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The University of Huddersfield
Department of Architecture and 3D Design – School of Art, Design & Architecture

IMPROVING THERMAL COMFORT THROUGH BUILDING ENVELOPE DESIGN IN THE 'SHOP-HOUSE' DWELLINGS IN HO CHI MINH CITY, VIETNAM

THANH HUNG DANG

A thesis submitted to the University of Huddersfield in partial fulfilment of the requirements for the degree of Doctor of Philosophy

Supervisors:

Prof Adrian Pitts – Main supervisor

Dr Yun Gao – Co-supervisor

Huddersfield, 31st August 2020

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Abstract

The complex interplay of growing issues in terms of urbanisation, population explosion, urban heat island, and climate change has negatively changed the multiscale urban environment, which has accelerated thermal discomfort in naturally ventilated residences in populous cities of Vietnam such as in Ho Chi Minh City. Among them, getting comfort is more difficult in 'shop-house' buildings, which are a popular vernacular residential typology in Vietnam, because of the tricky building form (thin, long, and sometimes high). Designers have had confusions about creating comfortable environments (low air temperatures and sufficient airflows) for occupants within buildings while the implementation of existing architectural standards shows insufficiency. Therefore, in the context of increasing urban unsatisfactory environments, more households and designers have an alternative option of using air-conditioners to get comfort. That links to the rise of energy consumption and pressures on the environment. Absorbing the problems in current practice in Vietnam, the thesis aims to find a potential approach to developing effective design guidance that supports architects to improve the performance of building envelope. The guidance will mainly focus on the opening design. With the design guide, designers can assess the environmental impacts of their design strategies applied to occupant comfort in 'shop-house' dwellings. The guidance potentially covers the key information researched as follows:

The interplay of two variables (temperature and air velocity) on the overall comfort sensation of residents in non-air-conditioned 'shop-houses'. Therefore, the thesis will produce a comfort zone, which links both comfortable temperatures and air velocities, to build an assessment framework for the environmental effect of various options in the design guidelines.

The effect of internal (building) and external (urban) factors on comfortable environments in 'shop-houses'. Those factors are analysed and devised in a systematic way of design guidance, which can reflect their complex relationship with the indoor environment and comfort.

Finally, a demonstration of the design guide for openings is published and tested for validity.

To obtain the aim of the thesis, the main methods of data collection were field surveys of occupant thermal and air movement perceptions and acceptability; and field measurements of physical environments indoor and outdoor buildings. There were two official on-site studies taken place in summer 2017 and spring 2018; additionally, a pilot study was conducted in warm summer 2016. The data were primarily analysed by statistical calculations of IBM SPSS and numerical simulations of DesignBuilder.

Keywords: shop-house, thermal and air movement comfort, urban pattern type, design guidance for openings, hot-humid climates.

Declarations

I declare that this thesis presented for the degree of Doctor of Philosophy has

i) Been produced completely by myself, without the collusion of any previous work

ii) Been merely the outcome of my work

iii) Not been submitted for any other degree or professional qualification

I confirm that the work submitted is my own, except where notably mentioned differently in the text which has been included. My contribution and the other authors to this thesis have been clearly stated below. I confirm that appropriate credit has been given within this work with reference made to the work of others.

A part of the work presented in Chapter 4 was previously published in the reference 3 and 5 as stated in the publication list where Dang, H. is myself as the main author of the work in collaboration with Pitts, A. as the co-author. These studies were conveyed all by myself.

Some analyses and a part of the work presented in Chapter 5 and 8 were previously published in the reference 4 as stated in the publication list where Dang, H. is myself as the main author of the work in collaboration with Pitts, A. as the co-author. These studies were conveyed all by myself.

Some of the results and part of the work presented in Chapter 7 were published previously in the reference 3, 4 and 5 as mentioned in the publication list where Dang, H. is myself as the main author of the work in collaboration with Pitts, A. as the co-author. These studies were conveyed all by myself.

Some of analyses and results shown in Sections 6.1 and 6.3 of Chapter 6 were published previously in the reference 1 as mentioned in the publication list where Dang, H. is myself as the main author of the work in collaboration with Pitts, A. as the co-author. These studies were conveyed all by myself.

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To the Vietnamese Government for the financial support within 4 years, from 2015 to 2019.

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Publication list

Peer-reviewed papers

1. Dang, H. & Pitts, A. (2020). Urban Morphology and Outdoor Microclimate around the "Shophouse" Dwellings in Ho Chi Minh City, Vietnam. Submitted for Buildings Journal. Buildings. MDPI: Basel. https://doi.org/10.3390/buildings10030040
2. Pitts, A., Dang, H. & Jones, E. R. (2019). Comfort, Ventilation and Health Issues in Dwellings of Ho Chi Minh City. The 1st International Conference on Comfort at the Extremes: Energy, Economy and Climate. Dubai: Ecohouse Initiative Ltd.
3. Dang, H. and Pitts, A. (2018). Variations of Microclimatic Conditions in Residential Neighbourhoods in Ho Chi Minh City. The 34th International Conference on Passive Low Energy Architecture: "Smart and Healthy within the 2-degree Limit". Hong Kong: PLEA.
4. Dang, H. & Pitts, A (2018). Thermal Environments and Comfort Perception in Shophouse Dwellings of Ho Chi Minh City, Vietnam. 10th International Conference – Windsor: Rethinking Comfort. Cumberland Lodge: NCEUB.
5. Dang, H. & Pitts, A. (2017). Influences of Buildings and Urban Typologies on the Study of Thermal Comfort in 'Shophouse' Dwellings in Ho Chi Minh City, Vietnam. The 33rd International Conference on Passive Low Energy Architecture: "City, Buildings, People: Toward Regenerative Environments". Edinburgh: PLEA

In the peer-reviewed process

6. Dang, H. & Pitts, A. (2020). Simultaneous Influences of Temperature and Airflow on Comfortable Perceptions in Residential Buildings in Vietnam. Submitted for the 35th International Conference on Passive Low Energy Architecture: "Planning Post Carbon Cities". A Coruna: PLEA

Table of contents

List of Figures

List of Tables

List of abbreviations and symbols

Abbreviations

HCMC	Ho Chi Minh City
HVAC	Heating, ventilation, and air conditioning
NV	Naturally ventilated
UHI	Urban heat island
TSV	Thermal sensation vote
PMV	Predicted mean vote
PPD	Predicted percentage of dissatisfied
WWR	Window to wall ratio
WFR	Window to floor ratio
OWR	Opening to wall ratio
OFR	Opening to floor ratio
EOWR	Effective opening to wall ratio
EOFR	Effective opening to floor ratio
CFD	Computational fluid dynamic
AC	Air-conditioned
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ISO	International Organization for Standardization
CEN	Comite Europeen de Normalisation
Eq	Equation
TCVN	Vietnamese Design Standard
MONRE	Ministry of Natural Resources and Environment
RCP	Representative Concentration Pathways

Symbols

T_{op}	Operative temperature, °C
T_{comf}, T_c	Comfort temperature, °C
T_{mrt}, TRAV	Mean radiant temperature, °C
T_a	Air temperature, °C
T_{cl}	Surface temperature of clothing, °C
T_{out}, T_o	Monthly mean outdoor air temperature, °C
T_{rm}	Running mean of outdoor temperatures, °C
T_g	Global temperature, °C
ET*	New effective temperature, °C
ET	Effective temperature, °C
V_a	Air velocity, m/s
ach	Air changes per hour, ACH
RH	Relative humidity, %
f_{cl}	Clothing area factor
clo	Clothing ensemble insulation, clo
M	Metabolic rate, met
A	Surface area of human body, m^2
h_c	Heat transfer coefficient counting for air velocity, kcal/m^2h°C
p_a	Water vapour pressure, mmHg
n	Mechanic efficiency
dT	Comfort temperature increased, °C
d	Diameter of the globe, m

Chapter 1 INTRODUCTION

1.1 Background

In contrast to housing in moderate or cold climates where heating is a priority to remain comfortable indoors, cooling is the main requirement for occupant thermal satisfaction in buildings in warm to hot climates across much of the year. This is especially true in naturally ventilated housing (Givoni B. , 1994). Commonly, cooling is provided by two mechanisms: natural air movement (which increases convection and evaporation heat loss for the human body) and mechanical cooling systems such as fans (which also increase convection and evaporation) and air-conditioners (which reduce the temperature of the indoor environment) (Dekay & Brown, 2014). A number of studies have revealed that natural airflow is capable of creating a comfortable and healthy environment for humans with energy savings for cooling in the housing of tropical regions (Olgyay & Olgyay, 1963; Givoni B., 1976; Tanabe & Kimura, 1989; Szokolay S. V., 1997, 2008; Antaryama, 2000; Srivajana, 2003; Nicol, 2004, 2011; Santamouris, 2006; Djamila, Chu, & Kumaresan, 2007, 2013; Nicol, Humphreys, & Roaf, 2012; Nguyen, 2013; Arens, et al., 2013). For example, in traditional houses in many regions of the world, many distinctive climate-responsive design strategies are optimised. In these, sufficient airflow through openings in walls and within buildings result in not only natural ventilation of living spaces but occupant comfort, pleasure, and communication with the nature surrounding. As a result, energy consumption can be reduced (Brager & de Dear, 1998; Tantasavasdi, Srebic, & Chen, 2001; Pham N. D., 2002; Trimarianto, 2003; Roaf & McGill, 2018). Furthermore, frequent exposure to an indoor environment without mechanical controls encourages a greater diversity of acclimatisation in such buildings (Gupta, Swamy, Dimri, & Pichan, 1981; de Dear & Brager, 2002). Those effects are also found in traditional dwellings in Vietnam, in particular, traditional vernacular 'shop-houses' in Ho Chi Minh City (HCMC). However, due to the accumulative pressures of society, economy, and urban environment in the city, getting thermal comfort in 'shop-house' dwellings becomes difficult, even in such traditional houses. Those pressures have influenced thermal expectations and behaviours of occupants (Nicol, 2011). Both householders and designers are quite likely to find an easier alternative using air-conditioners to seeking comfort instead of finding proper ways to optimise housing design and its operation under the continuing unavoidable changes. Most local architects pay little attention to the role of the building to provide means for occupant comfort, as a result, an increasing amount of energy is required. Major causes of increasing discomfort for dwellers in residential buildings of HCMC are described in the following sections.

1.1.1. Influences of urban climate change

Vietnam is located in Southeast Asia and experiences a sticky monsoon tropical climate with uniformly high air temperature and high humidity and generous rainfall throughout the year. In the southern lands of Vietnam, the climatic characteristics of monsoon tropics are more intensive, for example, in HCMC. In essence, retaining comfort and environmental delight is challenging in naturally residential buildings of the warm-humid tropics in comparison with other climates (Antaryama, 2000). Previous studies have proposed that the achievement of thermal comfort in a warm humid climate is by a combination of three design strategies: prevention of external heat gains, reduction of internal heat gains, and finally, provision of sufficient natural ventilation (Givoni B. , 1994; Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 2000; Antaryama, 2000; Dekay & Brown, 2014). A complex interplay of body sensations with the surrounding environment (air temperature, air movement, and humidity) defines the neutral perceptions of occupants in the equatorial regions (Tanabe & Kimura, 1994). Thermal neutrality of inhabitants in non-air-conditioned buildings largely correlates with changes in the outdoor climate (Humphreys, 1978). However, that correlation may be limited by the continuing impacts of climate change as known as global warming and the effects of urban heat island (UHI) in megacities as HCMC.

Since 2009, the Ministry of Natural Resources and Environment (MONRE) has evaluated potential climate change risks, updated their scenarios, and predicted their threats on the sustainable development of Vietnam (MoNRE, 2009; 2012; 2016). A number of studies have shown the weak resilience and adaptation of Vietnam when confronted with the acute vulnerabilities to inundation, drought, temperature rise, fluctuating seasonal duration, and other extreme weather events (Ho, 2007; MoNRE, 2009; Storch, 2009; World Bank Group, 2011). Between 2012 and 2015, climate change consequences happened faster and more severely. The changing climatical phenomena have been very evident in the south-central region of Vietnam (MoNRE, 2016).

Atmospheric warming has already occurred notably in HCMC. The compounded impacts of global warming and UHI have accelerated a city temperature rise and the greater variations of urban local climate among city neighbourhoods (Storch, Downes, & Moon, 2009). In the report of climate change in 2009 by MONRE, the city's annual mean temperature increased by 0.6°C between two periods – 1931 – 1940 and 1991 – 2000; additionally, the annual average temperature in 2007 was higher by 1°C and 0.5°C than the average value of those respective two periods above (MoNRE, 2009). The recorded meteorological data show that the annual average temperature rose by 2°C over summer months for the last 50 years in HCMC regardless of the effects of UHI around the city (Asian Development Bank, 2010). The latest climate change report of MONRE 2016 concludes an average rise of 0.14°C over every decade from 1985 to 2014. Considering the historical weather forecasts of Weather Underground within 2009 and 2018 in HCMC, Figure 1.1 depicts the increasing divergence of air temperatures, particularly for the maximum and minimum air temperatures by about 3°C over 10 years.

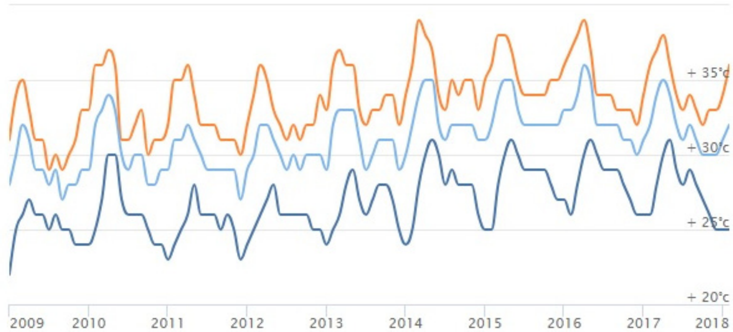


Figure 1.1 Change of air temperature in HCMC over 10 years (www.wunderground.com)

Combining with global warming at macro-scale, in Vietnam, the UHI effects due to intensifying urban development are exacerbating the risks of thermal discomfort and human health in HCMC (Storch, Downes, & Moon, 2009; Asian Development Bank, 2010). Those effects not only increase city air temperatures but prolong their duration; for example, summers are characterised as being hotter and occurring earlier as well as lasting longer in the city. During extremely hot periods of summer, citizens might have to endure prolonged daytime heat up to 40°C or even more, hence there is a concern for increased mortality due to heat stress in urban heat islands, particularly for senior citizens (World Bank Group, 2011). A reduction in thermal stress might be possible by growing more greenery and saving around 7 deaths per 1km² in HCMC (Tran, Doan, Kusaka, Seposo, & Honda, 2018).

Apart from warming air, the UHI effects over the city also implicate negative impacts on local climate and climatic variations among city districts in terms of heat, rainfall, evaporation, humidity levels, and wind distribution (Wong & Yu, 2005; Rajagopalan, Lim, & Jamei, 2014; Allegrini, Dorer, & Carmeliet, 2015). Studies on the urban climate influenced by UHI reveal warmer conditions of up to 10°C found in city central districts compared to typical temperatures in the suburban and rural areas in HCMC (Le & Nguyen, 2006; Tran & Ha, 2010). At daytime, the hot air around urban heat islands characterised by low pressure induces the collection of moist air from peri-urban areas and provides a good condition for cloud coverage and increases in humidity. However, wind flows through these areas are restricted by the compact pattern of construction (Rajagopalan, Lim, & Jamei, 2014).

Considering HCMC, most residences are naturally cooled, along with supplementary effects from fans and air-conditioners at certain times. This implies an exchange of climate indoors and outdoors. However, the long-term impacts of global warming and UHI effects in HCMC result in serious burdens to human health, nature, and the built environment, especially around highly-dense built-up regions (Eckert & Schinkel, 2009). Uncomfortable warmth and low airflows can be produced in local open spaces. Consequently, occupant behavioural adaptation can be limited and they spend more hours in air-conditioning spaces (Szokolay S. V., 1997). As a result, this causes negative sequences of further overheating of the urban environment, air pollution, and excessive household energy consumption for mechanical cooling (Asia Development Bank, 2013). Mitigating the impacts of urban heat island effects is advantageous for energy savings, urban and indoor thermal comfort, and alleviation of climate change.

1.1.2. Pressures of expanded population and urbanisation

The above explains the influences of global warming and UHI effects on human comfort and health in HCMC. Those consequences have arisen mainly due to human activities, among those, ongoing urbanisation and growing population are fundamental causes. They not only affect the land-use pattern, urban spatial structure, and settlement planning but contribute to excessive emissions of heat and pollutants in the environment in and around buildings (Storch, Downes, & Moon, 2009; Asian Development Bank, 2010; Storch & Downes, 2011).

After the economic reforming plan – “Doi Moi” across the country in the late 1980s, HCMC has experienced a period of rapid urbanisation and population explosion (JBIC, 1999; Downes, Rujner, Schmidt, & Storch, 2011). In 1989, the first national census reported the city population at about 3 million (Drakakis & Dixon, 1997). Owing to widespread economic growth, the inner city administrative boundary was expanded more than double in order to provide settlements for over 7 million people in 2009 (SO-HCMC, 2009; CPHSC, 2010). However, that number probably did not take account of over 2 million unofficial migrants (Storch & Downes, 2011). New jobs and the dynamic working environment have attracted a massive movement of workers from surrounding provinces. Those have significantly restrained the precise projection of urban planning, society management, and residents’ living standard in the city. In the early 2010s, the HCMC People’s Committee approved a master plan of the city in terms of economy and society until 2025 that includes an urban spatial and settlement planning of 10 million official residents plus 2.5 million temporary ones (HCMC People's Committee, 2013). Nevertheless, every prediction so far of population and urbanisation growth is probably failed and this is evidenced by the several revisions of the government plan approved later. Unofficial forecasts suppose that total city population can reach 13.9 million by that year (Cox, 2012).

According to the latest national census, urbanisation in southeast regions of Vietnam, including HCMC, was 57.2% in 2009 and 62.3% in 2014 (General Statistics Office, 2015). As shown in Figure 1.2, urban inhabitants doubled between 1999 and 2015 (DEMOGRAPHIA, 2015), and have been estimated at around 10 million by 2025 (Vietnamese Government, 2014). The pressure of increasing municipal population corresponds to the enhancement of infrastructure, larger built-up area, and excessive housing need. To serve the new developments by 2025, 38,000ha of available agricultural land will be built upon.

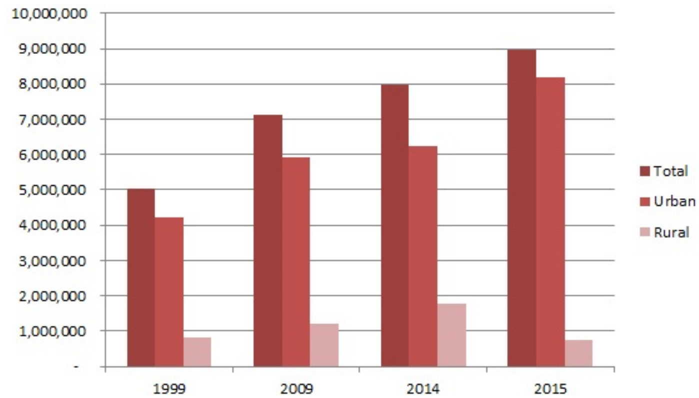


Figure 1.2 Population in the urban and rural area of HCMC (adapted from CPHSC, 2010 and DEMOGRAPHIA, 2015)

Figure 1.3 reveals the dramatical changes of city land-use pattern in 2010, 2015, and 2025 (Storch & Downes, 2011). The urbanisation has spread over the city in all directions. The future change in land-use will cause loss of a large area of conditional green land and open spaces; with consequent effects on the urban climate and flooding/drainage control in HCMC (Storch, Downes, Katzschner, & Nguyen, 2011). Unsuitable city planning can accelerate the physical tolerance of the urban system to climate change, along with the vulnerable impacts of heat pressure and inundation on human lives in the coming years (Katzschner & Burghardt, 2017).

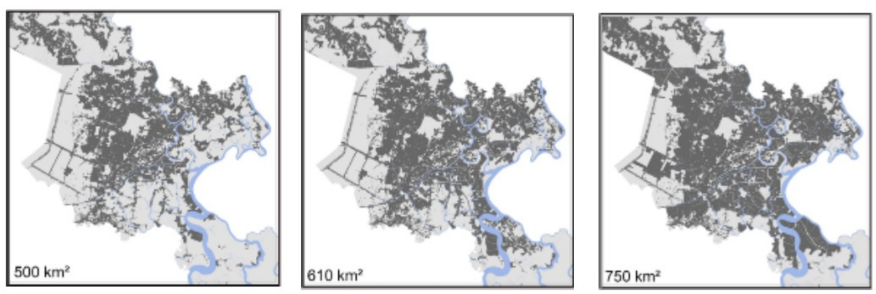


Figure 1.3 Changes in the urban land-use pattern in HCMC (Storch and Downes, 2011)

The population explosion results in a crisis of existing and planned housing supply and management in HCMC. Over 300 multi-scale residential building projects were developed around the city between 2015-2018 and the settlement plans will continue to grow in the coming years. In accordance with the Resolution 02-2014 issued by the Vietnamese Government, the total construction coverage area of accommodation occupied 161km² in 2010 and that will be planned up to 247km² corresponding to an increase of 53% by 2020 (HCMC People's Committee, 2013); however, the prediction is likely to be an underestimation because of neglecting the role of additional migrants. Between 2010-2014, a project undertaken by the University of Cottbus found 445.6km² (21.1%) of the total city area covered by dwellings, which is much more than the governmental statistics predicted (Downes & Storch, 2014). The distribution of households and population varies among four sub-regions: core-centre, former inner, new inner, and suburban (Figure 1.4). Changes in land cost, social need, household income, urban environmental quality are encouraging a decrease of citizens in inner-city neighbourhoods. According to population statistics in HCMC in 2002, occupancy in core-centre and former-inner districts was highly dense with density from 30,000-45,000 people/1km² (Gubbry, et al., 2002); however, that value significantly decreased in 2015 with the maximum density of around 28,000 people/1km² (Ho Chi Minh City Statistical Office, 2016).

