) at different times (morning, afternoon, evening, and night). The last questions were about the preferred view from the room (good view or no preference and broad or narrow view). It should be note, the students were obliged to fill in the questionnaire. This led to some students not answering the questions fully or not answering the questions seriously. All data was entered in Excel and SPS. All incomplete questionnaires were deleted. Descriptive statistics such as percentages, range (minimum and maximum), or arithmetic mean with standard deviation (SD) were used to summarize the characteristic of the students and their homes.

7.3 Results

7.3.1 General perception of the local climate

The subjects were 62% male and 38% female, aged between17-25. Figure 7.1 shows the general thermal perception and wind speed perception in summer. It was found that 50% of the subjects felt very hot and 60% indicated that the wind speed perception was low under local climate conditions. That means that thermal perception and wind speed perception are negatively perceived and that the local occupants are not satisfied with the thermal environment.

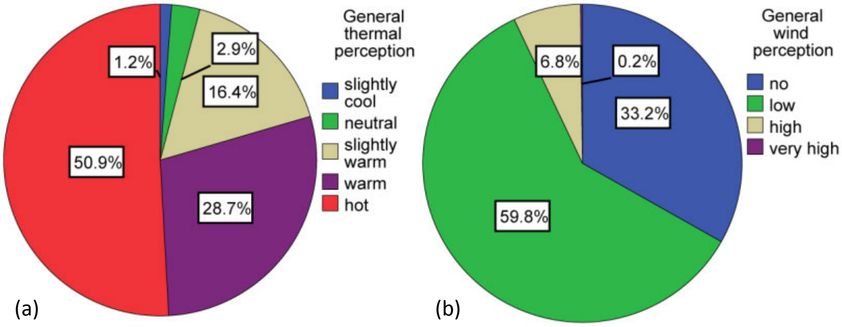

FIG. 7.1 General thermal and wind speed perception of the local climate (Chongqing, China, 2015) by 513 local college students of architecture.

7.3.2 The correlation of spatial openness and subjects' perception

Figure 7.2 shows the visual perception, wind speed perception and thermal perception according to the spatial openness. It is found that the visual perception increases from small opening to indoor space to semi-indoor space to big opening to outdoor space, thus from an enclosed space to an open space, which means the subjects think they can obtain a broader and better view in the more open spaces than in the enclosed spaces. The one-sided ANOVA analysis showed that there was a significant effect of the spatial openness on the view, $F(4, 2543) = 266$, $p < 0.01$, $w = .54$. Planned contrasts revealed that more spatial openness significantly increased the view, see figure 7.2(a).

The subjects feel they can catch more wind in the more open spaces than in the enclosed spaces, see figure 7.2(b). Performing a one-way independent ANOVA statistical analysis, the variants are significantly different ($p < 0.01$) according to Levene's test of homogeneity of variances. Therefore, the Brown-Forsythe robust test of equality of means is used. This test indicates a significant effect of the spatial openness on the wind speed perception, $F(4, 2485) = 213$, $p < .01$, $w = .50$. Planned contrasts revealed that wind speed perception is significantly lower in the indoor environment compared to the small opening environment, $t(735) = 13.6$, $p < 0.01$ (1-tailed), $r = .44$; wind speed perception is significantly higher in the semi-outdoor environments compared to the indoor environment, $t(713) = 17.8$, $p < 0.01$, $r = .55$; wind speed perception is significantly higher in the large opening environment compared to the semi-outdoor environment, $t(994) = 4.9$, $p < 0.01$, $r = .15$; wind speed perception is significantly lower in the outdoor environment compared to the big opening environment, $t(950) = 1.75$, $p < 0.05$, $r = .06$.

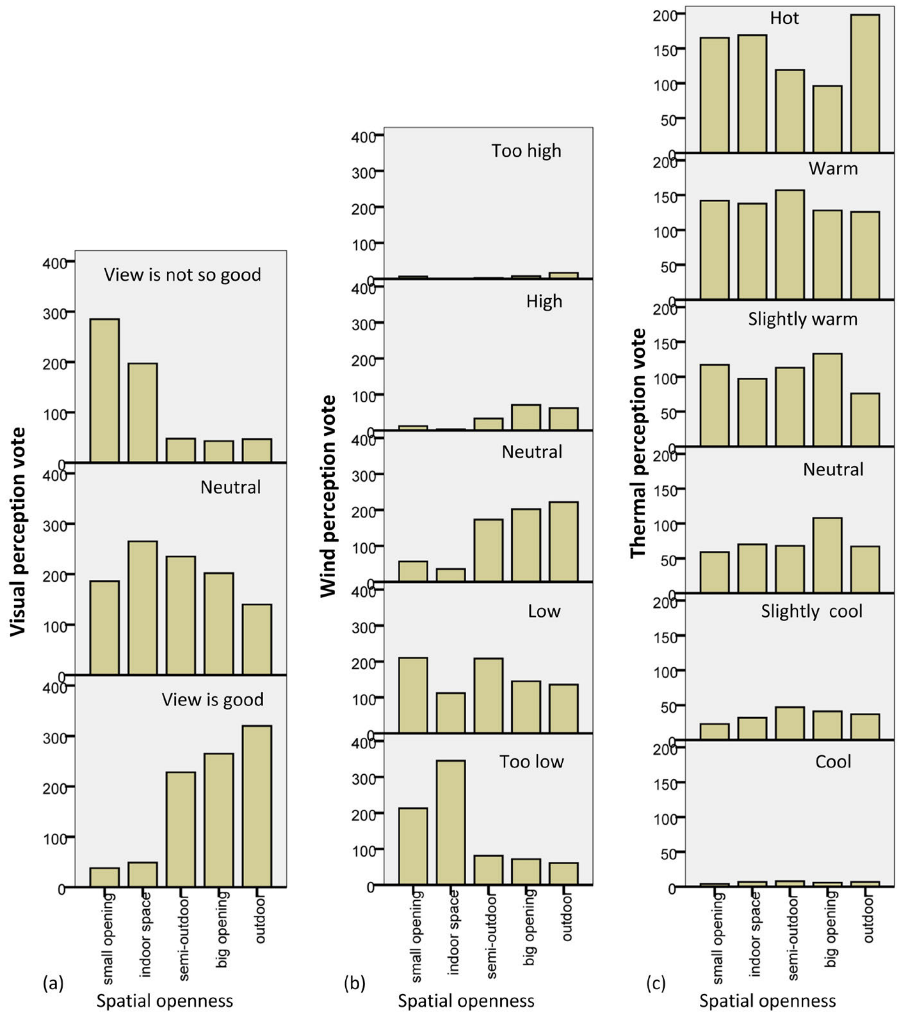

FIG. 7.2 Visual perception, wind speed perception and thermal perception according to spatial openness in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture.

A significant effect between spatial openness and thermal comfort is also expected for thermal perception from figure 7.2(c), with the exception of the outdoor environment which is perceived to be the hottest of all spatial environments. Performing a one-way independent ANOVA statistical analysis, the variants are significantly different ($p < 0.05$) according to Levene's test of homogeneity of variances. Therefore, the Brown-Forsythe robust test of equality of means is used. This test indicates a significant effect of the spatial openness on the thermal perception, $F(4, 2553) = 13.7$, $p < .01$, $w = .14$. Planned contrasts revealed that thermal perception is significantly hotter in the indoor environment compared to the small openings environments, $t(1016) = 1.82$, $p < 0.05$ (1-tailed), $r = .06$; thermal perception is significantly hotter in the semi-outdoor environments compared to the indoor environment, $t(1000) = 3.32$, $p< 0.01$, $r = .10$; thermal perception is significantly hotter in the large opening environment compared to the semi-outdoor environment, $t(934) = 1.7$, $p < 0.05$, $r = .06$. There was no significant effect between the thermal perception of the outdoor environment and the small opening environment. The effect sizes are smaller than expected. This is probably caused by the fact that more than 40 % of the students consider all spatial environments warm or hot.

A significant effect between visual perception, wind speed perception and thermal perception has been found from a one-way independent ANOVA statistical analysis for the three perception pairs, as shown in table 1. The variants are significantly different for all three pairs ($p < 0.01$) therefore the Brown-Forsythe robust test of equality of means is used to determine if there is a significant effect between thermal, wind speed and visual perception.

The correlation between visual perception and wind speed perception is the strongest $w = .39$. The correlation coefficient between thermal perception and wind speed perception is $w= 0.31$. The correlation between visual perception and thermal perception is relatively weak $w = .20$.

TABLE 7.1 Statistical results of the correlation between visual perception, wind speed perception and thermal perception in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture.

(a)		Wind perception (%)						
		too low	low	neutral	high	too high		Total
Visual perception	good	13.5	30.1	41.3	13.1	2.0		100
	neutral	32.3	35.6	26.2	5.2	0.6		100
	not so good	55.1	30.3	10.6	2.2	1.8		100
Total		31.1	32.4	27.8	7.3	1.4		100
		w=0.39, p < 0.01, F (4,240) = 102						

(b)		Thermal perception (%)						
		cool	slight cool	neutral	slight warm	warm	hot	total
Visual perception	good	2.0	10.4	19.8	18.2	24.8	24.8	100
	neutral	0.7	6.3	13.7	25.5	28.2	25.5	100
	not so good	1.0		7.9	17.6	28.8	41.4	100
Total		1.2	7.1	14.5	21.0	27.1	29.1	100
		w=0.20, p < 0.01, F (4,484) = 21						

(c)		Wind perception (%)						
		too low	low	neutral	high	too high		Total
Thermal perception	cool	36.7	16.7	23.3	23.3	0.0		100
	slight cool	14.0	25.3	33.7	23.6	3.4		100
	neutral	14.8	29.0	45.4	9.2	1.7		100
	slight warm	23.7	38.2	31.9	5.5	0.8		100
	warm	28.7	39.7	24.4	6.5	0.6		100
	hot	50.5	26.1	17.8	3.4	2.2		100
Total		31.0	32.6	27.7	7.2	1.4		100
		w=0.31, p < 0.01, F (4, 483) = 50						

On the basis of the questionnaire results described above, it is found that visual perception and wind speed perception and thermal perception are significantly different in different spatial environments. In general, a more open space is perceived as having a better view, a higher wind speed and a lower temperature. There are a few exceptions. The most open space, outdoor space, is perceived the hottest, probably because the solar radiation in open spaces, such as the outdoor space is stronger than in the indoor spaces. The indoor space is perceived to have a lower wind speed than the more enclosed small opening environment, probably because the description "indoor space" gives too little information about the window openings and students can have imagined closed windows. The outdoor space is not perceived as having a larger wind speed than the large opening environment. This is probably caused by the different activities in the outdoor space and the fact that when there is sun, a larger wind speed is necessary to feel comfortable.

7.3.3 Spatial preference

Figure 7.3 shows the subjects' general spatial preference in summer. It can be seen that more than 90% of the subjects prefer an environment with a good and broad view, and with considerable natural ventilation. The subjects' spatial preference with respect to the time of day is shown in figure 7.4. In the morning, the subjects show little spatial preference for the indoor space, semi-outdoor space or the outdoor space. This can be explained by the fact that the temperature differences between the different spatial environments are relatively small in the morning in the local summer climate. Hence, spatial preference is not strongly determined by the thermal environment, with other factors, such as activities, largely influencing the spatial choice. In the afternoon, half of the subjects prefer to stay in the indoor space, the second preference is the semi-outdoor space and the third preference is the outdoor space. This is probably due to the fact that the subjects know from experience that during the afternoon, as the outdoor temperature rises, the solar radiation in the outdoor and semi-outdoor space is stronger than in the indoor space. In the evening, more than 60% of the subjects prefer to stay in the semi-outdoor and outdoor space. This is probably because the indoor temperature is higher than the temperature in the outdoor or semi-outdoor space in the evening. Moreover, the subjects prefer to stay outside to catch more natural ventilation. At night, almost 40% of the subjects prefer the indoor spaces; however, some 45% of the subjects still prefer to stay in the semi-outdoor or outdoor space. This is probably because the heat in the indoor space is not easily dissipated at night, so that the indoor temperature is still high while the outside temperature has already dropped. The choice of activity is assumed to be the reason for the subjects to withdraw to the indoor space, although in terms of the thermal environment, subjects prefer to stay outside. An investigation by Fu (2002) in the studied region, showed that 60 to 90% of the local inhabitants complained that they were sleepless at night during summer due to the sweltering and sultry weather.

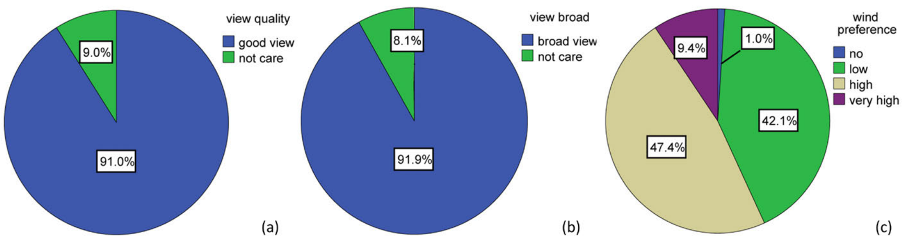

FIG. 7.3 Subjects' general spatial preference in summer in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

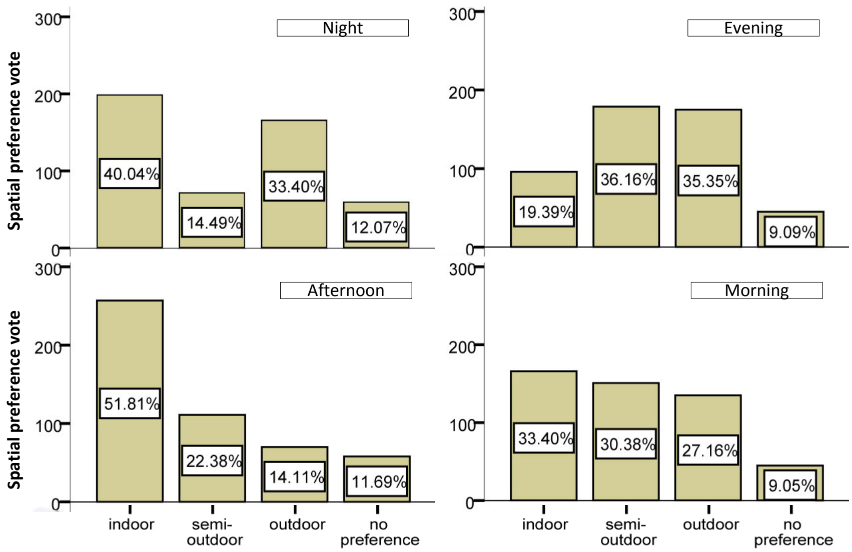

FIG. 7.4 Subjects' spatial preference respect to the time of day in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

7.4 Discussion

The questionnaire showed that, under hot and humid climate conditions, spatial openness features, occupants' visual perception, wind speed perception and thermal perception are all associated. The strongest correlation is between spatial openness and visual perception and wind speed perception. The correlation between wind speed perception and thermal perception is considerable as well. It may be inferred that if a certain space offers good openness, occupants are likely to have a positive visual and wind speed perception, and even thermal perception. In fact, wind speed perception is the key factor in the chain, see figure 7.5.

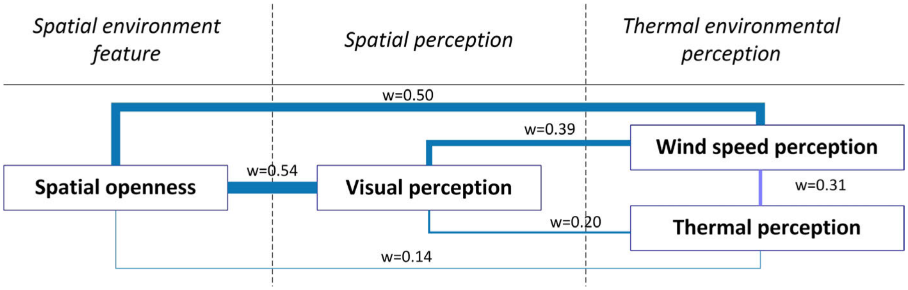

FIG. 7.5 The effect sizes between spatial openness, spatial perception and thermal environmental perceptions in a hot and humid climate (Chongqing, China, 2015) by 513 local college students of architecture

A lower effect size between spatial openness and thermal perception is found than was expected. This is probably caused by the fact that more than 40 % of the students consider all spatial environments warm or hot causing the variants to be were significantly different ($p < 0.01$) according to Levene's test of homogeneity of variances. The different comfort perceptions did not have the same order of preferences. The outside environment was the best visual perception, but the worst thermal perception and an average wind perception. Future research should be more specific on the description of the spatial environments if the expected high correlation between spatial openness and the comfort perceptions is to be found.

Occupants' spatial preference or movement in the domestic building is influenced by their perception with respect to the time of day. This can, besides the high amount of warm and hot votes, also explain the low effect size between spatial openness and thermal perception. The questionnaire did not ask this explicitly, but the opinion of the authors is that a large part of the spatial preference over the day is temperature dependent. This means that the time of day also influences the relationship between the spatial openness and the thermal perception.

The questionnaire proves that spatial boundary conditions can strongly influence occupants' comfort perception, and subsequently influence occupants' spatial choice and movement in a particular thermal environment, given the opportunity, as Humphreys (1997) pointed out: when people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like.

7.5 Conclusion

In this paper, local architectural students' spatial perception and comfort perception were investigated through a questionnaire. The main findings for a hot and humid climate are: a. Spatial openness of a particular space significantly effects occupants' visual perception, wind speed perception and thermal perception in a particular space. b. There is a strong effect size between spatial openness and visual and wind perception ($w = .50$ and $.54$); the effect size of the thermal perception is weaker ($w= .14$). c. The comfort perception is strongly influenced by the time of day, therefore visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort theory.

The authors' hypothesis that there is a large correlation between the concept spatial openness and comfort perception in people's minds has not been proven. The effect size between spatial openness and thermal perception is too low. However, the effect size between spatial openness and visual and wind speed perception is high, as expected. The low effect size is probably caused by a too large amount of warm and hot votes (< 40%) for all spatial environments, the fact that solar irradiation unconsciously influences the perceived temperature in the outdoor environment and the fact that the preferred spatial environment is shown to change over the day. More research, such as a more advanced questionnaire, is, therefore, needed for further proof.

As already mentioned, spatial openness significantly effects comfort perception for architectural students in a hot and humid climate. This means that architectural students in a hot and humid climate can distinguish the effects of spatial openness on the comfort perception. This fact can be used in the education in the early design stages for buildings in a hot and humid climate. This is important because significant mistakes in spatial design in the early design stages are difficult to adjust later.

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8 Output of part I:

Defining the relationship of spatial design, building microclimate and thermal summer comfort in dwellings

8.1 Summary of the works in part I

In part 1, a literature review was done to summarise and introduce the theoretical background knowledge of thermal comfort and passive cooling technology. The adaptive thermal comfort was explained because it is applicable to a free-running building which is the studied object of this research. The basic theory and design standards of adaptive thermal comfort were reviewed. A brief overview of passive cooling techniques was given. The techniques were then reviewed based on their relationships with urban morphology, building shape, layout, opening and “elements”.

The study started with a Chinese vernacular building (chapter 4) because these always use the passive way to achieve a comfortable living environment under the limitations of technology at that time. Firstly, the spatial design strategies for passive cooling of a Chinese vernacular house were investigated in a field survey. The design of modern rural houses under free-running conditions compared with the Chinese vernacular house. It was found that the modern rural house did not achieve a satisfactory thermal summer environment under free-running conditions, while the vernacular house did. Furthermore, the vernacular house was deeply analysed by field measurements and dynamic thermal simulations. It was found that the particular spatial design of the vernacular house has its own building microclimate, which is important for the occupants’ thermal summer comfort. The concept of building microclimate was identified. In this study, the scale of “building microclimate” refers to a type of microclimate, involving the indoor space and the spaces around the indoor spaces of a particular building. It is the extension of the indoor climate. The spatial scale is smaller than the urban fabric. It rarely covers an area more than several hundred meters wide, but is bigger than an indoor space alone. It is limited to one particular building, whether a small house or a big stadium. The building microclimate is mainly defined by the spatial and the thermo-physical properties. Similar to the influence of urban morphology on urban microclimate, the spatial configuration influences the building microclimate significantly. To have a particular microclimate at the building scale, some key factors of spatial configuration such as spatial diversity, spatial arrangement and boundary conditions between spaces should be identified.

The spatial design of modern house is different from the vernacular house due to the evolution of people’s lifestyle over a long period. Can a modern house have a good building microclimate? To answer this question, the spatial design and thermal environment of a modern house were analysed through field survey and simulation. It was found that a modern house can also have its own microclimate and that the microclimate of this particular building can provide considerable thermal comfort for the occupants in summer under local climate conditions.

Adaptive actions, for example movement, can explain why occupants can achieve thermal comfort in a building microclimate with diverse spaces. To find the relationship between the occupants’ spatial perception and thermal perception, a questionnaire was put forward. It was found that the spatial openness of a particular space significantly affects the occupants’ visual perception, wind speed perception and thermal perception. It was revealed that the occupants’ spatial perception and thermal perception are associated. The strongest correlation is between spatial openness and visual perception and wind speed perception. That means spatial boundary conditions can strongly influence occupants’ comfort perception, and subsequently influence the occupants’ spatial choice and movement in a particular thermal environment, given the opportunity, as Humphreys (1997) pointed out: when people are free to choose their location, it helps if there is plenty of thermal variety, giving them the opportunity to choose the places they like. The fundamental assumption of the adaptive approach is expressed by the adaptive principle: “if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort”. Nicol et al. (2012) proposed that there are at least five basic types of adaptive actions. One important adaptive action is selecting a different thermal environment. Occupant movement in a particular building microclimate is significant for thermal comfort. Occupants can change their location for different activities. Movement is possible between buildings, between rooms, around rooms, out of the sun and into the breeze, and so on (Nicol et al., 2012).

8.2 Conclusion

The main contributions of part 1 are the definition of “building microclimate” and the revelation of the relationship between spatial perception and adaptive thermal comfort. To form a suitable building microclimate is important for the occupants’ thermal summer comfort. Meanwhile, spatial configuration plays an important role in creating a particular building microclimate. There are two important aspects in a building microclimate providing thermal comfort for occupants. One is the thermal environment of the building microclimate, especially the wind environment. Second is the occupants’ movement in the building microclimate. The research in part 2 will focus on a design method using spatial analysis to predict and evaluate occupants’ movement behaviour and airflow behaviour in residential buildings, which are the key factors for the occupants’ thermal summer comfort in the studied area.

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PART 2

Space Design for Thermal Comfort

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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

8 This chapter is the original version which is published as: Du, X., Bokel, R., & van den Dobbelsteen, A. (2019b). Using spatial indicators to predict ventilation and energy performance-correlation analysis for an apartment building in five Chinese cities. Frontiers of Architectural Research. doi: 10.1016/j.foar.2019.01.005

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 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

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

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

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(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.

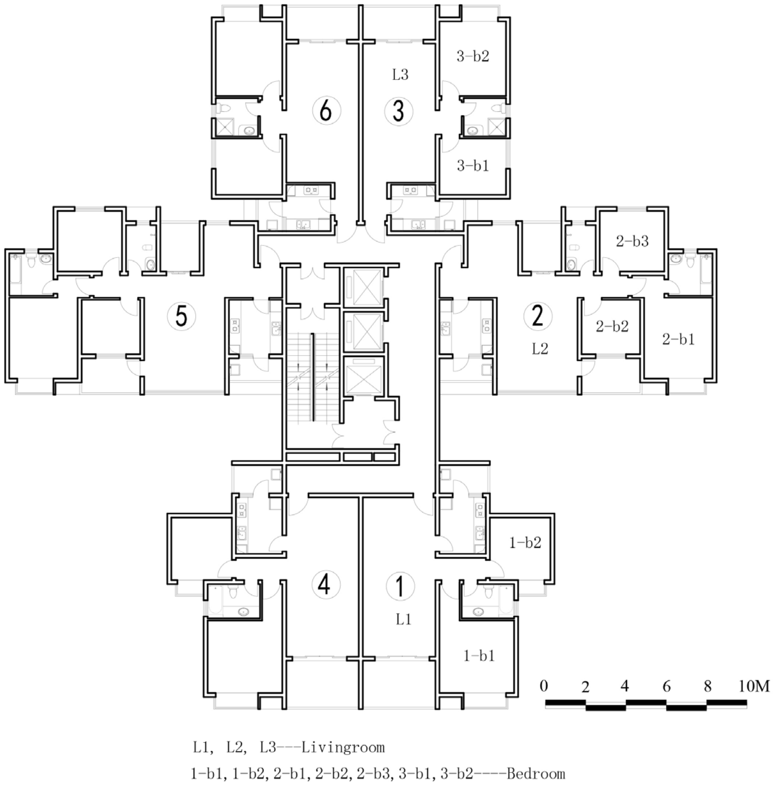

FIG. 9.1 The floor plan of the selected high-rise building (household 1,2 and 3 were analysed)

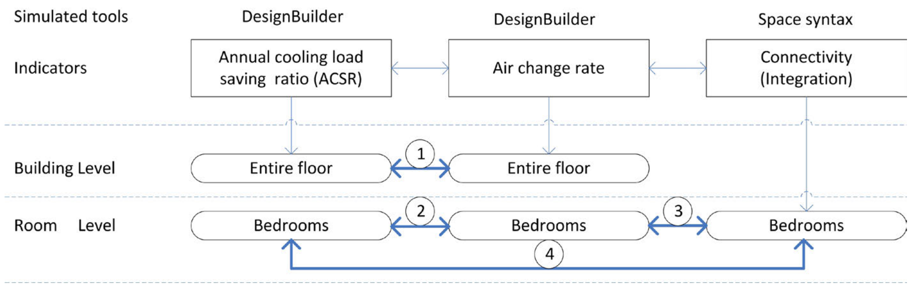

FIG. 9.2 The frame of the research method (1 / Correlation between ACSR and air change rate of the floor; 2 / Correlation between ACSR and air change rate of the rooms; 3/ Correlation between air change rate and connectivity of the rooms; 4 / Correlation between ACSR and connectivity of the rooms)

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.