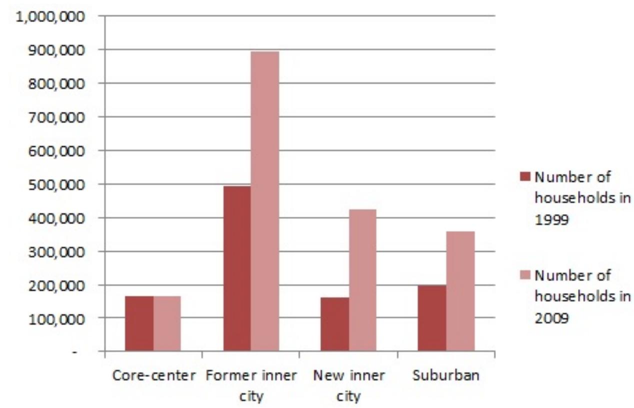


Figure 1.4 Numbers of households by a city zone in HCMC in 1999 and 2009 (adapted from CPHSC, 2010)

The higher concentration of population around the central districts adds to UHI effects. Around compact dwelling regions, the microclimate is influenced by thermal storage, heat emissions, poor ventilation, and less evaporation (Grimmond, 2007). Researchers combined a mapping method and climatological parameters to examine the characteristics of urban microclimate by zones (Downes, Rujner, Schmidt, & Storch, 2011). They found that the densification and expansion of the city without concerns about the environmental impacts exacerbates the vulnerabilities of the urban thermal comfortable conditions. Consequently, environmental satisfaction in residences, in particular, free-running housing can be influenced not only because of the larger effect of heat island thermal stress but the additional problems of light wind flows, increasing air pollutants, and environmental noise, to which residents are exposed. The discomfort probably causes increased energy use, greenhouse gas emissions, and health risks. Thus, at the urban scale, the correct structural and spatial planning of settlements contributes in a significantly positive way to tolerance and resilience to the impacts of UHI and climate change and additionally provides more pleasant urban environments (Moon, Downes, Rujner, & Storch, 2009). Moreover, living standard and indoor environmental quality in households will benefit from the better control of population growth and housing market.

1.1.3. Energy needs for cooling in residential buildings in Vietnam and HCMC

Increasing energy consumption for housing in Vietnam is linked to economic development, population growth, and urbanisation together with the extreme events of global warming and UHI effects

(Danish Energy Agency, 2017). In line with an energy report for Vietnam published in 2015, the total final energy supply of 49.3 MTOE indicated a share of 33% for householders in 2012 (ADB, 2015) (Figure 1.5). The energy demand in households constantly increases by about 11% - 15% every 5 years and will require a supply of 30,000 KTOE in 2035 to satisfy occupant activities and comfort conditioning systems related to the heat (Danish Energy Agency, 2017).

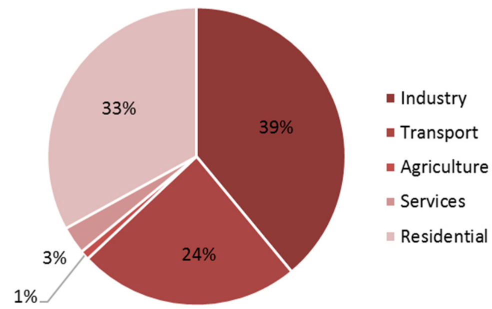


Figure 1.5 Final energy consumption by sector in Vietnam, 2012 (ADB, 2015)

A countrywide survey of 1,394 houses by Cimigo's group, along with the Census of Vietnam in 2009 showed household energy use has an association with housing type and geographical zone. The annual average energy expenditure was the highest in the southern regions of Vietnam – around 4,042kWh per household and 1,063kWh per capita, which is attributed to the warmer climate and more prosperous living conditions. A typical family paid on average about 200 GBP for monthly bills, in this, the cost of electricity accounted for 11% of total expenditure according to surveys in 2013 (Figure 1.6).

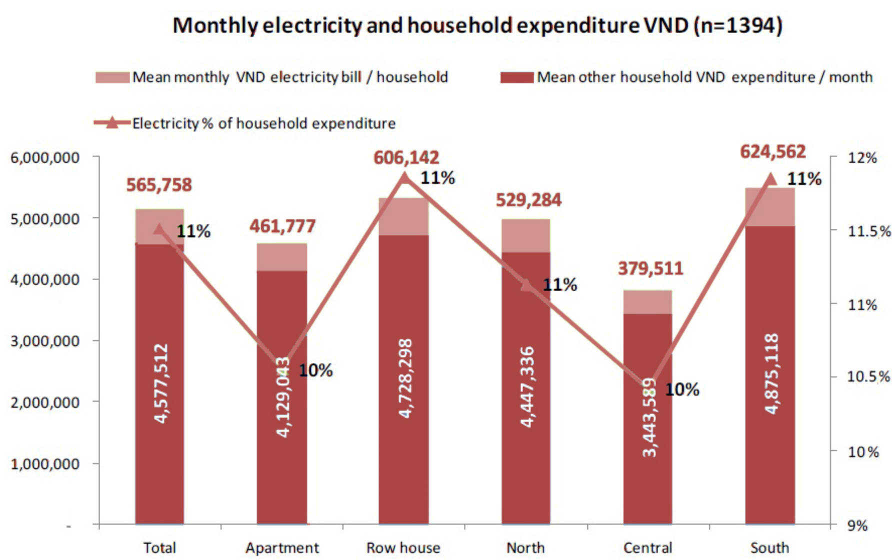


Figure 1.6 Monthly electricity and household expenditure VND (n=1394) (Parkes & Burrage, 2013)

However, recent field studies on energy consumption in the 'shop-house' dwellings in HCMC have shown that the monthly mean electricity bill has increased by 50% due to changes in energy prices and the growing demand. Moreover, there were variations of monthly electricity use in different housing types: row house and apartment - see Figure 1.6. The mean expenditure of energy in row houses was greater than that in the apartment and total (Parkes & Burrage, 2013).

In warm-humid climates, the demand from within the residential energy sector is divided into three groups: space cooling, water heating, cooking, and lighting and appliances. Considering the 1990s in Vietnam, few Vietnamese families owned air-conditioners, cooling was mainly from fans and most of the energy was used for lighting, cooking, water heating, appliances and production of pig feed. The enhancement of household income has changed patterns in using cooling systems (Nguyen & Lefevre, 1996). Another investigation conducted in over 330 houses in Vietnam between 2014-2015 indicated a rise in annual average energy use to 5,278KWh – 30% higher compared to the surveys in 2013, as well as, changes in the residential energy sector (Murakoshi, Xuan, Takayama, Nakagami, & Takaguchi, 2017). The space cooling used approximate 20% of total electricity use in the dwellings of HCMC over that period (Figure 1.7). Increased energy use in HCMC can be arisen due to several factors, such as higher household income, requirements of a better living standard, or pressures of the changing urban climate. Nevertheless, the higher the energy use, the greater the impacts on the living environment because of emissions of heat, dust, and contaminants in the air (Alison & Rajkovich, 2010). The annual CO_2 emissions per household in HCMC was 1.8 tons in 2014 and 2015. The amount of CO_2 was divided into the following: 1.2 tons by lighting and plug loads, 0.4 tons by space cooling, and 0.2 tons by others (Murakoshi, Xuan, Takayama, Nakagami, & Takaguchi, 2017). The assumption of CO_2 emitted next 20 years will be around 21m tons that only counts for the demand of energy in residential buildings (Danish Energy Agency, 2017).

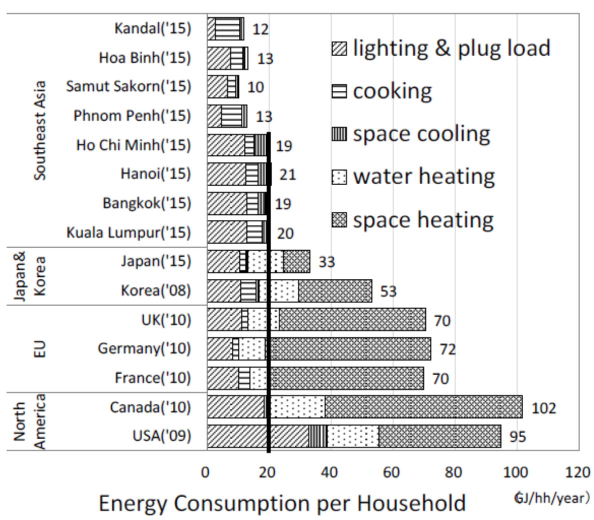


Figure 1.7 Energy consumption per household by final energy use (Chiharu Murakoshi, 2017)

Alongside the above findings, the Cimigo's team also found the insights of occupants' cooling preference in Vietnamese housings through their online survey for using mechanical cooling systems (fans and air-conditioners) to obtain comfort. The results included 48% of households owned air-conditioners and 45% of households used fans. At the moment, almost every family in HCMC owns at least one air-conditioner. This trend shows the rising cooling expectation of inhabitants and the true impacts of a warmer environment in the city. However, they are also concerned with increasing electricity cost, air quality and health dangers with the longer occupation of air-conditioning spaces. Most occupants prefer natural ventilation to cool buildings and their body; as a result, 79% of 1,394 households involved in the survey used openable windows/doors/openings to capture the wind for ventilating even though mechanical cooling systems still have advantages, particularly in summer. Consequently, a well-designed house not only responds well to the outdoor climate but provides a satisfactory and healthy environment for people living in the area by optimising natural cooling. Furthermore, passive building systems (natural cooling and lighting) can be effective methods of saving energy by improving occupant adaptive behaviours through easy access to operable building elements.

1.1.4. The practice of housing design in Vietnam

The technical regulations or construction codes related to residential buildings in Vietnam have been developed since the 1960s. They play a role in facilitating design strategies to ensure high building performance, security, comfort, health and well-being, less energy use, and fewer impacts on nature (Nicol, 2011). However, there may have a gap in the dissemination and implementation of design standards or technical manuals and the management of construction in reality. Additionally, the slow update of these documents questions whether the enacted standards are adequate and matched to the existing and future needs of the real built environment in the country (Tran Y. T., 2015).

A recent survey with architects conducted by the author in HCMC shows the current implementation and application of available housing design standards and guidelines in Vietnam. Many of architects found confusions. 29% of designers did not usually use any standard and guidance for their work (Figure 1.8a). In the five reasons suggested, three common causes were ‘Not know’ (32%), ‘Know but not use’ (21%), and ‘Less effective’ (37%) (Figure 1.8b).

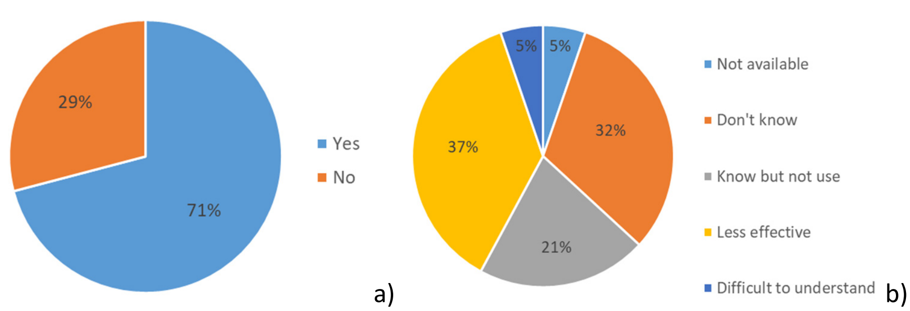


Figure 1.8 The current use of design standards (a) and guidelines in practice (b)

Despite the availability of national standards applied in the design of shop-houses, many designers did not access them. Meanwhile, others found less efficiency of them because those publications might not be compatible with the real context and need in the built environment in Vietnam or have a lack of clear and understandable presentation. Moreover, although the comfort conditions for shop-house buildings are determined in standards, there is a lack of effective guidelines supporting designers' work to propose suitable passive design strategies, which contribute to achieving indoor comfortable environments.

Additionally, the observations of architects' practices and clients' concerns show the variations of outcome to be achieved when designing or building a house, compared to the built environment of 5-10 years previously (Figure 1.9). The findings are that more designers are paying their attention to two principal aspects: aesthetics and comfort in buildings. More architects have proposed potential schemes that optimise climatic responsive design strategies in terms of natural ventilation and daylighting to improve comfort. Energy use and health and well-being are also among the main concerns of 50% of practitioners in the survey. However, there is a significant number of clients who choose the short-term savings associated with building cost rather than a long-term gain of energy efficiency. Occupants mostly worry about the construction cost (typically 80%) rather than building performance and indoor environmental conditions. Cognition of the risks of the changing urban climate on living environment causes occupants are beginning to think about the air quality and environmental condition in their living space. It is noticed that clients' preference can influence significantly on architects' ideas and desires toward a comfortable and healthy building.

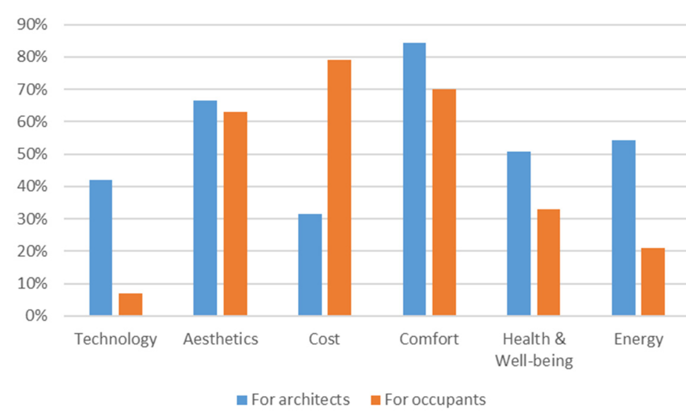


Figure 1.9 Features of the built environment of housings concerned by architects and households in Vietnam

The trend in housing design is changing in Vietnam at the moment, particularly in large cities such as HCMC. 95% of architects who took part in the surveys realised that a house responding well to its surroundings can bring the benefits of thermal comfort, health and well-being, and energy saving for occupants (Figure 1.10).

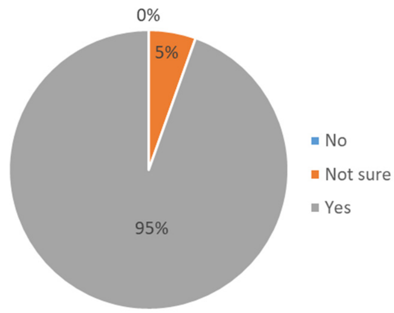


Figure 1.10 A survey for architects' cognition and challenges to housing design

However, an invisible wall likely exists between professionals and researchers to perfect the practical environment by dealing with a complex correlation among physical parameters, human perceptions and behaviours. It also necessitates the finding of optimal design solutions for buildings, which engage occupants' adaptive behaviour and enable them to seek comfort for themselves. That can seem to be a designing/designerly manner of sustainable comfort (Nicol, 2011). The job of an architect is to produce a specific building that intervenes and enables interactions between occupants and the environment through building elements. The role of scientists is to generalise research outcomes from experimental and empirical studies, analysis, calculations, etc. by applicable products in practice such as standards and design guidelines that contain the scientific assessments of environmental condition (temperature, air velocity, or relative humidity) or more detailed guidance. Probably, most architects in Vietnam have difficulties in finding support from appropriate guidelines framing the design strategies that would help them to achieve homes where people expect to be safe, comfortable, and healthy.

1.1.5. Section conclusions

Many studies conducted in different climate zones and building types have shown the impact of climate change on thermal comfort and energy demand in buildings, for example, in houses in Honduras's warm-humid climate (Gamero-Salinas, Sanchez-Ostiz, & Monge-Barrio, 2020); hospitals (Lomas & Giridharan, 2012), homes (Gatterell & McEvoy, 2005; Hacker & Holmes, 2007; Amoako-Attah & B-Jahromi, 2013), social housing apartments (Sameni, Gaterell, Montazami, & Ahmed, 2015) in the UK; or domestic and commercial buildings in Switzerland (Frank, 2005). Additionally, a few researchers have agreed that there should have more flexible and more adaptive comfort and energy-efficient standards for buildings rather than existing ones, which enhance occupant adaptive behaviours and building adaptation through design elements and physical structure (Janda & Busch, 1994; Kwok & Rajkovich, 2010).

Considering the future scenario of climate in Vietnam, the increasing global warming has concurrently affected the national and regional ambient environment: the rise of temperature, the increased number of hot days, and extreme thermal events since 1958 (Asia Development Bank, 2013).

The MONRE used a climatic model to simulate the increase of average annual temperature and its variability under different RCP scenarios in many cities in Vietnam including HCMC in different periods of within 2016 and 2100. Firstly, for RCP 4.5, that figure tends to rise by 0.7°C (0.4-1.2°C) between 2016-2035, 1.5°C (1.0-2.1°C) between 2046-2065, and 1.9°C (1.2-2.7°C) between 2080-2099. Secondly, with the RCP 8.5 model, the average annual temperature will rise from 0.9°C (0.5-1.3C), 2.0°C (1.4-2.8°C) to 3.5°C (2.8-4.7°C) (MoNRE, 2016). The vulnerability of urban thermal condition has been accelerated by urbanisation since the 1990s (Asian Development Bank, 2010). According to the currently approved planning orientation of HCMC in 2025 by the national government, the size of the city population and the urbanised area will be 10 million (original people) and 900-1000 km2 (40-45% of total city land) (Vietnamese Government, 2014). However, that approval was adjusted in 2017 for further visions by 2030 to 2050. Therewith, urbanisation of the city will get 70-75% and 90% respectively (Vietnamese Government, 2017).

The temperature rise caused by existing global warming coupled with UHI effects by accelerated urbanisation in HCMC has likely put citizens in the exacerbated vulnerability of human comfort, health, and well-being inside and outside buildings. That impact has negative implications for energy demand and economy by 2050 (Asian Development Bank, 2010). The environmental pressure will particularly occur with residential buildings and their inhabitants because of the dominant proportion of the building category in the real estate, the intensive energy supply, and the popular cooling mechanism of natural ventilation of dwellings. The warm and humid nature of tropical climate is disadvantageous to thermal satisfaction of inhabitants. The overheating risk will consequently change human thermal tolerance and preference, which links to adjusted adaptive thermal behaviours. Particularly, installing and operating air-conditioners in homes tends to increase to respond to warmer conditions in future years for maintaining thermal comfort with excessive energy consumption. However, the intensive use of air-conditioners should be avoided owing to implications for aggravated climate change and urban environment problems.

Comfort, health and well-being in buildings have been concerned by designers and residents. The compilation, implementation, and use of design standards contribute to achieving low-cost comfortable houses not only in HCMC but in Vietnam. Besides, the availability of effective design guidelines will be significant for architects' practice. The survey result with professionals above partly explains the limitation of implementation and use of current design standards. Their development requires the involvement of government, researchers, professionals in the industry, and occupants. Furthermore, their sufficiency and validity ask empirical and experimental studies on physical buildings, their physics, and their inhabitants in the correlation with the urban environment. The standards and guidelines should show acceptable thermal conditions for residential buildings, opportunities to access building controls by occupants, and optimisation of passive cooling designs. Those design tools should adapt to the change of global and city climate so that they contribute to creating comfortable and energy-efficient houses, which adapt and mitigate the climate change problem.

1.2 Research aim

The ‘Shop-house’ is a unique vernacular residential building typology found in Vietnam and other nations around South East Asia. Most ‘shop-house’ dwellings in the country including HCMC are naturally ventilated or mixed-mode system buildings. The intrinsic characteristic of ‘shop-house’ architecture is an awkward building form (thin, long, and sometimes high) as a ‘tube’ form, with additional restricted openings to the surroundings owing to a compact pattern of housing. Therefore, it is difficult to find rational ways in design to make use of, for example, wind flows to reduce discomfort. Under the accelerating pressures of urban climate, global warming, growing urbanisation and population, and increasing energy cost, questions about thermal comfort conditions, health, the safety of occupants are raised. Besides, scientists and designers are still searching for the best answer for how to adapt to unavoidable climate change and man-made environmental change and how to design and build a comfortable and energy-efficient house for the future.

There have been gaps in practice to design comfortable ‘shop-houses’ such as the insufficiency of existing national standards and the unavailability of design guidance to support architects’ work to meet recommendations into the standards. The standards have not covered or considered the impacts of global warming, the growth of urbanisation and population, and urban heat island effects on the environment indoor and outdoor housing. Thereby, they have not reflected real comfortable conditions for residents and residences. Designers are usually confused about the effect of passive design strategies used on building performance and comfort that they can provide. Meanwhile, the building design can be controlled by a complex interplay of climate, urban environment, and urban planning. Consequently, the research thesis aims to seek an approach of effective design guidance applied for the design of building envelope, particularly openings in naturally ventilated ‘shop-houses’. The proposal helps designers firstly understand and assess environmental performance, achievable comfort in the houses which they design, and then, suggests to them appropriate design methods related to opening variables to improve building comfort. The principles will be researched and incorporated into the potential guidance as follows:

- The influence of urban morphologies of ‘shop-house’ buildings on the building design and the indoor environment and comfort.

- The comfort zone linking the interaction of two variables (air temperature and air velocity) to overall human comfort sensations in non-air-conditioned shop-houses.

• Various design options of opening variables, which are adaptive to apply to various conditions of buildings and settlements. They help architects understand the environmental impacts and comfort level from the opening design strategies applied.

1.3 Research objectives

To achieve the aim identified, a total of seven research objectives are carried out as follows:

The first objective is to review available studies on human comfort, particularly research conducted in residential buildings in warm-humid regions including Vietnam. This step is fundamental to acquire theoretical knowledge related to comfort models, thermal and air movement perceptions and expectations, factors of comfort, and influences of urban and building design on comfort conditions in buildings in the tropics. Alongside those theories, experiences of previous comfort surveys can support needs to learn and modify to the specific context of naturally ventilated 'shop-houses' in HCMC.

The second objective is to understand in depth the architectural and planning characteristics of 'shop-house' dwellings in Vietnam, particularly in HCMC in relation to the categories of 'shop-house' building and urban form studied by the University of Cottbus in the city from 2010 to 2014.

The third objective is to conduct field questionnaire surveys and environmental measurements in 'shop-houses' in HCMC. This task is a crucial part of the whole project and took many months to carry out within 2016 and 2018. The comfort studies aim to investigate occupant sensations, preferences, and acceptability in the given thermal environment of 'shop-houses'. The analytical results are to find the neutral point and comfort zone of temperature and air movement for occupants in free-running 'shop-houses'.

The fourth objective is to investigate the climate indoor and outdoor buildings according to the classification of urban forms, which is reviewed to forage a potential correlation between comfortable environments and urban morphologies.

The fifth objective is to evaluate the design characteristics of 'shop-house' buildings, particularly opening configurations and to understand environmental characteristics within buildings by analysing some typical case studies. Based on the analysis, the contribution of opening design features to create indoor environmental conditions for occupant comfort is considered.

The sixth objective is to produce a demonstration of design guidelines in terms of building opening features. In that stage, the outcomes of previous objectives gathered together are to build various design options for testing and to establish an assessment framework for the comfort level when changes are made in opening parameters and their values for a 3D-estimated building model. Parametric analysis is mainly utilised to test environmental performances. Then, a sample version of the design guide is proposed.