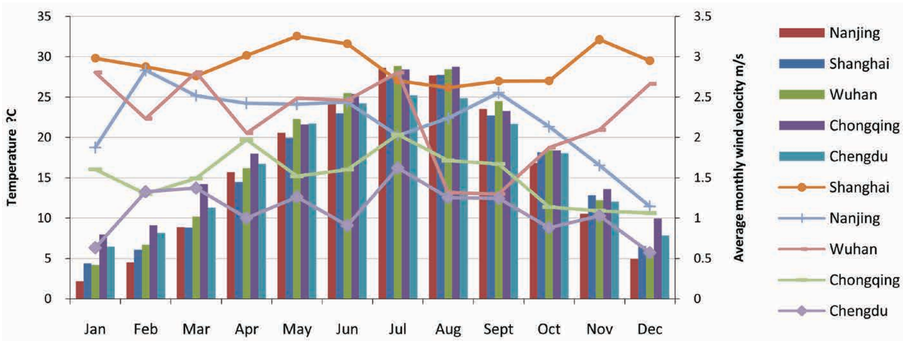

FIG. 9.3 The average monthly temperature and wind velocity of the five cities (the columns represent the average monthly temperatures and the lines represent the average monthly wind velocities)

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.

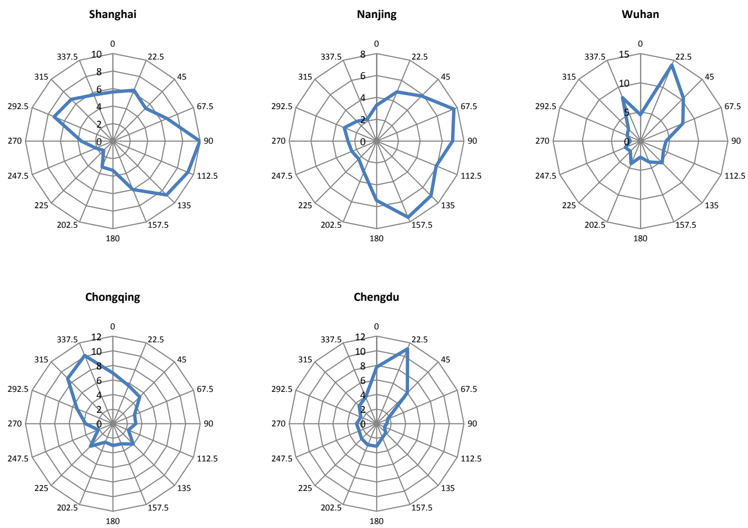

FIG. 9.4 The yearly wind rose of the five cities studied (based on the annual frequency of the wind direction) with 0 = north and 90 = east.

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

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.

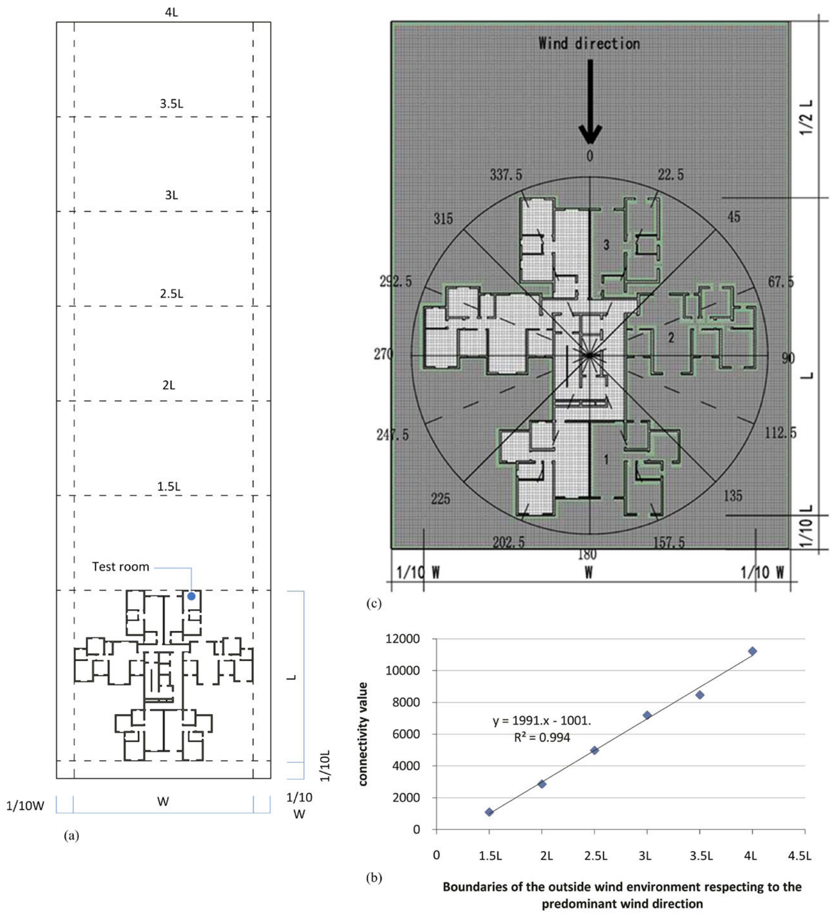

FIG. 9.5 The boundary setting of the floor plan for the VGA (a) the setting for the test VGA (b) the correlation between the boundaries and the connectivity value of the test room (c) the final setting of the outside wind environment boundary for the VGA (household 1,2 and 3 were analysed)

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.

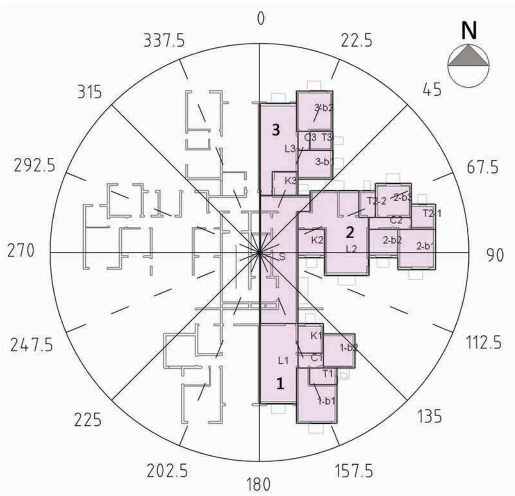

FIG. 9.6 The building model built in DesignBuilder (household 1,2 and 3 were analysed)

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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.

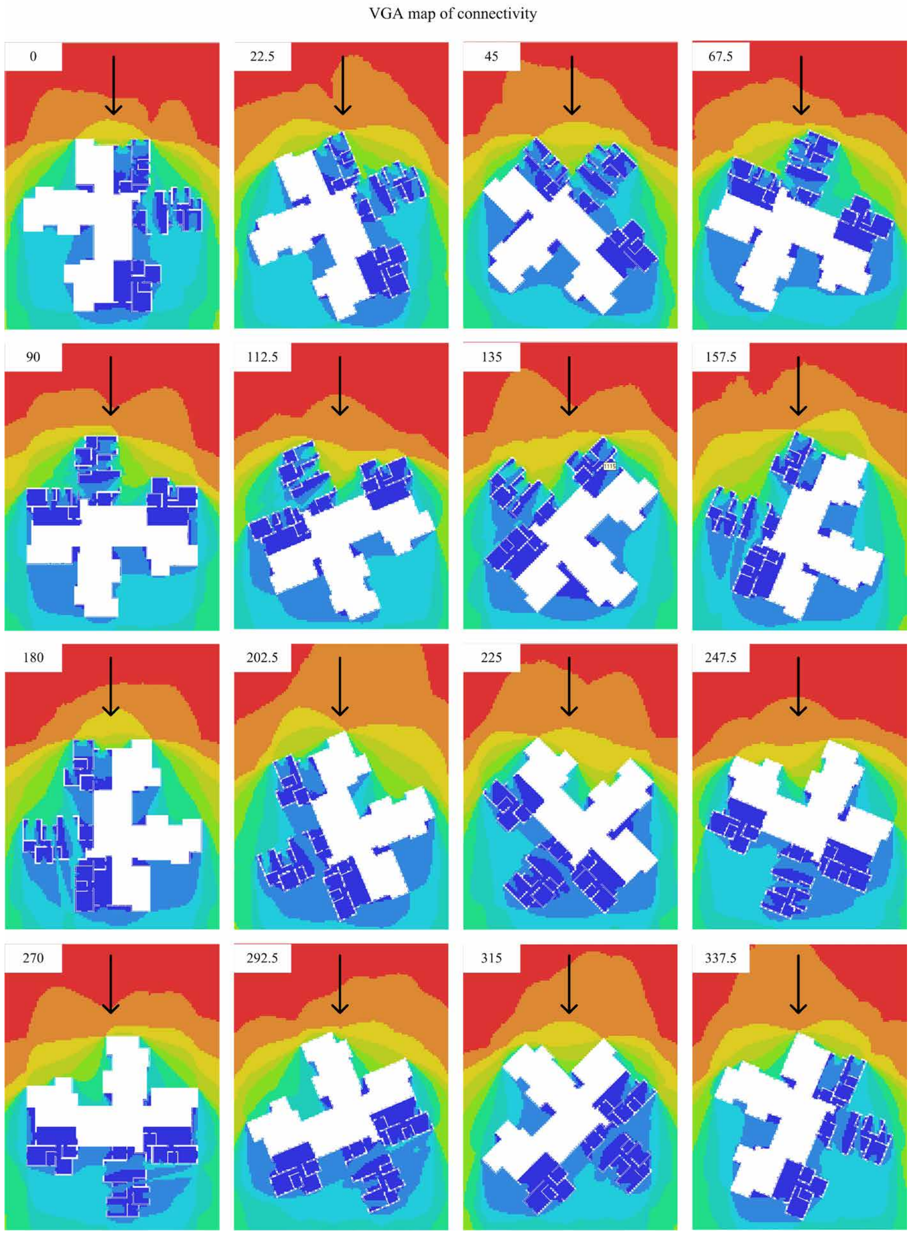

FIG. 9.7 The VGA map of the connectivity value corresponding to 16 different wind directions relative to the floor plan (0 = north and the arrow represents the wind direction; from red to deep blue, the connectivity is from big to small)

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.

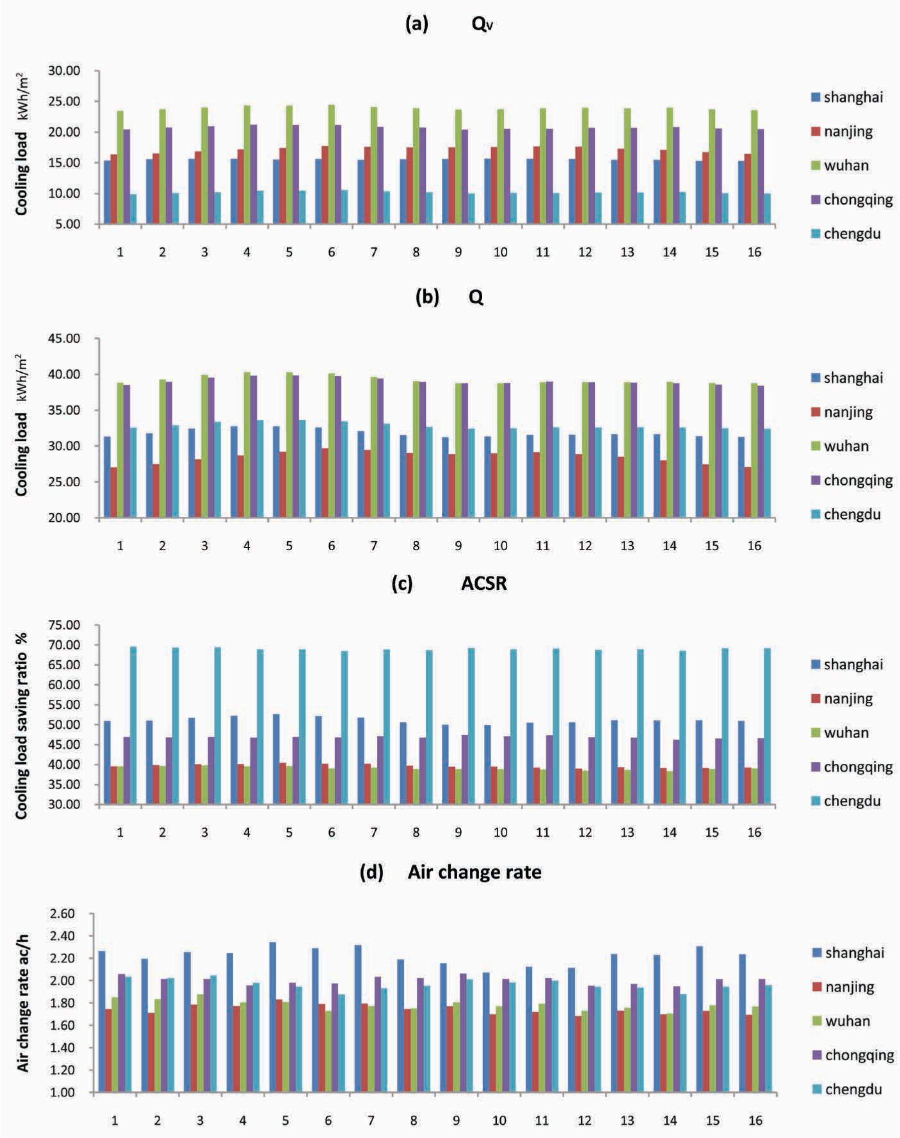

FIG. 9.8 The annual cooling load with natural ventilation, Qv (a), and without natural ventilation, Q (b), ACSR (c) and air change rate (d) of the five cities (when the window-to-wall ratio is 10%) for 16 building orientations (the orientation is from 0- 337.5 degree, see figure 9.7)

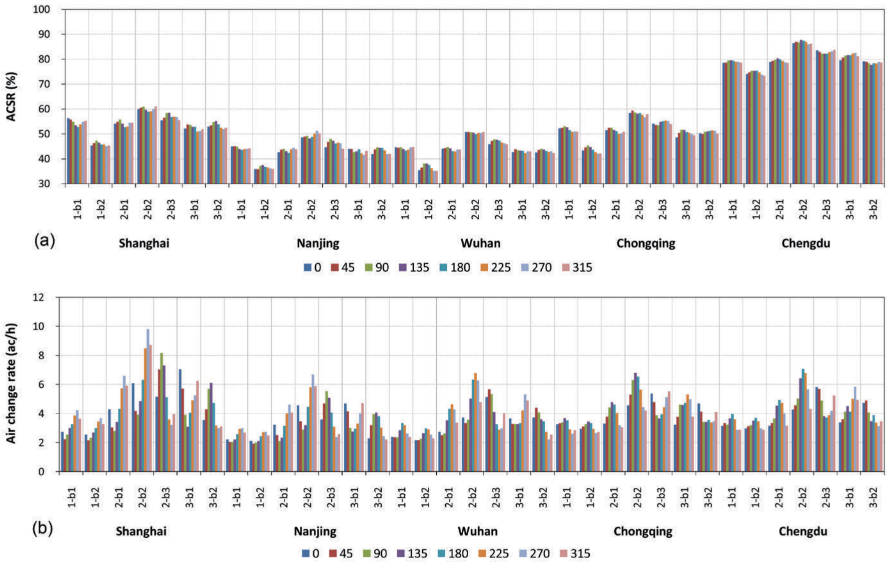

FIG. 9.9 The ACSR and air change rate per bedroom when the building orientation is 0,45, 90, 135, 180, 225, 270, 315 degrees with 0=north and 90=east in the five cities.

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).

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.

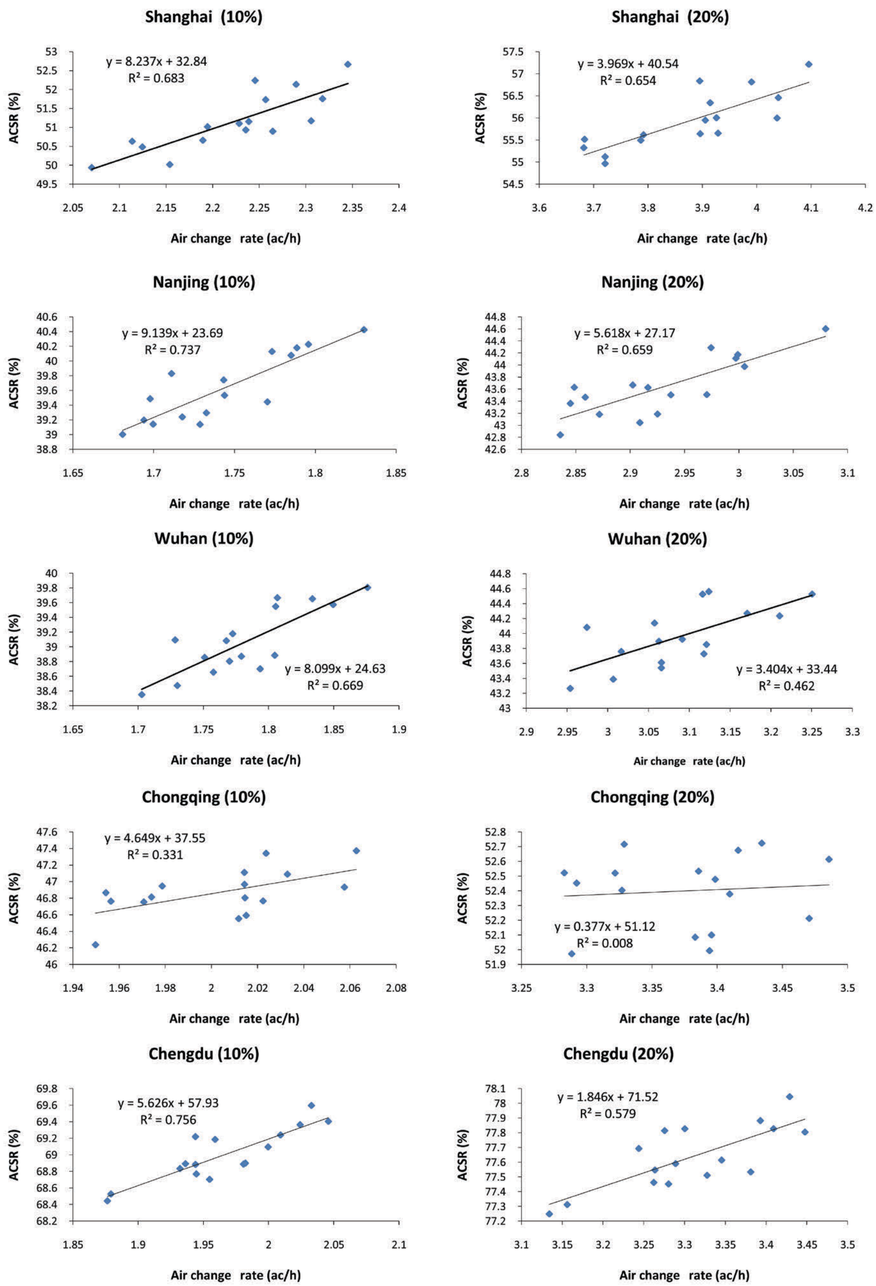

FIG. 9.10 The linear correlation between ACSR and annual air change rate of an entire floor for 16 different orientations and 2 different window-to-wall ratios.

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.

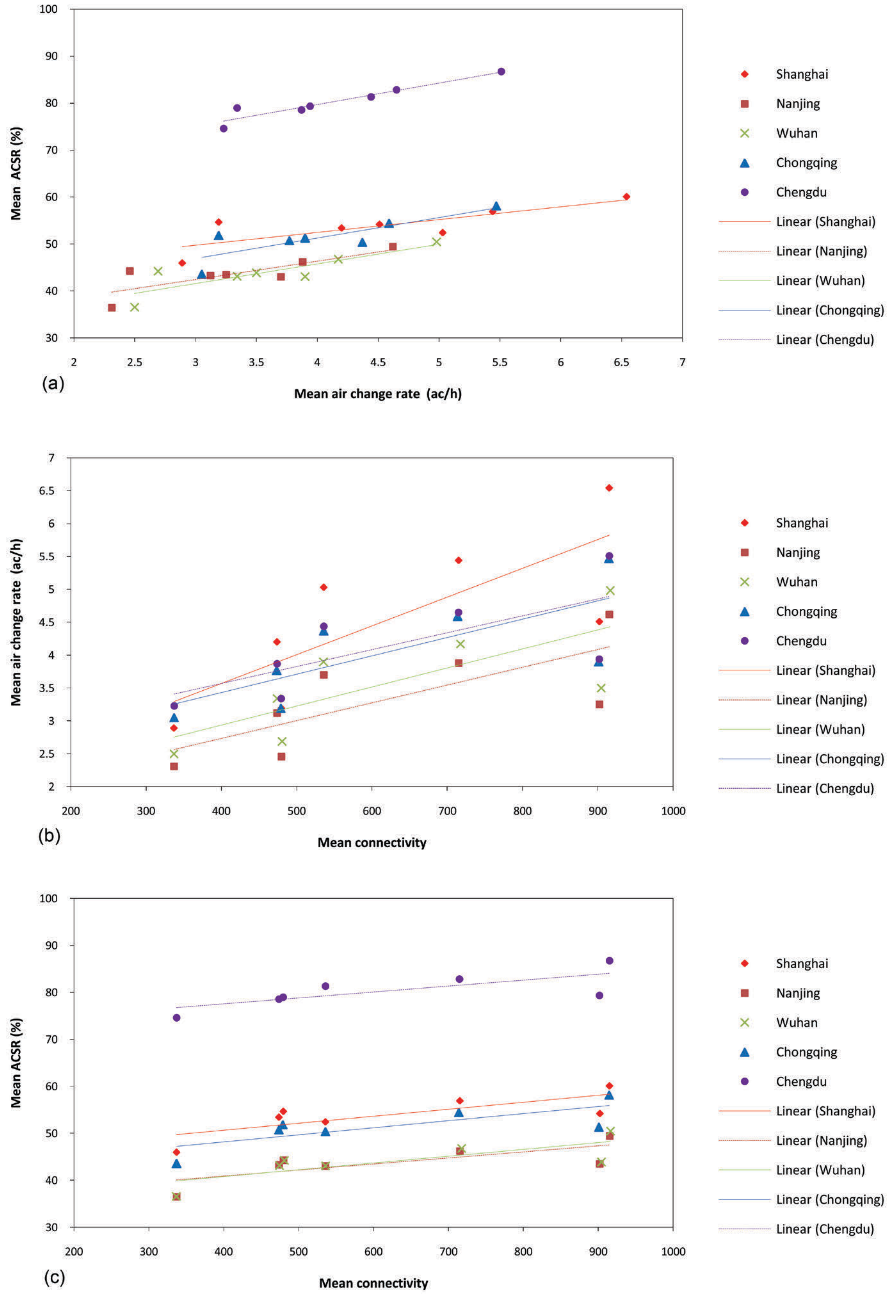

FIG. 9.11 The correlations between the average weighted connectivity value, ACSR and air change rate of the selected seven bedrooms in the five cities

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.

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).

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.

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10 Methods of spatial analysis for natural ventilation potential

10.1 Introduction

The basic theory of space syntax was described in section 2 of chapter 9. Some methods have been developed from the theory of spatial analysis to explore the spatial structure of buildings and cities. The DepthmapX-one graph-based representations and measures program (Turner, 2001) is one of the most important platforms for space syntax analysis. Convex and axial analysis, isovist and VGA analysis, as well as segment analysis are the methods involved in this programme (Al_Sayed, Turner, Hillier, Iida, & Penn, 2014). The axial and segment analysis are more suitable for the analysis at the urban scale. The convex analysis is suitable for the building scale and isovist and VGA analysis are suitable for both urban and building scale. Many cases have been studied to reveal the topological relationship between the spaces which is related to the social behaviour of human in building or urban scale via DepthmapX.

In this chapter, the traditional space syntax methods for building spatial analysis used in the Depthmap were discussed firstly. Then, the author shows how to extended the traditional methods for natural ventilation potential analysis.