The seventh objective is to evaluate the validity of the design guidance with key stakeholders in HCMC. The demonstration of guideline proposal is tested with professionals, who are working in the architectural industry. And then, a revision of the demonstration system will be issued.

1.4 Research methods

The fundamental research method used is empirical studies. The collection of various data types (thermal and air movement sensations, preferences, and acceptability; indoor and outdoor environments; and building and opening characteristics) was carried out for approximate 65 houses and 139 dwellers in hot and cool months within 2016 and 2018 in HCMC. Data were classified and analysed systematically according to housing and urban pattern types of 'shop-house'. The environment for occupant thermal neutrality may be different in residential neighbourhoods characterised by different urban morphologies, along with varying housing types. The detailed classification of housing and urban spatial structures is one of the valuable outcomes from a 4-year study in HCMC undertaken by the University of Cottbus, Germany. Statistical and computational methods were applied for analysis. Analytical results are generalised as the scientific dimensions used in the potential design guidelines to evaluate the comfortable condition and the effect of opening designs applied. After the principal information of the potential design guidance for openings was defined, a demonstration tool was proposed and tested for its validity via interviews and questionnaire surveys with the profession, including architects, lecturers, and engineers. The research design and techniques developed to reach the aim and objectives of the project will be revealed in details in Chapter 5.

1.5 Research scope

Comfort is affected by the context (de Dear & Brager, 2002). Primary contextual factors include various types of climate, building, cooling option, and people (Nicol & Humphreys, 2002). Numerous field studies conducted in various buildings and climates have shown that human thermal comfort is defined differently in varying contexts (Nicol & Roaf, 1996; de Dear & Foutain, 1994; Karyono, 2011; Djamila, Chu, & Kumaresan, 2013; Nguyen A. T., 2013). Consequently, the first consideration of this project is the context associated with variables: Vietnamese people, naturally conditioned 'shop-house' buildings and tropical climate. There are three prime reasons for selecting those terms. Reviewing the background section, HCMC is a typical sample of a populous city in Vietnam even over the world in which the environmental impacts for climate change and the urbanisation and population growth have exacerbated seriously. Those influences have accelerated strains on comfort, health, and well-being in residences.

Among three dwelling typologies found in HCMC, including shop-house, villa, and flat/apartment, the 'shop-house' occupies a large majority of the overall housing market. Meanwhile, the design of comfortable 'shop-houses' has confronted difficulties due to a lack of knowledge and support from effective design standards or guidelines. Consequently, the current thesis will investigate all of the contextual factors to discover comfortable conditions for free-running shop-houses and a designing system to support their good practices.

The second focus of the research is the age group of occupants investigated. All surveys by questionnaire were carried out with participants at 15-65 years-old. In accordance with ASHRAE Standard 55, ISO 7730, or CEN 15251, people within this age range are not overly sensitive to weather changes and can respond to and provide feedback about the immediate environment (ASHRAE, 2004; ISO, 2005; CEN, 2007). The later analyses and calculations are also related to the votes of these participants.

1.6 Thesis framework

Excepting Chapter 1 (Introduction) and Chapter 10 (Conclusion), the thesis is devised into three principal parts: Research fundamentals, Research measurements, and Research analyses. Each thesis part includes the chapters deliberately arranged in the critical thinking of the research story from understanding the topic and finding the potential research gaps to achieving the research outcomes. Individual sections reflect one or some research objectives.

Part 1 (Research fundamentals) combines previous relevant studies to the topic of the present research. This part consists of three chapters corresponding to the first and second objectives.

- Chapter 2 summarises theoretical knowledge of thermal comfort and variables influencing comfort conditions in occupied environments. In addition, experiences in previous comfort research in residential buildings in hot-humid climates. The chapter also discusses the sufficiency of existing international and national standards of the acceptable environment in buildings. Finally, the chapter reviews the effects of air movement on thermal comfort. All sub-sections of the literature are linked to the built environment of residential buildings (research and practice) in Vietnam. Those analyses are fundamentals to find out gaps for the project.

- Chapter 3 reviews the role of urban and building design in providing comfortable environments inside and outside the building. The theory of adaptive comfort concludes the correlation between indoor and outdoor climate. Consequently, in this chapter, planning characteristics of a settlement, for example, density, spacing, building pattern, and green spaces will be discussed because of their effect on the outdoor microclimate. Besides, on the building scale, the passive cooling strategies, particularly the use of various opening features and their influence on indoor thermal and airflow conditions will be reviewed.

- Chapter 4 provides key design features in the architecture and planning of 'shop-house' dwellings in Vietnam, particularly in HCMC. Those characteristics are shown by the timeline. An important section of this chapter concentrates on the outcomes of 'shop-house' building types and urban spatial patterns found by a research group from the University of Cottbus in HCMC. Those findings may relate to assessments of the comfortable environment in and around buildings. Through all contents presented in this chapter, the uniqueness of 'shop-house' dwelling typology in the architecture and planning of Vietnam is explained while possible restraints to getting comfort in 'shop-houses' can be understood.

Part 2 (Research measurements) includes three chapters that explain the details of the field studies in HCMC, along with their results and discussions. This part covers the third and fourth research objectives.

- Chapter 5 presents the understanding and employment of methodological theories in the current study. Three main constituents of research methodology, including philosophy, strategies, and techniques, are described. The primary research methods are questionnaire interviews, cross-sectional and longitudinal measurements of climates in samples selected by different building types and urban morphologies of 'shop-house' over HCMC. The on-site surveys aim to assess occupant thermal perceptions and environmental conditions controlling the comfort in naturally ventilated 'shop-houses'. The basic techniques of field research are designed. Three field studies were carried out with a pilot study and two official ones during summertime and springtime within 2016-2018 in HCMC.

- Chapter 6 discusses thermal conditions inside and outside 'shop-house' buildings based on measurements in the field. Those analyses are considered in the relationship with the urban morphologies of 'shop-house' found in Chapter 4. Furthermore, occupant thermal sensations, preferences, and acceptability in naturally ventilated 'shop-house' dwellings in HCMC are analysed in the wet and dry seasons. Then, taking together all current data discovers the range of thermal conditions which occupants find comfortable. That is determined to be one of the crucial outcomes of the thesis. The major analytical method used is statistics.

- Chapter 7 analyses air movement sensations, preferences, and acceptability of occupants in naturally conditioned 'shop-house' buildings. Those analyses find the interactive effect of thermal and airflow conditions on overall human comfort in the buildings. Then, the limits of air movement acceptability are discovered with respect to acceptable temperatures found in Chapter 6.

Part 3 (Research analyses) emphasises the building design, in particular, openings. The complex correlation among openings, interior environmental performances, and occupant comfort satisfaction is understood. At the finale of the project, a demonstration of design guidance for openings will be proposed. The last three research tasks are carried out.

- Chapter 8 represents the environmental investigation in 'shop-house' buildings in HCMC by cross-sectional and longitudinal measurements. Environmental conditions in 22 houses were examined in hot summer and cool spring. Furthermore, the physical environment in 3 of 22 houses was monitored over 11 months. All cases studied are categorised into different 'shop-house' building types and urban structures. The influence of building design and opening configurations on the indoor thermal environment for occupant comfort will be discovered.

- Chapter 9 is the final one that presents basic steps to propose the sample version of design guidelines for openings, which gather significant information to build effective guidance, such as the assessment framework for comfortable environments, the identification of design options covering opening variables, and the influence of building and urban factors. Parametric analyses were used to study the design cases. A demonstration of the design guide will be produced after tested the validity with professionals.

PART 1
RESEARCH FUNDAMENTALS

Chapter 2 LITERATURE REVIEW

Chapter 2 consists of five subsections that collect relevant knowledge and experience in comfort studies to the topic of the current work. The author shows an understanding of research and practice on human thermal conditions in built environments, then deduces potential gaps between the project and previous work as the reason for this project's generation. Every section is structured with two parts: the literature review and discussions.

The first section collects principal theories of human thermal comfort with two approaches – the heat balance model and adaptive comfort model. The question arises: which model is appropriate to apply in the built environment - free-running residential buildings in Vietnam's hot humid climate? The second section concentrates on previous work on overall thermal sensations and comfort of humans in residential buildings in the tropics. Experiences of research methods are learnt, with the insights of such studies' findings showing potential similarities or differences in applications in Vietnam's context. The third section continues to expand available studies on human comfort in Vietnam in order to assess achievements, gaps, and opportunities in research and practice. Section four evaluates the sufficiency of existing international and national standards of human thermal conditions being used in the built environment in Vietnam. Section five reviews the effects of air movement on thermal comfort and what air velocities are either desirable or undesirable for occupants in naturally ventilated spaces in the tropics.

2.1 Human thermal comfort and two approaches

Thermal comfort is defined as "*the condition of mind which expresses satisfaction with the thermal environment"* (ASHRAE, 2004; ISO, 2005). That definition raises some questions about how the mind perceives environmental signals and what the conditions of thermal satisfaction are (Djongyang, Tchinda, & Njomo, 2010). Thermal satisfaction is such a complex subjective interplay with the thermal environment considering the influences of physical variables and other personal and contributing factors (Szokolay S. V., 2008; Ogbonna & Harris, 2008; Nicol, 2011). Firstly, the human body itself is an intelligent adjustable mechanism when perceiving the changes of the surrounding environment through the sensory receptor cells of the skin surface. Then, tangibles are delivered and processed at the brain (Szokolay S. V., 2008). The body's reaction will dissipate heat to the environment for restoring the normal core-body temperature about 37°C (Fanger P. O., 1970; Szokolay S. V., 2008). The dominant effect comes from air temperature while air movement is a factor to accelerate heat convection and evaporative heat losses on the skin (Szokolay S. V., 2008). The body can normally accept a fairly narrow range of temperatures with minimal physiological efforts and only a narrow band is comprehended as an acceptable thermal range (Szokolay S. V., 2008; Djongyang, Tchinda, & Njomo, 2010).

Thermal satisfaction or acceptability of the human is derived as thermal sensations that range from 'slightly warm', 'neutral', and to 'slightly cool'. Different people are different thermal sensations, even though they are occupying in spaces with a similar climate and thermal environment (Kuchen & Fisch, 2009; Djongyang, Tchinda, & Njomo, 2010). Or, the occupants, who are grouped with alike ethnicity, are exposed to varying climates in two nations; consequently, their thermal acceptability varies (Humphreys, 1994). Under different conditions of building type, cooling type, climate type, culture, geographic location, and ethnic background, single persons build their expectation and preference of thermal environment (de Dear, Brager, & Cooper, 1997; Nicol, 2011; Forgiarini, Vasquez, & Lamberts, 2015). Accumulative thermal experiences in a particular context can affect thermal sensations, expectation, and satisfaction of people. Thus, beyond the physical and physiological aspects, the contextual and psychological features act a remarkable role to govern the occupant comfort (de Dear & Brager, 2002).

In the range of acceptable temperatures, the mean value perceived by occupants reflects a sensation of neither cool nor warm of the indoor thermal environment; this is usually referred to as comfort or neutral temperature. Two approaches commonly coexist to assume comfort temperatures of indoor climate as follows: the heat balance model using the database from laboratories and the adaptive model derived from large field studies on occupants' thermal perceptions in real buildings.

2.1.1 Heat balance approach

The heat balance approach is embodied in the predicted mean vote (PMV) model that was developed by Fanger at the Laboratory of Heating and Air Conditioning of the Technical University of Denmark and Kansas State University from the 1960s onwards (Fabbri, 2015). The comfort model by Fanger predicts conditions for human thermal neutrality and it relies on extensive experiments in laboratories and climate chambers in temperate climatic regions (Hoof, 2008). The heat balance model is a theoretical combination of the energy balance and the physiology of heat regulation to define desired temperatures for building occupants (Djongyang, Tchinda, & Njomo, 2010). In a given environment, the human body produces heat and exchanges heat with the environment; the body thermoregulatory system operates processes as sweating or shivering to remain a stable state between heat loss by diffusion and evaporation from body and heat production by metabolism (Hoof, 2008). The balance of thermal exchange preliminarily achieves a neutral thermal sensation (Charles, 2003). In 1967, Fanger studied influences on the body's physiological processes (related to mean skin temperature and sweat rate) and on heat balance when the body almost senses neutrality. This occurred in the laboratory with 183 students and their physiological reactions were a result of different activities. Then, he published a basic comfort equation derived from the body' thermal balance formula that is based on two linear correlations of activity level and two respective variables: sweat rate and mean skin temperature (Fanger P. O., 1967).

To facilitate use in practice, Fanger expanded that equation from using the data of thousand students who took part in experiments in a climate chamber (2.8x5.6m), where indoor environmental variables were controlled well. The expanded equation is eventually derived as the PMV model (Eq1) (Fanger P. O., 1970) incorporating six exclusive factors: four physical factors (temperature, radiant temperature, air velocity, and humidity), and two personal factors (clothing insulation and activity) (Djongyang, Tchinda, & Njomo, 2010; Fabbri, 2015).

$$PMV = \left(0.352 * e^{-0.042\left(\frac{M}{A}\right)} + 0.032\right) * \left[\frac{M}{A} * (1-n) - 0.35 * \left[43 - 0.061 * \frac{M}{A} * (1-n) - \rho_a\right] - 0.42 * \left[\frac{M}{A} * (1-n) - 50\right] - 0.023 * \frac{M}{A} * (44 - \rho_a) - 0.0014 * \frac{M}{A} * (34 - T_a) - 3.4 * 10^{-8} * f_{cl} * [(f_{cl} + 273)^4 - (T_{mrt} + 273)^4] - f_{cl} * h_c * (T_{cl} - T_a)\right] \quad \text{(Eq1)}$$

where T_a = air temperature (°C)

T_{mrt} = mean radiant temperature (°C)

T_{cl} = surface temperature of clothing (°C)

f_{cl} = clothing area factor

M = metabolic rate (met)

A = surface area of human body (m^2)

P_a = water vapour pressure (mmHg)

n = mechanic efficiency

h_c = heat transfer coefficient counting for air velocity (kcal/m^2h°C)

In the PMV-based formula, thermal comfort is described as "*the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for comfort for a given activity"* (Fanger P. O., 1970; Djongyang, Tchinda, & Njomo, 2010). Three conditions of thermal comfort identified by Fanger in steady-state environments include the heat balance of body, mean skin temperature and sweat rate in certain limits, and no local discomfort (draughts, vertical temperature difference, or radiant asymmetry) (Fanger P. O., 1970).

The final result of that model is a comfort index as known as the PMV index that is a numerical value represents the mean response of a large population to the indoor thermal environment related to ASHRAE 7-point scale: hot (3), warm (2), slightly warm (1), neutral (0), slightly cool (-1), cool (-2), and cold (-3) (Nicol, 2004). Within the range of three scales ('slightly warm', 'neutral', and 'slightly cool'), the human body satisfies the indoor climate. Meanwhile, some subjects are dissatisfied with their given environment and their thermal sensation is shown in one of four outer scales (Hoof, 2008). The PMV index was then integrated with another index - Predicted Percentage of Dissatisfied (PPD) that is used to assume the percentage of people who have the cognition of thermal dissatisfaction.

$$PPD = 100 - 95 * \exp(-0.03353 * PMV^4 - 0.219 * PMV^2) \quad \text{(Eq2)}$$

The PMV-PPD principle by Fanger is widely accepted to predict occupant comfort sensations in buildings by quantifying the impacts of all the above major variables regardless of geographical location, cooling/heating systems, activities, and clothing habits. Thus, that model has been used in the existing international standards to describe indoor comfortable thermal conditions since the 1980s (Fanger & Toftum, 2002). Many studies have shown that the PMV-PPD-based predictions of occupant thermal perceptions are accurate in near-sedentary activity and static environments, for example, in mechanically heated or cooled office buildings (Tanabe & Kimura, 1987; Doherty & Arens, 1988; de Dear, Leow, & Ameen, 1991; de Dear, Brager, & Cooper, 1997; de Dear R. , 2004; Yang, Yan, & Lam, 2014). By way of explaining this judgement, the heat balance approach was fundamentally studied in climate chambers, which means that the exchange between participants and the surroundings is ignored (Fabbri, 2015). Additionally, changing clothing and activity levels was unallowable in experiments; nevertheless, such changes often occur in practice (Rupp, Vasquez, & Lamberts, 2015). Thereby, the heat balance approach raises errors when used in the contexts where people regularly interact with the environment, for example, in NV buildings where occupants are dynamic recipients with the surrounding conditions (de Dear & Brager, 2002; Yang, Yan, & Lam, 2014). Another comfort approach is needed.

2.1.2 Adaptive comfort approach

The approach of the adaptive comfort model was preliminarily suggested by Humphreys (Humphreys, 1976). This ongoing principle has advanced for over three decades from numerous field surveys in wide-ranging climates and with the support of meta-analyses, for example, Humphreys's work in 1976 and 1978 (Humphreys, 1976; 1978), Auliciems and de Dear in the late 1980s (Auliciems & de Dear, 1986; Auliciems, 1989), the field studies of Nicol and Roaf in the hot climate of Pakistan (Nicol & Roaf, 1996), and de Dear and Brager in the middle of the 1990s (de Dear, Brager, & Cooper, 1997). The sensation of comfort in accordance with this approach not only is controlled by physiological processes to remain the body temperature but is a result of thermoregulatory behaviours (Nicol, 2011). Consequently, the adaptive model for thermal comfort is *"If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort"* (Nicol, Humphreys, & Roaf, 2012). Some primary points of this model should be noticed in the following:

Analysing worldwide comfort surveys, Humphreys found linkages between room temperature and subjective thermal responses to the environmental condition in such rooms, and between mean indoor and outdoor air temperature (Humphreys, 1976). For buildings which are neither heated nor cooled, the adaptive model ultimately indicates that the thermal neutrality of inhabitants is assumed in close relation to outdoor seasonal temperatures (Eq3) (Humphreys, 1978).

$$T_{comf} = A * T_{out} + B \quad \text{(Eq3)}$$

where T_{comf} = comfort temperature (°C)

T_{out} = monthly mean outdoor air temperature (°C)

A, B = constants

Considering the above algorithm, internal comfort temperatures are defined by only one variable; that is the outdoor temperature. This means that the other factors mentioned in the PMV model (air velocity, relative humidity, mean radiant temperature, garment insulation, and activity level) are ignored in the calculation; claimed to be because these parameters partially incorporate into the effect of the outdoor temperature (Halawa & Hoof, 2012). This is determined to be an obvious imperfection of the adaptive comfort model (Fanger & Toftum, 2002). However, referring to the adaptive model, comfort temperatures are predicted by thermal sensation votes against a spontaneous thermal environment to which occupants are exposed (Nicol & Humphreys, 2002). Based on the database of comfort field studies, subjects express their thermal perceptions in conditions where they can vary: daily clothes, activities, and postures; therefore, occupant comfort sensations are already a function of these features (Humphreys, 1979; Djongyang, Tchinda, & Njomo, 2010). To support this report, efforts in research found the relationship between clothing insulation values and differences in the outdoor climate (Nicol, Raja, Allaudin, & Jamy, 1999; Karyono, 2000; Morgan & de Dear, 2003). Moreover, the posture and metabolic rate of a given activity are also changeable with varying temperatures (Baker & Standeven, 1995; Raja & Nicol, 1997). To incorporate the other environmental parameters into the external temperature, attempts have been made to validate this correlation (Halawa & Hoof, 2012). The influence of these variables on thermal responses of people has been clarified, particularly in the hot-humid tropics (Tanabe & Kimura, 1994; Nicol, 2004; Djamila, Chu, & Kumaresan, 2007; Nicol, Humphreys, & Roaf, 2012). Meanwhile, humidity is concluded as a coupled aspect of temperature for thermal subjective responses (Nicol, 2004; Djamila, Chu, & Kumaresan, 2014), air velocity and mean radiant temperature cannot easily be shown as a function of outdoor temperature (Halawa & Hoof, 2012).

Nicol (2011) reported that the adaptive model similarly operates in buildings that are cooled by any mechanisms; however, the different ventilation types shape the indoor environment and opportunities for users' adaptation differently. For example, in HVAC buildings, inhabitants' comfort temperatures indoors will separate from dependence upon outdoor temperatures. In contrast, in NV buildings, the two are coupled (Nicol, 2011). When plotting all data of neutral temperatures and monthly mean outdoor temperatures from a wide range of surveys in NV and AC buildings on the same analysis, a strong linear regression was observed between the two variables in free-running buildings whilst a complex relationship is in others (Figure 2.1) (Humphreys, 1978). Thereby, the model of adaptive comfort is beneficial to predict the neutral temperature in NV buildings (Djamila, Chu, & Kumaresan, 2012).

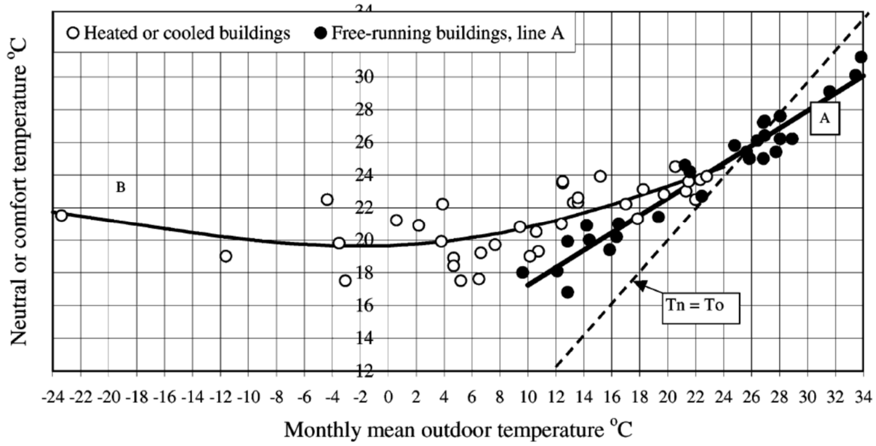


Figure 2.1 Neutral temperatures against monthly mean outdoor temperatures (Humphreys, 1978)

Apart from the outdoor temperature, the assumption of comfort temperatures also associates with thermal expectations and preferences, which are the notable factors in the adaptive model (Brager & de Dear, 2001; Nicol & Humphreys, 2002). De Dear and Brager summarised the divergence of occupant thermal expectations in close and open buildings (de Dear, Brager, & Cooper, 1997). Expectation and preference derived from an accumulation of tolerance and interactions with a specific environmental condition over a long period modify thermal sensations and acceptability of people; therefore, their responses to building services also change (Nicol & Humphreys, 2002; de Dear & Brager, 2002). To interpret those, the contextual term and thermal accumulative experiences are determined to have significant effects (de Dear & Brager, 2002; Becker & Paciuk, 2009). The context is defined into three angles: climate, building, and time (Nicol & Humphreys, 2002). The results of comfort surveys also show that the comfort temperature might not be the same as the preferred temperature of building occupants (de Dear & Brager, 2002; Humphreys & Hancock, 2007). That conclusion was found in field studies in public housings in Singapore (de Dear, Leow, & Foo, 1991) and residences in Indonesia (Feriadi & Wong, 2004).