10.2 Traditional space syntax methods for spatial analysis

10.2.1 Convex analysis

The convex analysis uses a topological graph representation of a buildings. Figure 10.1 shows an example for decoding a building layout designed by Frank Gehry using the convex space representation (Al_Sayed et al., 2014). Figure 10.1(a) is the original layout of the house. The spaces of the building are represented by a set of convex spaces. In this case, the convex spaces are convex polygons which are shown in grey in figure 10.1(b). In each convex space, all pairs of points are inter-visible. These spaces are linked where there is direct access from one space to another. The relationship between the convex spaces is then represented by a graph where the convex spaces are represented by nodes (figure 10.1(c)). The different Connectivity value for each node can be calculated and highlighted (figure 10.1(d)). The values of Connectivity are then illuminated on the convex map to reveal the spatial structure of the building layout (figure 10.1(e)).

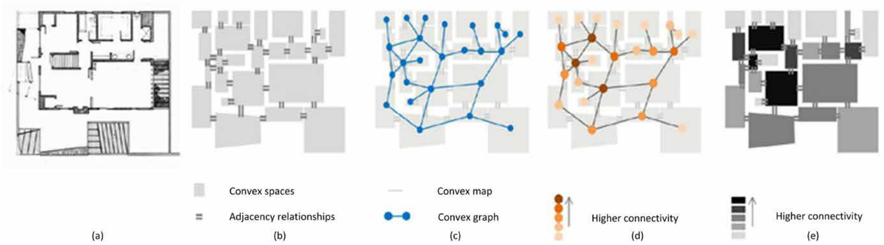

FIG. 10.1 The convex representation of Space Syntax method: (a) original layout of the house; (b) spaces of the building were represented by a set of convex spaces; (c) convex spaces are represented by a graph;(d) the value of connectivity is highlighted;(e) the value of connectivity is illuminated on the convex map (Al_ Sayed et al., 2014)

The topological relationship of the convex spaces of the layout can also be represented by a "justified graph" (figure 10.2) which was first proposed by Hillier and Hanson (1984). A justified graph shows the spatial network of spaces from one root space to all others. Each convex space is represented as a circle and the connection between two spaces are represented with a line. From a root space, all spaces that are one syntactic step away are put on the first level above the root space, all spaces that are two steps away are placed on the second row, etc. The convex spaces can be classified into four types (Al_Sayed et al., 2014), see also figure 10.2.

1 Types that are characterised as dead-end spaces and connect to no more than one space in a graph (a)
2 Types that connect to two or more spaces in a graph without being part of any ring of movement (b)
3 Types that are usually positioned on one ring of movement (c)
4 Types of spaces that must be in a joint location connecting two or more rings (d)

A justified graph might be deep or shallow, depending on the relationship of the root space to other spaces (Al_Sayed et al., 2014). From the justified graph, some global (integration and choice) and local (connectivity and control) syntactic measures can be calculated which are described in section 9.2 of chapter 9.

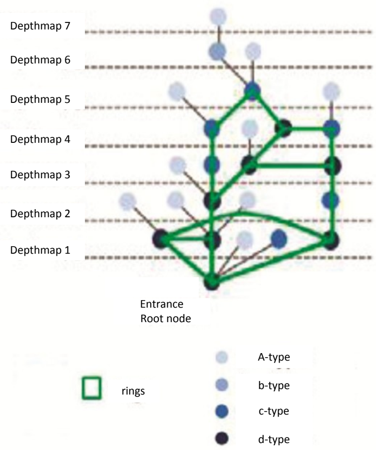

FIG. 10.2 The "justified graph" of Frank Gehry's house from the entrance root node (Al_Sayed et al., 2014)

10.2.2 Isovist and VGA analysis

An isovist (viewshed) is the area in a spatial environment directly visible from a point. The isovist was first introduced by Benedikt (1979). An isovist is a physical body bound by a closed polygon; hence it has geometric properties such as area and length of perimeter (figure 10.3). Table 10.1 lists the commonly used isovist variables, measures and related spatial perceptive indicators. The isovist method can quantitatively measure the visibility features of a spatial environment: the inter-visibility between each pair of points in a layout and how that builds into the visual configurations of the built environment (Al_Sayed et al., 2014). The isovist theory reveals that the visual configuration is strongly related to people's spatial perception from a certain position. The visual perception is correlated with people's behaviour, such as movement.

Turner, Doxa, O'Sullivan, and Penn (2001) developed the visibility graph analysis, which extends both isovist and current graph-based analysis of architectural space to form a new methodology for the investigation of configuration relationship. "The measurement of local and global characteristics of the graph, for each vertex, or for the system as a whole, is of interest from an architectural perspective, allowing us to describe a configuration with reference to accessibility and visibility, to compare from location to location within a system, and to compare systems with different geometries" (Turner et al., 2001).In the visibility graph, each point is notated as a node and inter-visibility is the condition for linking one node to the other. The visual relationships between different nodes in the system can be calculated using different local and global measures (Al_Sayed et al., 2014).

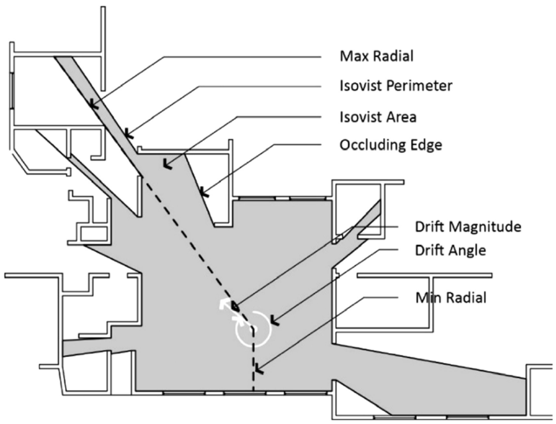

FIG. 10.3 The concept of isovist and the measures (Lee, Ostwald, & Lee, 2017)

TABLE 10.1 Isovist variables, measures and perceptual indicators

Isovist variables	Measures	Spatial experience
Isovist area (A)	Area of isovist polygon	Spaciousness, enclosure and openness
Isovist perimeter (P)	Perimeter of isovist polygon	Spaciousness, enclosure and openness
Maximum radial line (RLl)	Length of the longest single radial line used to generate the isovist	Openness
Minimum radial line (RLs)	Length of the shortest single radial line used to generate the isovist	Enclosure
Occlusivity (O)	Total length of all occluded edges	Mystery
Jaggedness (J)	The radio of perimeter2 to area. A high J value indicates a more visually complex isovist	Complexity, openness
Drift magnitude	Distance from observation point to centre of mass of isovist polygon	Visual pull strength
Drift angle	Angle between occupant facing direction and centre of mass of isovist polygon	Visual pull direction

10.3 Extension of the traditional space syntax methods for natural ventilation potential analysis

In chapter 9, the relationship between the spatial indicators in the space syntax method and the air flow behaviour in a building was found to be related for a case study. There is potential using the space syntax method to predict the air flow performance of buildings. The basic assumption is that there are common characteristics of people flows and air flows related to the spatial configuration. Therefore, the spatial measures in the space syntax method can also predict the air flow behaviour in buildings and cities. However, people movement behaviour is not exactly the same as the air flow behaviour, even though some characteristics are both correlated to the spatial configuration. Thus, an extension of the traditional space syntax method is necessary when this method is used for the air flow analysis.

In the traditional space syntax method, the relationships between spaces in the building or the city are the main concerns. This is because the logical relationship of connection of the inter-spaces can influence the route choice of people (Bhatia, Chalup, & Ostwald, 2013; Holscher & Brosamle, 2012; Li, Xiao, Ye, Xu, & Law, 2016).

The outside environment is not considered. In the building scale analysis, the outdoor environment is generally considered as one node at the entrance. Nevertheless, if the natural ventilation behaviour is concerned, the outside environment is the most important factor. Therefore, in this study the important extension of the traditional space syntax method is the focus on the connection between the indoor spaces and the outdoor spaces. Figure10.4 shows an example of the graphic expression of the traditional space syntax method and the new proposed method by the author. Figure 10.4(a) shows a building layout and the inter-connections with nine spaces. The logical connections of the spaces can be expressed by the justified graph (figure 10.4 (c)). Figure 10.4(b) shows a building layout where the outside environment is involved. The connections of the indoor spaces and the outside environment is expressed. The justified graph is showed in figure 10.4(d). As we can see, the outside space is represented as a circle and the indoor spaces are represented as circles with numbers. The outside nodes are involved in the space syntax measures. In a particular spatial structure, in the case of one node with low depth or high connectivity and integration value, the space represented by the node has high accessibility in the whole spatial system and high potential to obtain airflows from the other spaces, especially the outside spaces. However, this assumption derives from the analogy between airflow movement and human movement.

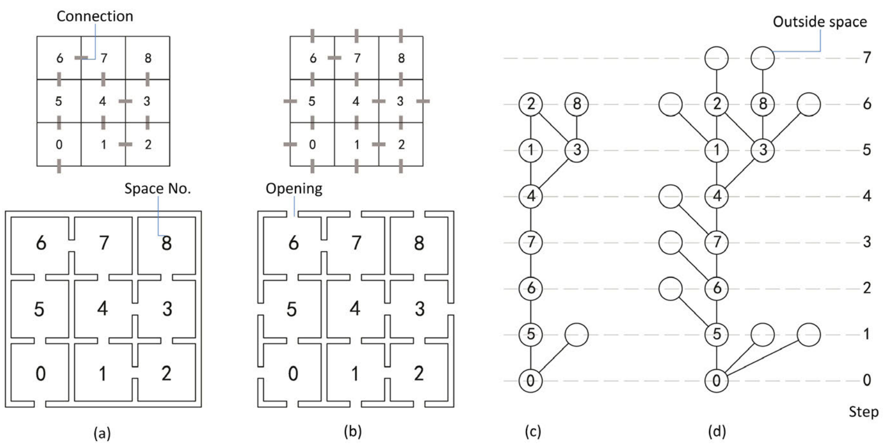

FIG. 10.4 An example of the traditional space syntax method and the new proposed method (a) the building layout and the inter-connections with nine spaces (b) the building layout and the connections of the nine inter-spaces and outside environment (c) the justified graph of the nine inter-spaces from space “0” (d) the justified graph of the nine inter-spaces and the outside spaces from space “0”

The opening size and location, which are significant for airflow and are not significant for human movement, are not represented in the justified graph. Figure 10.5 shows five layouts with nine spaces. The logical connections of the nine spaces are the same for the five layouts. Figure 10.5(f) shows the justified graphs of spaces “0”, “1”, “2” and “4” of the five layouts. It is obvious that the air flow performance in the five layouts is different. But the justified graphs are not. This means that a justified graph cannot evaluate the airflow behaviour completely through representing the convex space as a node and measuring the logical connections of the nodes.

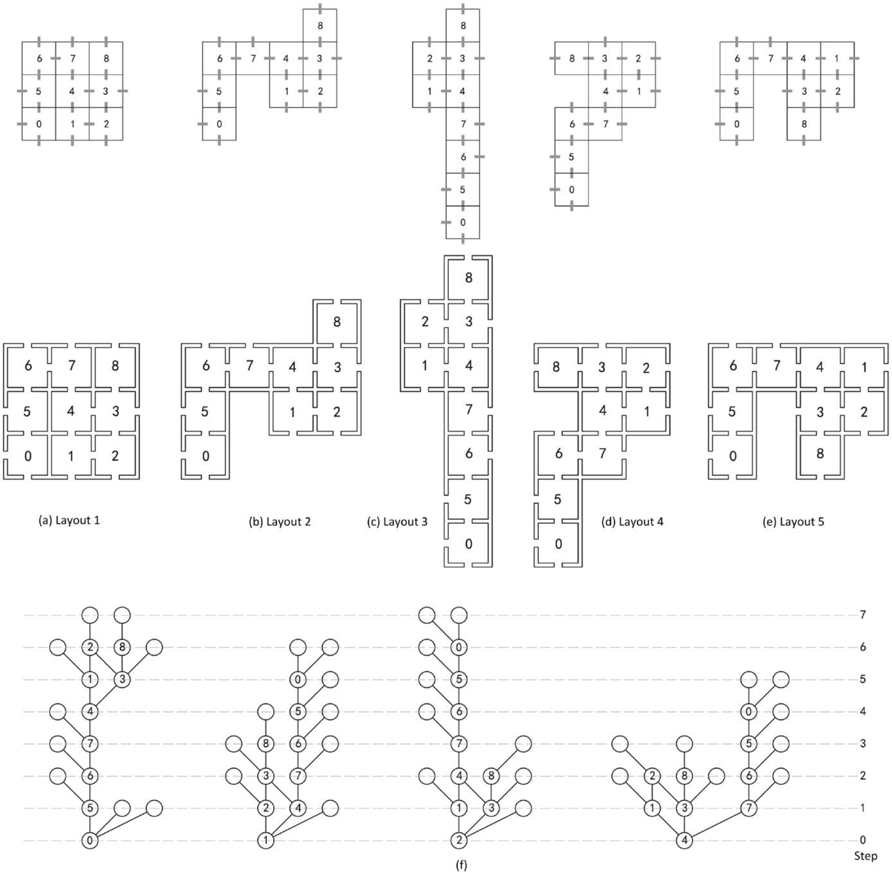

FIG. 10.5 Five layouts with nine spaces and the justified graph of space “0”, “1”, “2” and “4”

Fortunately, the VGA analysis considers not only the logical connection of spaces but also the visual relationship between the spaces through the measures of connectivity value and visual integration. This relationship is related to the opening size and the location of the spaces. Figure 10.6 shows the connectivity and integration maps, and figure 10.7 shows the variation of the connectivity value and visual integration value of the five layouts in the VGA analysis. In this VGA analysis, to involve the outside environment, the outside border was extended to a certain scale. As we can see, respecting different layouts, the connectivity and visual integration value of room 0, room 1, room 2 and room 4 are different. Therefore, the VGA analysis method seems the best choice of the space syntax analysis method for the airflow analysis.

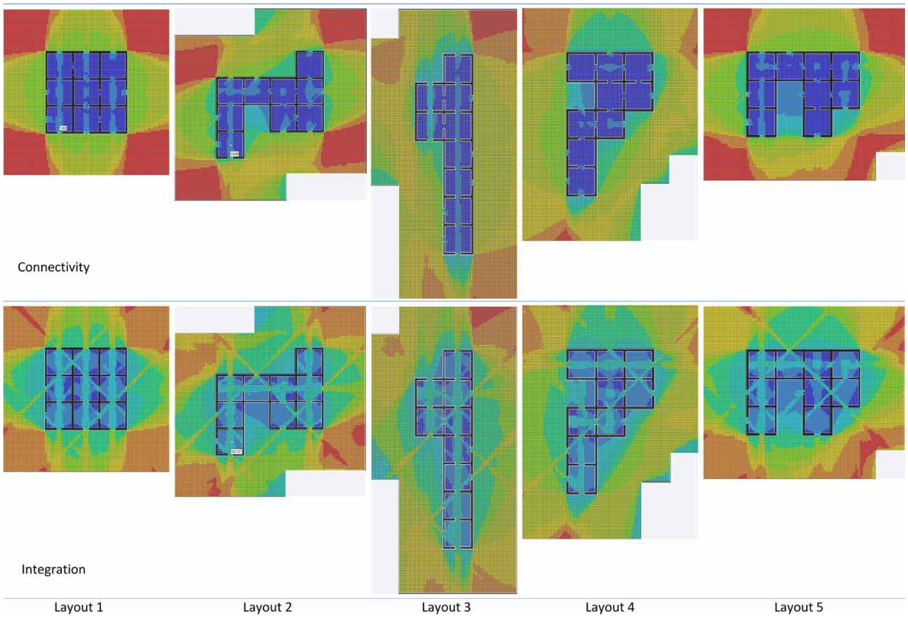

FIG. 10.6 The connectivity and integration maps of the five layouts

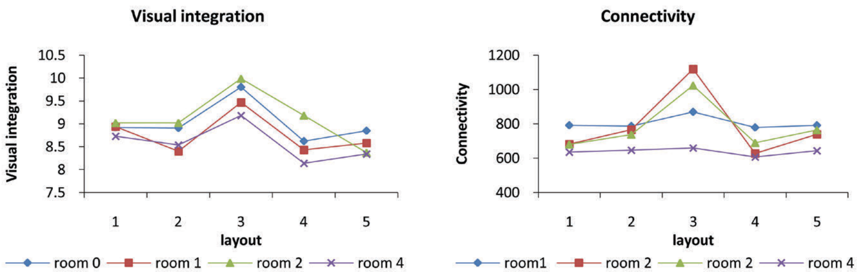

FIG. 10.7 The variation of the connectivity value and visual integration value of the five layouts in the VGA analysis

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As mentioned in section 10.2.2, many measures in the isovist are related to the boundary conditions between the spaces such as the opening size and the location on the walls between the spaces (figure 10.3). The parameters can reflect the spaciousness, enclosure and openness of spaces in a particular environment (table 10.1). Therefore, the isovist analysis is considered to be applicable for airflow analysis as well. Figure 8 shows the example of the measure of isovist area in a room with different openings to the outside environment. There are two openings in the room. The width of every opening is assumed as W in case 1, 2 and 3 (figure 10.8 (a)(b)(c). In case 4 (figure 10.8(d)), every opening is assumed as 2.5 times W. The outside environment is extended to a certain area. The green colour represents the isovist and the value is shown in the room. As we can see, in case 1, 2 and 3, the isovist area is different, which is caused by the difference of the location of the openings, even though the total opening area is the same. Case 2 shows the highest isovist area, which means it has the best openness to the outside environment and the highest potential for natural ventilation. Comparing case 4 to case 1, 2 and 3, the isovist area in case 4is much larger than others. This is because the room has the largest opening area in case 4. Therefore, case 4 has the highest potential to achieve natural ventilation.

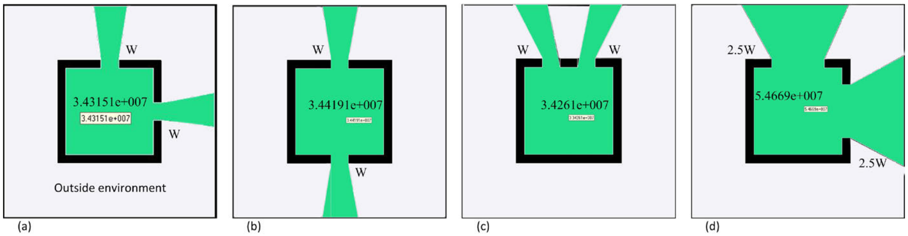

FIG. 10.8 The measure of isovist area in a room with different openings to the outside environment

10.4 Conclusion

In this chapter, the spatial analysis method, which was extended from the traditional space syntax method, was introduced for the analysis of natural ventilation potential. Both the logical relationship between the spaces and the boundary conditions can influence the accessibility of a particular spatial configuration, and then influence the natural ventilation potential. The convex method can show the logical relationship of spaces, but cannot reflect the natural ventilation potential completely. It can be developed for the preliminary analysis because it is easy and clear to show the relationship of the spaces which is important for architects to deliberate the solution through a graphical method. The extended VGA method is the best choice for the natural ventilation potential analysis for a spatial configuration. The isovist measure can be used for the natural ventilation potential for a single space.

In the next two chapters, the extended methods in the Depthmap program will be applied for the evaluation of natural ventilation potential of Chinese rural house design layout.

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11 Spatial configuration evaluation of Chinese rural houses through visual graph analysis for adaptive thermal comfort

11.1 Introduction

In chapter 9, it was found that the spatial indicators can reflect the airflow performance. There is a positive or linear correlation between the spatial indicators (connectivity, integration and depth) and the airflow indicator (airflow rate). The indicators that reflect the accessibility of the spatial configuration, i.e. connectivity, integration and depth, reflect the potential of achieving natural ventilation of a particular spatial configuration. In the other words, a high degree of connectivity, integration and low depth value mean a high accessibility of the spatial configuration and a high potential of obtaining natural ventilation. This result is useful for the architectural design practice, especially in the early design stage. In chapter 10, the extended space syntax methods in the program of Depthmap for natural ventilation potential analysis were proposed by the author. In this chapter 11, the proposed methods for spatial analysis will be used for design practice. The spatial configurations of a number of Chinese rural house designs in the area studied will be evaluated in terms of natural ventilation potential for thermal summer comfort by the proposed spatial analysis methods.

The rural houses as a case study in this research is chosen because the Chinese rural houses normally using passive ways to achieve thermal comfort in summer, therefore the spatial configuration for natural ventilation is important, as the author concluded in part 1 in this thesis. In addition, the rural population in China accounts for 40% of the total population with a total amount of approximately 560 million at the end of 2018 (NBSC, 2018). At the end of 2014, there were more than 585,451 villages in China and the rural housing area is at present 22.6 billion m², within a total area of more than 40 billion m² of China's urban and rural housing together. The amount of rural housing is constantly rising. According to 2010 data, the total floor space of newly built houses is 1.6 billion m², and half of them are rural residential buildings (NBSC, 2018). Therefore, improving the living environment for Chinese rural residential buildings is important for the sustainable development of China. Moreover, previous studies have been carried out on the sustainable development of Chinese rural residential building. However, many investigations and studies related to energy conservation and indoor thermal comfort have been proposed for northern China's rural houses (Jin & Zhou, 2008; Lai, Zhang, Wei, & Zhang, 2011; Sun, 2003; Yang, Yang, Yan, & Liu, 2011; Zhao & Jin, 2007; Zheng, Li, & Yang, 2008), focusing on winter comfort. Studies of the Chinese rural residential building in the hot humid climate regions are scarce (Han, Zhang, & Zhou, 2009; Jin, Meng, Zhao, Zhang, & Chen, 2013; Liu, Tan, Chen, Chu, & Zhang, 2013; Xie & Shi, 2012). Studies of spatial configuration for passive cooling of rural residential building design are very scarce.

11.2 Rural house design in the area studied

The rural houses studied are located in the rural area of Chongqing, China. Chongqing is located in the Sichuan Basin in the western part of the hot summer and cold winter zone. The annual average temperature is 18°C, the highest temperature in a typical climate year is 37.7°C in August, the lowest temperature is 2°C in January and the annual relative humidity is around 70-80%. The maximum average temperature reaches 28.1°C in July and the relative humidity is generally between 75-80% in summer. In summer, the prevailing wind comes from the north-west and the average wind velocity is 1.6m/s. The summer here is extremely hot, humid and uncomfortable. Therefore, the use of air conditioning is continually rising in the studied rural area.

11.2.1 Improvement opportunities for rural houses design

The Chinese government has put forwarded several important policies to improve the living environment of Chinese rural areas because of the huge unbalanced development between urban and rural areas. According to Chinese policies, the local governments provide financial and technical support for rural residents to build or rebuild their houses in order to improve the occupants' living conditions.

There are three routes to improve rural residential buildings.

- The first route is to protect and renovate existing buildings in the historical traditional villages. For historical houses, the major refurbishment is to replace parts that are damaged, and to improve the poor facilities, i.e., bathroom and kitchen. The local government plays a major role in the reconstruction process.
- The second route is to move rural residents to a new site and build a new village or town. The advantage of this route is that it is easier to build infrastructure, which is necessary for improved living environments than that the rural residents build their houses isolated. However, new residential buildings in a new village or town are ever more similar to urban residential buildings, which have many critical problems.
- The third route is to renovate the existing building or demolish and rebuild on the same site as the independent house, when the occupant does not want to move. In this way, the occupants are responsible for the construction of their own houses. The local government provides some financial and technical supports to the farmers.

In the Chongqing area, in recent years a great number of rural residential buildings have been built, refurbished or rebuilt. In 2017, around 8.7 million square metre of rural residential buildings was finished (NBSC, 2018). Figure 11.1 shows some of the rural residential buildings built in the Chongqing area, as investigated by the authors. Dwelling types 1-8 are built in the new rural communities by the local government. Dwelling types 9-16 are built by the occupants themselves, but the local government proposed some suggestions on, for example, the appearance. Dwelling types 17-28 are completely built by the occupants themselves. The living environment and the residential communities are changing rapidly. The living environment has been improved significantly.

However, there are still many critical problems in the local rural house design, especially in the thermal design which this study focuses on. The rural environment is further extremely suited for passive techniques due to a lower building density, a lower air pollution rate, and lower thermal expectations than in urban areas. However, through this investigation, we found that the passive cooling techniques are not commonly used by the local occupants and the thermal environment of the existing rural houses is unsatisfactory. Many of the rural houses lost the ideas for passive cooling used in traditional houses and they copy the city model, in which many environmental problems have been found. For example, the use of air-conditioning is growing in rural houses, but most of the houses do not have insulation in the outer wall due to the low price of the house and the cheap construction. To save energy, the opening area in the outside wall was reduced in some of the rural houses. But this reduces the potential for natural ventilation as well. Consequently, it is a great opportunity to implement research knowledge in the countryside construction to improve the building performance of the rural houses.

FIG. 11.1 Typical rural residential buildings built in the Chongqing area in recent years (photographed by author)

11.2.2 The local occupant's living habits in summer

Occupants' living habits are significant for the design of a house and for the passive cooling strategy. In the rural area studied, the occupants' living habits are different from the living habits in urban areas. To adapt to the hot and humid summer climate, the local rural residents have typical living habits. As findings from a field survey by the author, the following aspects should be taken into account:

- Even with the increase in air-conditioning use in the rural area, most of the occupants have adapted to the free-running building environment.
- The occupants move between the different spaces in the house. In the morning, they prefer the courtyard, veranda or the inside of the house. In the afternoon, they always stay in the living room or on the veranda. In the evening, they prefer to stay on the veranda or in the courtyard. If there is good ventilation, they also prefer to stay in the living room. The living room is an especially important space: most of the activities take place here.
- Generally, the occupants go to the bedroom after the heat has disappeared through the open windows. Sometimes, on the hottest days, they sleep on a temporary bed in the living room if there is no air conditioning used in the bedrooms.
- The occupants prefer to dress in short and thin clothes. Their arms and legs are generally uncovered the whole day.
- The occupants use a hand fan or a mechanical fan for cooling. If air-conditioning is used, generally, it is only used in the bedrooms.