The temperature required for comfort is individual due to the variations of unique characteristics (physics, physiology, and psychology) influencing the thermal perception among subjects in a thermal environment experienced (de Dear & Brager, 2002; Nicol, 2011). As a consequence, under a particular context, the degree of discomfort drives inhabitants' adaptive behaviours to environmental conditions for seeking their comfort and their adaptation varies under different contexts (de Dear, Brager, & Cooper, 1997). In free-running buildings, occupants have a variety of adaptive actions, such as drinking cool water, taking a bath, changing garments, altering activity, moving to cooler places nearby cooling supply, opening windows/doors, or turning on air-conditioners and fans (Djongyang, Tchinda, & Njomo, 2010). The actions are devised into three mechanisms: behavioural adaptation, physiological adaptation, and psychological adaptation (Brager & de Dear, 1998; Zhang, Wang, Chen, Meng, & Zhao, 2010).

The contribution of adaptive approach has been significant in practical design over the last 30 years by estimating temperatures in buildings which occupants will find comfortable for themselves, particularly in NV buildings (Nicol & Humphreys, 2002). Consequently, the adaptive model has been recognised in the thermal comfort standards of ASHRAE 55 or CEN15251 since 2004 (ASHRAE, 2004; Olesen & Brager, 2004; CEN, 2007). The adaptive equation is applied to define neutral temperatures corresponding to the running mean outdoor temperatures (maximum, minimum, and mean values). By considering these distributions, designers can evaluate the appropriate applications of passive design strategies in terms of heating and cooling in a particular climate. Hence, buildings are maintained in comfort, along with a reduction of energy use (Nicol, Humphreys, & Roaf, 2012).

2.1.3 Discussion

In practical applications of the two current models, many field studies have shown that the PMV-PPD model works well in buildings in which their thermal environment exist regardless of surrounding conditions (Nicol, 2004), but fail in explaining occupant thermal sensations in buildings with variability in the indoor thermal climate and interactions between the building and its users (de Dear & Brager, 2002; Nicol, 2011). Using the adaptive model is, therefore, more proper in NV buildings, especially in hot to warm climates (de Dear & Brager, 2002; Fanger & Toftum, 2002; Becker & Paciuk, 2009). Fanger and Toftum also agreed and suggested the extension of the available heat balance principle is necessary for applications in such those environments (Fanger & Toftum, 2002). The errors in PMV are attributed to two reasons including a restrictive environmental boundary of that model in applications and neglect of psychological factors influencing occupant thermal perceptions in open buildings (Fanger & Toftum, 2002; Nicol, 2004; Djamila, Chu, & Kumaresan, 2012).

Table 2.1 Range of indoor conditions when applying the PMV model (ISO, 2005)

Variable	Symbol	Units	Lower limit	Upper limit
Air temperature	Ta	°C	10	30
Radiant temperature	Tr	°C	10	40
Water vapour pressure	p_a	Pa	0	2700
Air movement	Va	m/s	0	1
Clothing insulation	I_{cl}	m².k/W (clo)	0 (0)	0.31 (2)
Metabolic rate	M	Met (W/m²)	0.8 (46)	4 (232)
Predicted Mean Vote	PMV		-2	+2

Table 2.1 describes the conditions of thermal predictions based on the PMV model, such as the maximum indoor air temperature of 30°C, air velocities lower than 1m/s, and the band of thermal

sensation indices within -2 and +2. These limitations are not common in free-running buildings in the warm-humid tropics (Djamila, Chu, & Kumaresan, 2012). As a result, the comfort model by Fanger usually undervalues the actual thermal tolerance of people in hot or warm environments where subjects can find satisfaction at temperatures even more than 30°C (Mallick, 1996; Nicol, 2004; Indraganti, 2010a).

Additionally, determining an acceptable range of temperatures around the neutrality is significant in the built environment, even more than the achievement of the optimum temperature for comfort (Arens, Humphreys, Zhang, & de Dear, 2010; Nicol, Humphreys, & Roaf, 2012). A wider range of pleasant thermal climate results in not only a reduction in the percentage of people who are dissatisfied with the thermal environment but energy use is less because of lower cooling needs for air-conditioning systems (Nicol & Humphreys, 2002; Yang, Yan, & Lam, 2014). The band of comfortable temperatures assumed by the heat balance approach is narrower and lower than the predictions of the adaptive model in non-air-conditioned buildings in hot or warm climates (de Dear, Leow, & Foo, 1991; Busch J. , 1992; de Dear & Foutain, 1994; Feriadi & Wong, 2004; Nicol, 2004; Taweekun & Tantiwichien, 2013). Contrary to the qualification for use of the PMV model in the steady-state environmental conditions, for example, mechanically cooled buildings, in the real situations of open spaces, the discomfort will cause people to take actions to control the environmental and body conditions to suit their thermally acceptable statement (Auliciems, 1989; Brager & de Dear, 1998). It implies a wider acceptability of indoor environments (Nicol & Humphreys, 2002; Djamila, Chu, & Kumaresan, 2012).

Table 2.2 Adaption comfort models for neutral temperature predictions

No	Model	Authors
1	$T_c = 11.9 + 0.534T_{out}$	Humphreys
2	$T_c = 9.22 + 0.48T_a + 0.14T_{out}$	Auliciems (reanalysing Humphreys' data)
3	$T_c = 17.6 + 0.31T_{out}$	Auliciems and de Dear
4	$T_c = 17 + 0.38T_{out}$	Nicol and Roaf
5	$T_c = 17.8 + 0.31T_{out}$	ASHRAE Standard 55, Brager and de Dear
6	$T_c = 18.8 + 0.33T_{rm}$	EN15251

Table 2.2 summarises the existing adaptive comfort models that have been devised from using numerous worldwide field studies since the mid-70s (Humphreys, 1978; Auliciems & de Dear, 1986; Nicol & Roaf, 1996; Raja & Nicol, 1997; de Dear & Brager, 2002). Some of them have been validated in an international standard of environmental thermal conditions (ASHRAE, 2004; CEN, 2007). The first model was generalised by Humphreys (1978), and then, the raw data used in Humphreys' research were reanalysed by Auliciems (1986) to deduce the model (2); and another (3) was generated from 52 studies in both close and open buildings (Szokolay S. V., 1997). The regression (4) is derived from the studies of Nicol and Roaf in Pakistan. The equation (5) is a function of the extensive empirical studies conducted over four continents (de Dear, Brager, & Cooper, 1997).

Those models have revealed their benefits that help designers predict the range of comfortable environments in non-air-conditioned buildings; they have been applied for all building types and all climate zones. However, some discrepancies are observed in the real situations between residences and offices or between different climates. To strengthen this argument, firstly, the above six comfort equations are extracted from the database collected in office building studies where the pattern of clothing and activity of subjects is similar; additionally, sitting in the deeper places of room restrains people to access building controls (Djongyang, Tchinda, & Njomo, 2010). In contrast, residents in such dwellings experience the different levels of behavioural adjustments (de Dear, Brager, & Cooper, 1997). They have the freedom to change their clothes or wear seasonal outfits; and the degrees of personal adaptation and environmental adjustments are more diverse (Djamila, Chu, & Kumaresan, 2012). The desired temperature differed by 1.5°C between people having a higher control of operable windows and the group with a lower degree of control (Brager, de Dear, & Paliaga, 2004). Field studies on thermal comfort at Finland also showed a wider range of comfortable environments for occupants in homes compared to in offices, which afford less control and personal adaptive behaviours for the users (Karjalainen, 2009). Moreover, the observations of occupant thermal responses to indoor similar thermal conditions in two hot-dry and hot-humid climates also show a difference, especially people in the hot-humid tropics due to the influence of annual high moisture, the existing adaptive model, therefore, predicts with less accuracy (Nicol, 2004; Toe & Kubota, 2013).

In short, the above discussions clarify the possibility to use the adaptive model for thermal comfort analysis instead of the heat balance model in free-running buildings, particularly in hot to warm climates. On the other hand, its validity in residential buildings in the tropics is questionable, for example, 'shop-house' dwellings in HCMC (Djamila, Chu, & Kumaresan, 2012). That doubt is also highlighted by Fanger and Toftum and it needs to be researched with more field studies in the tropical areas (Fanger & Toftum, 2002). It will be worth considering a new adaptive comfort model or an extension of the current equations that will be applied widely in housings in warm-humid regions (Toe & Kubota, 2013).

2.2 Comfort studies in residential buildings in the warm-humid tropics

2.2.1 A global database of comfort measurements

A recent publication summarises an extensive comfort database that has been collected from worldwide comfort surveys covering a wide range of environments, building types, and climates for over two decades (Ličina, et al., 2018). A total of 81,846 completed raw data sets are classified into the continent, climate zone, and measuring season as shown in Figure 2.2. The chart shows that up to 12% and 3% of field studies were carried out in generally tropical regions and tropical monsoon nations, respectively. Most data were found in the places at higher latitude. In tropical regions, studies on comfort have concentrated in some countries of SE Asia, Brazil, Mexico, especially in India. The division of the database by building type shows that occupant thermal perceptions and thermal environments in office buildings have been predominantly investigated (about 68%) including both mechanically and naturally cooling mechanisms while the number of fieldwork studies in multifamily houses has been fewer - about 12%. Moreover, the measurements categorised by ventilation systems also show different proportions in the following of HVAC buildings (35%), free-running buildings (47%), hybrid buildings (14%), and mechanically ventilated buildings (2%).

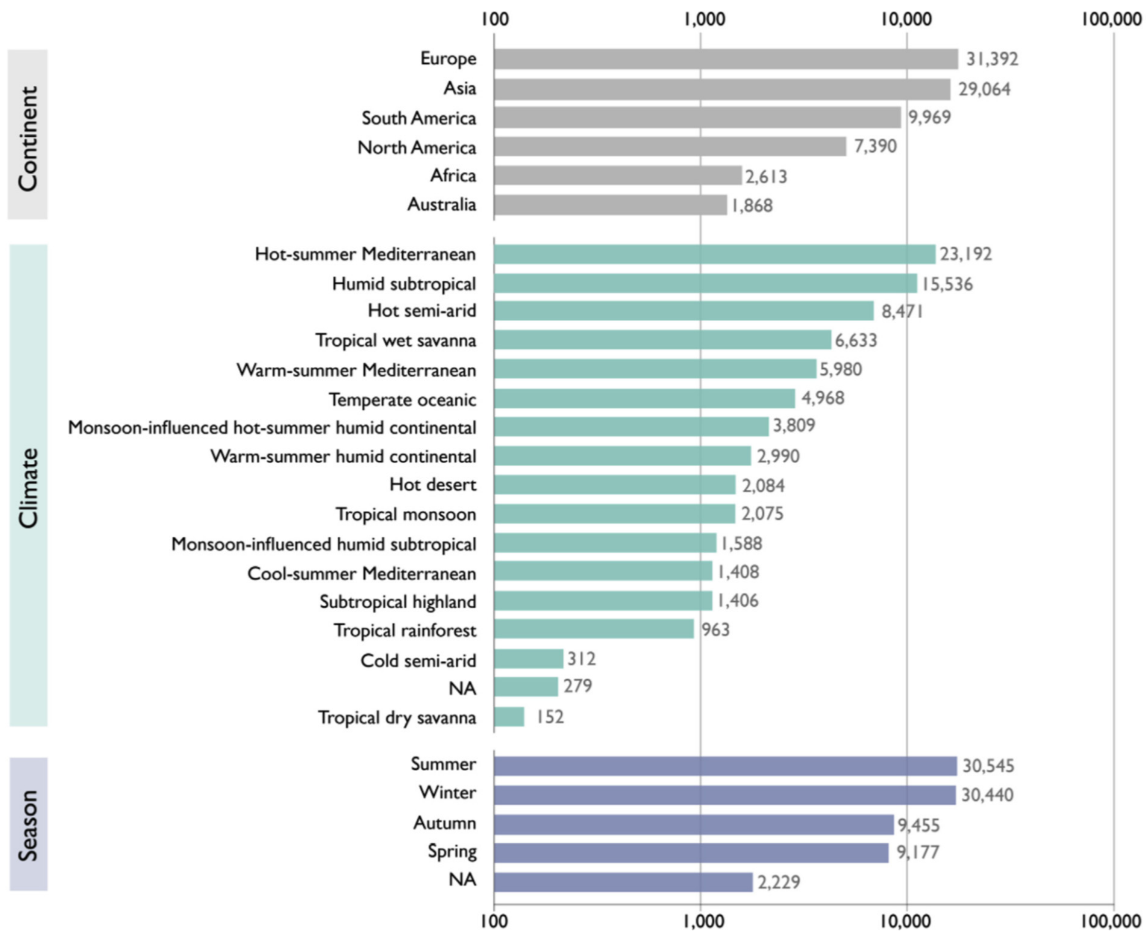


Figure 2.2 Distribution of field studies conducted over the continents and climates (Licina, et al., 2018)

2.2.2 Comfort in residential buildings in the tropics

Further analysis of the group of comfort research projects in the tropics shows studies in the field carried out since 1936 in some SE Asian nations, and others in the same climate zone. For example, the first observations started in Bandung, Indonesia by Mom and Weisenborn (Mom, Courtice, Kip, & Wiesebron, 1974); the research of Webb, Ellis, de Dear, and Wong in Singapore in the 1950s, 1990s, and 2000s (Webb, 1959; Ellis, 1953; de Dear & Foutain, 1994; Wong, et al., 2002); in Port Moresby in 1967 and 1979 (Ballantyne, Hill, & Spencer, 1977); the extensive measurements in southern India (Indraganti, 2010a; 2010b; Mishra & Ramgopal, 2014; 2015), in Bangkok, Thailand (Busch J. , 1992) (Rangsiraksa, 2006); in Malaysia (Djamila, Chu, & Kumaresan, 2013), in some cities of Indonesia (Karyono, 2000; Henry & Wong, 2004), in Brazil (Candido, deDear, Lamberts, & Bittencourt, 2010); and recent studies in Vietnam (Nguyen, et al., 2003; Nguyen A. T., 2013). The major findings of those projects are described more detailed in Table 2.3. At first glance, the comfort studies were conducted by both methods of experimental and experiential in various building types (small-scale house, high-rise apartment, office, and school), additionally in buildings that are cooled naturally and mechanically. Importantly, Table 2.3 contains the findings of neutral temperature and comfort range extracted from the database found in ASHRAE collection in 2018 and other published sources. Some conclusions are prompted by comparison among these outcomes.

Table 2.3 Neutral temperatures for buildings found in the tropics

Authors	Year	Method	Place	Country	Ethnic	No of subjects	Building types	Neutral temperature (°C)
Mom	1937	Climate chamber	Bandung	Indonesia	Indonesian, European	20	N/A	26
Webb	1950	Field study	Singapore	Singapore	Malaysian, European	16	House & Office	26.2 ET
Ellis	1952	Field study	Singapore Hong Kong	Singapore Hong Kong	N/A	5,211	Transport	30
	1953	Field study	Singapore	Singapore	Eurasian, Chinese, Indian,	118	Education	26.4
Ballantyne	1967	Field study	Port Moresby	Papua New Guinea	Caucasian	34	N/A	25.6 Ta
	1979	Climate chamber			Caucasian Melanesian	28 64	N/A	25.0 Ta 26.7 Ta
Busch	1988	Field study	Bangkok	Thailand	Thai	1,100	Office	28.5 ET (NV) 24.5 ET (AC)
de Dear	1990	Climate chamber	Singapore	Singapore	Singaporean	32	N/A	25.4
						98		27.6 (70%RH)
		Field study				583	Public housing	28.5 Top (NV)
						235		24.2 Top (AC)
Karyono	1993	Field study	Jakarta	Indonesia	Indonesian	596	Office	26.4 Top
Feriadi & Wong	2000 - 2001	Field study	Jakarta	Indonesia	Indonesian	525	House	29.2 Top
			Singapore	Singapore	Singaporean	257	Public housing	26.9 Top
Rangsiraksa	2002-2003	Field study	Bangkok	Thailand	Thai	1,300	House & Office	28 (NV) 25 (AC)
Hang Nguyen	2003	Climate chamber	Hanoi	Vietnam	Vietnamese	40	N/A	24-29 Ta
Djamila	2007	Field study	Kota Kinanalu	Malaysia	Malaysian	949	House	30 Top
Indraganti	2008	Field study	Hyderabad	India	Indian	100	Apartment	29.2 Tg (26-32.5 Tg)
Candido	2010	Field study	Maceio	Brazil	Brazilian	2,075	Education	26-31 Top
Nguyen	2012	Field study	Danang	Vietnam	Vietnamese	1,200	Education	28.9 Ta
Indraganti & Ooka	2012	Field study	Chennai Hyderabad	India	Indian	1,658	Office	27.6 Tg (NV) & 27 Tg (AC) 28.1 Tg (NV) & 26.1 Tg (AC)
Mishra & Ramgopal	2014	Climate chamber	Kharagpur	India	Indian	121	Education	26.5 Top (22-32 Top)

Firstly, there is a remarkable discrepancy of the desired temperature in the range of 2-4°C between people in NV and AC buildings. Occupants of HVAC buildings are exposed to the homogenous condition of the thermal environment, they also prefer cooler temperatures, and their feedback to deviations of surroundings is not high. In contrast, in buildings without air-conditioners, thermal dissatisfaction is perceived and seems to match the thermal environment. The comfortable temperature found is a significant fundamental to set the temperature threshold for the operation of HVAC systems. People in open buildings can accept a warmer condition of the environment due to a correlation of both indoor and outdoor conditions; therefore, energy consumption for cooling is less, in particular, in summer months.

Secondly, evaluating a comfortable thermal environment in various building typologies also shows the variations of human thermal sensations. In detail, the mean neutrality of occupants in working environments is observed at 27.3°C, which is certainly similar to that in educational buildings but cooler than the average comfortable temperature in urban houses (29°C) and public housings (28.2°C). Building types imply the difference in many characteristics such as building form, construction technology, building fabric, solutions of passive design, and cooling systems (Nicol & Humphreys, 2002). Consequently, the particular kinds of buildings offer for habitats a distinct indoor thermal environment and possibilities to feedback mechanisms (de Dear, Brager, & Cooper, 1997). The specific use of every building also asks for variable manners in clothing and activity (Busch J. , 1992; Karyono, 2000). Non-air-conditioned housings in the tropics provide the wider availability of environmental controls through building means and local cooling (doors, windows, blinds, or fans), or personal behaviours (bathing, changing clothes, or altering seats) compare to the conditional boundary in offices and schools. This results in an allowance of warmer comfortable temperatures by residents.

Thirdly, although whole outcomes have been found in the same zone of the tropical climate, occupant thermal comfort differs among geographic locations at macro-scale (SE Asia, South Asia, and South America) even at micro-scale of the nations in SE Asia. This report can help explain the effect of ethnicity, culture, and traditional customs on human thermal perceptions and expectations. Malaysians find their comfort at 30°C that is the highest value in tropical regions, on the other hand, the neutral temperature for Singaporeans and Indians is the lowest around 27.5°C.

Fourthly, there is a significant difference in subjective thermal sensations between recent research and others over the past 30 years. The values of neutral temperature are generally predicted by subjective responses to the simultaneous thermal conditions that respondents experience. Both outdoor and indoor thermal environments are likely changeable with more vulnerabilities owing to the pressures of climate change and man-made modifications over a long-term period. Thus, a time frame for a specific context of climate, building, and people is significant in defining a particular comfort condition, which means that comfort temperature is changed continually (Nicol & Humphreys, 2002).

Finally, another issue worthy of attention is that the difference between empirical and climate chamber studies also leads to the variable values of neutral temperature found in the tropics. This can affect which limits are set for indoor environment in test chambers compared to the real circumstances of field studies. In addition, occupant adaptation may be narrower in the given thermal environment in experimental studies (de Dear & Brager, 2002; Djongyang, Tchinda, & Njomo, 2010).

2.2.3 Discussion

Referring to the ASHRAE comfort database, the number of studies in tropical climates generally and in monsoon tropical regions particularly, and in residential buildings are modest. This partly explains less precision in the current recognisable comfort models that are derived from most data in office buildings, to predict the thermal sensations of dwellers in free-running houses in the tropics. Moreover, despite exposure to a similar climatic condition, the findings of field studies in warm-humid climates clarify differences in neutral temperature among building typologies and cooling mechanisms. Also, focusing on the fieldwork in tropical residences, occupant thermal perceptions differ among geographical locations and ethnic backgrounds. These judgements robustly support one of the theories of the adaptive principle, which is the effects of contextual terms and past thermal history on human thermal sensations (de Dear & Brager, 2002).

Some comfort studies found in SE Asia show inadequacy in research and practice against the real need of the built environment, especially in residential buildings. Three reasons, including being the largest proportion of that building type in real estate; high sensitivity of thermal comfort due to the increasing impacts of climate; and less accurate predictions of the existing adaptive models, motivate more research on comfort in housings in SE Asia. The studies can be considered for expansion in various dwelling subdivisions, for example, 'shop-house', detached house, and flat/apartment, which are three common dwelling typologies in SE Asian nations. This research plan may be worthwhile because 'shop-house' dwellings are a repetitive and unique residential typology in many countries in SE Asia including Vietnam. Besides, of the three housing types, most available comfort studies have been undertaken in villas and high-rise apartments while comfortable conditions in 'shop-houses' are awkward to achieve because of tricky building form and planning.

Linked to the context of Vietnam, the Vietnamese 'shop-house' buildings have distinctive characteristics in architecture and planning; and the Vietnamese householders own identities of culture, tradition, and anthropometry. Consequently, the identification of thermal comfort and adaptation of residents in 'shop-house' dwellings in Vietnam is an interesting research question and further field studies need to be carried out. In addition, they are significant in qualifying the validity of existing comfort outcomes found in residential buildings in other countries in the region.

2.3 Comfort studies in Vietnam

2.3.1 Review of current studies

Comfort studies have been carried out since the 1960s in Vietnam. However, it is certain that the number is modest in comparison with other neighbour nations in SE Asia (Table 2.4). Initial work merely modified the available findings from worldwide comfort surveys to assume thermally comfortable indoor environments in the Vietnam context (Pham N. D., 2002).