11.2.3 Dwelling types proposed by the local government

The great difference between the urban and rural living environment encourages the local government to improve the rural living environment. Based on the investigation of local rural occupants' living habits and demands in 2011, the local building construction sector of Chongqing proposed 24 dwellings for the rural occupants to choose from. Figure 11.2 shows the floor plans and typical appearance of the 24 types of dwellings. The dwellings are divided into three price categories. Translated from the Chinese they are called: economic house, practical house and well-off house. All of the houses have two floors. The houses can be free-standing houses or terraced houses. Table 1 shows the basic information of the proposed dwellings.

Comparing the proposed dwelling types by the government and the existing dwellings, the living standard of the proposed dwelling types is much better. For example, the indoor layout is improved for modern life; the function and service facilities are more complete than before.

The general features of the house designs are:

- Double width (a width of two rooms) was used for the small area house types and triple width (a width of three rooms) was used for the large area house types.
- Some of the house designs have a room for business (such as a small store).
- The living room and dining room are the major public spaces on the ground floor. The kitchen, bathroom, storage room and bedroom are the private rooms. There are 1 to 2 bedrooms on the ground floor. In some dwellings, there is no separate dining room, but the dining room is included in the living room or kitchen.
- Some of them use a corridor to connect the different rooms and in some of them, the rooms are connected directly.
- Of the 24 types of dwellings, 22 have a courtyard, 8 have 2 courtyards, 3 have a patio.
- All of the dwellings were designed with transitional spaces (verandas). Most of them have these at the main entrance. Some of them have a veranda at the back entrance.
- All of the types have at least a terrace or a balcony on the first floor.
- Some of the windows and doors are according to traditional style, in which windows and doors can be opened completely.
- Building orientation was not proposed for any type of dwelling.
- Most of the dwellings have no shading devices for the windows.

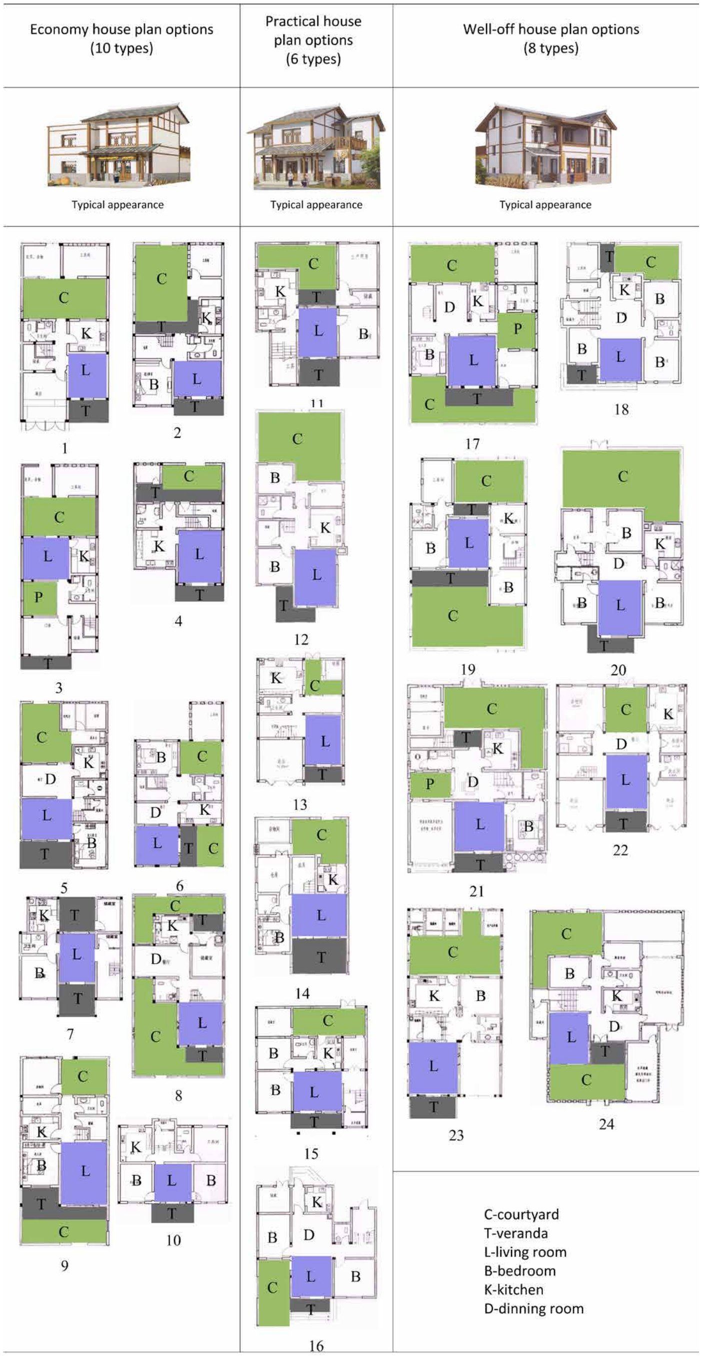

FIG. 11.2 The ground floor plans and typical appearance of the 24 types of dwellings proposed by the local government (CCC, 2011)

TABLE 11.1 Basic information of the dwelling types proposed by local government

No.	Plot area (m²)	Area of building (m²)	Area of courtyard (m²)	Total Area (m²)	Area of ground floor (m²)	Area of first floor (m²)	Width (m)	Depth (m)	occupants	Living room +dining room	Dining room	Bedroom	Terrace	Balcony	Veranda	type
1	126	98	28	155	98	57	7.8(2)	16.1	3-4	1	0	3	1	1	1	Economic
2	138	100	38	159	100	59	8.7(2)	15.8	3-4	1	0	3	1	0	1	Economic
3	135	95	40	159	95	64	7.2(2)	18.3	3-4	1	0	2	1	0	1	Economic
4	93	72	21	132	72	59	8.1(2)	11.1	3-4	1	0	2	0	0	1	Economic
5	126	100	26	155	100	55	8.4(2)	16.2	3-4	1	1	3	2	1	2	Economic
6	133	105	28	179	105	74	9(2)	16.8	4-5	1	1	3	1	0	1	Economic
7	85	85	0	165	85	80	9.6(3)	9.6	4-5	1+1	0	4	1	1	2	Economic
8	226	100	126	181	100	81	9.1(2)	24.3	4-5	1+1	1	3	1	1	2	Economic
9	147	94	53	175	94	81	8.1(2)	13.8	4-5	1	0	4	2	0	2	Economic
10	98	98	0	167	98	69	11.4(3)	8.8	3-4	1	0	4	1	0	1	Economic
11	122	101	21	164	101	63	10.8(3)	12.6	3-5	1	0	3	1	1	2	Practical
12	154	104	48	182	104	78	7.8(2)	13.8	5-6	1+1	0	4	1	1	1	Practical
13	106	91	15	180	91	89	8.4(2)	12.0	3-5	1	0	3	1	1	2	Practical
14	120	99	21	177	99	78	8.7(2)	12.9	5-6	1+1	0	4	1	1	2	Practical
15	130	106	24	190	106	84	11.1(3)	12.0	5-6	1+1	1	5	2	1	1	Practical
16	133	112	21	192	112	80	11.7(3)	11.1	3-5	1+1	0	5	2	0	2	Practical
17	222	135	87	234	135	99	12.3(3)	17.6	5-6	1	1	4	1	0	2	Well-off
18	150	128	22	228	128	100	11.4(3)	13.4	5-6	1+1	0	6	1	2	2	Well-off
19	253	138	115	244	138	106	12.3(3)	15.6	4-5	1+1	0	4	1	1	2	Well-off
20	197	128	69	224	128	96	11.7(3)	11.7	5-6	1+1	0	5	1	1	1	Well-off
21	160	117	43	221	117	104	11.1(3)	14.4	5-6	1+1	1	4	1	1	2	Well-off
22	169	150	19	293	150	143	12.3(3)	13.5	5-6	1+1	0	5	0	1	2	Well-off
23	158	126	32	203	126	77	8.7(2)	17.4	4-5	1_1	0	3	1	0	1	Well-off
24	277	179	98	283	179	104	15.4(3)	19.4	5-6	1+1	1	4	2	1	2	Well-off

11.3 Methods

In this study, in order to investigate the spatial features of the local rural house quantitatively, 12 house types proposed by the local government were selected for the extended space syntax analysis in terms of VGA and isovist analysis. Because most of the public area of all the types is on the ground floor, only the ground floor was studied. In figure 11.10, the layouts of the 12 selected types were shown.

The VGA analysis consists of two parts. Part one is focused on the occupants' movement behaviour on the ground floor; it is a traditional VGA analysis. The boundary in the analysis is the border of the layout in which the indoor spaces and courtyards are involved. The doors are assumed completely opened so that the occupants can pass through. The windows are assumed closed because they are not for occupants' movement. In the second part, VGA and isovist analysis are focused on the accessibility of the air movement on the ground floor. The method was proposed in chapter 10. In order to include the influence of natural ventilation, the boundary was extended 5 meters outside the outline of the layout (figure 11.4). The courtyards and veranda were included in the outside environment. Because the proposed types are for farmers in this area, the orientation of the houses are not fixed. Therefore, the wind direction is not considered at this stage, i.e. the wind can come from all directions. The doors and windows are assumed completed opened to encourage the largest cross ventilation. The connectivity (C value), visual integration (I value) and mean depth (D value) were selected as indicators. According to the method proposed in chapter 10, a higher connectivity and integration value, and a lower mean depth mean that a particular layout is more accessible for people movement and airflow. And, a higher isovist area in a particular space means more openness for air flow.

11.4 Results

11.4.1 Results of the visibility graph analysis (VGA)

Results of occupants' movement

Figure 11.3 shows the connectivity map, visual integration map, mean depth map and convex map for occupants' movement. The following can be seen:

1. For all types, the courtyards, corridor, living room and dining room always show high C and I values and a low D value. These spaces are the public spaces. Courtyards and corridors always have the highest C and I value and lowest D value.
2. For all types, relatively low C and I values and a high D value were observed in the bathrooms, kitchens, bedrooms and storerooms. The bathroom always has the lowest C and I value and highest D value.
3. For types 1,2,6 and 11, the living room, the most important public space does not have a very uniform distribution of the C, I and D values, i.e., some parts of the space have high C and I values and a low D value and some have low C and I values and a high D value.
4. The convex map shows the living rooms of type 4, 7, 8 and 10 have the highest C and I values and lowest D value comparing to other rooms, corridor and courtyards. However, the living room of type 5 and 6 have very low C and I values and a high D value.

The results of the occupants' movement analysis show that the accessibility in the public spaces (courtyard, corridor, dining room and living room) is the best. The occupants' living habits described in section 11.2.2 show that the occupants perform most of their activities in these spaces as well. Therefore, it can be concluded that the indictors in space syntax analysis not just reflect the occupants' movement behaviour but also show the occupants' preference of spaces and how long they would like to stay. or they prefer to move to these spaces. The corridor is used more for traffic space. This matches with the occupants' behaviour described in section 11.2.2. Most of the design of the 12 layouts are good with respect to occupants' behaviour. If the indoor space is considered, types4, 7, 8, and 10 are the best, while types 2, 5,6 and 12 are not so good.

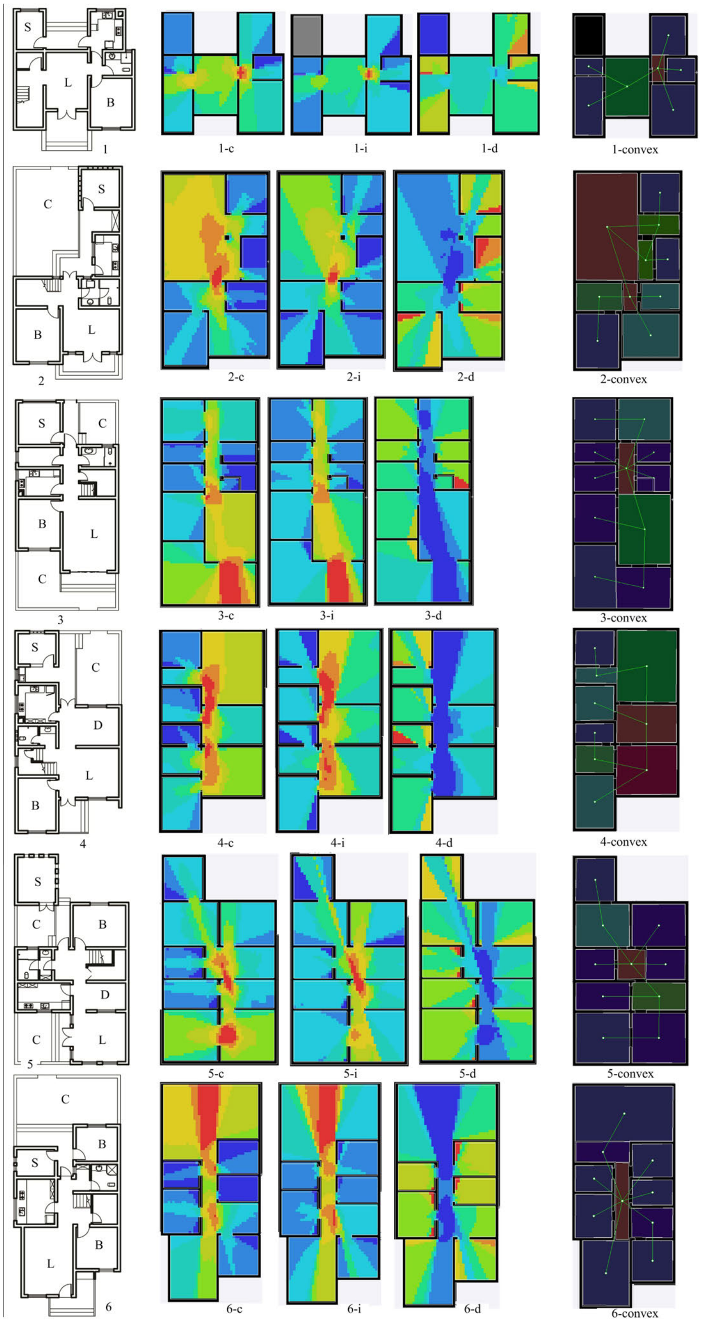

FIG. 11.3 / 1 The layout of the selected 12 house types and occupants' movement analysis (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; 1-convex: convex map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

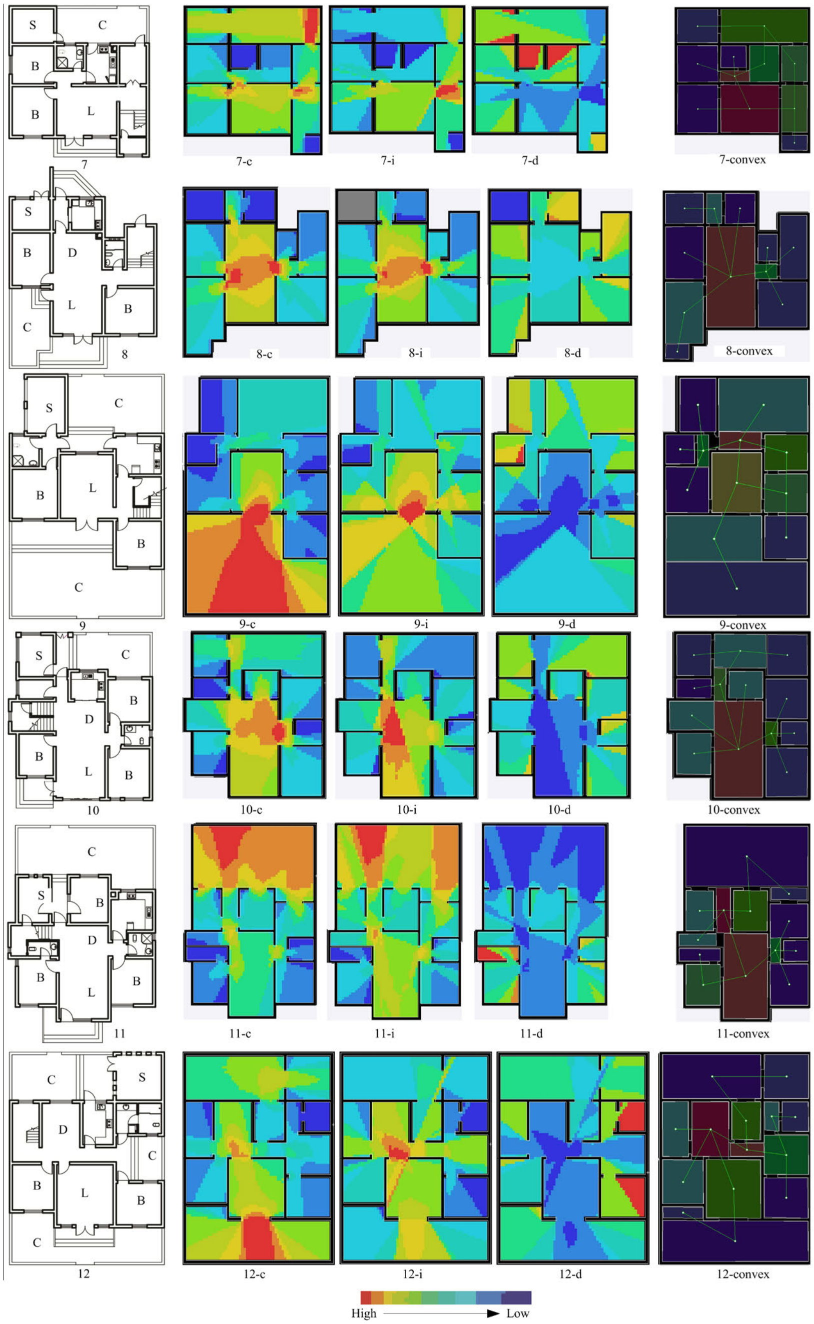

FIG. 11.3 / 2 The layout of the selected 12 house types and occupants' movement analysis (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; 1-convex: convex map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

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Results of the air movement analysis

Figure 11.4 shows the connectivity map, visual integration map and mean depth map for air movement. It can be seen:

1. The corridors, living rooms and dining rooms show relatively higher C and I values and a lower D value for all types. Especially the corridors have the highest C and I values and the lowest D value (except the outside spaces).
2. The relative lower C and I values and a high D value were observed in the bathrooms, kitchens, bedrooms and storerooms.
3. In type 8, 9,10,11, and 12, the highest C and I values and lowest D value (except the outside spaces) were observed in the living rooms or dining rooms, especially in type 9.

The results of the air movement analysis show that the air accessibility in the public spaces (corridor, dining room and living room) is the best. That means there are more opportunities in the corridor, dining room and living room to achieve natural cross-ventilation than in other rooms (except the outside spaces).

Table 11.2 shows the mean integration, mean connectivity and mean depth values of the entire layout and the living room, and figure 5 shows the comparison between the different types.

Firstly, the indicators of the living room were compared. As we can see, type 10 has the highest integration, followed by type 9; type 1 has the lowest integration, followed by type 7 (figure11.5 (a)). Type 10 has the highest connectivity, followed by type 9; type 1 has the lowest connectivity, followed by type 6 (figure 11.5 (b)). Type 10 has the lowest depth, followed by type 9; type 1 has the highest depth, followed by type 7 (figure 11.5 (c)). All of the indicators show that the living room of type 10 has the greatest potential for natural ventilation, followed by type 9. However, type 1 has the worst conditions for natural cross-ventilation, followed by type 7. Comparing the design of types 10 and 9 and types 1 and 7,some design features can be found that the potential of natural cross-ventilation of type 10 and 9 is better than type 1 and 7. In type 10, the living room can get the cross-ventilation through the opening on one side and the corridor and kitchen on another side. In type 9, the living room has openings on two sides through which the cross-ventilation can pass directly. The opening area of the living room in type 10 is larger than in type 9, which causes the connectivity and integration of type 10 to be a little bit greater than of type 9. In type 1 and 7, the living room has only one side opening directly to the outside environment, which makes cross-ventilation difficult.

Secondly, the indicators of the whole layout of the ground floor were compared. The variation of the indicators for the layout is smaller than for the living room. Type 10 has the highest integration, connectivity value and lowest depth value; type 1 has the lowest integration, connectivity value and highest depth. This indicates that type 10 has the best and case 1 has the worst potential for natural ventilation, even at the whole floor scale. The spatial configuration of type 10 is much better than type 1 in terms of achieving natural cross-ventilation.

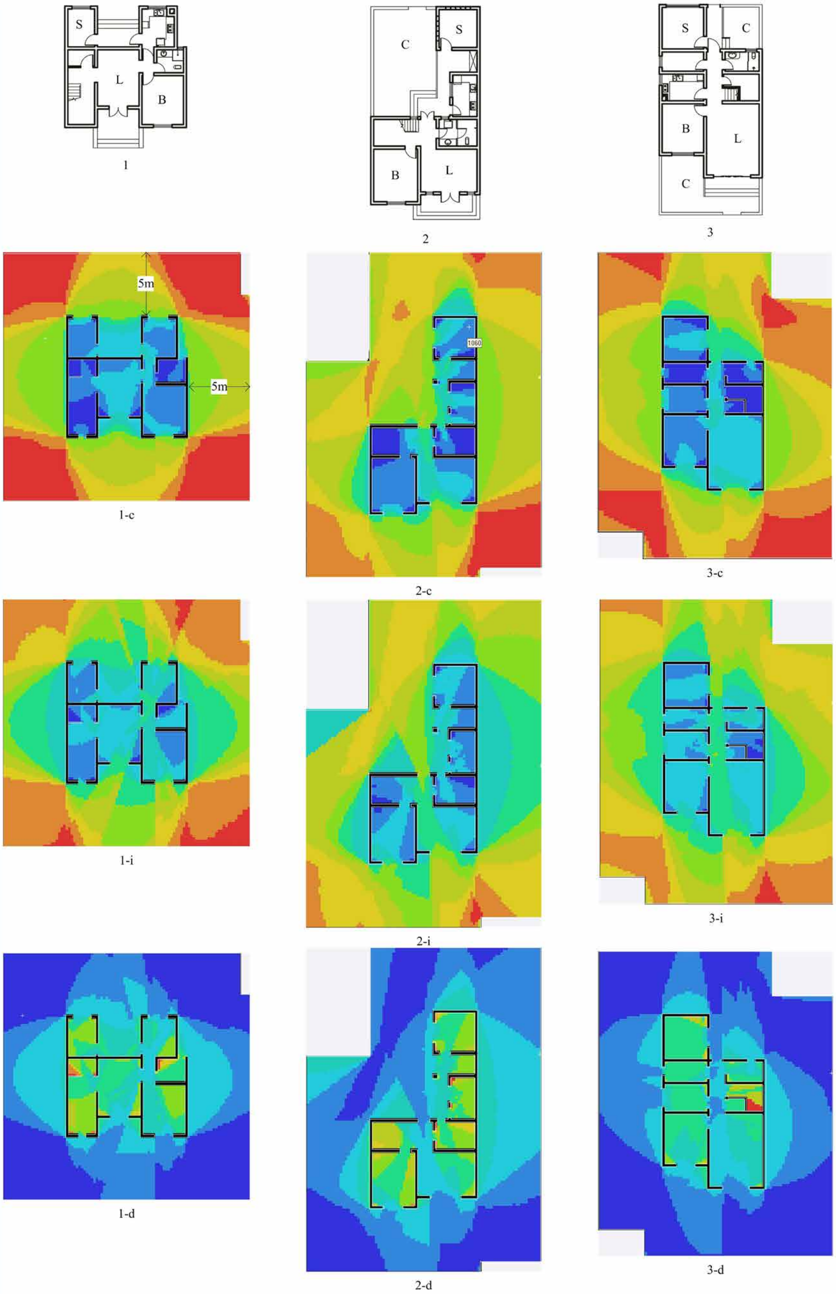

FIG. 11.4 / 1 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

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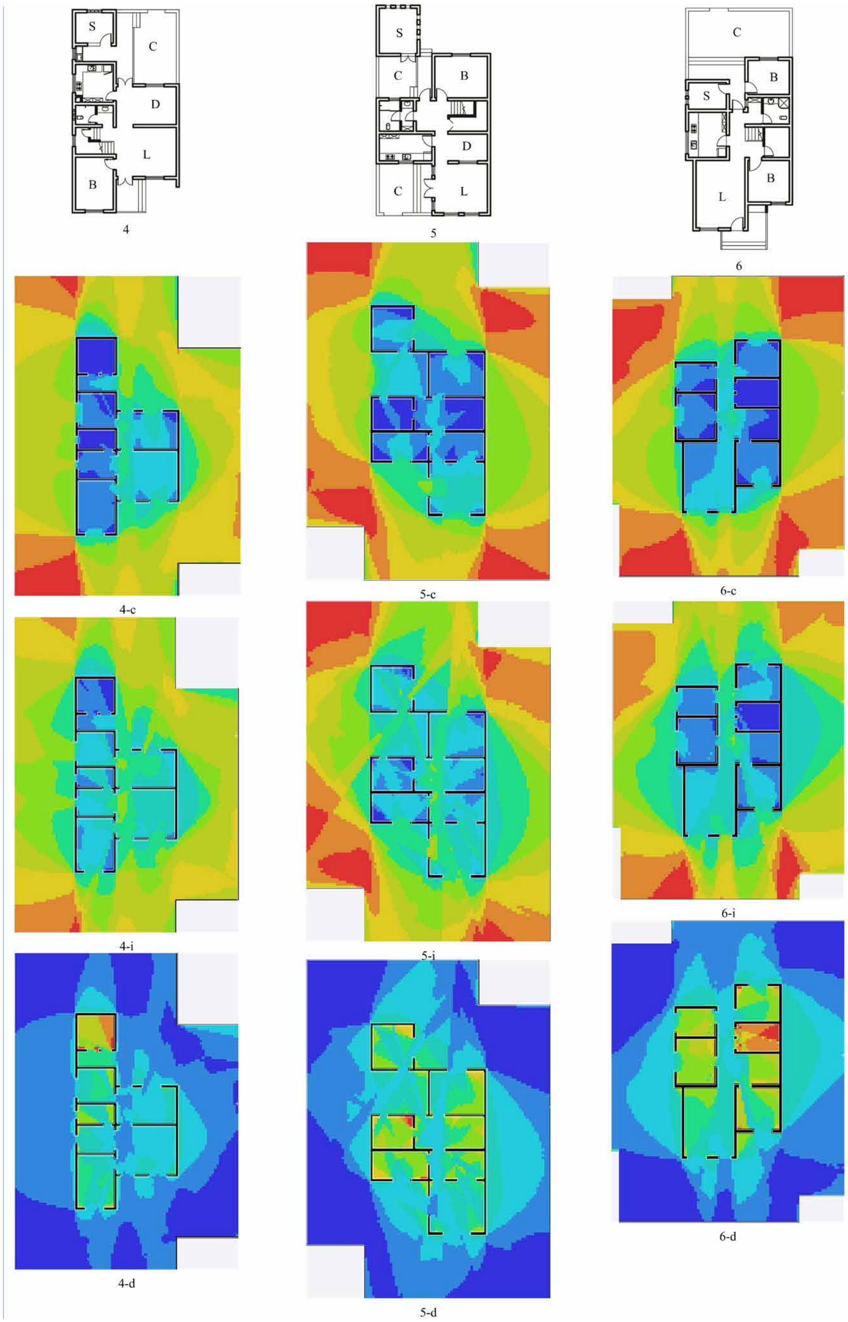

FIG. 11.4 / 2 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

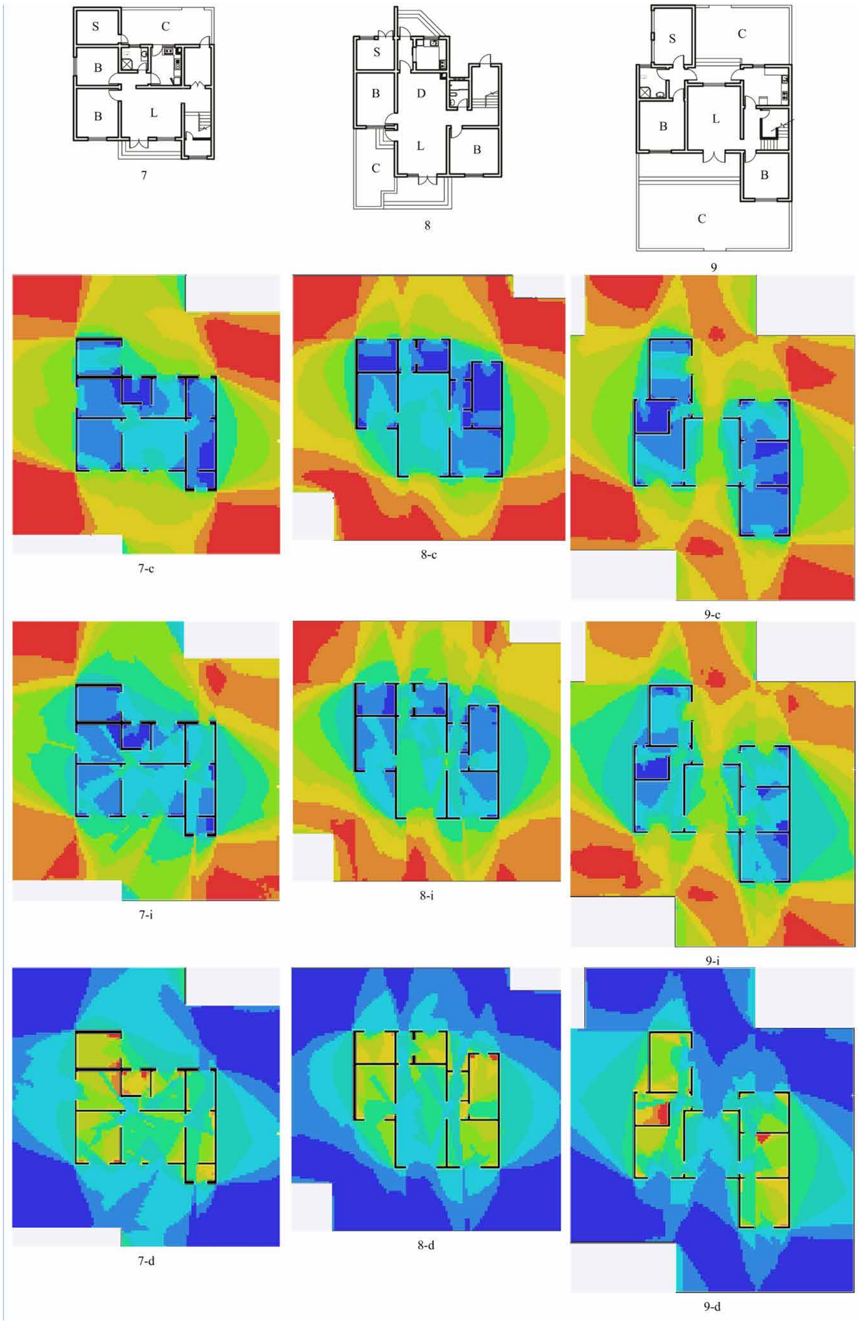

FIG. 11.4 / 3 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

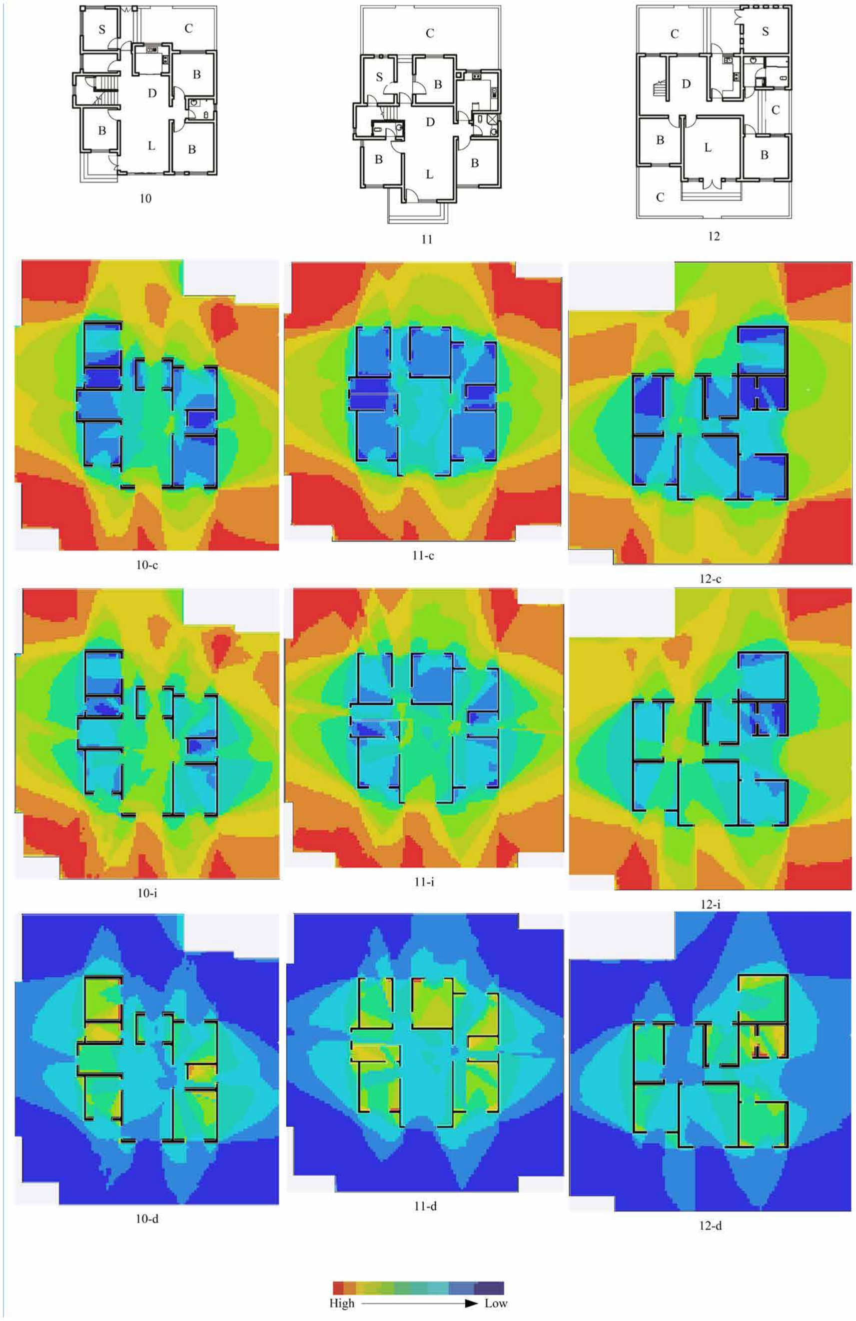

FIG. 11.4 / 4 Air movement analysis of the selected 12 types of floor plans (1: the number of house type; 1-c: connectivity map; 1-i: integration map; 1-d: mean depth map; L: living room; B: bedroom; D: dining room; C: courtyard; S: storage room)

TABLE 11.2 The mean integration, connectivity and depth value of the entire layout and the living room

House types	Mean Integration		Mean Connectivity		Mean Depth	
	Layout	Living room	Layout	Living room	Layout	Living room
1	14.81	*9.61*	3197	*1070*	1.78	*2.12*
2	14.44	*11.28*	3393	*1571*	1.79	*1.98*
3	14.71	*10.67*	3457	*1448*	1.79	*2.03*
4	14.61	*11.78*	3381	*1747*	1.78	*1.93*
5	13.88	*11.13*	3400	*1907*	1.83	*2*
6	14.59	*11.02*	3315	*1390*	1.79	*1.99*
7	13.79	*9.87*	3288	*1517*	1.83	*2.1*
8	14.11	*11.32*	3268	*1685*	1.82	*1.97*
9	14.12	*12.64*	3454	*2447*	1.82	*1.88*
10	15.19	*13.62*	3600	*2478*	1.75	*1.8*
11	14.45	*12.31*	3363	*1792*	1.8	*1.89*
12	13.63	*10.88*	3443	*1637*	1.86	*2.03*

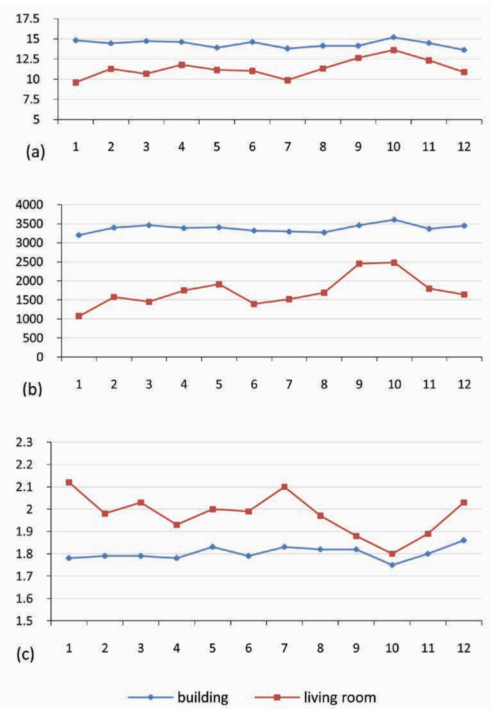

FIG. 11.5 Comparing of the mean integration (a), connectivity (b) and depth value (c) of the layout and the living room

11.4.2 Results of isovist analysis

Figure 11.6 shows the isovist viewshed polygons in the living room of different types and table 11.3 lists the measured isovist variables. The viewpoint is in the middle of the living room. In this study, the isovist area not only expresses the visual area, but also the area where natural ventilation is most effective. Figure 11.7 shows the comparison of the isovist area (a) and perimeter (b). The results show the isovist area of type 9 is the largest, followed by type 10, and the isovist area of type 1 is the lowest, followed by type 6. The perimeter value of the types also shows the same trends. The results mean that the living rooms of type 9 and 10 are more open than the other types, and that these have a greater chance of natural ventilation.

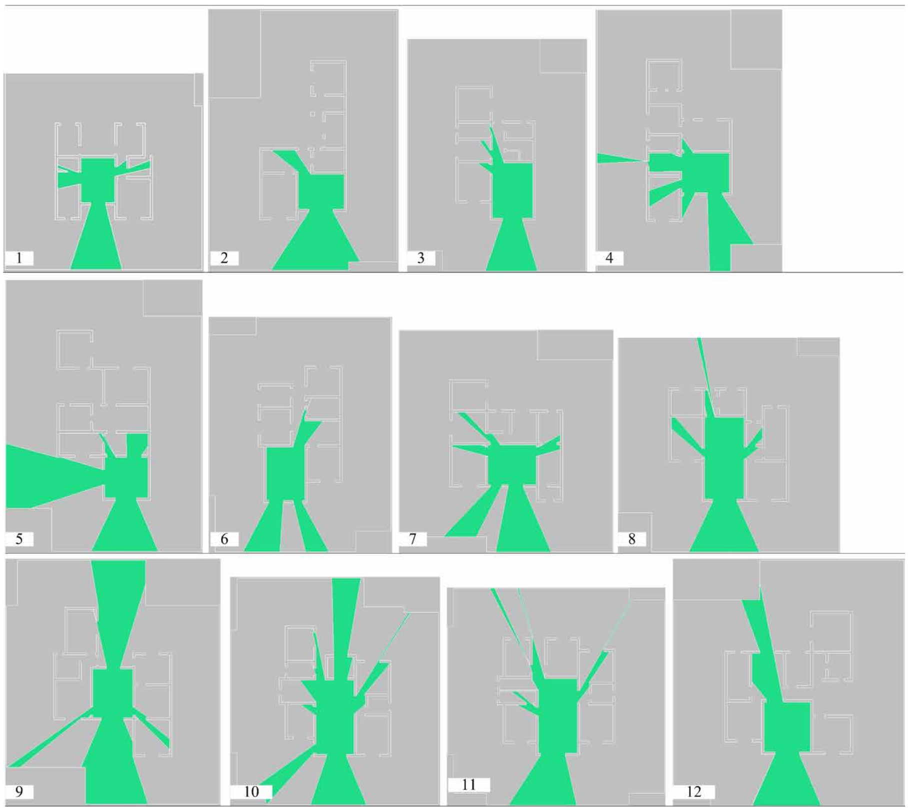

FIG. 11.6 Isovist viewshed polygons in the living room of different types

TABLE 11.3 Measured isovist variables in the living room

Ref	Area	Compactness	Drift Angle	Max Radial	Min Radial	Occlusivity	Perimeter
1	4.44E+007	0.17	266	9543	1598	33489	57340
2	5.31E+007	0.34	260	9326	1680	18941	44036
3	4.92E+007	0.26	263	9065	2049	22811	48924
4	5.63E+007	0.13	253	11273	1788	43615	73827
5	8.60E+007	0.20	197	12345	1884	40451	73288
6	4.86E+007	0.18	273	9401	1945	32686	57414
7	6.15E+007	0.14	259	10185	1807	45018	73930
8	6.58E+007	0.14	230	14060	1901	45114	78163
9	12.20E+007	0.14	86	14512	2093	65127	106061
10	9.45E+007	0.08	94	16056	1945	82812	119007
11	6.47E+007	0.07	215	15718	1875	74248	105952
12	6.57E+007	0.16	165	14362	2234	41467	71096

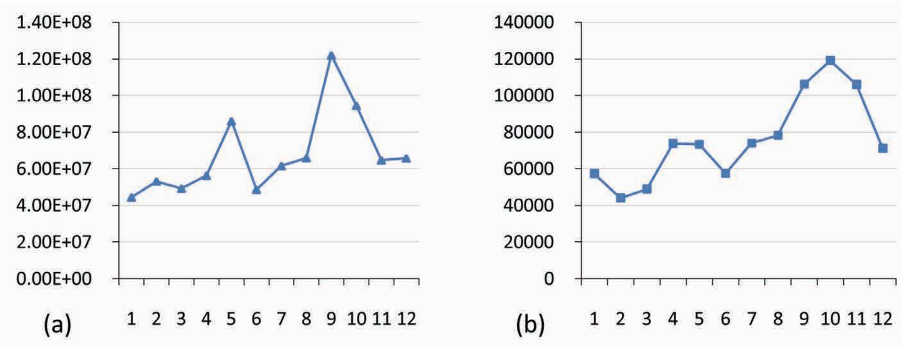

FIG. 11.7 Comparison of the isovist area (a) and perimeter (b)

11.5 Discussion and conclusions

Comparison of the occupants' behaviour analysis and the air movement analysis, the public spaces show relative high accessibility in terms of high connectivity and integration values and a low mean depth value in both the occupants' behaviour and air behaviour. This means that the space that has the highest potential to obtain natural ventilation is also the area most public and most used. In this sense, the layouts of the 12 types are good.

Combining the results of VGA and isovist analysis, the spatial features for natural cross-ventilation and thermal summer comfort of the proposed houses by the local government can be summarised as follows:

1 Most of the types have clear public spaces and a central area: courtyards, a corridor and a living room (sometimes dining room is involved). The occupants perform most of their activities in these public spaces. Fortunately, in these public spaces, there is higher potential to obtain natural cross-ventilation according to the spatial analysis. According to the adaptive thermal comfort theory, occupants always take actions to adapt the thermal environment to achieve thermal comfort. Movement is one important adaptive behaviour for the local occupants. In this case, the VGA analysis proved that the occupants' movement behaviour can be matched with the air movement. So, the occupants prefer to move the public space to where they can easier obtain natural ventilation.

1 In some of the types, the accessibility and openness of the public spaces are generally better than other spaces, but within a single public space, the potential to obtain natural ventilation is different in different locations, especially in the living room. In some cases, only a part of the spaces in the living room have a high potential to obtain natural ventilation.

2 The public space is not so diverse in most of the types. The courtyard is the major outdoor space and the veranda is the major semi-outdoor space. For the indoor space, the dining room and living room were set together in most of the types. The lack of diversity of the public spaces in the indoor spaces makes that the occupants have little choices for their movements.

3 The accessibility and openness of the layout and the public spaces still needs to improve. In some of the types, the mean integration and connectivity value are very low, both in the entire layout and the living room, which means a low potential for natural ventilation. In this sense, some of the layout designs of the proposed houses are not so good for natural cross-ventilation.

4 Considering the local occupants' living habits, the high accessibility and high potential to achieve natural ventilation of the public spaces in the rural houses design, the public spaces should be the focuses in the local house design for passive cooling. The private spaces, such as the bedrooms, are difficult to achieve natural ventilation for thermal comfort due to the private design which makes them enclosed.

Type 10 will be chosen as the optimised layout design for the new house design in the next chapter.

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12 Coupling occupants' behaviour and natural ventilation potential analysis in the design of a Chinese rural house

12.1 Introduction

In chapter 11, the VGA analysis method proposed by the author was used for the evaluation of the layout designs of Chinese rural houses proposed by the local government. Type 10 was selected as best design type, because it can most easily achieve thermal summer comfort for occupants in passive ways. The optimised layout has a high potential to achieve natural cross-ventilation, especially in the public spaces, which are important for the local occupants' thermal summer comfort in hot and humid climates. Chapter 11 also shows occupants' movement behaviour in the spaces. The public spaces in the house are the most attractive spaces for occupants. This is related to the occupants' spatial perception. This helps the occupants to enjoy the natural ventilation in the public spaces because there is a high potential to achieve natural ventilation there.

In this chapter, the optimised layout design of chapter 11 will be developed for a new rural house design in the studied area. The focus of the design is still on the occupants' behaviour and natural ventilation potential with respect to the spatial configuration. This study will demonstrate how to use the VGA analysis method for the optimisation of spatial configuration, coupling occupants' behaviour and natural ventilation analysis to design practice.

12.2 Methods

Firstly, the optimised layout (type 10) proposed by the local government is analysed through the space syntax method in terms of occupants' behaviour and natural ventilation potential. Secondly, the optimised layout is improved to create a better potential to provide thermal summer comfort in the new house design. Other design factors such as site, occupants' demands and function are also considered. Finally, the results of the spatial analysis related to natural ventilation potential are validated through CFD simulation.

12.3 Spatial analysis of the optimised layout design by the local government

12.3.1 Occupants' movement behaviour

The occupants' movement behaviour was analysed through the convex map and VGA analysis. The boundary of the analysis is the border of the layout in which the indoor spaces and courtyards are involved. The doors are assumed completely opened so that the occupants can pass through. The windows are assumed closed because they are not for occupants' movement. Figure 12.1 shows the optimised layout of the rural house and the results of the behaviour analysis. Figure 12.1 (b) shows the function distribution of the spaces. As we can see, the traffic space and public spaces are set at the middle of the layout, and the private spaces are set on both sizes around the public spaces. This gives the bedrooms and bath room good privacy. The living room, which includes the dining room, shows a high connectivity and visual integration value (figure 12.1 (c)(d)(e)). That means it is the centre of the other spaces. The occupants perform most of their activities in the living room. However, there are two main disadvantages that need to be improved. Firstly, a part of the traffic spaces is included in the living room (figure 12.1 (b)). It influences the use of the living room. Secondly, there is only one public indoor space (living room) and one public outdoor space (courtyard). There is a lack of spatial diversity.

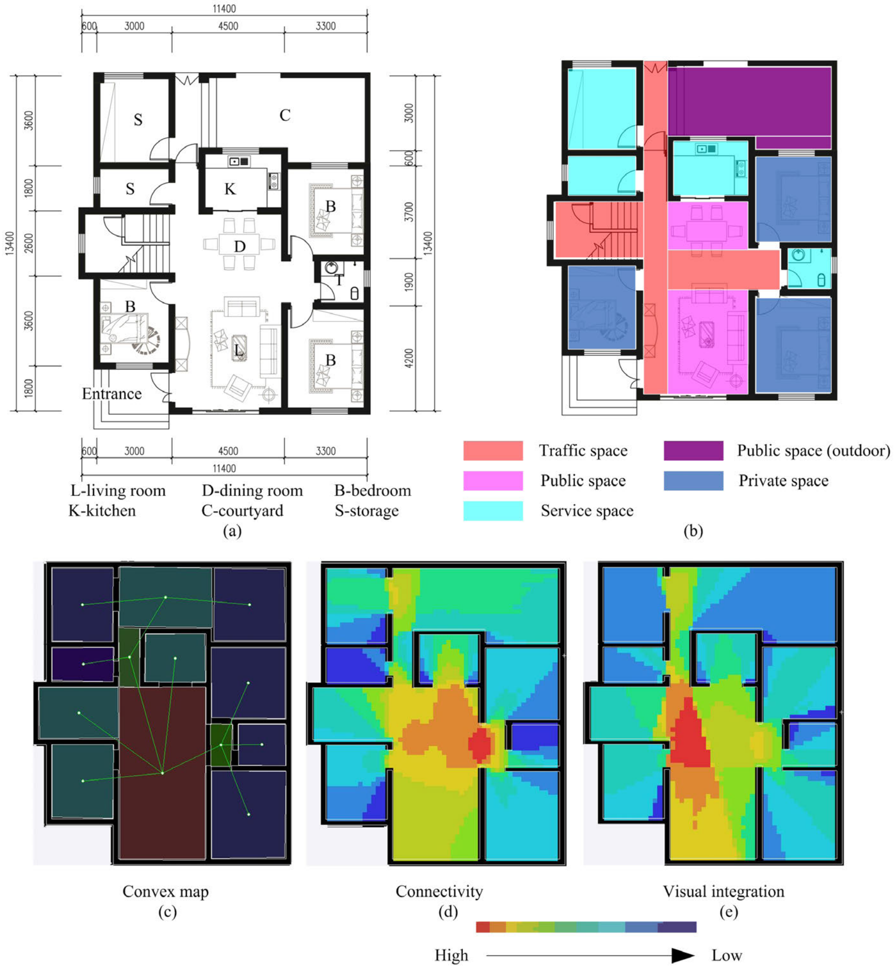

FIG. 12.1 The optimised layout of the rural house and the results of the behaviour analysis.
(a) optimised layout; (b) functional analysis; (c) convex map; (d) connectivity map; (e) visual integration map

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12.3.2 Natural ventilation potential analysis

The natural ventilation potential of the spatial configuration was analysed by VGA. In order to involve the outside environment in the analysis, the boundary of the layout was extended to a certain scale, see figure 12.2 (a). In order to reflect the real situation, the wind direction should also be considered in this analysis. It was assumed that the building's main facades with larger openings face the prevailing wind direction to obtain the largest natural ventilation. In the prevailing wind direction, to represent the influence of wind direction in the VGA analysis, the outside environment was extended much farther than in other directions (figure 12.2 (a)). Figure 12.2 (b)(c) shows the connectivity map of the VGA analysis. As we can see, the connectivity value near the windows is higher than in the adjacent indoor spaces. This reflects the real situation that the points near the openings have more opportunities to obtain the outside wind flow. Especially for openings in the prevailing wind direction, the connectivity value is much higher than in other spaces. The rooms that face the prevailing wind direction (the storage room, the kitchen and the bedroom) have a much higher average connectivity value as well (figure 12.2 (c)). The kitchen has the highest. this is because the wind comes from the above, as we assumed. The living room has the second highest connectivity value. This is due to the large openings of the living room. It is also found that the connectivity value of the living room is evenly distributed, but for the rooms on the windward side with a high average connectivity value, the distribution is not uniform. In some of the locations in the rooms, such as the corner near the window, the connectivity value is low. In other rooms, which do not face the wind direction (other two bedrooms, toilet, stair and another storage room), the connectivity value is relatively low. The VGA analysis shows that the most important public space-living room has a high potential to obtain natural cross-ventilation. The space matches the occupants' movement analysis above in terms of space. The living room is the space with most occupant activity and it has a high potential to achieve natural ventilation. However, some improvements are needed to enhance the natural ventilation potential of the current layout design. The kitchen is close to the living room. The wind has to cross the kitchen and then flow to the living room. This weakens the natural ventilation of the living room. Another is the fact that the depth of the living room is relatively great in the wind direction. This makes it more difficult of wind to pass through the living room.