Pham Duc Nguyen as a pioneer developed his first fieldwork in 2002. He investigated the thermal sensations of 12 subjects including 6 males and 6 females, who were living in a student accommodation hall in Vinh (Pham N. D., 2002). Vinh, which is a coastal city in northern Vietnam, experiences the average annual temperatures between 34°C and 15.5°C (IBST, 2009). The age level of all participants ranged within 19-27. The climate in students' sleeping rooms was controlled naturally. A total of 12 students wore summer clothes (0.5clo) and performed a light activity (1met) during testing. The surveys of thermal comfort lasted over 3 days with the intervals of 2 hours. After each shift, the students responded to their thermal sensations to the room environment with the ASHRAE 7-point scale. Simultaneously, changes in environmental parameters in the rooms (temperature, surface temperatures, humidity, and air velocity) were measured and monitored. The results showed that 80% of respondents accepted conditions of 28.5-29.2°C with 90% RH or 30.5°C with 80% RH. However, the value of neutral temperature was not defined. In other words, the thermal acceptability of students at those air temperatures explained an extension of comfort band for the Vietnamese at a warmer zone and that the upper limit of comfort can be expanded more in summer. Pham supposed that his work's outputs are initial observations about the occupant thermal perceptions in NV buildings in Vietnam and they are not valid enough to apply to the larger population because of less adequate research techniques and small sample size.

Table 2.4 Available thermal comfort studies in Vietnam

Authors	City	Year	Season	Building types	Cooling	Method	No of subjects	Neutral temperature (°C)	Comfort zone (°C)
Tuan Nguyen	Danang	2012	Warm	School	Natural	Field study	1,200	27.9 (Top), 27.1 (ET)	N/A
Hang Nguyen	Hanoi	2003	Cold	School	N/A	Experiment	40	N/A	24-29 Ta
Nguyen Pham	Vinh	2002	Warm	Student hall	Natural	Field study	12	N/A	Upper limit 28.5-29.2 Ta (RH90%) 30.5 Ta (RH80%)

In 2003, a group of researchers in Hanoi conducted comfort experiments with 40 students in a climate chamber during winter (Nguyen, et al., 2003). Their research aimed to find a range of comfortable temperatures for the Vietnamese. Hanoi, which is a large city in the northern part of Vietnam, is characterised by a cold winter. The mean annual temperature is 23°C; however, the temperature can drop at 3°C in cold months (IBST, 2009). Participants included 21 males and 19 females. Their anthropometric indices such as age, weight, height, and body mass were collected before the experiments. The students' clothing pattern was short-sleeved T-shirts and light cotton pants, and they sat on a chair to read books when taking part in the surveys. The environmental condition in the climate chamber was originally set at 22°C and 40% RH. Throughout testing, the subjects voted for their thermal experiences to the environment where they were occupying by the ASHRAE scale. The responses were repeated after every 20 minutes corresponding to a rise of room temperature by 1°C until the subjects felt uncomfortable (Table 2.5). All votes combined in Table 2.5 show that more than 90% of respondents accepted a thermal environment within 24-29°C described at three sensations: slightly cool, neutral, and slightly warm. The research group concluded that the acceptable temperature range found through their studies is higher than the band (20-24°C) recommended by ISO-7730 (ISO, 2005).

Table 2.5 The number of responses according to changes in room air temperature (Nguyen, et al., 2003)

Room temperature (°C)	Number of participants who felt comfort						Total (N=40)	%
	Male (n=21)			Female (n=19)				
	Slightly cool	Neutral	Slightly warm	Slightly cool	Neutral	Slightly warm		
22	10	1	1	3	2	0	17	42.5
23	8	5	0	4	7	2	26	65
24	7	7	5	7	11	1	38	95
25	4	11	5	3	10	6	39	97.5
26	4	7	10	1	6	12	40	100
27	2	4	15	1	3	15	40	100
28	2	2	16	1	5	13	39	97.5
29	1	1	17	0	2	15	36	90
30	1	0	5	1	0	3	10	25

Nguyen Anh Tuan carried out further research between 2010-2013. His project mainly proposed optimal design packages to achieve sustainable housing in Vietnam (Nguyen A. T., 2013). One of the valuable research findings is the publication of an adaptive comfort model for hot-humid SE Asia that is derived from the meta-analysis of raw data collected by previous researchers in the tropics (Eq4) (Nguyen, Singh, & Reiter, 2012).

$$T_{comf} = 0.341xT_{out} + 18.83 \quad \text{(Eq4)}$$

where T_{comf} = comfort temperature (°C)

T_{out} = monthly mean outdoor air temperature (°C)

Table 2.6 depicts the principal details of field studies used for analysing. A total of 5,176 data sets were used, among them, 3,430 and 1,746 samples were found in naturally ventilated and air-conditioned buildings, respectively. In comparison with the existing models in Table 2.2, his model suggests a slightly higher comfortable temperature due to the higher coefficient of regression gradient. The results of the analysis also showed that the comfort temperature in HVAC buildings is not associated with outdoor temperatures. Furthermore, occupants in free-running buildings can tolerate a warmer condition of 2°C than in mechanically cooled buildings.

Table 2.6 Surveys used in meta-analysis of the comfort model in SE Asia (adapted from Nguyen, 2013)

Authors	Year	Building type	Place	Country	No of subjects	Building types	Type of survey
de Dear	1987	NV	Singapore	Wet equatorial	583	Public housing	Cross-sectional
Busch	1990	NV	Bangkok	Tropical savana	391	Office	Cross-sectional
Karyono	1995	NV	Jakarta	Wet equatorial	97	Office	Cross-sectional
Wong	2001	NV	Singapore	Wet equatorial	538	House	Cross-sectional
Feriadi	2002	NV	Jakarta	Wet equatorial	525	Public housing	Hybrid
Hussein	2009	NV	Joha Bahru	Wet equatorial	375	N/A	Cross-sectional
Zhang	2009-2010	NV	Guangzhou	Tropical savana	921	School	Longitudinal
de Dear	1986	AC	Singapore	Wet equatorial	235	Public housing	Cross-sectional
Busch	1990	AC	Bangkok	Tropical savana	776	Office	Cross-sectional
Karyono	1995	AC	Jakarta	Wet equatorial	458	Office	Cross-sectional
Andamon	2002	AC	Manila	Wet equatorial	277	Office	Longitudinal

In addition, to examine that comfort model's validity in Vietnam, Nguyen applied quantitative studies on thermal sensations of 1,200 students who were studying in the universities in Danang in summer 2012 (Nguyen A. T., 2013). Danang is a beautiful beach city in the middle of Vietnam. The average outdoor temperature was 30°C across three summer months of April, May, and June. Surveys were carried out twice a month. All students were asked for personal information such as age, gender, weight, and their sitting position in their classroom. Meanwhile, they responded to the questionnaire of their actual thermal sensations, the physical variables of the immediate environment were measured. Using the linear regression, neutral temperature over summer was 27.8°C. In addition, this value observed on-site positively changed according to surrounding climate: 27.9°C in April, 29.6°C in May, and 29.3°C in June corresponding to an outdoor temperature of 28.7°C, 30.2°C, and 30.7°C. Collate to the comfort temperatures predicted by Equation 4, the difference is slight. In comparison with the comfortable condition from the whole studies in SE Asia (27.9°C), it reveals that people in SE Asia including the Vietnamese likely share the same thermal perceptions (Nguyen, Singh, & Reiter, 2012).

2.3.2 Discussion

Comfort studies found in Vietnam indicate a paucity of findings contribute to practice and research in Vietnam. In the three above comfort studies, the latest work of Nguyen (2013) may be the most significant in applying in research and practice in Vietnam owing to a suitable research method and sample size used for his study. However, the application of this model in the reality of hot-humid tropics in SE Asia should be revised (Toe & Kubota, 2013). The first doubt relates to the sampling method for the meta-analysis. Nguyen et al. (2012) addressed that the comfort model like (Eq 4) is a function of the database from the surveys in NV buildings in humid tropical regions (Table 2.6); nevertheless, some measurements were taken in mild cold-dry seasons or in places where tropical climate only occurs at a certain time (Toe & Kubota, 2013). Thereby, inhomogeneity in the data pattern can lead to conflicting results when the model is applied in hot-humid climates. A collective database in a similar climatic condition is more suitable for analysis. Toe and Kubota found a significant discrepancy in gradient coefficient of approximately 0.3 between two linear regressions predicted by Nguyen and by Toe and Kubota, which was built based on the data in a uniformly hot-humid climate. From the counter-arguments of Toe and Kubota, the validity of Equation 4 to predict comfort temperatures in the built environment of Vietnam proved by Nguyen should also be considered again.

Another question for that model is the context of building and subjects in applications in Vietnam. The discussions in Section 2.3 explain the variations of occupant thermal perceptions among building typologies, locations, or even housing inhabitants with different ethnicities. Much work gains this opinion (de Dear, Brager, & Cooper, 1997; Nicol & Humphreys, 2002; Djamila, Chu, & Kumaresan, 2012). The adaptive model found by Nguyen is also devised to define a comfort zone in residential buildings in Vietnam. Whereas, all data for prediction included results in various building types: housing, workplace, and school. Moreover, the neutral temperatures over summer found from using data in free-running classrooms in Danang may lack the accuracy to use in dwelling buildings. Additionally, the climate in Danang is greatly distinctive from the other parts of the country because of the effect of the sea. Thus, a wide application of that model for residential buildings across Vietnam should be evaluated again.

The analyses in Section 2.3 also raise a necessity to find a comfort model or a range of acceptable temperatures for using in residential buildings in Vietnam because of their distinct characteristics. However, most studies in Vietnam have focused on comfort in other building types. Research on thermal sensations of occupants and thermal environments in residential buildings has been lacking.

2.4 The existing international and national standards of thermal comfort condition

2.4.1 An overview of existing international standards

Three recognisable international comfort standards are American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 55, the European standard EN 15251, and finally, International Organisation for Standardisation (ISO) 7730. All these standards are associated with the various comfort models to define comfortable thermal environments indoors. More details of the standards are below.

ISO 7730 has used the heat balance approach of the human body to predict the subjective responses to the thermal environment (comfort and discomfort) under the influences of six thermal variables (Nicol, 2004) that are introduced in Section 2.1.1. Thermal sensation for the body is calculated by the PMV formula (Eq1) (ISO, 2005). For calculations, four environmental factors are measured while two physical factors in terms of activity and garment insulation are facilitated by the tables attached to the standard. The thermal sensation index, which is a result of such formula, is averaged from thermal individual votes of a large group of people occupying the same environment, whereas a number of subjects feel uncomfortable in such environment. A percentage of dissatisfied people is assumed by the PPD index (Eq2). Dissatisfaction with the thermal environment may be caused by the vertical temperature difference, draught, or temperature asymmetry. As a consequence, the ISO standard recommends the requirements of thermal comfort within ±0.5 PMV corresponding to 90% of occupants finding comfort in the thermal environment and 85 % of occupants not finding discomfort from draughts (ISO, 2005). Furthermore, the standard also categories buildings in accordance with three 'Classes' of the indoor environment presented by the bands of PMV values as shown in Table 2.7. This categorisation is also applied in EN 15251 and ASHRAE 55.

Table 2.7 Classes of buildings in ISO 7730 (ISO, 2005)

Category	**PPD** Predicted percentage discomfort	**DR** Draft rating	**Local discomfort**	**PMV** Predicted mean vote
A	< 6%	< 10%	< 3–10%	−0.2 < PMV < +0.2
B	< 10%	< 20%	< 5–10%	−0.5 < PMV < +0.5
C	< 15%	< 30%	< 10–15%	−0.7 < PMV < +0.7

Both EN Standard 15251 and ASHRAE Standard 55 have adopted two comfort approaches to assume human thermal perceptions according to building cooling modes. While the PMV-based predictions show the validity in static thermal conditions, for example, HVAC buildings, the adaptive model is used for assumptions in NV buildings (Nicol, 2011). Standard EN 15251 establishes indoor environmental conditions to calculate the energy use of buildings by practitioners (Nicol & Wilson, 2010). Apart from the criteria of indoor thermal environment, the standard also covers other aspects of the environment including lighting, noise, and indoor air quality (CEN, 2007). Unlike ISO 7730, EN 15251 classifies buildings by their nature and occupant thermal expectations rather than the indoor environment quality in such buildings as described in Table 2.8 (Nicol, Humphreys, & Roaf, 2012).

Table 2.8 Categories and limits for NV and AC buildings in EN 15251 (Nicol, Humphreys & Roaf, 2012)

Class/Category	Description	Limitation PMV	Limitation K
I	High level of expectation only used for spaces coccupied by very sensitive and fragile persons	± 0.2	± 2
II	Nornam expectation for new buildings and renovations	± 0.5	± 3
III	A moderate expectations (used for existing buildings)	± 0.7	± 4

Table 2.8 includes limitations about PMV (HVAC buildings) and temperature deviation (free-running buildings). The way of setting the classes categorised is an attempt for the criteria to be applied in various contexts of building type, cooling mechanisms, type of occupants, climate, and geography (Nicol & Wilson, 2010).

All three classes I, II, and III are aligned with categories A, B, and C in ISO 7730, in which, Class II is determined to be a normal criterion. The adaptive comfort model in EN15251 is derived from the database of the European SCATs project across five nations in Europe (CEN, 2007). For non-air-conditioned buildings, indoor comfort temperatures are identified by Equation 5 associated with the running mean of outdoor temperatures:

$$T_{comf} = 0.33xT_{rm} + 18.8 \qquad \text{(Eq5)}$$

where T_{comf} = comfort temperature (°C)

T_{rm} = running mean of outdoor temperature (°C)

The band of thermal acceptability around the value of neutrality is standardised by coefficient K according to three classes as shown in Table 2.8 and Figure 2.3. In Figure 2.3, the model is applied when the values of outdoor running mean temperature lie within the zone that is defined by lower limit at 15°C and 30°C, and the upper limit at 10°C and 30°C. Particularly in residential design, the standard recommends a range of indoor temperatures for hourly energy calculations between 23-26°C in the cooling season and 20-25°C in the heating season. These criteria are used for residences that belong to category II and the assumptions of clothing value – 0.5clo, sedentary activity – 1.2met (CEN, 2007).

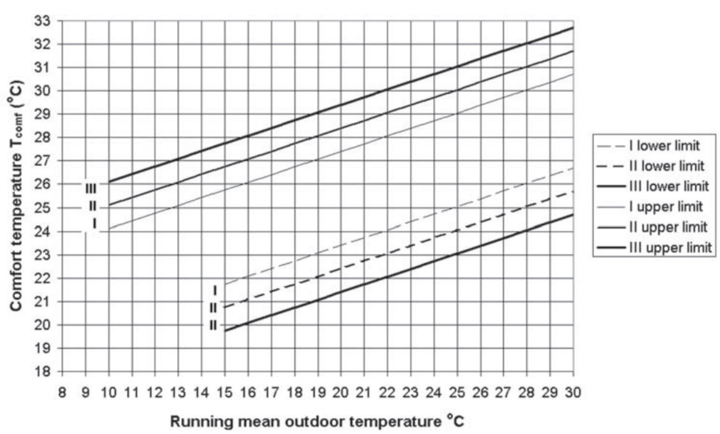


Figure 2.3 A range of acceptable temperatures for NV buildings (CEB, 2007)

The comfort standard widely known over the world is ASHRAE Standard 55 since the 1980s. Before 2004, the old ASHRAE standard mainly used the PMV model for the predictions of thermally acceptable range in buildings (ASHRAE, 1992). The ASHRAE has then included the adaptive model to apply to NV buildings (ASHRAE, 2004). That comfort model was derived from using the 21,000 sets of raw data that were collected by various field studies in 160 different workplaces over four continents and a wide range of climatic conditions (de Dear & Brager, 2002). The valid data for this extensive work satisfies the requirements of the standardised protocol, measuring techniques, types of variables, and database structure. ASHRAE Standard 55 uses a correlation between indoor comfort operative temperature and mean outdoor air temperature to define a comfort zone in free-running buildings based on the below equation (Eq6).

$$T_{comf} = 0.31xT_o + 17.8 \qquad \text{(Eq6)}$$

where T_{comf} = comfort temperature (°C)

T_o = monthly mean outdoor air temperature (°C)

To was defined as the monthly mean outdoor temperature in the previous versions of the standard 55; however, it has been replaced by prevailing mean outdoor temperature since the latest version in 2013. The prevailing mean outdoor temperature is a numerical value of mean daily outdoor temperatures over a period of days (ASHRAE, 2013a). This action is to some extent to express an advantage to predict temperatures for comfort according to the variability of the daily or yearly weather, which is a difficulty to permit dynamic thermal simulation if using a historic monthly mean of outdoor temperature (Nicol, Humphreys, & Roaf, 2012).

The range of temperatures for comfort is defined by 80% and 90% of occupants accepting the thermal environment corresponding to the deviation of 3.5K and 2.5K (Figure 2.4). In Figure 2.4, the graph is limited between outdoor temperatures ranged from 10°C to 33°C. The determination of that range relies on the measured data from the field studies used. For cooler and warmer conditions than the limits, the chart is not valid anymore; and therefore, the thermal sensation can be predicted by the PMV (de Dear & Brager, 2002).

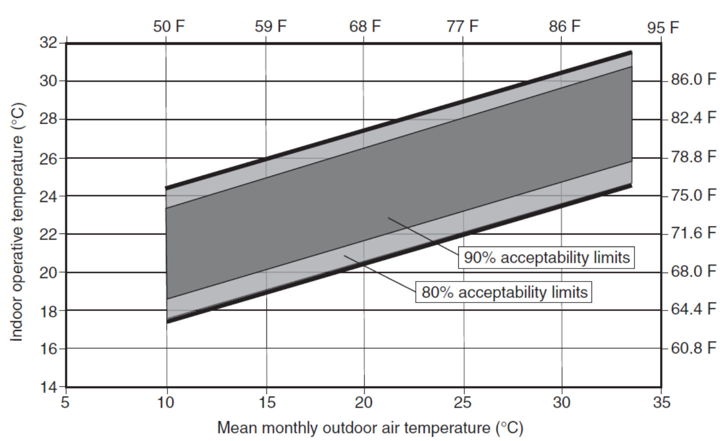


Figure 2.4 A range of acceptable temperatures for NV buildings (ASHRAE Standard 55, 2004)

2.4.2 National standards in Vietnam

In Vietnam, three existing national construction codes helping designers determine thermally comfortable environments in buildings include TCVN 7438:2004 and TCVN 306:2004, and finally, TCVN 9411-2012 that is particularly relevant to 'shop-house' dwelling design (NIA, 2004; VSQI, 2005; VIAP, 2012). TCVN 7438:2004 is the latest standard version for determining thermal conditions for comfort in the built environment in Vietnam. This standard refers to ISO 7730-1994, therefore, the detailed criteria mentioned in TCVN 7438 in terms of the predictive method of thermal sensation and building categorisation with the indoor environment are likely corresponding to the ISO 7730 standard.

TCVN 306:2004 guides architects to define and evaluate the quality of microclimate in new and existing dwelling and public buildings in Vietnam. Microclimatic indices consist of room temperature, air velocity, relative humidity, radiant temperature and operative temperature. Each thermal variable is required for a distinct measurement method and conditions in applications (NIA, 2004). In accordance with the standard, a satisfactory environment in a room or a building is embodied by a comfort zone for the Vietnamese as shown in Table 2.9. The limit for thermal acceptability of people is categorised by two types of temperature (air temperature and effective temperature) in individual seasons (cool and warm). Building occupants find comfortable in a thermal environment within 21.5°C and 29.5°C (air temperature). Besides the specification of acceptable thermal environments for comfort, TCVN 306 also mentions the factors of local comfort in the occupied zone such as the vertical differences of air temperature within ±2°C, air velocity within ±0.07m/s, and relative humidity within ±7% around the acceptable zone.

Table 2.9 Comfort zone for the Vietnamese (NIA, 2004)

Zone	Sensation	Effective temperature, °C ET		Air temperature, °C Ta (RH=80%, V=0.3-0.5m/s)	
		Cool season	Warm season	Cool season	Warm season
Cold	Cold	≤17.3		≤19.8	
	Cool	18.5		N/A	
Comfortable	Slightly cool	20	N/A	21.5	N/A
	Neutral	23.3	24.4	24.5	25.5
	Slightly warm	26.5	27	29	29.5
Hot	Warm		28.5		N/A
	Hot		≥29.2		≥31.5

TCVN 9411:2012 is acknowledged as an effective design standard applied for a particular building type - row houses in Vietnam. The standard comprises various aspects related to planning, architecture, engineering of row houses under different urban conditions; and indoor environment including ventilation, lighting, and acoustics (VIAP, 2012). Thereby, TCVN 9411 combines many materials of published standards of other categories. For the criteria of comfortable conditions in row houses, the standard defines a comfort range and allowable excess of various environmental parameters (air temperature, relative humidity, and air velocity) in both warm and cool seasons. Table 2.10 proposes the band of thermal acceptability between 25-29°C in the warm season and 20-24°C in cool months. The wind environment is determined to be pleasant for occupants when air velocity ranges from 0.5-1.0m/s or even up to 1.5m/s in warm months.

Table 2.10 Thermally acceptable conditions in Vietnamese housings (TCVN 9411:2012)

Season	Ta (°C)		RH (%)		V (m/S)	
	Comfortable	Limit	Comfortable	Limit	Comfortable	Limit
Cool	22-24	20-22	70-75	75-80	0.2-0.3	0.5
Warm	25-28	29	75	80	0.5-1.0	1.5

2.4.3 Discussion

Thermal comfort standards act a significant role in building sustainability by guiding designers to decide suitable design strategies that provide comfort, health, and productivity for inhabitants through an indoor pleasant environment; and influence energy efficiency in such the building due to its services, its operation, and its provision of controls (Nicol & Humphreys, 2002; de Dear & Brager, 2002; Haneda, Tanabe, Nishihara, & Nakamura, 2008; Yao, Li, & Liu, 2009; Nicol & Wilson, 2010). The international and regional standards to define good practice would indicate requisite categories including "*the indoor environments likely to provide comfort, the range of acceptable environment, and an acceptable rate of change*" (Nicol & Humphreys, 2002). However, they have shown some restrictions on applications in real environments of NV residential buildings in warm-humid climates.