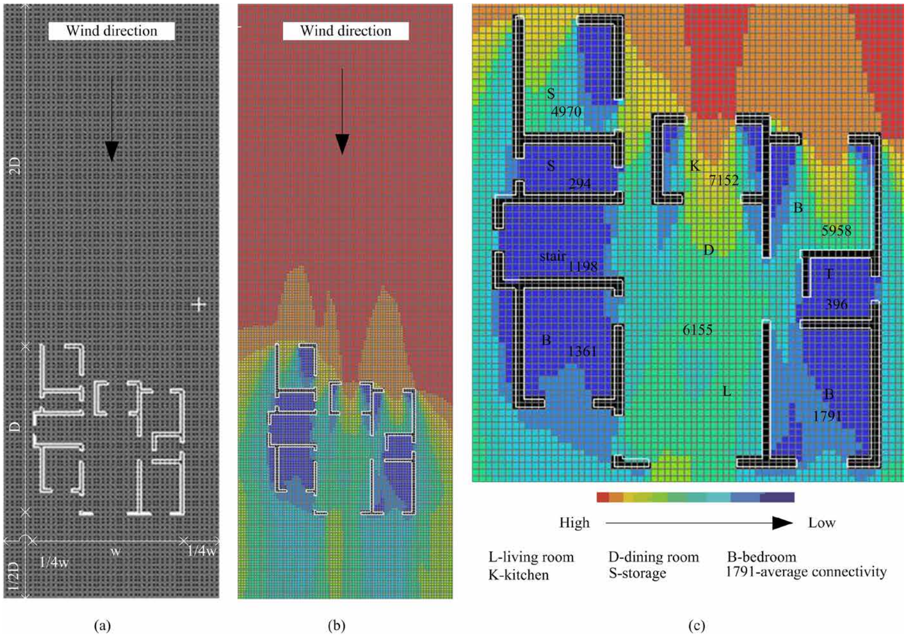

FIG. 12.2 The boundary setting in the VGA analysis (a) and the results of connectivity map (b)(c)

12.4 The new house design

12.4.1 General introduction of the new house design

The site for the house is located in a small village, on a hilly terrain, in a valley in Chongqing (figure 12.3 (a)). The site area is approximately 427 square metres and is surrounded by farmland (figure 12.3(b)). In front of the site (south-west), there is a small lake and behind the site (north-east), there is a small hill (figure 12.3(b)(c)). There are no buildings surrounding the site. The natural environment is good.

FIG. 12.3 Terrain of the site (left), view from the small hill (top right) and view from the lake side (bottom right)

The house owners are a middle-aged couple. Four residents live here: the couple and their old parents. However, there are some temporary residents: their daughter, sisters, brothers and relatives possibly live there for a short period, especially during the holidays. Therefore, the owners request four bedrooms and two toilets. A living room, dining room and kitchen are also necessary. They also hope to have a courtyard. The total area of the house is approximately 200 square metres. Two stories are expected. The residents do not exactly understand passive cooling, but they do hope to reduce the electricity usage in terms of reducing the use of air conditioning in summer. They hope the budget is a maximum of 25,000 euro.

12.4.2 General design process of the layout

The new house design will originate from the optimized house type 10. The layout design of type 10 will be improved for the new house coupling occupants’ behaviour and natural ventilation potential analysis for a better thermal comfort. In this case study, only the ground floor will be analysed in detail by the space syntax methods. The layout of the first floor will be designed based on the layout of the ground floor and other functional demands.

Figure 12.4 shows the general design process to create the layout of the new house originating from the initial design. The initial design is the prototype which is created by the designer or existing design. in this case, the prototype is the optimized layout proposed by the local government. The 2nd step is to use convex method to analyse the initial layout. The convex method was chosen for the preliminary analysis of the evolution of the layout because the convex method can reflect the logical relationship of the spaces simpler and clearer, even though the convex map cannot completely reflect the natural ventilation potential for a spatial configuration, as mentioned in chapter 10. In this step, the first is to decode the layout into convex spaces and then build the connections of the spaces which are connected directly. It should be noted that the outdoor environment should be involved which was mentioned in chapter 10. The spatial features in terms of public space, private space, public service space and traffic space are identified. The 3rd step is to identify the core public spaces in the spatial structure. It has been mentioned that public spaces are the most important spaces in the spatial structure because most of the occupants' activities happen there. The occupants' behaviour and natural ventilation potential in the public spaces are the focus in this study. Therefore, identifying the approximate shape and the relationship between the public space and other spaces is an important step in the design process. The 4th step is the evolution of the public spaces and other inter-spaces based on three aspects: functional demands, occupants' behaviour and natural ventilation potential. Step 3 and step 4 are interactive processes. If the public spaces were adjusted in step 4, the public space should be identified returning to step 3. Step 3 and step 4 are the most important steps in the design process. The graphic based analysis is very helpful to the evolution of the design. The 5th step is to identify the approximate shape and location of all spaces after the logical relationship of the spaces is confirmed in step 4. The 6th step is to adjust the location of the openings connecting the indoor and outdoor spaces. The 7th step is to give the actual size and location of the rooms and the openings. The 8th step is to add the semi-outdoor spaces and courtyards to the layout as we clarified that these kinds of spaces are important for the building microclimate in part 1. The 9th step is the evaluation of the new proposed layout design using spatial analysis method which was proposed in chapter 10. The occupants' behaviour and natural ventilation potential are coupled analysed. If the results are better than the initial design, the final design can be proposed. If not, the whole process can be repeat again.

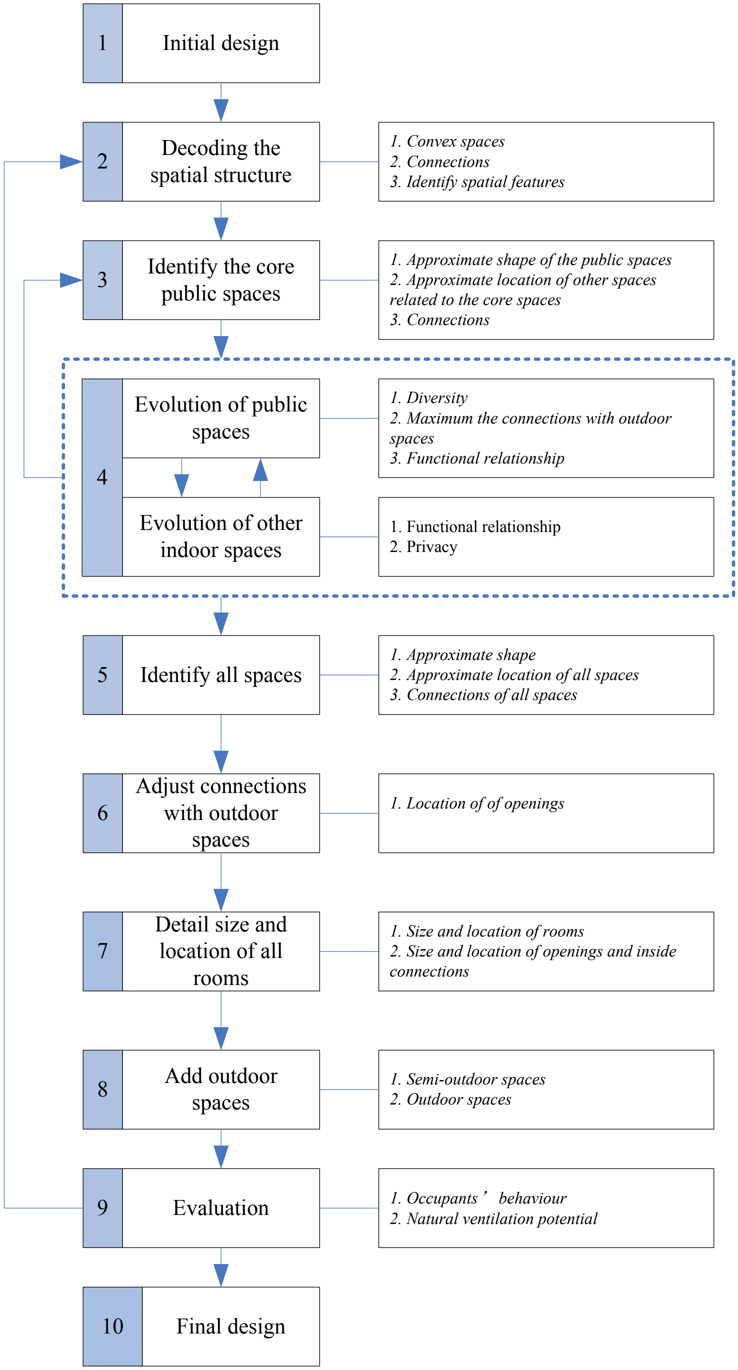

FIG. 12.4 General design process to create the layout of the new house

12.4.3 Evolution of the initial layout of type 10

Figure 12.5 shows the evolution process of the initial layout of type 10, and table 1 illustrated the objectives and actions of each step.

The 1st step is to draw the initial layout of type 10. The 2nd step is to decode the initial layout. The rooms were decoded into convex spaces were represented as nodes, and the outdoor spaces were represented by black nodes. Related spaces are connected with a line. The spaces were classified into public space, service space, traffic space and private space by different colours. The 3rd step is to identify the core public spaces. In this step, a graph shows the first time to identify the core public space. The living room (involve dining room) is the only core public space at the current design. Because rectangle is the most common shape of rooms in architectural design and there is no special demand by the occupant, the public space was identified as a rectangle. The location of other spaces related to the public space was set. The connections of the spaces were represented as lines. The 4th step is the evolution process of the space structure. The first is to satisfy the occupants' demands and improve the diversity of the public space. The storage room and one bed room were replaced by a independent dining room and a patio, see step 4a. After this adjustment, there are three public spaces. Therefore, the next step returned to the 3rd step to identify the newly added public spaces, which was shown in graph 3b and 3c. Both the shape of the patio and the dining room were set as rectangle. The patio was set on the left of the living and the dining room was next to the patio. The entrance was moved to the patio. The next step went to the 4th step again. Graph 4b shows the move of the kitchen from above the living room to connect with the dining room. This is a functional demand. It also makes sure that the living room has more space to connect to the outdoor environment. The spatial structure of the rooms on the right of the living room was kept the original design because the design is good for functions and privacy of the bedrooms and bathroom. After the steps above, the logical relationship of the inter-spaces was confirmed. The 5th step is to identify the approximate shape and location of all spaces. All the room's shapes were set as rectangles. The 6th step is to adjust openings to connect to the outdoor spaces. Two openings were set at above the patio and the living room to enhance the natural cross ventilation. The opening connected to the stair was moved from the left of the stairs to below the stairs. After this step, the logical relationship between the inter-spaces and outdoor spaces confirmed. The 7th step is to specific the actual size and location of the rooms and openings. All three aspects: function, occupants' behaviour and natural ventilation potential should be considered in this step. The living room was deigned more independent and narrower and wider. The openings in the living room were set as large as possible for natural ventilation. The 8th step is to add the semi-outdoor space-veranda in the front of the living room and patio, and on the back of the patio. A front courtyard and a back courtyard were set at the front and back of the layout.

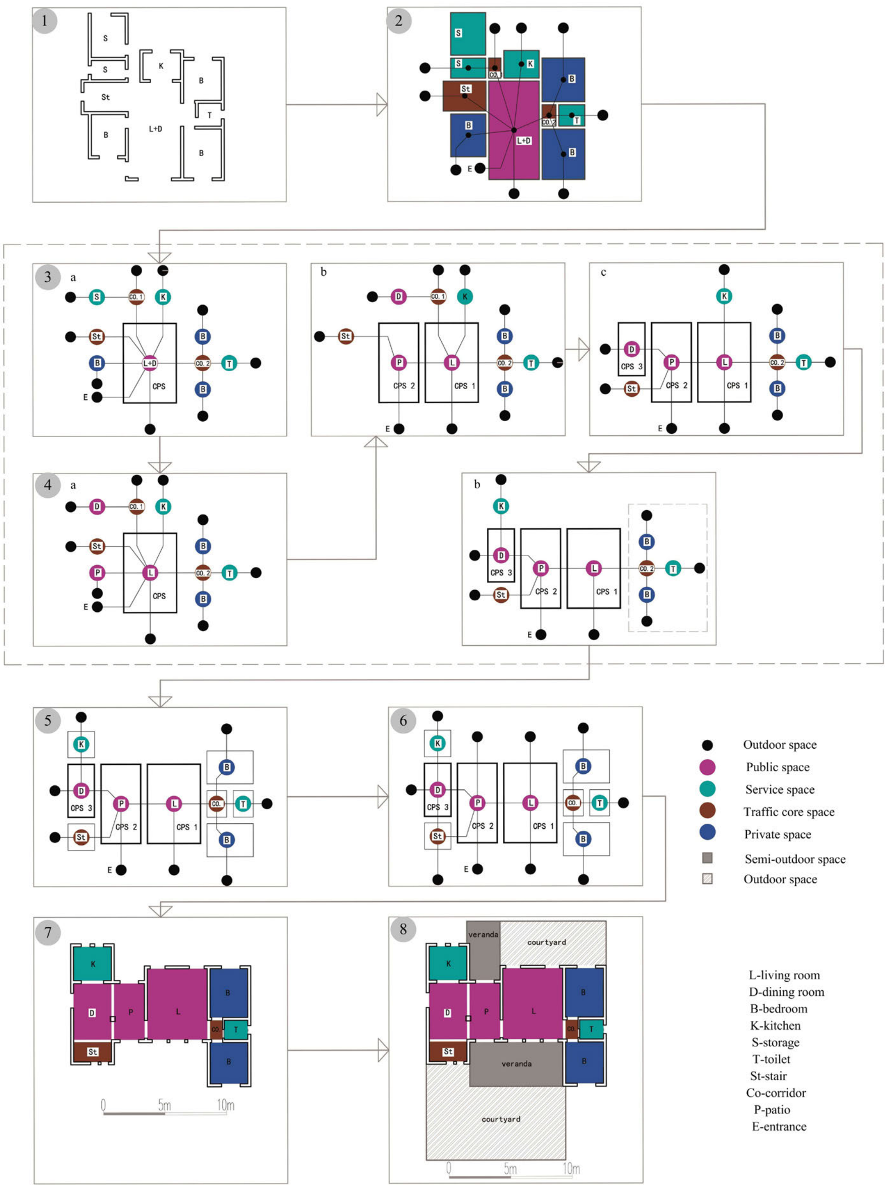

FIG. 12.5 The evolution process of the layout

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TABLE 12.1 Objectives and actions of each step of the design process

Steps	Objectives	Actions in detail
1	-	-
2	Decoding the initial layout	1. The layout was decoded into convex spaces and the outdoor spaces were represented by black nodes 2. The connections between the indoor and outdoor spaces were built 3. The spatial features were distinguished by colour
3	**3a** Identify the core public space	1. The living room (involve dining room) is the core public space 2. The shape of the public space is a rectangle 3. The location of other spaces related to the public space were set 4. The connections of the spaces were built
	3b Identify the new public space-patio	1. The shape of the patio is a rectangle 2. The location of the patio is on the left of the living room 3. The entrance is moved to connect to the patio
	3c Identify the new public space-dining room	1. The shape of the dining room is a rectangle 2. The location of the dining room is on the left of the patio
4	**4a** 1. Functional demands 2. Improve the diversity of the public spaces	1. Delete storage rooms and one bedroom 2. Separate the dining room and living room and set the dining room as public space 3. Add a patio as public space 4. The patio took the place of the bedroom and the dining room took the place of storage room
	4b 1. Functional demands 2. Maximum the connections of the public spaces to the outdoor spaces	1. Move the kitchen from the above of the living room and to close the dining room 2. Keep the spatial structure of the rooms on the right of the living room
5	Identify the approximate shape and location of all spaces	1. The shape of all the rooms are rectangle 2. The location is set at the node
6	Adjust openings connect to the outdoor spaces	1. Two openings were set at the above of the patio and the living room 2. The opening connected to the stair was moved from the left of the stair to the below of the stair
7	Specific the actual size and location of the rooms and openings	1. Make living room more independent 2. Make the living room narrower and wider 3. Make the opening larger in the living room
8	Make the space more divers in the building microclimate	1. Add the semi-outdoor space-veranda in the front of the living room and patio, and on the back of the patio 2. Add a front courtyard and a back courtyard
9	Evaluation (see section 12.4.4)	-
10	Final design (see section 12.6.2)	-

12.4.4 Spatial analysis (evaluation) of the new layout design

After the evolution of the initial layout which was described in the previous section, the new layout of the house was proposed (figure 12.6). Consequently, the spatial configuration of the layout can be evaluated through the spatial analysis method in terms of VGA analysis.

FIG. 12.6 The new proposed layout of the house

12.4.4.1 Occupants' movement behaviour

The analysis method is similar to the method described in section 12.3. Figure 12.7 shows the occupants' behaviour features on the ground floor and first floor of the new house. In the convex map, the living room shows a high integration rate. Following are the entrance, dining room, patio and front veranda. In the VGA analysis, the front courtyard and the front veranda have the highest connectivity and visual integration value on the ground floor. Following are the living room, patio, back veranda and dining room, for which the connectivity and visual integration value are high to low. In the private rooms (bathroom, bedroom and kitchen), the connectivity and visual integration are very low. On the first floor, the terrace, corridor and the family room have a high connectivity and visual integration. The alterable space has a relatively high connectivity and visual integration. The bathroom and bedrooms have a low connectivity and visual integration. The results show that the design of the two plans suit the occupants' behaviour well, which means that for their activities in public and private spaces occupants have a good privacy.

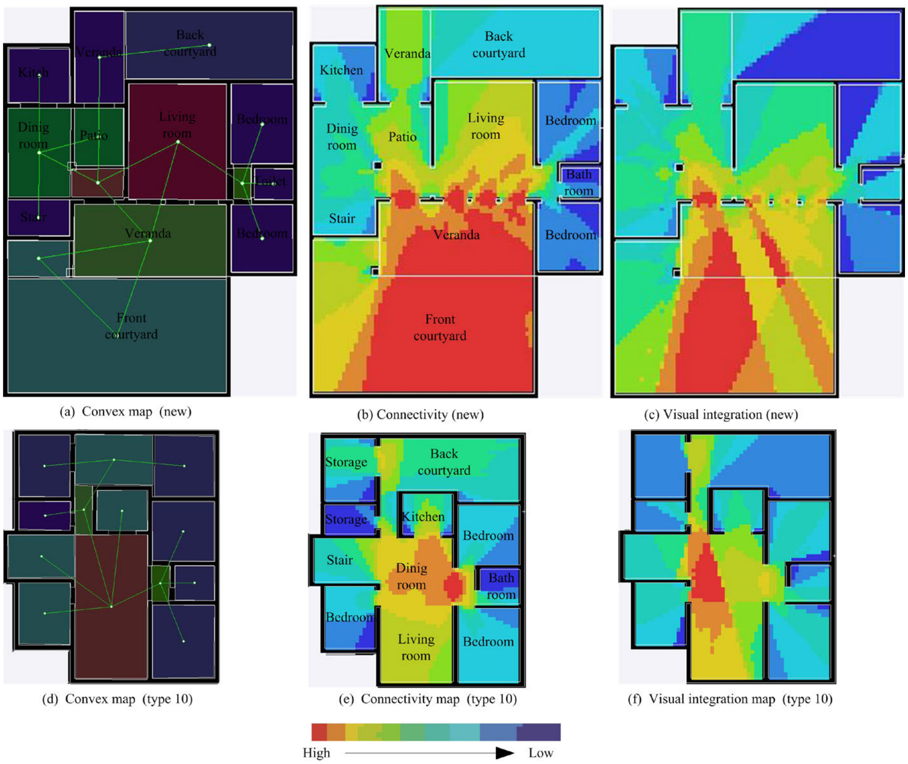

FIG. 12.7 Occupants' behaviour features of the new house and comparison with type 10

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12.4.4.2 Natural ventilation potential analysis

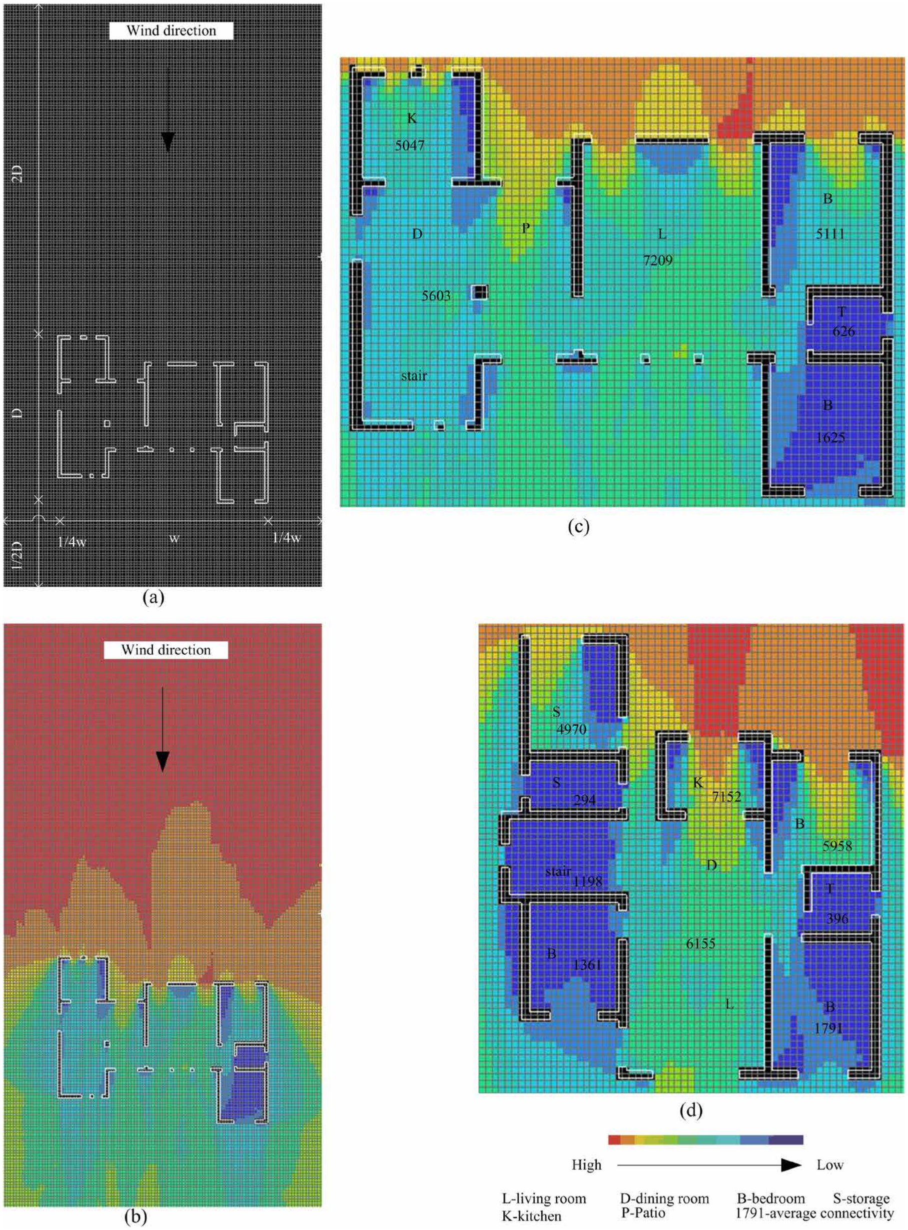

FIG. 12.8 Natural ventilation potential analysis of the new house and comparison with type 10 (a) the boundary setting of the VGA analysis (b)(c) connectivity value of the new house (d) connectivity map of type 10

Figure 12.8 shows the natural ventilation potential of the ground floor. Figure 12.8 (a) shows the boundary setting of the VGA analysis and figure 12.8 (b)(c) show the results for the connectivity value. Similar to the results of the original layout, the connectivity value near the windows is higher than the corresponding indoor spaces. Especially for openings at the above of the layout, the connectivity value is much higher than other spaces. The living room has the highest connectivity value. This is due to the large openings of the living room and the openings directly facing the wind direction. It is also found that the connectivity value of the living room is evenly distributed. The second highest connectivity value is in the space of the dining room, patio and stairs. In the bedroom and toilet, the connectivity value is lower. The results can be matched with the occupants' behaviour analysis, which means the occupants have most of their activities in the spaces with a high potential to achieve natural cross-ventilation.