In three international standards, ISO 7730 by principally using the heat balance model shows its errors in assuming occupant thermal comfort in buildings which are not mechanically cooled or heated, particularly in free-running dwellings (Becker & Paciuk, 2009; Yang, Yan, Xu, & Lam, 2013; Yan, Mao, & Yang, 2017). That is discussed in Section 2.1.3. Under the hot-humid conditions, the thermal sensation of people is overestimated by ISO 7730 rather than their actual responses on the ASHRAE scale (Nicol, 2004). Regarding its failures, a number of comfort surveys in naturally cooled residences in the tropics have acknowledged that occupants found their thermal satisfaction at temperatures which are predicted as discomfort by the ISO standard (Feriadi & Wong, 2004; Rangsiraksa, 2006; Tablada, Troyer, Blocken, Carmeliet, & Verschure, 2009; Peng, 2010). Additionally, Nicol expressed the view that the particular clothing levels (0.5clo or 1.0clo) assumed in the standard does not reflect on the people's diverse dress in the real circumstances of warm climates (Nicol, 2004). For example, the average index of garment insulation was only 0.26clo in NV dwellings and 0.4clo in mechanically cooled offices in Singapore (de Dear, Leow, & Foo, 1991). The similarity is found in graphical and analytical methods to identify the comfort zone into the ASHRAE standard (ASHRAE, 2013a). Thereby, using the predictions of ISO 7730 may encourage the use of mechanical cooling systems than necessary (Nicol, 2004; Rupp, Vasquez, & Lamberts, 2015).

The comfort standards of ASHRAE and EN using the adaptive model are more plausible to predict thermal sensation and to increase energy efficiency in naturally cooled dwellings in a tropical context. Furthermore, the available comfort models of two standards seem to be validated for use with residential buildings, although they are derived from numerous database in office buildings where the indoor environment and clothing level are constantly consistent, along with the narrow degree of behavioural adaptation (de Dear & Brager, 2002; Nicol & Wilson, 2010; Djamila, Chu, & Kumaresan, 2012). However, some evidence has shown their weaknesses to be applied in tropical houses, particularly in SE Asia. A few examples are de Dear (de Dear, Leow, & Foo, 1991), Wong (Wong, et al., 2002), Feriadi (Feriadi & Wong, 2004), Rangiraksa (Rangsiraksa, 2006), Djamila (Djamila, Chu, & Kumaresan, 2013) whose fieldwork found actual neutral temperatures for occupants are 3-5°C higher than the recommendations by ASHRAE Standard 55 and EN 15251 (24°C±1) (Karyono, 2011). Constant thermal experience with the hot condition, the availability of building controls and personally adaptive opportunities in open houses are factors to explain the higher preferred temperatures of residents, which closely correlate with higher external temperature. The availability and opportunity of adaptive behaviours have not been included in the current standards (Karyono, 2011; Nicol, 2011).

Moreover, the range of thermal acceptability defined by the standards is limited at maximal mean outdoor air temperatures, for example, 33°C (ASHRAE Standard 55) and 30°C (EN 15251). However, exceeding those thresholds is common in hot-humid climates, hence, a question is whether the graphs shown in Figures 2.3-4 are still validated or not. Halawa and Hoof (2012) also highlighted that doubt. Brager and de Dear have ever expressed their view that predictions for subjective thermal responses using the models of ASHRAE 55 and EN 15251 have been unreliable under warm environments (de Dear & Brager, 2002). Field studies in the tropics found that subjects can be comfortable at outdoor temperatures over 30°C even 33°C due to the influences of air movement (Candido, deDear, Lamberts, & Bittencourt, 2010; Indraganti, 2010a; Djamila, Chu, & Kumaresan, 2013). Nicol (2004) and Toe and Kubota (2013) confirmed the effect of air velocity on occupant thermal tolerance in hot conditions.

For the national comfort standards relying on the PMV-PPD model, they are suitable for applying in moderate thermal conditions while the indoor environment of most Vietnamese houses is naturally controlled by operable windows and doors or openings between buildings. TCVN 9411:2012 and 306:2006 identify the acceptable range of temperatures used in dwellings around Vietnam; however, they should be reviewed for several reasons. First of all, that range, which is estimated from the available studies and international standards around the world, is not introduced clearly in these standards. Compared to the findings of already field studies in residential buildings in the tropics, the comfortable temperatures recommended into the standards may not be validated to apply in the context of Vietnam. The necessity for a database conducted in the dwellings in Vietnam is highlighted. Secondly, there is a slight difference in the bandwidth of temperatures between two standards although they are used in designing houses enabling comfort. Furthermore, into TCVN 306:2004, the lower limit of the comfort zone in the warm season is not mentioned. Thirdly, based on the theory of adaptive comfort, indoor comfort temperatures are proportional to outdoor temperatures. Despite in the similar tropical zone, the various geographical characteristics across the country lead the remarkable variations among regional climates, which raises a question that the comfort range identified in different seasons can be applied for all regions in Vietnam.

The above discussions show a need for more comfort studies for the future updates of the international and regional comfort standards in NV housings in hot-humid climates. The current standards based on a database in offices cannot be generalised to use for residential buildings. Particularly, the comfort zone for the Vietnamese in free-running houses should be revised, that is significant in the design of houses to match the real conditions and to reduce household energy use. Additionally, apart from thermal acceptability - a fundamental term to identify for practical applications, air movement also has a contribution to occupant thermal perceptions in warm-humid climates. For that reason, the research on air movement sensations and the combination of air movement acceptability into the comfort standards are worthwhile.

2.5 The effects of air movement on thermal comfort

2.5.1 Satisfaction or draft

Heat and humidity are two principal factors to cause discomfort in NV buildings in tropical climates because of the presence of a hot and humid condition (Trimarianto, 2003; Nicol, 2004). However, enhancing air movement can create a possible cooling effect and restore occupant thermal satisfaction at hot temperatures and wetness (Allard, 1998; Toftum, 2004; Szokolay S. V., 2008). Furthermore, compared to the use of mechanical cooling systems, the operation of airflows is taken into account a cost-effective solution due to no costs of energy, maintenance, and operation (Allard, 1998; Sorgato, Melo, & Lamberts, 2016). The availability of proper airflows results in three different functions: the reduction of air temperature by replacing hot air indoors by cooler air from outdoors and an increase of the rate of convective and evaporative heat losses from the skin surface as a mechanism of physiological cooling (Olgyay & Olgyay, 1963; Peterbridge, 1974; Givoni B. , 1991; 1994; Szokolay S. V., 1997; Antaryama, 2000). Furthermore, the provision of fresh air and the dissipation of odours and contaminations maintain a healthy and well-being environment indoors (Szokolay S. V., 1997). The two effects of air movement (the fresh air provision and the removal of heat) depend on the volumetric rate (m^3/s or L/s) while the evaporative cooling is measured by the intensity of air velocity (m/s) (Szokolay S. V., 1997). Besides, the rate of heat exchange in the interior has a relationship with the indoor airspeed (Givoni B. , 1994). Nevertheless, in reality, wind/airflow is the most complex variable to control because of the variability of the physical building, occupant behaviours, and urban environments (Givoni B. , 1976; Allard, 1998; Pham N. D., 2002; Tantasavasdi, Srebic, & Chen, 2001). Within an occupied zone, low or high air velocities can be a result of the comfort or discomfort of occupants, for example, high airspeed can cause draught while the wind of low speeds will reduce the indoor air quality (CIBSE, Comfort, 2006).

Table 2.11 Subjective reactions to air movement level (Szokolay S. V., 2008)

< 0.25 m/s	unnoticed
0.25-0.5 m/s	pleasant
0.50-1.00 m/s	awareness of air movement
1.00-1.50 m/s	draughty
>1.50 m/s	annoying

Szokolay classified the five different levels of subjective reactions to air movement as shown in Table 2.11 (Szokolay S. V., 2008). From this table, occupants feel pleasant with the wind velocities within 0.25 and 0.5m/s and can be acceptable in the wind environment of 0.5 and 1.0m/s. The draught problem operates when the air velocity ranges between 1.0 and 1.5m/s. However, the air movement sensations depend upon not only air velocity but air temperature (McIntyre D. , 1978; Griefahn, KuKnemund, & Gehring, 2001). As a result, occupants are still satisfactory at air velocities closer to or higher than 1.0m/s in hot environments (Szokolay S. V., 1997). Moreover, the perception of air movement is also subjective; therefore, it changes under different personal factors such as gender, levels of fatigue, age, activity, and clothing habits (Toftum, 2004).

Air movement can cause local thermal discomfort known as draught, which influences overall human thermal sensation. Referring to the definition in ASHRAE 55-2004, "*draught is unwanted local cooling of the body caused by local convective cooling"* (ASHRAE, 2004). Consequently, it is regulated by many factors including air temperature, airspeed, turbulence intensity, activity, and clothing (Fanger & Pedersen, 1977; Fanger, Melikov, Hanzawa, & Ring, 1988; Toftum, 2004). Additionally, the sensitivity to draught varies in the different parts of the body regardless of the velocities of wind, particularly around the head region (head, neck, ears, and shoulders) while the discomfort does not occur in the leg region (ankles, feet, and legs) (ASHRAE, 2004). Draught sensation differs in different environmental conditions: between naturally ventilated and air-conditioning spaces, or between warm and moderate/cool climates. The identification of maximum allowable airspeeds for particular environments may reduce complaints of draught, reduce energy consumption, and provide preferable environments for occupants (Zhang, et al., 2007; Candido, deDear, Lamberts, & Bittencourt, 2010). The question is how wide the range of acceptable air movement is in naturally cooled buildings of hot-humid conditions.

In moderate or cool environments, draught is a notable factor in design to avoid local discomfort (Toftum, 2004) and the draught rating depends upon three thermal parameters (airspeed, its fluctuation, and air temperature) affecting receptors in the skin (Fanger & Pedersen, 1977; Fanger & Christensen, 1986; Fanger, Melikov, Hanzawa, & Ring, 1988). Thereby, in the environments which people do not have control, the current standards such as ASHRAE 55 and ISO recommend that the air velocity caused by building and HVAC systems does not exceed 0.2m/s to avoid a risk of draught (ISO, 2005; ASHRAE, 2004).

However, using the ASHRAE RP-884 database in different climates (de Dear R. , 1998), Toftum investigated air movement preference of occupants, who found comfort from 'slightly cool' to 'slightly warm' in HVAC office buildings (Toftum, 2004). For analysis, the variables of metabolic rate from 1.1 met to 1.4 met and temperatures from 22.5°C to 23.5°C were used. Two bins of indoor airflow researched were <0.2m/s and >0.2m/s. The results demonstrated that office staffs were less sensitive to draught discomfort even they preferred more air movement, particularly when occupants felt neutral or slightly warm. Subjects feeling slightly cool also preferred more airflow; however, increased air velocity would cause them a risk of draught. This means that a cool thermal sensation is proportional to draught complaints (Rohles, Woods, & Nevins, 1974; Tanabe & Kimura, 1994; Toftum, 2004; Candido C. M., 2010). Furthermore, draught is mitigated at activities of higher metabolic rate (Toftum & Nielsen, 1996; Griefahn & Kunemund, 2001).

Under warm conditions, in NV buildings, occupants not only are less sensitive to air movement but prefer higher velocities of wind (de Dear & Foutain, 1994; Cena & de Dear, 1999). Warm discomfort is compensated by increased air velocities (CEN, 2007). A lot of researchers have looked at the aspect of air movement and in different locations to assess its impact on comfort. The research however still has some gaps and needs more attention, the main findings of previous work can be summarised in Table 2.12.

Many studies have been conducted by two surveying methods in the laboratory and the field to examine what a maximum acceptable air velocity by occupants in relation to their maximum thermal acceptability is. Examples of chamber studies are Fanger and McIntyre (Fanger, Østergaard, Olesen, & Madsen, 1974; McIntyre D. , 1978), Rohles et al. (Rohles, Woods, & Nevins, 1974; Rohles, Konz, & Jones, 1983), Scheatzle (Scheatzle, Yellott, & Wu, 1989), Tanabe and Kimura in Japan (Tanabe & Kimura, 1989; 1994; Kimura & Tanabe, 1993), and Srivajana in Thailand (Srivajana, 2003). Those works differently discovered corresponding couples of maximum temperature and airspeed, which people accept as shown in Table 2.12. Gathering the findings of researchers together, high air velocities between 0.8-2.25m/s can intervene occupant thermal tolerance of warmer conditions with maximum temperatures ranged 27-32°C. In those previous studies, Srivajana found the highest acceptable temperature and air movement of 32°C and 2.25m/s through experiments with 128 college students in naturally ventilated schools a hot-humid city of Thailand in 2002 (Srivajana, 2003). However, the researcher recommends that airspeeds greater than 0.9m/s cause annoyance. Toftum advised that the more pleasant environment for occupants is characterised by lower air velocity and temperature within the comfort zone (Toftum, 2004).

Table 2.12 Previous studies on the effect of air movement on comfort

Researchers	Research method	Climatic condition	Country	Building type	Maximum acceptable temperature (°C)	Maximum acceptable air velocity (m/s)	Reference
Fanger and McIntyre	Chamber study	N/A	N/A	N/A	28	0.8	(Fanger, Østergaard, Olesen, & Madsen, 1974) (McIntyre D. , 1978)
Rohles et al.	Chamber study	N/A	N/A	N/A	29	1.0	(Rohles, Konz, & Jones, 1983)
Rohles et al.	Chamber study	N/A	N/A	N/A	the upper limit + 1K	0.5	(Rohles, Woods, & Nevins, 1974)
Scheatzle	Chamber study	N/A	N/A	N/A	28	1.02	(Scheatzle, Yellott, & Wu, 1989)
Tanabe and Kimura	Chamber study	Hot-humid	Japan	School	27 (RH 50%) 29 (RH50%) 29 (RH80%) 31 (RH 50%)	1.0 1.2 1.4 1.6	(Tanabe & Kimura, 1989)(Kimura & Tanabe, 1993)(Tanabe & Kimura, 1994)
Srivajana	Chamber study	Hot-humid	Thailand	School	30 (RH 80%) 32 (RH 80%)	1.8 2.25 0.9 defined as the draft limit	(Srivajana, 2003)
Mallick	Field study	Hot-humid	Bangladesh	House	the upper limit + 2K the upper limit + 3K	0.3 0.45	(Mallick, 1996)
Richard de Dear et al.	Field study	Hot-humid	Singapore	House & Office		0.8 defined as the draft limit	(de Dear, Leow, & Foo, 1991)
Nicol	Field study	Hot-dry	India and Iraq	N/A	the upper limit + 4K	Sufficient airflow	(Nicol, 1973)
Sharma and Ali	Field study	Hot-humid	India	Public	the upper limit + 4K	Sufficient airflow	(Sharma & Ali, 1986)
Nicol et al.	Field study	Hot-dry	Pakistan	Commercial	the upper limit + 2K	0.45	(Nicol, Raja, Allaudin, & Jamy, 1999)
Szokolay	Combine previous studies	Hot-humid	N/A	N/A	the upper limit + 6K the upper limit + 7K	1.5 2.0	(Szokolay S. V., 1997)

Unlike the laboratory studies, where environments are controlled, real conditions of buildings, along with their environment and subjects have a wide variability. Those factors influence the thermal and air movement perception of occupants. Existing field studies on the significance of air movement for human comfort have been carried out using subjects in various building typologies of hot climates, for example, Nicol in India and Iraq (Nicol, 1973), Sharma and Ali in India (Sharma & Ali, 1986), de Dear et al. in Singapore (de Dear, Leow, & Foo, 1991), Mallick in Bangladesh (Mallick, 1996), and Nicol et al. in Pakistan (Nicol, Raja, Allaudin, & Jamy, 1999). Among those, de Dear and his colleagues in Singapore defined the airflow of 0.8m/s as the draft limit for inhabitants in occupant-controlled naturally conditioned spaces. Meanwhile, other research found varying velocities of air movement that may extend the upper comfort limit, for instance, where 0.3m/s is available, the extension can be 2K (Mallick, 1996). Brought available studies on the effect of air movement in the tropics, Szokolay concluded that the extension of the upper comfort limit could be wider up to 7K if the airspeed is 2m/s (Szokolay S. V., 1997).

To facilitate use in practice, Humphreys and Nicol suggested a model define the value of increased temperature when air velocity is raised in the environment with the air velocity above 0.1m/s (Eq7) (Nicol, 2004). The model is generalised as Figure 2.5. According to the curve of Figure 2.5, the optimum of comfort temperature can be increased by 3K under the effect of maximal airspeed of 1m/s.

$$dT = 7 - \frac{50}{4+10V^{0.5}} \ (°C) \qquad \text{(Eq7)}$$

where dT = comfort temperature increased (°C)

V = air velocity (m/s)

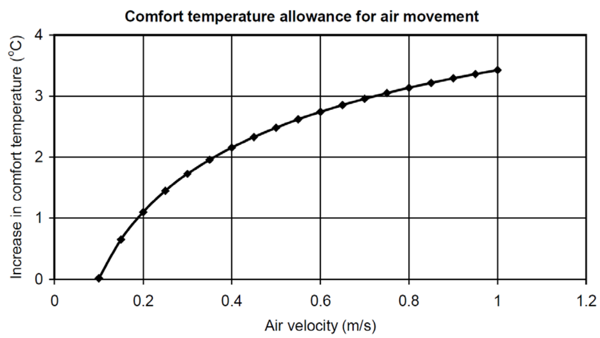


Figure 2.5 The increase in comfort temperature for different airspeeds (Nicol, 2004)

Most comfort studies have attempted to predict thermal perceptions and to identify comfortable temperatures for inhabitants in buildings ventilated by different cooling systems. Particularly, experimental and empirical research in hot climates has found a counterbalance to the maximum thermal tolerance of occupants by the effect of air movement. However, Candido (2010) analysed that air movement partly counts for overall subjective comfort in the tropics, which means that the range of acceptable temperatures is identified in the correlation of air movement acceptability.

Table 2.13 Minimum airspeeds required to achieve 80% and 90% acceptability related to operative temperature (Candido, de Dear, Lamberts & Bittencourt, 2010)

Operative temperature (°C)	Air movement acceptability	
	V80, m/s	V90, m/s
26	0.4	0.5
27	0.5	0.6
28	0.5	0.6
29	0.6	0.7
30	0.7	0.9
31	0.7	N/a

Based on the thousand data collected in naturally ventilated universities in Brazil during hot and cool seasons, she found the minimum limits of air velocity corresponding to each level of acceptable operative temperature as shown in Table 2.13 (Candido C. M., 2010). Her findings also confirmed that subjects in hot-humid climates prefer higher air movement for their perceptible pleasure rather than the notion of draught (Candido, deDear, Lamberts, & Bittencourt, 2010).

The influence of air movement on overall human thermal perception in the tropics is more robust when Toe and Kubota found an adaptive comfort model (Eq8) by using all ASHRAE RP-684 raw data of field studies which were conducted only in such climates (Toe & Kubota, 2013). Compared to the recognisable adaptive models, particularly, Eq5 and 6 shown in Section 2.5, the regression coefficient of Eq8 almost doubles. They interpreted that air movement is a significant factor resulting in the difference in the gradient of the adaptive formula in hot-humid climates.

$$T_{comf} = 0.57xT_{out} + 13.8 \qquad \text{(Eq8)}$$

where T_{comf} = comfort temperature (°C)

T_{out} = monthly mean outdoor air temperature (°C)

The recommendations of maximum allowable air velocity in natural spaces differentiate among the international and regional standards. ASHRAE 55 and EN 15251 recommend that under the warm conditions characterised by operative temperatures above 25.5°C, sufficient air movement may offset warmer temperatures. The standards also suggest the availability of 0.5m/s and 1m/s air velocity can raise the comfort threshold by 2°C and 3°C, respectively. However, indoor airflow should not exceed 0.8m/s due to the draught discomfort (CEN, 2007; ASHRAE, 2013a).

Meanwhile, for the national standards in Vietnam, TCVN 9411:2012 mainly used for 'shop-houses' has defined the two ranges of acceptable air velocities: 0.2-0.5m/s and 0.5-1.5m/s applied in cool and warm environments, respectively (VIAP, 2012). Moreover, the airspeed limits correspond to the seasonal comfort zone between 20-24°C and 25-29°C. However, another - TCVN 306:2004, which emphasises on the indoor microclimate in dwelling and public buildings in Vietnam, shows conflict with a range of acceptable airspeeds from 0.3-0.5m/s in relation to comfortable temperatures of 21.5-29.5°C (NIA, 2004).

2.5.2 Discussion

This review of previous studies and current standards related to air movement perception found important insights. Firstly, in free-running buildings of the tropics, the air movement sensation of occupants bears no resemblance to the recommendation of draught limit (0.2m/s) into the international standards. People not only desire more airflow but are satisfied with higher air velocities around or higher than 0.8m/s suggested by ASHRAE 55 in non-air-conditioned spaces, for example, 0.9m/s (Candido, deDear, Lamberts, & Bittencourt, 2010), 1.6m/s (Tanabe & Kimura, 1989), or 1.8m/s (Srivajana, 2003).

Secondly, high air movement can restore occupant comfort even extend their tolerance in warmer environments in open spaces in hot-humid climates. More than 30% of occupants in tropical regions found comfortable at warmer temperatures than the upper comfort limit if sufficient airflow is available (Toe & Kubota, 2013). People can endure 3K warmer environments where the presence of air movement is 1m/s (Nicol, 2004). Therefore, the cooling effect of air movement on the comfort limit is significant in reducing the cooling load of building service systems.

Thirdly, existing experimental and empirical studies have focused on overall human thermal sensations and comfort ranges. Other have found acceptable air velocities to expand the comfort limit at warmer temperatures in hot climates. Combined the findings of the previous work on indoor acceptable air movement, a range of 0.2-1.6m/s has been recommended for NV buildings in the tropics. However, few researchers have been concerned with air movement acceptability in relation to thermal comfort. A hypothesis of physiological comfort is created that although building occupants accept slightly warm environments compared to the desired temperature, elevated air velocities in such environments restore their comfort by removing sensible and latent heat from the body (Candido, de Dear, Lamberts, & Bittencourt, 2008).

Fourthly, when comparing the outcomes of studies discussed above, there are variations of acceptable airspeeds and temperatures due to differences in research techniques (empirical and experimental); and sample types - climate (hot-humid or hot-dry), people (student, officer, or resident), building (residence, workplace, or school), and cooling system (natural or mechanical).

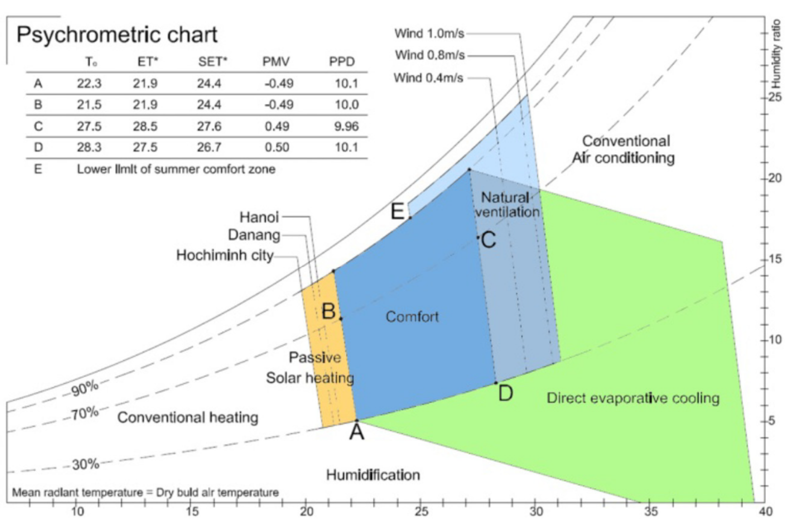


Figure 2.6 Psychometric chart for the built environment in Vietnam (Nguyen, 2014)

Linked to the Vietnam context, using Typical Meteorological Year Data sets, along with graphical analyses, Nguyen predicted a further extension of the comfort zone for Vietnamese people under different intensities of wind between 0.4 and 1m/s (Figure 2.6) (Nguyen & Reiter, 2014). The provision of effective natural ventilation can show 32% improvement of occupant comfort in HCMC, 25% in Hanoi, and 22% in Danang. This means that the effect of natural ventilation on comfort varies in the distinct characteristics of regional climates.

Despite the acceptable air velocities suggested in the Vietnam construction standards (TCVN 9411:2012 and TCVN 306:2004), their sufficiency and implementation in practice should be reassessed because of a lack of database by both empirical and experimental studies to produce. Additionally, the recommendations have used for naturally and mechanically ventilated buildings that can inaccurately reflect the real environment inside buildings cooled by different mechanisms. Moreover, there is probably no homogeneity in the comfortable conditions issued between two construction codes – 9411:2012 and 306:2004. That problem can confuse users.

Taken all discussions above together, the present research aims to find a relationship between thermal and air movement perceptions and acceptability in 'shop-house' buildings in HCMC. A question is: Which are the comfortable and acceptable airspeeds for residents' thermal satisfaction in naturally ventilated shop-houses in HCMC? They are different or similar to the recommendations of the standards or the outcomes of existing studies in the tropics.

Another concern is that with some suggestions of maximum or acceptable air velocities to be set to retain comfort inside buildings, whether these are achieved in real buildings is separately questionable because previous field studies in the tropics have found the real calm condition of air movement in free-running buildings. Consequently, the possibility depends on enhancing appropriate urban designs and optimising passive building means or using fans. The indoor sufficient air movement may be no available due to the impact of urban conditions, such as neighbour buildings, the density of buildings, vegetation around, or building orientation. Furthermore, the role of designers is very worthwhile to ensure the satisfactory environment in the building (low air temperatures, acceptable humidity, and good air movement) by proposing passive design strategies for the building. Therefore, to achieve the acceptable air velocities can ask for appropriate guidelines in design for architects.

2.6 Conclusions

As the above reviews and discussions of relevant literature, a total of six gaps in knowledge/requirements for further information for this research project are identified:

- The current heat-balance and adaptive comfort models have shown the limitations when applied to predict the occupant thermal sensations in buildings in the tropics, especially in residential buildings. Thereby, the first gap is the lack of both empirical and experimental studies on thermal comfort in the context of Vietnamese people, housings, and climate to discover the environments for occupant thermal satisfaction.

- The existing national and international standards related to thermal environmental conditions for human occupancy are difficult to implement in practice, particularly in housing design, in Vietnam. The physical conditions for occupant comfort in the houses recommended by the local standards undervalue the real perception and tolerance of people to the locally warm-humid environment. Updating the standards corresponding to the comfort database in a real environment is significant in saving energy consumption in residences. This is the second gap.

- The predominant effect of air temperature on occupant comfort has been evidenced by many studies across the globe and over many decades. In hot-humid climates, the effect of air movement significantly contributes to providing thermal comfort, health, and well-being, and reducing energy use for cooling in the building. Most residential buildings in Vietnam are naturally ventilated. Thereby, the occupants' overall comfort is governed by both thermal and air movement perceptions. The third requirement is to understand the air movement sensation/preference of people, and in turn, to find a range of air velocities corresponding to thermal acceptability for residential buildings in Vietnam. Combining an understanding of acceptable combinations of thermal conditions and air movement can be used to produce a framework of assessment, which can then be an effective support for the practical work of designers.

- The study concentrates on the thermal environments for comfort in residential buildings, particularly 'shop-house' dwellings in Vietnam. Consequently, systematic knowledge of urban and building typologies of 'shop-houses' in the specific context of HCMC will benefit the understanding of optimal planning and architectural characteristics of each type, which will contribute to the design guidelines later.

- Outdoor environmental conditions have a close relationship with thermal comfort in naturally ventilated 'shop-houses' in Vietnam. The urban morphologies affect microclimates around buildings. Therefore, a better understanding of the environmental interaction in and around 'shop-house' dwellings is required. The physical compositions of residential neighbourhoods should be studied, which will be considered to develop design options for buildings that can achieve comfortable environments inside according to a particular urban morphology of 'shop-house'.

- There is a need for systematic design guidance for building envelop, particularly openings to support the designers who are confused about how to optimise the thermal performance indoors. The effective design guide for getting comfortable 'shop-house' buildings in Vietnam should be developed by better understanding a complex interplay of various parameters including the physical building, building physics, building users, the surrounding context, and local climate.

Chapter 3 INFLUENCE OF DESIGN ON THERMAL COMFORT

The previous chapter discussed the conditions of a thermally comfortable environment and a potential reduction of cooling energy under the availability of sufficient airflow in NV buildings in hot-humid regions. The close correlation between indoor and outdoor environments is certain in those buildings; therefore, to design a comfortable house by effective natural ventilation relies on applying suitable designs at both urban and building scales (Givoni B. , 1994). At the urban scale, outdoor pleasant microclimates contribute to reducing the environmental loads to which buildings are subjected. Meanwhile, for single buildings, architects also criticise which proper design strategies are used to respond to their surroundings for achieving indoor satisfactory environments. This chapter reviews the relationship between urban constituents and outdoor microclimate in neighbourhoods and between the building design focusing on opening configurations and the interior microclimate. The chapter includes three subsections: the principles of natural ventilation used in building design; the effect of urban morphology on the outdoor microclimate; and the influence of opening variables on the indoor thermal and air movement environment.

3.1. Principles of natural ventilation

3.1.1 Natural driving forces

"Natural airflow is caused by pressure difference" (Szokolay S. V., 2008). Moreover, the wind will flow from positive pressure zone toward the negative pressure zone (Tang, Viet, & Nguyen, 2007). There are two physical mechanisms to drive natural ventilation: wind and thermal buoyancy (Kleiven, 2003).

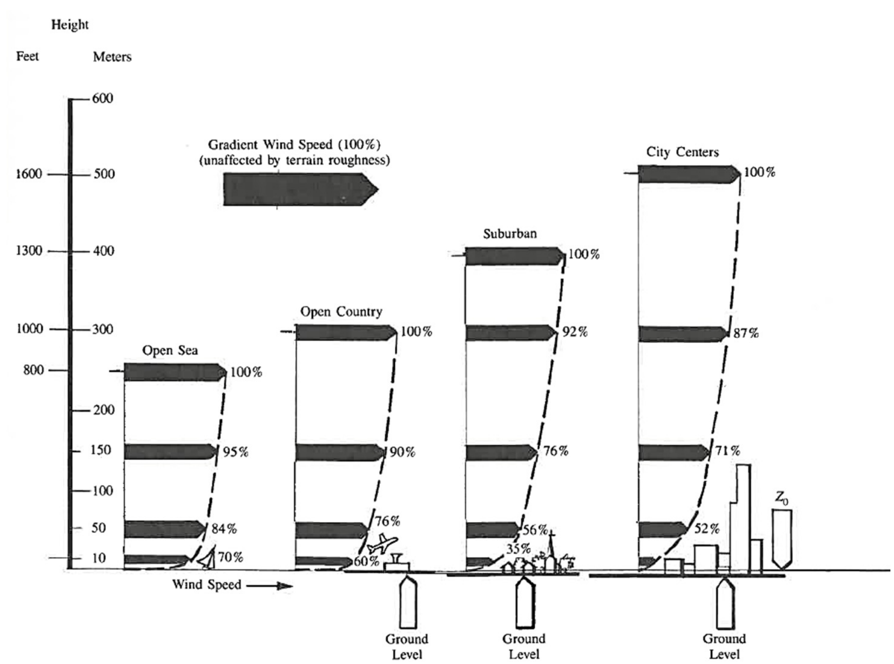


Figure 3.1 Vertical profiles of mean wind speed over various terrains (Cowan, 1991)

Firstly, air motion through building openings is due to the differences in wind pressure over building envelop when the outdoor wind hits such building (Givoni B. , 1976). The air pressure on openings facing incident winds (upward sides) is elevated while the pressure is reduced on the leeward sides, as a result, the air will move due to pressure differences. The rate of indoor air velocities is proportional to the variations of wind pressure between windward and leeward surfaces (Pham N. D., 2002). In reality, wind pressures on buildings are not consistent at the same time of day or year. Furthermore, the characteristics of incident winds including airspeed, direction, and velocity consistency significantly vary in different landscape conditions and height, which also affect the performance of wind environment inside (Cowan, 1991; Rennie & Parand, 1998; Pham N. D., 2002). For example, wind velocities are intense in more open locations, such as airports, rural and coastal areas relative to in compact city districts because of fewer obstructions to block and rub the wind above ground level (Figure 3.1) (Dekay & Brown, 2014). Therefore, in built-up areas, ventilation of buildings relying on natural winds is restricted (Rennie & Parand, 1998). In addition, wind pressure also changes with building height. It means that the upper floors of building face higher airspeeds. Consequently, the building fabric at the top of the building should be considered in the design to adapt to stronger wind pressure and to allow ventilation indoors.

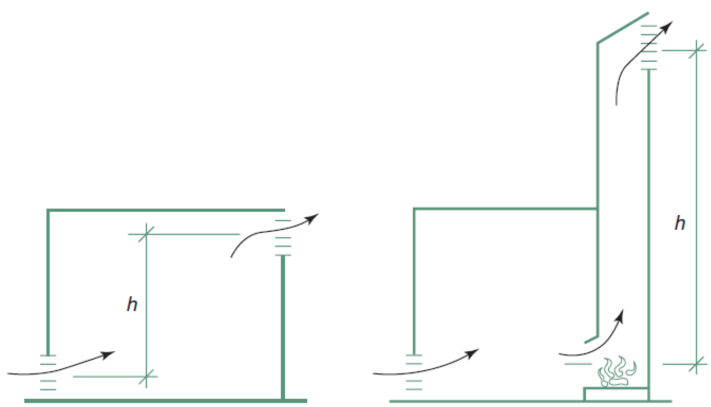


Figure 3.2 Stack effect in a room and a chimney (Szokolay S. V., 2008)

Secondly, thermal buoyancy ventilation operates based on the divergence of air density between the inside and the outside. The air movement driven by that mechanism is commonly known as the stack effect (Szokolay S. V., 2008). In a building with indoor warmer air than outdoor air, the warm air (negative pressure) tends to rise and escapes through outlets placed at higher locations above the floor. Then, a volume of cooler outside air (positive pressure) will displace through inlet openings at the lower part of the building (Figure 3.2) (Rennie & Parand, 1998; Szokolay S. V., 2008). In contrast, if the internal air is cooler, the phenomenon of downdraught will be produced. The displacement between internal and external air, therefore, drives air movement. A good example of stack ventilation is the rising of warm air and smoke in chimneys (Figure 3.2). The size of stack effect is proportional to two factors including the difference in temperature between indoor and outdoor air and in height between inlets and outlets (Rennie & Parand, 1998; Tang, Viet, & Nguyen, 2007). For low-rise buildings or not much difference between indoor and outdoor temperature, the stack ventilation may be less effective. In those cases, the use of taller staircases like as a chimney may be combined with solar chimney, may be useful to improve the effect of vertical ventilation (Khedari, Boonsri, & Hirunlabh, 2000).

3.1.2 Ventilation principles

Based on the fundamentals of two natural driving forces, wind induction into a building is related to the building configuration and its fabric, for example, courtyards, openings, light wells, wing walls, and wind tower, etc. (Kleiven, 2003). Three main definitions of ventilating a building include single-sided ventilation, cross-ventilation, and stack ventilation (Szokolay S. V., 2008). Each affects the airflow characteristics such as velocity, pattern, fluctuation, and consistency. Depending on conditions in and around the building, one or more ventilation principles occurs and may optimise the indoor air movement.

Single-sided ventilation operates based on wind force when opening(s) is located only one side of the upward building surface. The winds come in and out on the same side (Rennie & Parand, 1998). This ventilation type is commonly used for the cellular apartments, buildings, or rooms which windows/doors are opened only on one side while other sides are blocked or internal doors are closed. Two mechanisms to ventilate a one-sided room are wind turbulence with a single opening and buoyancy effect with some openings at different heights in a single wall. As mentioned above, the buoyancy effect within a room is controlled by the difference in temperature between the internal and external air, the difference in height between openings, and the opening areas (Kleiven, 2003). In addition, opening types may also affect ventilation mechanisms. To optimise the effect of single-sided ventilation normally the ratio of room depth and its height should be optimised at 2.5:1 (Figure 3.3). In comparison with other ventilation types, the air movement environment driven through a single side has the least effective.

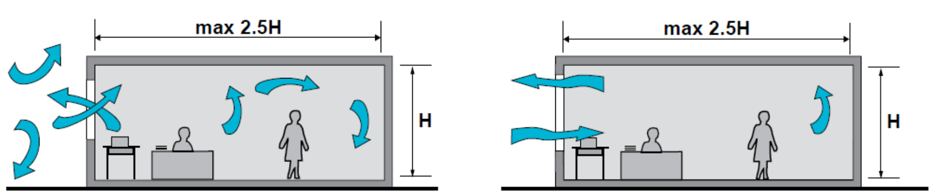


Figure 3.3 Two possible mechanisms of single-sided ventilation (Rennie & Parand, 1998)

As with the single-sided ventilation, cross-ventilation is also affected by wind forces; however, it occurs when openings are organised at both sides of a building/space. The wind normally enters at the windward side and is exhausted at the leeward side (Kleiven, 2003). The indoor wind movement in cross-ventilation is the strongest of the three ventilation options (Rennie & Parand, 1998). The velocity, path, and duration of airflow within a room depend on not only the direction and velocity of outdoor winds against a building but separation on building plans, obstructions of furniture, and opening configurations (Dekay & Brown, 2014). To maintain ventilation across an occupied zone is that the limit of room depth is not 5 times greater than the height of the room (Figure 3.4) (Rennie & Parand, 1998).

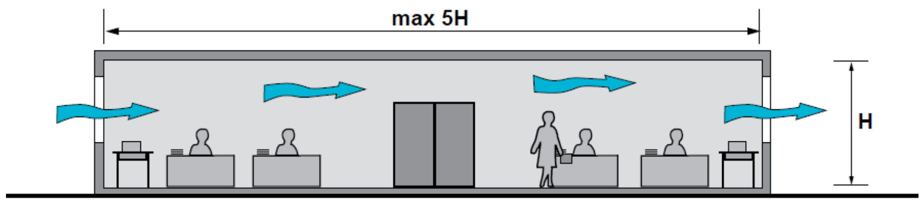


Figure 3.4 Double-sided ventilation (Rennie & Parand, 1998)

In the hot-humid tropics, the employment of cross-ventilation through operable windows is beneficial to enhance occupant thermal comfort in NV buildings (Givoni B. , 1976; Szokolay S. V., 1997; Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 2000). However, the indoor temperature can be elevated by ventilation with warmer outdoor air. Despite a warmer environment indoors than a given temperature limit, comfort may be created by higher velocities of cross-ventilated winds due to the mechanism of physiological cooling (Givoni B. , 1994; Rennie & Parand, 1998).

Stack effect is associated with the vertical movement of air. It may not be found or useful for all building types and urban environments; however, it shows a sufficient cooling effect in some circumstances where the operation of wind force has obstacles. For example, in deep plan buildings where the effect of single or double-sided ventilation may be calm for rooms at the middle and rear, or where buildings are enclosed within high-density neighbourhoods, the principle of stack effect can be applied. Within such buildings, integrated voids, light wells, or staircases can play the role of a stack for airflow.

In practice, the three variations of stack, single-sided, and cross-ventilation often occur together; therefore, calculating the size of ventilation effects is more complicated. Night-time ventilation may also occur with different impacts. Over the night, the difference between indoor and outdoor temperature is different from that in the daytime, the access of outdoor cooler air can cool the building envelop, finishing, and furniture (Givoni B. , 1994; Rennie & Parand, 1998). The strategy of nocturnal ventilation cooling can be used for buildings in the tropics (Givoni B. , 1994; Khedari, Waewsak, Thepa, & Hirunlabh, 2000).

3.2 Urban morphology variables and outdoor comfort

Many previously empirical and experimental studies conducted in various climatic zones have shown the influences of urban geometry on outdoor microclimate, for example, in laboratories (Shashua-Bar, Tzamir, & Hoffman, 2004; Rajagopalan, Lim, & Jamei, 2014; Zhang, Lee, Gu, & Cheng, 2011); in real urban cases, such as in Dubai (Thapar & Yannas, 2007), in Dhaka, Bangladesh (Ahmed, 2003), in Colombo, Sri Lanka (Johansson & Emmanuel, 2006), in Gaza (Asfour, 2010), in Tino, Greece (Andreou, 2014), in northern China (Tong, et al., 2017; 2018). The primary elements making up the morphologies of a block, district, or city consist of buildings, streets, trees, and water surfaces (Dekay & Brown, 2014). The dimensions of urban planning in terms of land-use, road and building pattern, construction coverage, building configurations, vegetation, landscape materials, and open spaces control the performance of site resources of sun, light, and indirectly airflow within buildings. Wind flow depends on regional/macro features but is also affected and can be reduced or magnified by building group arrangements (Givoni B. , 1994). Additionally, these urban constituents control heat and humidity. The design of the urban realm in conjunction with climatic concerns contributes to obtaining a pleasant environment for a neighbourhood or a city (Golany, 1996).

- Building patterns

In hot-humid climates, winds act an important role to remove excess heat from the streets and to reach all buildings for the provision of cross-ventilation (Trimarianto, 2003; Dekay & Brown, 2014). The pattern of wind through settlements changes with different spatial structures (Patz, Campbell-Lendrum, Holloway, & Foley, 2005). Asfour (2010) using the analytical method of computational fluid dynamic (CFD) determined that the grouping pattern of buildings, as well as their orientation with respect to air movement, has a remarkable influence on wind behaviour and uniformity of air pressure. The researcher also concluded that the building forms containing central open spaces and facing the prevailing wind could make better use of air currents and capture wind around open spaces for passive cooling (Asfour, 2010). Zhang et al. (2011) support the dependence of wind pattern upon the building layout and wind direction through their experiments in the wind tunnel and CFD research.

Allegrini and his colleagues carried out CFD simulations to investigate the variations of thermal environment among six different urban building morphologies (Allegrini, Dorer, & Carmeliet, 2015). They found the complex interactions of building geometry, building pattern, and spacing to the performance of temperature and wind within such urban cases under the examinations of uniform building height, spacing, and orientation. The wind flow pattern within six urban forms analysed varies. That consequence differently influences air temperature inside urban areas due to the potential for heat removal. For examples of the urban patterns formed by cubical or elongated buildings, the façade temperatures are similar while the temperature in cubical building blocks is lower for a more effective wind environment between building blocks. Besides in their research, the façade temperature markedly reduces in more complex building patterns due to the overshadowing effect.

In relation to the orientation of a building or a building group, the site is encouraged to permit more than one orientation that likely benefits microclimatic improvement in and around buildings (Trimarianto, 2003).

A potential wind environment within a group of buildings depends on the pattern of staggering (Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 2000). With this arrangement, wind speed distribution is more uniform and without stagnant air zones around buildings relative to the normal pattern (Tantasavasdi, Srebic, & Chen, 2001). Additionally, further research on the relationship between building geometry and wind distribution showed that buildings with square shape would present a better air movement environment than those with rectangular shapes in an urban layout investigated.

- Building height and spacing

Three major wind regimes related to airflow over building arrays are isolated roughness flow, wake interference flow, and skimming flow (Oke, 1979). Those are categorised by the ratio of building height (H) to the gap between building rows (W). Therefore, two factors of building geometry and spacing affect the flow structures and wind velocity (Serteser & Ok, 2009). Lee et al. (1980) using cuboid models identified that the minimum ratio (H/W) should be 0.4 to get the wind distribution around the settlements of both normal and staggered urban patterns (Lee, Hussain, & Soliman, 1980). However, for the normal urban form particularly, the spacing between building arrays recommended is 5-7 times as much as their respective heights to encourage wind that can reach buildings after flowing over recirculating zones (Olgyay & Olgyay, 1963; Evans, 1980; Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 2000). Santosa suggested more details about acceptable spacing between building sides and between building rows as follows: 1:1 and 3:1 to building height in the grid pattern (Santosa, 1995).

Although the wind will flow easier through wider gaps, in areas with fewer trees solar heat can be stored in street or construction surfaces, that results in increased outdoor air temperature by 4.5°C in comparison with referred meteorological temperatures (Shashua-Bar, Tzamir, & Hoffman, 2004). The narrower spacing among buildings is, the more shade is created than wide streets (Dekay & Brown, 2014).

- Building density

The coverage of the construction area is a planning category in relation to the urban spatial pattern. Within a high-density neighbourhood, the spacing between buildings is so narrow and there is much overshadowing. As a result, the airspeed and direction of incident regional winds are changed by friction or blockage of buildings with different orientations. Linked to the design of individual buildings in compact urban areas, the use of passive cooling indoors by natural winds becomes restricted because of the surrounding convoluted wind environment (Trimarianto, 2003). The analysis of wind flow around residential blocks in the wind tunnel by Kubota et al. (2008) demonstrated that the air velocity decreases dramatically when increased the dwelling coverage ratio (Kubota, Miura, Tominaga, & Mochida, 2008).

In dense urban settlements, streets and alleys are shaded during the daytime, the thermal condition at a pedestrian level is more comfortable due to low mean radiant temperatures around (Dekay & Brown, 2014). Experimental and field studies have shown differences in the outdoor thermal environment between residential quarters with low, medium and high coverage ratio. Average ambient temperature is more satisfactory for residents in high-density neighbourhoods; however, wind flows around houses are average low velocity (Tantasavasdi, Srebic, & Chen, 2001; Emmanuel, Rosenlund, & Johansson, 2007; Kakon, Mishima, & Kojima, 2009; Andreou, 2014; Allegrini, Dorer, & Carmeliet, 2015).