12.4.5 Comparison of the layout design of the new house and the optimised house

Comparing the results of the spatial analysis of the new house and the original house design proposed by the local government, the average connectivity value in the public spaces of the new house is higher than in the original house. This indicates that the visibility and accessibility of the new house is better than the original house in that the new house has more potential to obtain natural cross-ventilation in the public spaces. The occupants' behaviour fits the air movement behaviour better in the new house than the original house.

12.5 Validation of the spatial analysis through CFD simulation

The correlation between the spatial indicator and the airflow performance were studied in chapter 9. Here, for the rural house design, the spatial analysis method for natural ventilation potential through VGA analysis was validated by a CFD simulation.

The CFD simulation was performed for the ground floor of the optimised local government house and the new house. The ANSYS19.1 program was used for the CFD simulation and the platform of workben19.1was used for the model building, grid setting, parameter setting and post processing. The prevailing wind direction was assumed from the above of the layout, which is the same in the VGA analysis. The local climate data of Chongqing was used for the input. The outdoor wind boundary was set to 50mx50m. The Realised k-e model was used.

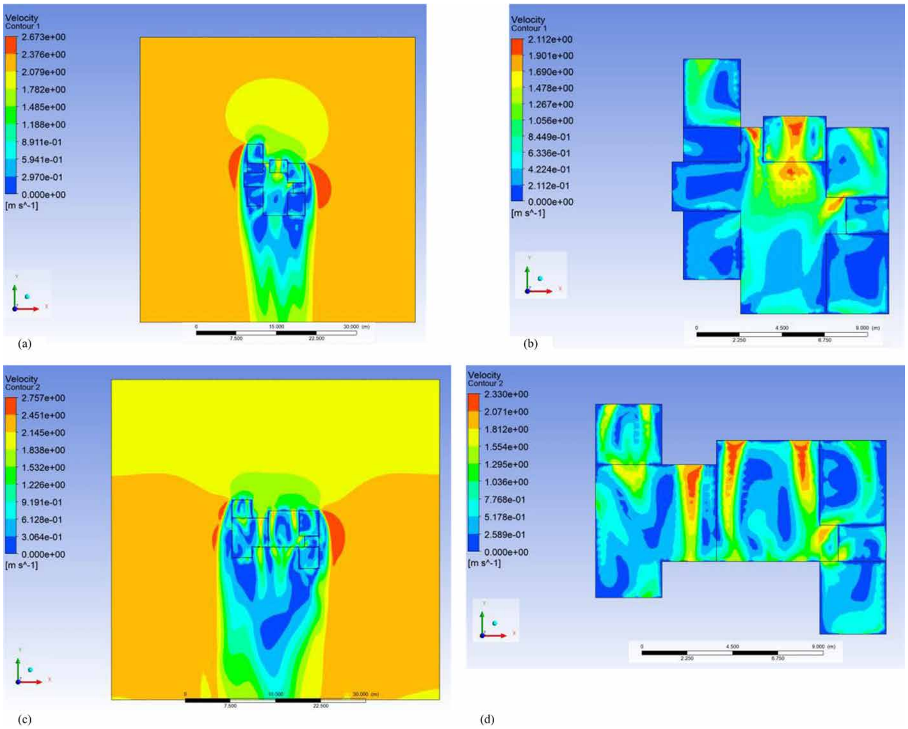

FIG. 12.9 Wind velocity distribution (height of 1.5m) of the optimised house and the new house
(a) (b) wind velocity map of the optimised house ((a) involves the outdoor space); (c) (d) wind velocity map of the new house ((c) involves the outdoor space)

Figure 12.9 shows the wind velocity map at a height of 1.5 m. It can be seen that the average wind velocity through the new house is greater than through the original house. In the new house, the wind passes easier through the public spaces (living room, dining room and patio) than in the original house (living room). Comparing the wind velocity maps and the connectivity maps in the VGA analysis, the distribution of the connectivity and the wind velocity were found as similar trends. To prove that, the correlation of the two indicators was analysed through statistical method.

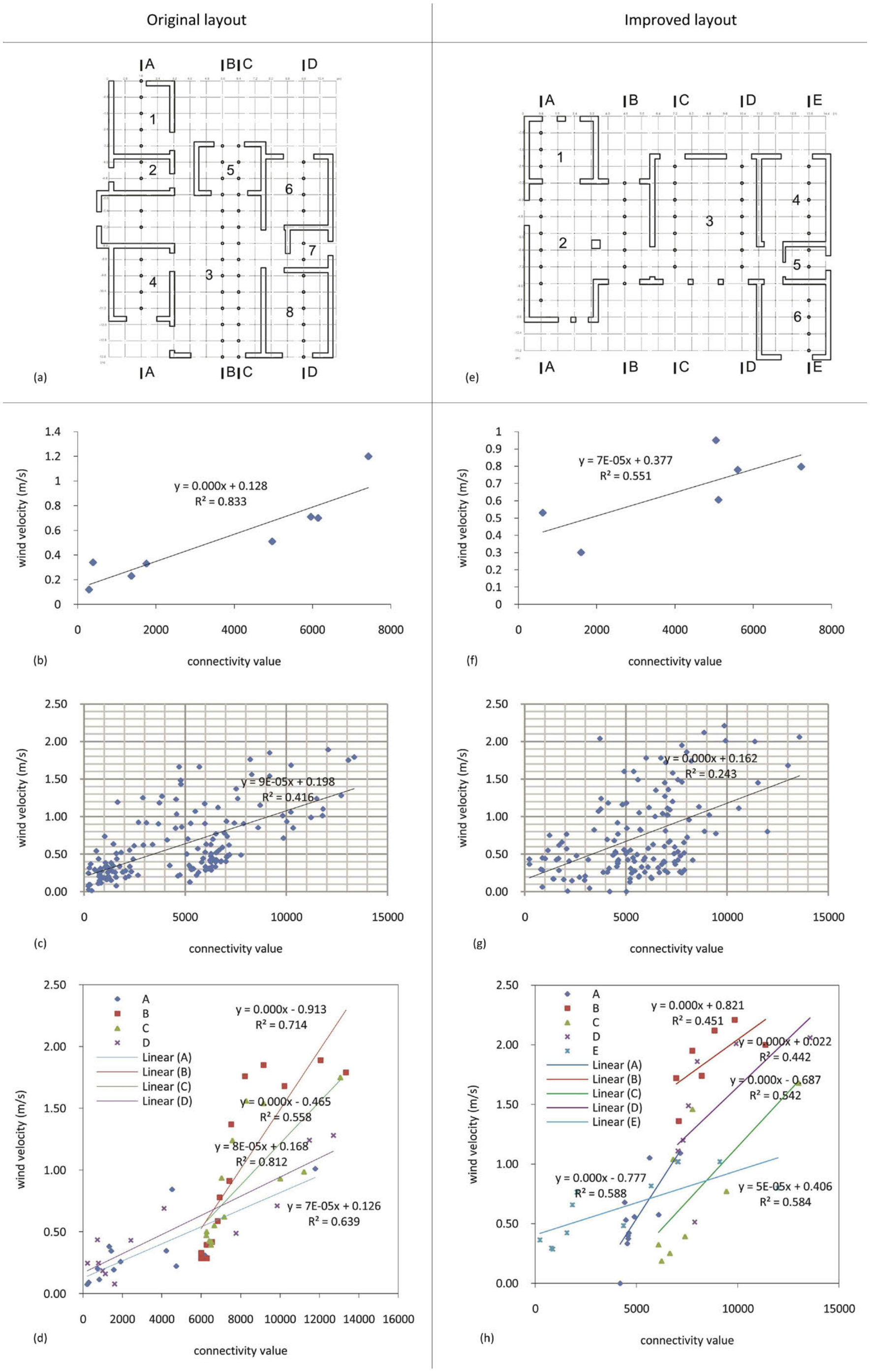

FIG. 12.10 Correlation analysis between the connectivity and the wind velocity

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Because the grid setting is different in the CFD simulation and the VGA analysis, and due to the huge number of grids in the CFD simulation (around 8 million), part of the data was selected for the correlation analysis. Figure 12.10 (a) and (e) show the selected data of the two layouts. First is the average data of the rooms. There are 8 rooms in the original layout and 6 rooms in the improved layout. The linear correlation between the average connectivity and wind velocity is shown in figure 12.10 (b)(f). The coefficients of determination R^2 are 0.83 and 0.55. The linear correlation is significant. Second are the selected points of all the rooms. The rooms were divided by a 800x800mm grid. The data (connectivity and wind velocity) near the grid points were chosen for the correlation analysis.
The linear correlation between the connectivity and wind velocity are shown in figure 12.10 (c)(g). The coefficients of determination R^2 are 0.42 and 0.24. The correlation between the two factors is significant but the linear relationship is low. Third is the key point data on section A, B, C and D in the original layout and section A, B, C, D and E in the improved layout. The linear correlation between the connectivity and wind velocity is shown in figure 12.10 (d)(h). The coefficients of determination R^2 are 0.44 and 0.91. The linear relationship between the two factors in the key points is significant.

The data analysis above revealed the positive correlation between the connectivity value and the wind velocity. The assumption that the spatial indicator and the airflow indicator are associated, which was found in chapter 9, is proved again in this case. That means the spatial indicator can reflect the trends of some features of airflow in the cross-ventilation. The spaces that have the highest potential to obtain cross-ventilation can be identified through the spatial analysis methods. Even the spatial indicator cannot reflect the real value of the airflow features, it is still valuable for the analysis of the spatial configuration in the early design stage. The advantages were described in chapter 9. For example, in this case, the connectivity value can be calculated in several minutes, however the CFD simulation took several hours for one model. Considering the time to build the model and to adjust the input parameters, much more time is needed for the CFD simulation.

12.6 Final design

This study focuses on the layout design of the new house. The layout of the ground floor of the new house was proposed by the author which was evolved from the optimized layout design proposed by the local government. However, in order to show the design of the new house completely, the general architectural design contents in the early design stage are briefly described in the following sections. Other issues related to sustainable design strategies for energy efficiency and thermal comfort are not discussed in this chapter.

12.6.1 General layout of the house on the site

Figure 12.11 shows the general layout of the house on the site. The house is in front of the small hill and faces the lake. The width is 14.6 meters and the depth is 11.6 meters. A front courtyard was set in front of the house and a back courtyard was set between the house the small hill. The major entrance is set at the west of the front courtyard.

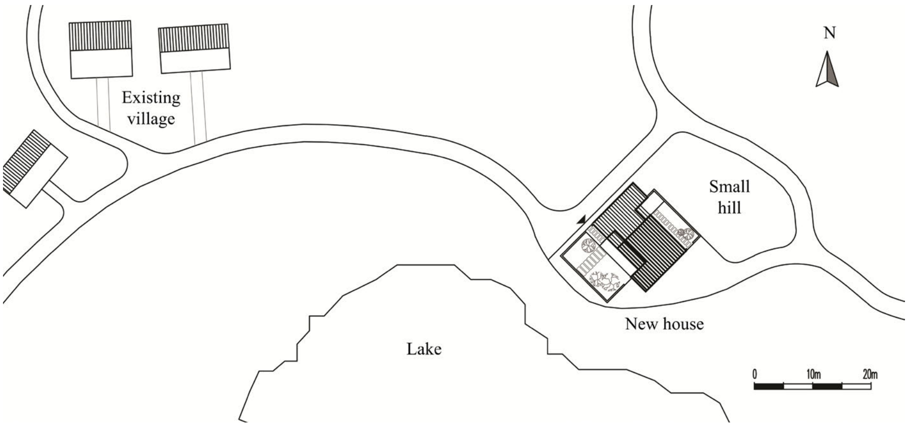

FIG. 12.11 General layout of the house on the site

12.6.2 Floor plans

Figure 12.12 shows the final layout design of the new house and the functional distribution. Because the occupants need four bedrooms and plan to arrange two bedrooms on the ground floor and two bedrooms on the first floor, one bedroom of the original layout was deleted. Because the occupants do not want storage rooms, the storage rooms were deleted as well. To enhance the spatial diversity and satisfy the occupants' requests, the dining room was separated from the living room to the left. To make the living room obtain natural cross-ventilation directly, the kitchen was moved to the left, to close off the dining room. Therefore, the living room can open windows or doors on two sides to obtain cross-ventilation. In order to enhance the spatial diversity and to increase the public space, a patio was set between the living room and dining room. In order to enhance the diversity of the house, two verandas and courtyards were set in the front and back of the layout. The final spatial structure of the ground floor is shown in figure 12.12(a). The living room is in the middle of the layout. On the left of the living room, there are kitchen, dining room and stair. Right of the living room there are two bedrooms and a bathroom. The entrance and lobby are between the living room and the dining room. There is a patio located between the dining room and the living room and the patio faces the lobby. One large courtyard was designed in front of the building and one small courtyard behind the building. Accordingly, there are two verandas in front of and behind of the building.

Based on the shape of the ground floor, the layout of the first floor was proposed as well (figure 12.12(c)). On the first floor, there are two bedrooms and a bathroom as private spaces. A family room was set close to the patio. A special alterable room was designed in the middle of the layout. The changeable separations of this room can be opened and closed. Normally, the separations are opened. This space is a public space. If there are more residents, this room can be closed as bedroom. This design fits the occupants' demands. There is a corridor connecting the rooms. It was designed wider so that some activities can be performed in this corridor. A big terrace was designed in front of the corridor and a small balcony was designed behind the alterable room.

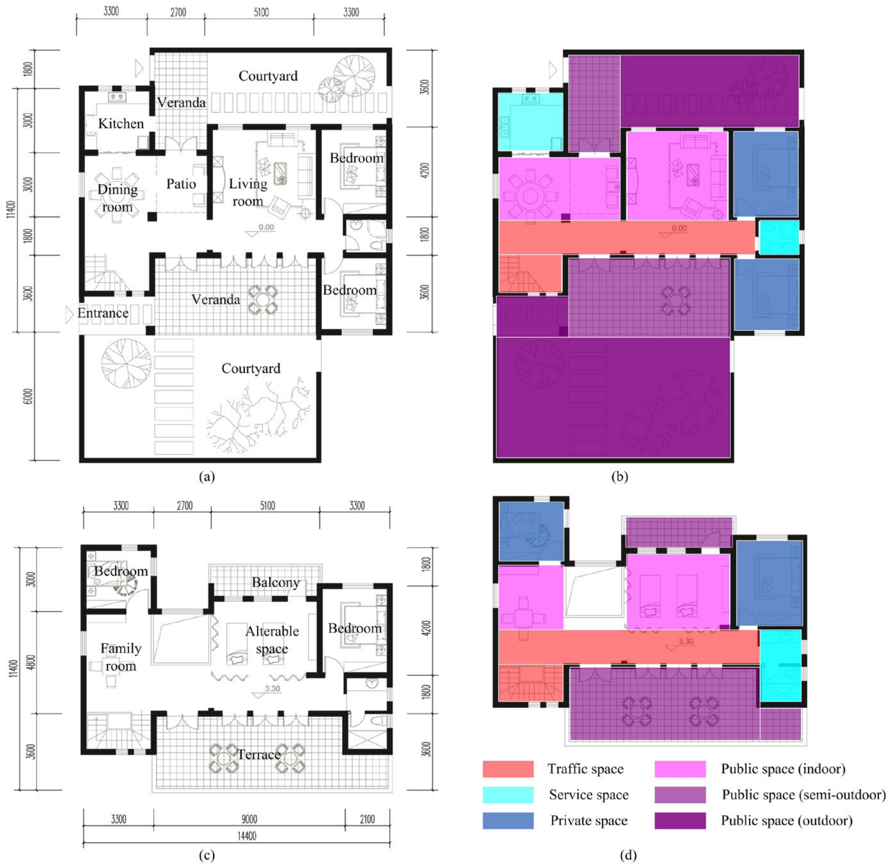

FIG. 12.12 The layout of the new house and the functional distribution.
(a) ground floor;(b) functional distribution of the ground floor;(c) first floor; (d) functional distribution of the first floor

Table 12.2 shows the comparison of the basic information of the new house and the original house. It can be found that the building area of the ground floor, the first floor and the total area are almost the same. However, the new house has more diverse spaces and more public area for the occupants' activities.

TABLE 12.2 Comparison of the basic information of the new house and the original house

	Plot area (m^2)	Area of building (m^2)	Area of courtyard (m^2)	Total Area (m^2)	Area of ground floor (m^2)	Area of first floor (m^2)	Width (m)	Depth (m)	occupants	Type
type10	150	128	22	228	128	100	11.4(3)	13.4	5-6	Well-off
New house	232	128	104	227	128	99	14.6(4)	11.6	4-6	Well-off

	Living room +dining room	Dining room	Bedroom	Family room	Terrace	Balcony	Veranda	Patio	Courtyard
type10	1+1	0	6	0	1	2	2	0	1
New house	1	1	4+(1)	1	1	1	2	1	2

12.6.3 Façade design

The main focus of the façade design is the opening in the facades. The natural ventilation performance is defined by two aspects: the spatial configuration and the boundary conditions of the spaces connecting to the outdoor environment. Obviously, a larger opening means a greater ventilation potential. However, the opening area cannot unlimitedly increase because a larger opening area means more solar radiation, which is not preferred for thermal summer comfort. In the area studied, the size of the opening area in the façade is identified as window-to-wall ratio. The maximum window-to-wall ratio is identified in “The design standards on residential building energy saving 65%” (DJB 50-071-2016) (table 12.3). In this case, in the living room, which is the most important public space, the opening area was designed as large as possible to enhance more natural ventilation. But the window-to-wall ratio is still controlled under the limited value of the design standard. The maximum window-to-wall ratio is 0.56, which is smaller than the limit value of 0.60. For other rooms, the window-to-wall ratio is between 0.18 and 0.25, which is under the limit value of the standard. The windows can be opened completely. This is similar to the traditional windows of Chinese vernacular buildings. Figure 12.13 shows the elevations of the house.

TABLE 12.3 The limit value of widow-to-wall ratio on different building orientations

Orientation	Limit value of window to wall ratio
NW 60° -NE 60°	≤0.40
NE 60°-SE 30°, NW60°-SW 30°	≤0.35
SE30°-SW 30°	≤0.45
One room of one house (any orientations)	≤0.60

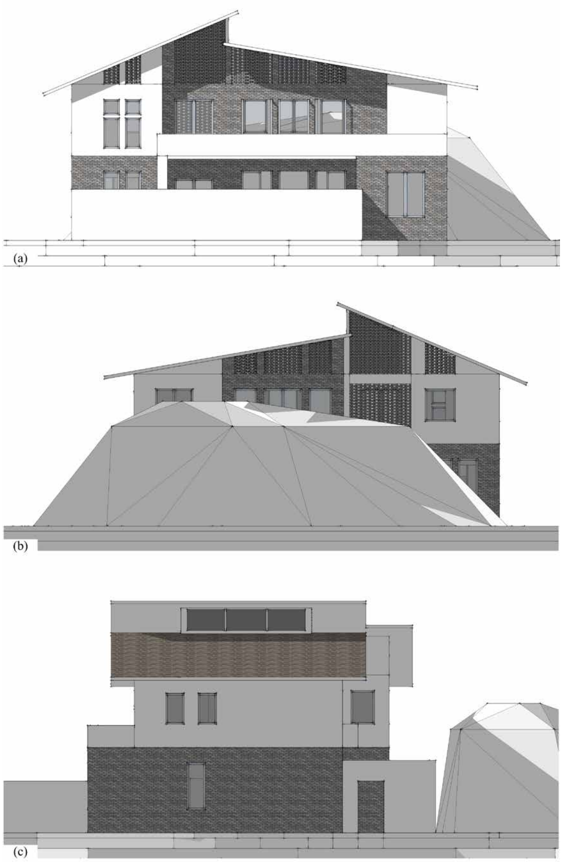

FIG. 12.13 The elevations of the house
(a) south-west elevation; (b) north-east elevation; (c) south east elevation

12.6.4 Appearance and structural design

The appearance combines the traditional and modern house design in the studied area (figure 12.14). The roof is designed as a double roof. One is a flat floor and another is a pitched floor. Between the two layers of the floor, the air can pass through. The idea is that the cross-ventilation can take away the heat during summer daytime.

Brick and a partly reinforced concrete structure are used for the house. This kind of structure is very common in this area. Therefore, local bricks are used. It is relatively cheap for the house owner. One layer of the roof is concrete and another is local black tiles.

There is no insulation on the wall and roof. There are three reasons for that. Firstly, insulation is not commonly used in the rural area because most of the rural houses are built by the farmers themselves; there is no design procedure, even if there are design standards for energy saving in rural residential buildings. Secondly, the rural house owner wanted to reduce the budget. Thirdly, if they do not use air conditioning, insulation is not useful for cooling.

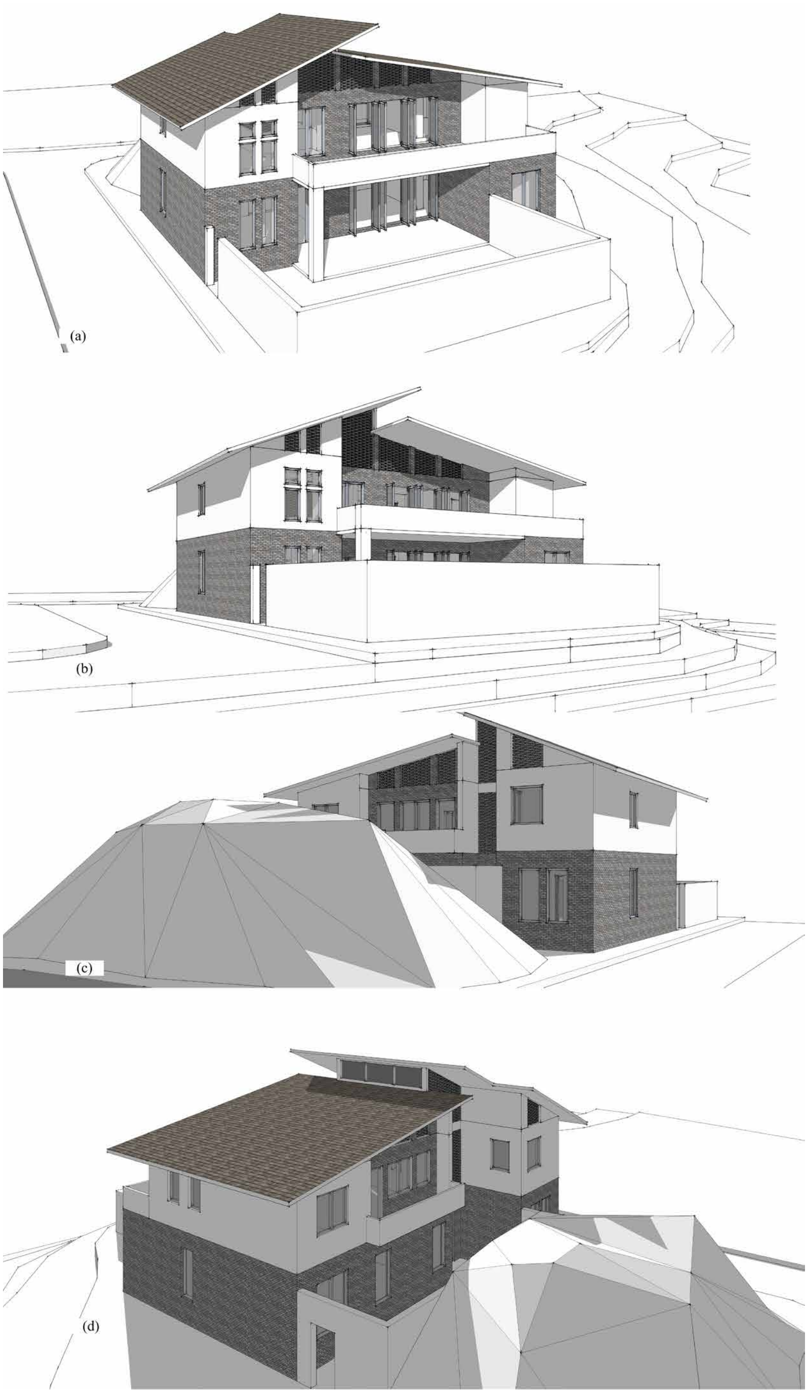

FIG. 12.14 The sketches of the new house

12.7 Conclusion

In this chapter, the optimised layout for a house proposed by the local government was analysed through the space syntax method and it was improved in a new house design. The results of the spatial analysis related to natural ventilation potential were validated through CFD simulation.

The goal of the improvements was to provide more diverse spaces for the occupants to choose from, to enhance cross-ventilation and to establish a favourable building microclimate. The improved house design provides more public spaces for the occupants, both on the ground floor and the first floor. This enhanced the diversity of the living spaces. As a conclusion from chapter 4, the local occupants would like to stay in the more open spaces during summer; the improved house gives this opportunity for the occupants. Through spatial analysis, it can be concluded that the accessibility and openness of the improved house and the major public rooms is better than the houses proposed by the local government (the ground floor). According to the conclusion in chapter 7, the high accessibility and openness mean the high potential to achieve cross natural ventilation. The occupants' behaviour model can be matched with the air movement behaviour. This means the spaces which the occupants prefer to stay are the spaces which have the high potential to obtain natural ventilation.

The studied case is still under construction. Future research will continue to field measurement to evaluate the building microclimate and thermal comfort of the house.

13 Conclusion

13.1 Introduction

The main objective of this dissertation is to find the main factors of building spatial configuration that affecting the thermal summer environment, the possibility of occupants to achieve thermal comfort there in, and to propose a spatial design method as the passive cooling strategy for summer thermal comfort. In accordance with the objective, the research questions were put forward in section 1.5 of chapter 1. For every sub-question, there is a respective chapter to answer it, see figure 1.3 in section 1.6 of chapter 1. In chapter 8, some conclusions of part I of this dissertation were summarised. In this chapter, the research questions are answered. In addition, the limitation of this research and recommendations for future practice and research will be mentioned as well.

13.2 Answer to the research questions

The main question of this research is:

What is the relationship between spatial configuration, thermal environment and thermal summer comfort of occupants and how to apply spatial configuration as the passive cooling strategy in architectural design in the early stages?

The main question will be answered by addressing the sub-questions.

13.2.1 Answer to sub-question 1,2 and 3 (mainly chapter 4 and 5)

1. What are the major spatial design characteristics of a Chinese vernacular buildings for passive cooling in hot and humid climate?
2. What are the thermal summer environment features of Chinese vernacular building within a particular spatial configuration?
3. How can occupants achieve thermal comfort in a Chinese vernacular building?

To answer these three questions, a typical Chinese vernacular courtyard house was investigated in a hot and humid climate. In addition, some rural modern houses near the vernacular house were compared with it. The spatial configuration, the spatial boundary conditions, the vegetation in the space and the human activity in the space were analysed for a vernacular house and for modern rural houses. Also, field measurements were conducted to evaluate the thermal summer environment in the vernacular and a modern house. The results of measurements were compared with a dynamic thermal and a CFD simulation in the vernacular house as well. The results show that the most important spatial design characteristics of the vernacular house are spatial diversity and a suitable spatial configuration. The vernacular house combined different kinds of spaces, while the modern house's spaces are simple. Indoor space, semi-outdoor space and outdoor space are the basic space types which are broadly used for the spatial diversity in the vernacular house. Courtyards and patios are the core components for the spatial configuration of the house which is surrounded by corridors and indoor spaces. Every indoor room is adjacent to a patio or corridor, instead of being directly exposed to the outside environment. The diverse spatial design and the suitable spatial configuration make the thermal summer environment of the vernacular house much better than the modern house. The vernacular house has its own "building microclimate", which is in accordance with the main character of microclimate in terms of different distributions of solar gain, air temperature and wind velocity in different spaces. "Building microclimate" can help to create comfortable thermal conditions for the occupants in summer, especially in hot and humid climate areas. The essence of architectural bioclimatic design is to understand the local climate and utilise appropriate spatial design strategies to create or modify the building microclimate required for a comfortable living environment. The contribution of the "building microclimate" lies in two aspects: first, the temperature in the "building microclimate" could be lower than the outdoor environment. Second, related to different spaces, the "building microclimate" provides different thermal environments and different thermal sensations of occupants. The "building microclimate" is important for occupants' thermal comfort under the free-running model of the vernacular house. The diversity in spatial configuration and thermal environment make it possible that the occupants can choose their preferred space and thermal environment to achieve relative thermal comfort. A “Building microclimate” provides this opportunity by taking into account all spaces (indoor, semi-outdoor and outdoor) of a single building.

13.2.2 Answer to sub-question 4 (mainly chapter 6)

4 Is it possible to convert the spatial design strategies found in Chinese vernacular buildings to the modern house design?

To answer this question, a modern house with spatial diversity in a hot and humid climate was investigated to clarify the relationship between spatial configuration, building microclimate and thermal comfort. Firstly, the spatial configuration of the house was analysed in detail. The spatial geometric features, spatial boundary conditions, and human activities in the building were categorised. Secondly, field measurements were conducted to investigate the microclimate of the house. The air temperature, relative humidity and wind velocity were monitored on typical summer days. Thirdly, a dynamic thermal simulation was performed to predict the thermal comfort performance of the building over the period of an entire summer. The simulated results were compared with the measurements, and the adaptive thermal comfort approach was used to evaluate the thermal comfort. The modern house studied was found to have a varied spatial configuration, similar to local vernacular buildings, which produces diverse thermal environments in the building. Under the local climate conditions, the microclimate of this specific building could provide considerable thermal comfort for the occupants in summer. This case study shows that it is possible to obtain a building microclimate through spatial configuration, not only in vernacular buildings but also in a modern building design. Diverse spaces and environments are valuable for an occupant’s thermal sensation in hot and humid climate regions. In modern architectural design, spatial design is not just for aesthetics, function and landscape, but also for the building microclimate and performance, and especially for the thermal performance. Eliminating spatial diversity results in a lack of appropriate building microclimate and thermal performance. This case is an example even though the modern house is different from the vernacular house. Because the life model is different, spatial configuration can be as one of the major passive cooling strategies to achieve thermal summer comfort of occupants.

13.2.3 Answer to sub-question 5 (mainly chapter 7)

5 What is the relationship between the occupants' spatial and thermal perception?

Studying the relationship between the spatial environment and the way the spatial environment is perceived can yield important insights into the way architectural design can create more comfortable living environments. Spatial openness is an important spatial perception that was studied in chapter 7 to find the correlation with perception of comfort (visual, wind speed and thermal) in people's minds. There is a common sense for the occupants who live in the hot and humid climate that thermal comfort perception in people's minds is related to the spatial openness. The investigation was based on a questionnaire of 513 local Chinese college architecture students in 2015.Five different spatial environments with different spatial openness were described in writing, such as indoor space, semi-outdoor space, outdoor space, a room with a large operable area and a room with a small operable area. The three perceptions were visual perception, thermal perception and wind perception. For the different spatial environment, the comfort perception over the day was also investigated. A similar questionnaire was given to Dutch architecture students, but the results were inconclusive due to the low number of responses. The main findings are: a. spatial openness of a particular space significantly affects occupants' visual perception, wind speed perception and thermal perception. b. There is a strong effect between spatial openness and visual and wind perception; the effect of the thermal perception is weaker. c. The comfort perception is strongly influenced by the time of day; therefore, visual perception, wind perception and thermal perception can influence occupant movement between different spaces as is the advice of the adaptive thermal comfort.

13.2.4 Answer to sub-question 6 (mainly chapter 9)

6 Is there a potential to use spatial indicators to predict the ventilation performance for thermal comfort in the early design stages?

To answer this question, a case study was performed in chapter 9. In chapter 9, the author investigated 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 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 rate – are linearly correlated, not just at the building level but also at the room level. R^2, the correlation coefficient of determination is between 0.53 and 0.90. Although there are many limitations as mentioned above, this study reveals the potential to use the spatial indicator to predict the airflow 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.

13.2.5 Answer to sub-question 7 (mainly chapter 10,11,12)

7 How can a space design method be used in the design practice?

To answer this question, the space syntax method was extended for the analysis of the natural ventilation potential. A rural house design in a hot and humid climate was chosen as the case study. The rural house was chosen because it is a free-running model, which is different from an urban house and more suitable to adopt passive cooling strategies for thermal summer comfort of occupants. The extended space syntax method was first used to evaluate a number of rural residential buildings in the studied area proposed by the government. The advantages and disadvantages of the proposed houses in terms of spatial configuration were studied.

Secondly, the extended space syntax method was used to improve the optimised house proposed by the local government towards a new rural house design. The goal of the improvement is to provide more diverse spaces for the occupants to choose, enhance the cross ventilation. The design method and process were proposed in chapter 12. From the initial design to the final design, the main steps in the design process are: decoding the layout, identify the public spaces, evolution of public and other spaces, identify all spaces, adjust connections with outdoor environment, identify the detail size and location of all rooms, add outdoor spaces and evaluation using the extended space syntax method. The improved house design provides more public spaces for the occupants, both on the ground and the first floor. This enhanced the diversity of the living spaces. As concluded in chapter 5, the local occupants would like to stay in the more open spaces during summer; the improved house gives this opportunity to the occupants. From the spatial analysis, it can be concluded that the accessibility and openness of the improved house and the major public rooms is better than the houses proposed by the local government (the ground floor). As concluded in chapter 10, the high accessibility and openness mean a high potential to achieve natural cross-ventilation. The occupants' living habits show that the occupants perform most of their activities in these spaces as well. Therefore, it can be concluded that the indictors in space syntax analysis not just reflect the occupants' movement behaviour but also show the occupants' preference of spaces and how long they would like to stay. The fundamental idea of space syntax theory is to find the relationship between the spatial configuration of city or architecture and the underlying human behaviour and social meaning. The kind of human behaviour-movement –is well explained in spatial configuration analysis especially in the urban scale. In this study, it was found that movement is not just a means to pass through, but also means the preference to stay. In these case studies, it was found that the occupants' movement behaviour model can be matched with the air movement behaviour. This means that the spaces that the occupants prefer to stay in are the spaces that have a high potential to obtain natural ventilation. The CFD simulations in chapter 12 proved that the extended space syntax method can evaluate and predict the airflow behaviour in the early design stage. The extended VGA analysis method is easy to use in design practice.

However, there are still some limitations of the space design method for passive cooling in the design practice. Architectural design is a complex process and is influenced by complex factors. For example, for the bedrooms, privacy is an important factor for the space design. Enhancing the openness or accessibility of these private spaces is difficult. Other design strategies, such as improving the insulation and shading of the walls, can be used for passive cooling as well.

13.3 Conclusion of findings

The main findings of part I were described in chapter 8. The concept of "building microclimate" was identified. Also, the importance of spatial diversity and spatial configuration for building microclimate and occupants' movement for adaptive thermal comfort were found. The relationship between the spatial perception and adaptive thermal comfort was revealed.

The main findings of part II are the potential of using spatial indicators to predict the airflow performance of buildings. The new application of the extended space syntax method is proposed to help architects and designers in designing a modern building that is thermally more comfortable and that has a lower energy demand.

13.4 Limitations of this research

In chapter 4, 5, 6, 8, 9, 10, 11 and 12, the limitations of the specific studies have been mentioned in the discussion or conclusion parts. Below is the summary of the limitations of this research.

Measurements

The measurements were performed in a vernacular house, a rural house and a modern urban house. The main parameters related to thermal environment and adaptive thermal comfort – air temperature, relative humidity and wind velocity – were obtained. However, because of the limitations of the equipment, some of the measurements were imperfect and some of the parameters were missing. Firstly, the outdoor environment near the measured houses was not measured completely because of a lack of micro-climate stations. This limitation influenced the accuracy of the simulation results because we cannot use the accuracy climate data near the houses to do the simulations. Secondly, the measurement time was several days, which was not so long. This could miss some information compared to a long-period monitor. Thirdly, the difficulty to measure the wind velocity. A manual anemometer was used to measure the wind velocity. It is difficult to measure the wind velocity for a long time and to measure more points. Sometimes the indoor wind velocity was small, which caused inaccuracy of the measurements. Fourthly, some measurement parameters were missed, for example the radiation measurement. In addition, the houses were measured without occupants. Therefore, the influence of occupants on the thermal environment is missed.

Simulation

The thermal environment of the studied cases was simulated by the software of Designbuilder. The climate data used was from the database of Energyplus. Even though the selected climate station of the database in the area studied is close to the studied house, which maybe also caused some inaccuracy of the simulation. To avoid the inaccuracy, most of the simulations were validated by the field measurements in this research.
Another limitation of the software is that the inability to simulate the outdoor environment. Therefore, some assumptions and simplifications were made for the outdoor spaces and semi-outdoor spaces in the simulations.

The spatial analysis of the cases was performed in Depthmap. This software was designed for the spatial configuration analysis, especially for occupant movement behaviour in a particular building layout. The author assumed the program also has the potential for air movement analysis. Therefore, there are some limitations of the software used for the air movement analysis. This caused inaccuracy of the simulation results, which might decrease the correlation value between the spatial indicators and airflow parameter. This detail was discussed in chapter 9.

Questionnaire

The questionnaire was used for the investigation of the occupants' spatial perception and thermal environment perception. The investigation was performed through asking questions in texts of students, which had some limitations because the subjects cannot feel the real scene. Two groups of subjects were asked questions, but there were not enough responses from one group. The comparison of different subjects was missing. Asking the questions may cause dispersion of the answers because of spatial perception related to 3D space.

Comfort standard

The adaptive thermal comfort theory was applied to evaluate the thermal comfort of occupants. The theory was studied in the studied area and some equations for comfort temperature calculation were proposed. However, the equation was not proposed in the local design standard for thermal comfort evaluation. As mentioned in section 2.1.6, the adaptive prediction mean vote was put forward in the standard. Therefore, the equation proposed by the local researcher or by ASHRAE was applied. That might be not so authoritative or very suitable for local occupants.

13.5 Recommendations for future research and development

For future research, the following three topics related to spatial design and passive cooling are recommended:

Building microclimate related topics

The concept of “building microclimate” was first identified in this dissertation. The function of building microclimate for passive cooling is the integration of different passive cooling techniques, such as solar control, thermal mass, evaporative cooling and natural ventilation. This research focused on the contribution of spatial diversity to building microclimate. Future research should pay attention to other factors that can influence the building microclimate in. For example, garden design in the courtyard and patio, and material use as thermal mass are significant to cool the environment. This has been found in the vernacular houses. How to integrate all the aspects to create a good building microclimate in summer is a big issue to discuss. Furthermore, the scale of building microclimate should be studied to distinguish from the urban microclimate. The relationship between urban microclimate and building microclimate should be studied deeply as well. To perform these studies, more detailed measurements and suitable simulation methods should be done for more cases.

Spatial perception and thermal environment perception

The occupants’ thermal comfort is strongly related to their perception. Perception is a series of processes in which consciousness perceives, senses, pays attention to and perceives external and internal information. It includes both physiological and psychological processes. In architectural design, the occupants’ spatial perception is one of the most important factors to evaluate the spatial design. Spatial perception can influence occupants’ behaviour. Some results drew conclusions about the relationship between spatial perception and human behaviour in the research field of architectural spatial perception. In the research field of thermal comfort, a lot of studies focused on the relationship between occupants’ thermal comfort and behaviour. However, research about the relationship between the spatial perception, thermal perception and human behaviour is rare. This topic is valuable as topic for deeper studies, because it is important for both spatial design and thermal comfort. Some new research methods could be used for this study. For example, VR (virtual reality) technique can be used for a study of the occupants’ visual perception, which is one of the most important spatial perceptions.

Integrated spatial design method for human behaviour and airflow analysis

This research found that there is a correlation between the spatial indicators and airflow parameters and that there is potential to apply the spatial analysis method to analyse the airflow behaviour. However, because it is a new research field, this research is just a preliminary attempt. For example, some spatial indicators: connectivity, integration, mean depth, isovist area and perimeter were explored for the correlation study. It was found that all of the indicators are associated with the airflow parameters. However, which one is the best? It should be investigated in further research. More cases are also needed to be investigated and the underlying mechanism of the correlation found should be revealed by numerical analysis.

In this research, it is also proposed that the spatial indicators not only reflect the movement behaviour but also reflect the time of stay and the preference of occupants. The spatial analysis in space syntax can foresee more functional outcomes related human behaviour in an urban or an architectural environment. It is an interesting topic for further study.

The findings in this research are also valuable for the study in an urban scale. As we know, the urban wind environment is much complex than the building scale and the prediction is still difficult. The simulation of the urban wind environment always means huge computing resources, huge time consumption and high costs. If the proposed methods in this research can be used in the urban scale, it can help the urban planner to predict the preliminary wind environment and understand people's behaviour in the city. The public spaces of the city can be set at suitable places where people can get more natural ventilation for comfort. Therefore, this study could be used for the urban scale in the future.

Other spatial analysis methods are also worth exploring if they have the potential to predict the airflow behaviour. Furthermore, an integrated computer program might be developed for both the spatial and airflow analysis.

13.6 Value of this dissertation

This research has some innovative findings in the cross disciplines of architectural spatial design, passive cooling and thermal comfort. Some ideas are first proposed in this research. The findings and new ideas have social, scientific and engineering implications. This research can contribute for the sustainable development of Chinese building construction. It can help the residential building design for occupants with low and medium incomes by decreasing the use of air conditioning and improving the living environment for thermal comfort as well. This research is also valuable for the passive or zero energy house design in the Netherlands and the European Mediterranean area. This research will enrich the green building science by introducing the theory and the applications for adaptive thermal comfort, principles of passive cooling by means of spatial design. In the architectural design practice, the proposed design method can be developed for application in projects.

APPENDIX A

Questionnaire

日期Date	2015年10月12 日		
地点 Location	重庆Chongqing		
性别Gender:		A / 男Male	B / 女Female
年龄（17-25之间）Age (Between 17 and 25)		A / 是Yes	B / 否No

请在以下你满意的选项打钩：

1 你对本地夏季气候总的感受是
How do you generally feel in the local climate in summer? (Please tick only one)

A / 较凉爽Slightly cool	B / 不冷不热Neutral	C / 较热Slightly warm	D / 热Warm	E / 很热Hot

2 你对本地夏季风环境总的感受是
How do you generally feel in the local wind environment in summer? (Please tick only one)

A / 没有风No wind	B / 风速较低Low speed	C / 风速较高High speed	D / 风速很高Very high speed

3 对于你现在居住的房子, 你最想改变的是
Which of the following changes would you like make to your living space at home?

A / 增加窗户可开启面积 Increase operable window size	E / 减小窗户可开启面积 Decrease operable window size
B / 让客厅更开敞,视野更开阔 Make the living room opener	F / 让客厅更封闭 Make the living room more enclosed
C / 设置阳台或露台（或增加面积） Add a balcony or terrace	G / 去掉阳台或露台（或减小面积） Remove a balcony or terrace
D / 设置庭院或天井（或增加面积） Add a courtyard or patio	H / 去掉庭院或天井（或减小面积） Remove a courtyard or patio

4 在夏季, 你是否觉得本地传统民居比现代住宅更凉爽？
In summer, do you think it is more comfortable in the local vernacular house than in the modern house?

A / 是Yes	B / 否No

5 在夏季, 如果没有空调, 你对以下空间的视觉感受是
What is your opinion of the visual perception in the following spaces (without air conditioning) in summer?

	视觉感受Visual perception		
	A / 视野, 景观好 The view is good	B / 视野, 景观一般 Neutral	C / 视野, 景观不好 The view is not so good
5.1/ 室内空间(一般的房间如卧室, 客厅等) Indoor space			
5.2 / 半室外空间 (外廊, 门廊, 阳台, 亭子, 花架下等) Semi-outdoor space (porch, outside corridor, balcony)			
5.3 / 室外空间 (庭院, 天井等) Outdoor space (courtyard, patio)			
5.4 / 开了大面积窗户或洞口的房间 A room with a large operable area			
5.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area			

6 在夏季，如果没有空调，你对以下空间的热感受是
What is your opinion of the thermal perception in the following spaces (without air conditioning) in summer?

	热感受Thermal perception					
	A / 冷 Cool	B / 较凉 Slight cool	C / 中等 Neutral	D / 较热 Slight warm	E / 热 Warm	F / 很热 Hot
6.1/ 室内空间 (一般的房间如卧室，客厅等) Indoor space						
6.2 / 半室外空间 (外廊, 门廊, 阳台, 亭子, 花架等) Semi-outdoor space (porch, outside corridor, balcony)						
6.3 / 室外空间 (庭院, 天井等) Outdoor space (courtyard, patio)						
6.4 / 开了大面积窗户或洞口的房间 A room with a large operable area						
6.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area						

7 在夏季, 如果没有空调, 你对以下空间的风环境感受是
What is your opinion of the wind environment in the following spaces (without air conditioning) in summer?

	风速Wind speed perception				
	A / 很低 Too low	B / 低 Low	C / 中等 Neutral	D / 高 High	E / 很高 Too high
7.1/ 室内空间 (般的房间如卧室, 客厅等) Indoor space					
7.2 / 半室外空间 (外廊, 门廊, 阳台, 亭子, 花架下等) Semi-outdoor space (porch, outside corridor, balcony)					
7.3 / 室外空间 (庭院, 天井等) Outdoor space (courtyard, patio)					
7.4 / 开了大面积窗户或洞口的房间 A room with a large operable area					
7.5 / 开了较小面积窗户或洞口的房间 A room with a small operable area					

8 在夏季，如果没有空调，你喜欢呆在以下的什么地方Where do you prefer to stay in summer (without air conditioning)?

8A

	A / 室内空间 Indoor space	B / 半室外空间 (外廊, 门廊, 阳台, 亭子等) Semi-outdoor space	C / 室外空间 (庭院, 天井等) Outdoor space	D / 没有倾向 No preference
8A.1/ 早上Morning (9:00-12:00AM)				
8A.2/ 下午Afternoon(13:00-5:00PM)				
8A.3 / 傍晚Evening (7:00-10:00PM)				
8A.4 / 晚上Night (0:00-8:00 AM)				

8B

	A / 开了大面积窗户或洞口的房间 A room with a large operable area	B / 开了较小面积窗户或洞口的房间 A room with a small operable area	C / 没有倾向 No preference
8B.1 / 早上Morning (9:00-12:00 AM)			
8B.2 / 下午Afternoon (13:00-5:00 PM)			
8B.3 / 傍晚Evening (7:00-10:00 PM)			
8B.4 / 晚上Night (0:00-8:00 AM)			

8C

A / 一个有较好视野和景观的地方A place with a good view	B / 我不在乎视野和景观的好坏I do not care about the view

8D

A / 一个有开阔视野的地方The room has a broad view	B / 我不在乎视野的开阔与否I do not care

8E

A / 没有风的地方 A place with no wind	B / 有较低风速的地方 A place with low speed wind	C / 有较高风速的地方 A place with high speed wind	D / 有很高风速的地方 A place with very high speed wind

9 你对以上问题有什么建议吗Do you have any comments about this questionnaire?

***谢谢!** Thank you!*

TOC

About the author

Xiaoyu Du obtained his MSc in Building Technology at Chongqing University, China. From 2002 to present, he taught at the department of building technology, Faculty of Architecture and Urban Planning, Chongqing University. He is an associate professor in Chongqing university currently. He has a long experience of teaching in multi-disciplines related to architectural design and designing practice. He teaches complex building design, building construction, detailed design and green building innovation related technologies for undergraduate and graduate students. He participated and finished some education and research projects, and published papers and book chapters. He also finished many design projects for residential communities and public buildings in China. He joined the faculty of architecture and the built environment, TU Delft as a guest researcher in 2011.

His research and teaching interests focus on complex building design, building construction and detailed design, space and spatial perception, zero-energy building design, adaptive thermal comfort, passive cooling technology and building performance simulation and evaluation.

List of publications related to the PhD research

Du, X., Bokel, R., & van den Dobbelsteen, A. (2016). Architectural Spatial Design Strategies for Summer Microclimate Control in Buildings: A Comparative Case Study of Chinese Vernacular and Modern Houses. *Journal of Asian Architecture and Building Engineering, 15*(2), 327-334. doi: 10.3130/jaabe.15.327

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19#10

Space Design for Thermal Comfort and Energy Efficiency in Summer

Passive cooling strategies for hot humid climates, inspired by Chinese vernacular architecture

Xiaoyu Du

Space is the empty part of the building, but its volume is important for the activities of occupants. Architects define the general spatial structures of buildings mainly in the early design stages, and the spatial properties, the connection of the spaces and the boundary conditions of them are significant for the building function and performance. This research first clarified the relationship between spatial configuration of buildings, thermal environment and thermal comfort of occupants in summer. The author got the inspiration from Chinese vernacular architecture. The concept of "building microclimate" was defined and the revelation of the relationship between spatial perception and adaptive thermal comfort was clarified. Secondly, the potential of using spatial indicators to predict the airflow performance of buildings was found. The new application of the extended space syntax method is proposed to help architects and designers in the early design stages in designing a modern building that is thermally more comfortable and that has a lower energy demand. This research has some innovative findings in the interdiscipline of architectural spatial design, passive cooling and thermal comfort. It will enrich the green building science by introducing the theory and the applications for adaptive thermal comfort, principles of passive cooling by means of spatial design.

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