- Streets

The road system, coupled with buildings and their layout, controls wind induction around a neighbourhood or a city (Dekay & Brown, 2014). Two major features of the streets in the design are width and orientation (Golany, 1996). The highest velocity winds in the streets are observed when the streets and the prevailing wind are parallel while perpendicular streets yield lower airspeed and more turbulence and the most wind blows over buildings (Yannas, 1995). In the tropics, the street orientation is 20-30° oblique to the predominant wind to maximise wind reaching all buildings (Dekay & Brown, 2014). Golany stated that the straight and parallel layout of streets will encourage wind flows into and within the urban block; on the other hand, the perpendicular pattern of them reduces air velocity (Golany, 1996).

Using parametric analyses, Andreou investigated the urban canyon microclimate between two street geometries in the traditional settlements planned by narrow and irregular roads and the modern ones with a wide and regular circulation pattern in Greece. The outcome showed that the road geometry of traditional settlements positively affects the urban environment and human comfort due to the shadowing effect (Andreou, 2014). Golany advises suitable street width for cities in different climates (Golany, 1996). For example, winding and narrow roads in hot-dry regions are potential to obstruct the impact of cold or hot winds and intense sunlight and to establish shadowed areas while wider streets encourage to ventilate the city; however, they also need to be shaded from solar radiation by vegetation in tropical climates. Additionally, the street material should be considered, for example, the asphalt roads can store and radiate large amounts of heat (Golany, 1996; Tong, et al., 2018).

- Vegetation & open spaces

Trees organised in the middle or sides of the streets moderate microclimate surrounding by absorbing dust and pollutants in the air, reducing noise from vehicles, minimising solar radiation, providing more shade areas (Golany, 1996). The type of trees (height, the density of leaves, and canopy width), as well as their density, are necessary considerations in vegetation for improving the urban climate in terms of heat reduction, ventilation gain, and relative humidity regulation (Dekay & Brown, 2014). Consequently, in tropical regions, the vegetation shows benefits for not only urban comfort but the aesthetics of city (Golany, 1996; Pham N. D., 2002; Tang, Viet, & Nguyen, 2007).

The scattered occupancy of greenery around urban areas increases the heat absorption from the sun in the ground layer and building envelope, which rises the air and surface temperature due to solar radiation (Oke, 1982). On the other hand, vegetation involves reducing the daily minimum temperature by 0.7°C and the average night-time temperature by 0.5°C in city districts in northern China (Tong, et al., 2018). Tong et al. evaluated the relationship of the urban morphology against the microclimate and comfort around Tianjin, China in 2015 by using weather stations to measure thermal variables at 46 different locations in the city (Tong, et al., 2017). Findings indicated the effect of vegetation on mitigating UHI effects and regulating the urban climate. Adding trees alongside roads reduces radiated heat from streets and building fabrics; therefore, outdoor temperatures can be lowered in summer.

In parallel with the growth of trees along streets, zoning them combined with water areas in open spaces potentially regulates the urban climate at the different scales of urban block or city depending on different sizes and proximity of public spaces (Golany, 1996). In hot climates, large green spaces decrease thermal stress by providing evaporative cooling, enhancing humidity, and supporting convective cooling, particularly in summer (Johansson & Emmanuel, 2006; Tong, et al., 2017). However, the size and detailed design of open spaces are considered in different climates. For example, in hot-dry regions, a system of small dispersed green spaces is more appropriate than larger open areas, which are desirable in hot-humid cities (Golany, 1996).

3.3 Opening configurations and occupant comfort

In the given outdoor environment, architects are responsible for understanding its characteristics and then seeking and applying appropriate passive design strategies for buildings to respond to that environment. Those can potentially touch the building fabric, the spatial layout within the building, landscape, and building systems to create a pleasant environment indoors for occupants. The design considerations should be from the schematic design stage for the effect of building operation and environmental performance further (Dekay & Brown, 2014). In the scope of the thesis, this section discusses the influence of opening designs on comfortable environments, particularly in residential buildings in warm-humid climates. With respect to the function and location of openings on the building fabric, they are classified into the following categories: windows, doors, screens, and vents/ventilators (Allard, 1998). Several empirical, experimental, and numerical studies have shown a close relationship between indoor thermal profiles and opening parameters (orientation, size, type, shape, placement, organisation, and material) (Ajibola, 1997; Hassan, Shaalan, & El-Shazly, 2004; Liping & Hien, 2006; 2007; Liping, Hien, & Shuo, 2007; Gao & Lee, 2010; Al-Tamimi, Fadzil, & Harun, 2011; Heiselberg, Bjon, & Nielsen, 2016; Sacht & Lukiantchuki, 2017; Elshafei, Negm, Bady, & Suzuki, 2017).

- Orientation

Openings on the building fabric are constantly exposed to both sun and wind for cooling, lighting, and heating for interior spaces (Givoni B. , 1976). In tropical regions, optimising the orientation of openings in design results in two aims: minimising solar heat gain and maximising natural ventilation (Konya, 1980; Al-Tamimi, Fadzil, & Harun, 2011). The solar energy entering through windows can heat indoor air, as a result, causes thermal discomfort and increases cooling loads, especially in summer. However, the impact of the sun can be assumed and mitigated by shading strategies, such as trees, overhangs, or louvres, the use of high thermal resistant building materials (Givoni B. , 1991; Akbari, Davis, Dorsano, Huang, & Winnett, 1992). Meanwhile, the interaction with the winds is more complicated to control (Sorgato, Melo, & Lamberts, 2016). The suitable selection of opening orientation, along with their size can reduce the impact of solar radiation elevating indoor air temperature by effective natural ventilation (Al-Tamimi, Fadzil, & Harun, 2011). Thus, the identification of opening orientation with respect to the prevailing winds of a particular area largely influences airflow in interior spaces, in particular in the hot-humid tropics (Givoni B. , 1994; Ajibola, 1997).

In relation to opening orientation, the openings located on the long facade of buildings should orient south or north for the allowance of winds and the prevention of solar heat from both west and east directions (Szokolay S. V., 2008; Aflaki, Mahyuddin, Mahmoud, & Baharum, 2015). The field measurements in a student accommodation hall in Penang, Malaysia showed a higher percentage of thermal acceptable hours in rooms with windows facing south or north relative to east and west (Al-Tamimi, Fadzil, & Harun, 2011). Similar findings were found in research by computational analysis on high-rise residential buildings in Singapore (Liping & Hien, 2006; 2007) and in Hong Kong (Gao & Lee, 2011). The deviation of thermal comfort percentage was around 20%. Furthermore, these studies also determined that such rooms with windows in east orientation are less hot than in the west direction. However, in the regions at low latitudes, predominant winds mainly blow from west and east, thus, a confliction is possible to define the best orientation between a minimum of solar heat and an optimum of ventilation (Givoni B. , 1994). For those cases, inducing wind flow is more priority in buildings in the tropics; thereby, suitable design details should be considered for shading openings but capturing the eastern or western wind for ventilation (Olgyay & Olgyay, 1963; Trimarianto, 2003; Liping, Hien, & Shuo, 2007; Dekay & Brown, 2014). In the restrictive condition of the site facing east or west, the orientation of building and openings should be 45° oblique to such directions to optimise ventilation and avoid direct sunlight (Konya, 1980; Liping, Hien, & Shuo, 2007).

Reviewing previous documents, the varying recommendations to optimise the opening orientation to the incident wind are found to maximise indoor air movement. Most research has agreed that the velocity of wind through openings can be optimal when they perpendicularly face the predominant wind of a locality (Olgyay & Olgyay, 1963; Boutet, 1987; Szokolay S. V., 1990; Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 2000; Hassan, Shaalan, & El-Shazly, 2004; Gao & Lee, 2010; Sacht & Lukiantchuki, 2017). Ajibola's investigations into the 550 housing units of 25 housing types in Nigeria showed that 95% of building windows are perpendicular to the incoming wind (Ajibola, 1997). Whereas, the worst performance of indoor airflow happens when the wind blows parallel to openings (Sacht & Lukiantchuki, 2017) or at the angle of 270° with them (Gao & Lee, 2010).

Another suggestion is that openings should be 45° oblique to the wind incidence (Givoni B. , 1976). However, wind pressure on windward sides can reduce by 50% with that angle of wind direction (Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 1973). The result of weaker air movement indoors when the wind hits the window at an angle of 45° compared to 0° was determined by CFD analyses (Hassan, Shaalan, & El-Shazly, 2004). Additionally, they also found a difference in wind distribution within a given physical model between two different wind directions. Meanwhile, through the investigation of indoor air movement in flats in Hong Kong, Burnett et al. (2005) concluded the most adequate natural ventilation occurred when such angle was 30°C (Burnett, Bojić, & Yik, 2005). Some studies identified that the best performance of natural ventilation in the building is achievable with a wider range of angles between openings and prevailing wind than the particular values, for example, 0° to 30° (Chand, 1976) (Dekay & Brown, 2014), 0° to 45° (Hassan, Shaalan, & El-Shazly, 2004). Givoni (1994) determined that the oblique winds to the openings within 30° and 120° could provide proper cross ventilation when they are organised in the windward and leeward building sides (Givoni B. , 1994).

- Opening size (window to wall ratios – WWR and window to floor ratios - WFR)

The ratios between window to wall/floor area are a dimension of building design having an impact on both heat gain and wind distribution in the building, especially in a hot humid climate. In this respect, larger openings can achieve larger indoor airspeeds (Konya, 1980; Givoni B. , 1994). That conclusion is determined through some studies in the field and wind tunnels (Hassan, Shaalan, & El-Shazly, 2004; Al-Tamimi, Fadzil, & Harun, 2011; Elshafei, Negm, Bady, & Suzuki, 2017). However, a contradictory issue is that thermal stress can be a significant problem if direct sunlight penetrates through unshaded openings (Givoni B. , 1994). For such unshaded windows, the WWR must be limited to 15%. Additionally, the risk of overheating is possible if the window area is more than 30% of the wall area at western or eastern facade (Trimarianto, 2003).

For rooms with single-sided ventilation, the effect of opening size on internal ventilation in the building is small, particularly when the incident wind is perpendicular to the wall surface (Givoni B. , 1994). However, if such an angle of winds is oblique, the opening area has a considerable effect on ventilation indoors (Tang, Viet, & Nguyen, 2007). Moreover, in the case of additional openings, not only positioned in the windward wall, the air movement in the room significantly improves (Tang, Viet, & Nguyen, 2007).

Table 3.1 Changes of indoor airspeed following by the ratio of inlet and outlet area (Olgyay, 1963)

F1/F2	a	F1/F2	a
1:1	1	1:5	1.4
1:2	1.27	2:1	0.63
1:3	1.35	4:1	0.35
1:4	1.38	4:3	0.86
F1: inlet area			
F2: outlet area			
a: coefficient of decreased or increased airspeed			

Meanwhile, in cross-ventilated rooms, the airflow rate and air velocity rise if inlet and outlet openings are larger (Konya, 1980; Givoni B. , 1994; Mochia, Yoshino, Takeda, Kakegawa, & Miyauchi, 2005). For given number and size of openings, the best values of airflow rate and airspeed occur when inlets and outlets are equal in the area (Givoni B. , 1994; Pham N. D., 2002; Tang, Viet, & Nguyen, 2007). If the size of leeward openings is more than in the windward side, the speed and air change rate in the room is accelerated (Konya, 1980; Allard, 1998). In contrast, in the case of similar outlet area, increasing inlet size produces low interior airspeeds as shown in Table 3.1 (Olgyay & Olgyay, 1963).

Alongside other factors of openings (shape and placement), the category of the area largely affect the internal wind performance in terms of flow rate, airspeed, and distribution in space (Givoni B. , 1994; Tang, Viet, & Nguyen, 2007). Based on the experiments in wind tunnels, Givoni and Chand determined two criteria of opening size influencing proper air velocity in the interior known as the window to wall area ratio (30-50%) (Chand, 1976; Givoni B. , 1976). Referring to that range of WWR, Ajibola investigated airflow in hundreds of functional rooms (living room, bedroom, and studying room) of university housings in Nigeria (Ajibola, 1997). The research observed more sufficient air movement in spaces having WWR within 30-50%. Be similar to Ajibola's work, Al-Tamimi et al. measured the comfort level in the student rooms that were ventilated and unventilated with three WWR variations (0%, 25%, and 50%) in the tropical climate of Malaysia (Al-Tamimi, Fadzil, & Harun, 2011). They stated that the significant improvement of thermal comfort in naturally ventilated spaces with WWR of 25%. That WWR figure is also determined to be a good limit to achieve the satisfactory air movement for thermal comfort in the free-running residences in Singapore (Liping, Hien, & Shuo, 2007) and single-sided ventilated spaces (Hassan, Shaalan, & El-Shazly, 2004).

Besides the parameter of WWR, Givoni and Chand also suggested that window to floor area ratios should be between 20-30%. Some studies have used that range of WFR to evaluate the thermal performance in the building (Amaral, Rodrigues, Gaspar, & Gomes, 2016; Sacht & Lukiantchuki, 2017). Sacht and Lukiantchuki assumed the airflow pattern in a hypothetical naturally conditioned room proposed with the WFR of 10% and 20%. The distribution, flow rate, and velocity of the wind perform better because of larger openings. Using the similar research technique to test the effect of WFR on the indoor environment in the context of Portugal, Amaral el at. shown that the desirable band of WFR for environmental impacts lies between 13% and 40% and overheating risks are possible if the WFR is 60%. However, they also noticed that the selection of WFR is also considered in relation to the building orientation, opening types, and seasonal climates (Amaral, Rodrigues, Gaspar, & Gomes, 2016).

Bring the findings above together, the limits of WWR and WFR to achieve a good naturally ventilated space/building can be wider between 25-50% and between 20-40%, respectively. However, larger openings against the exposed wall or floor area may cause the risk of overheating (Chand, 1976; Liping & Hien, 2006; 2007; Amaral, Rodrigues, Gaspar, & Gomes, 2016). Investigations of comfortable and uncomfortable environments in flats in Singapore, the number of uncomfortable hours in the flats designed with larger openings in exposed walls was more (Liping & Hien, 2007). In those cases, the external heat gain rises the indoor air temperature and therefore encounters occupant thermal tolerance despite increased air velocity when the opening area increases. In warm climates, the façade design with large or full openings are common to maximise airflow; however, they need to be shaded to protect from solar radiation (Koenigsberger O. H., Ingersoll, Mayhew, & Szokolay, 1973).

- Opening type

Opening types involve controlling thermal conditions in the building (Givoni B. , 1994; Tang, Viet, & Nguyen, 2007). Various window or door types such as double-hung, sliding, casement, and pivot differently affect the air pattern around the room and govern the direction and velocity of the flow (Givoni B. , 1994; Sacht & Lukiantchuki, 2017). Gao and Lee carried out the CFD simulations to examine the effect of three window types including end-slider, top-hung, and side-hung on the natural ventilation conditions of flats in Hong Kong (Gao & Lee, 2010). Findings show the best air movement when applying the end-slider windows; on the other hand, the worst performance of natural cooling is when using the top-hung windows. In comparison with the side-hung windows, the ventilation effect of sliding windows is more than 17.2%. Besides sliding windows/doors, folding ones are also recommended to employ in warm-humid climates (Konya, 1980).

By the numerical analyses, Wang et al. found the divergence of thermal profiles in single-sided ventilated rooms that were tested with various window types under a similarity of window area (Wang, Zhang, Wang, & Battaglia, 2018). The six window types investigated consist of the vertical slide window, tilt window, awning window, horizontal pivot window, turn window, and vertical pivot window. They are normally used in residential buildings. In windward conditions, the horizontal and vertical pivot windows produce the highest air change rate whilst the tilt window shows the worst performance with increased wind speed. On the contrary, in leeward conditions, the airflow rate provided by the tilt and horizontal pivot windows is larger than others are. Additionally, the ventilation performances of them are greatly similar. That finding is similar when using the vertical pivot, turn, and vertical slider windows. The researchers also suppose that the use of which window types should be considered under the profile of local weather conditions.

- Opening placement

The placement of openings (centre or off-centre), particularly inlets, governs the distribution of airflow within the occupied zone (Konya, 1980; Tang, Viet, & Nguyen, 2007). Moreover, combining with other opening factors, for example, area and type, the air pattern and velocity is improved significantly when changing the position of openings. In a reference room, increasing the area of a window located in the centre of the windward wall provides the better ventilation condition than the off-centre window at all angles of wind incidence (Hassan, Shaalan, & El-Shazly, 2004). A similar observation was found when using CFD analyses to test air movement in the buildings of Tohoku University, Japan (Mochia, Yoshino, Takeda, Kakegawa, & Miyauchi, 2005).

Hawendi and Gao (2016) carried out the three-dimensional computational analyses to examine the wind distribution in various cross-ventilated rooms of a low-rise building applied to different opening positions. They tested three scenarios of inlet and outlet placement as shown in Figure 3.5: case A – central inlets and outlets, case B – left side inlets and outlets, and case C – right side of inlets and left side of outlets. The outputs show that the air movement in case A is the most comfortable due to the weaker recirculation zones in all rooms. In addition, the flow rate in case A is greater than case B and slightly different compared to case C. Both case A and C result in high ventilation effectiveness because of the high air exchange rate through rooms (Hawendi & Gao, 2016).

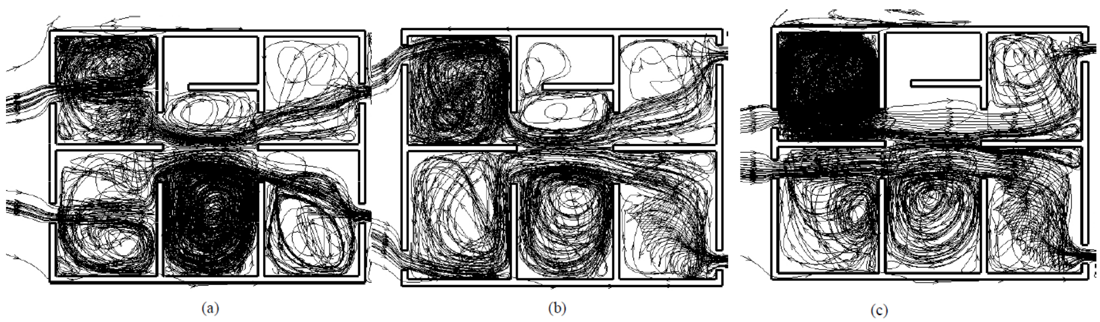


Figure 3.5 The pattern of wind flow in three cases of opening positions (Hawendi & Gao, 2016)

The effect of opening placement on the ventilation efficiency should also be considered in the relationship with the room geometry and ventilation system. Rabanillo-Herrero et al. conducted numerical simulations to test that correlation in an L-shape room (Rabanillo-Herrero, Padilla-Marcos, Feijó-Muñoz, Gil-Valverde, & Meiss, 2020). In the case of a single-sided ventilated room, the air change rate in the room having an opening in the windward wall is poorer relative to another opening positioned nearby. However, the distance between them is not significant for the change of flow rate inside. Moreover, in another case of cross-ventilated room, if the inlet is placed close to the corner and far from the outlet, the velocity and distribution of airflow are much improvable.

- Opening location

The location of openings not only can produce different natural ventilation principles (single-sided, double-sided, or stack effect) but regulates the indoor flow pattern and rate (Dekay & Brown, 2014). The position of outlets relative to inlets is not alignment, which can produce the effect of stack ventilation within the built-up space (Tang, Viet, & Nguyen, 2007; Szokolay S. V., 2008). In a similar inlet position, the speed of the internal air stream is higher when outlets are placed at the lower part of the leeward wall (Shetabivash, 2015). Moreover, under the operation of cross-ventilation, the location of inlet and outlet openings in adjacent or opposite walls provide different airflow rates (Tang, Viet, & Nguyen, 2007).

In the study of Ajibola in the university accommodations in Nigeria, five types of opening location were found including rooms with only single opening locate don windward side (I), rooms with openings on opposite walls, in which, one facing the prevailing wind (II), rooms with openings on adjacent walls (III), rooms with three openings, in which, two of them playing a role of inlets and one on the opposite side (IV), rooms with three openings that are located in the following of two on the windward side and one on the adjacent wall (V). From the results of on-site investigations, the types of I, II & III are popular to use in the opening design. 53% of all given spaces are using the principle of cross-ventilation with openings located on opposite walls. Meanwhile, 25% of building rooms were designed with only one opening facing the incident wind for applying single-sided ventilation (Ajibola, 1997).

Elshafei et al. studied on the influence of window locations on thermal environments in a residential building in New Borg El Arab city by using CFD simulations (Elshafei, Negm, Bady, & Suzuki, 2017). Adding a new opening in the opposite wall of a room with an already windward window improves the environmental performance inside bedrooms and halls of the building. The air temperature significantly reduces and air velocity increases by 4 times after changes.

- Opening shape

The shape of openings is various in practice, such as rectangular, circular, elliptical, triangle, round top, and octagon (Allard, 1998). Among them, windows/doors of the rectangle (vertical or horizontal) or square are more common. Between the vertical and horizontal plane of the free-opening area of openings, a more consistent indoor air pattern is created when the wind enters through the opening of vertical and straight shape (Dekay & Brown, 2014). Consequently, "*the height of the inlets may define the level of the main indoor airflow*" (Givoni B. , 1994). Shetabivash (2015) simulated the airflow recirculation by CFD in a reference building analysed with horizontal and/or vertical and square inlets and outlets (Shetabivash, 2015). The researcher finds the changed horizontal flow paths when replacing horizontal to vertical openings in the windward surface. Different shapes of inlet opening affect the airflow angle after through the opening despite the similar incident wind; therefore, the airflow circulation zone is differently formed in the room. In three opening shapes studied including vertical rectangle, horizontal rectangle, and square, the air movement within the space of square openings is the most sufficient by the highest volume flow rate and airspeed. Through simulated cases, the author concluded that the windward inlet majorly influences the ventilation efficiency and airflow pattern in cross-ventilated rooms/buildings, particularly their two factors: position and shape.

- Impact of window shading devices

Shading of openings is important in façade design of tropical buildings to minimise the risk of overheating from the sun (Konya, 1980; Elshafei, Negm, Bady, & Suzuki, 2017). The configuration of vertical and horizontal projections on the wall can induce the outdoor winds and control the distribution of air movement in the interior (Tang, Viet, & Nguyen, 2007; Dekay & Brown, 2014). Liping and Hien examined the thermal environment in a flat with various shading designs in Singapore in the dry season of May (Liping & Hien, 2007). The study was planned with three cases of overhang depth: 0, 60, and 90cm on different 4 orientations of the building: south, north, east, and west. The conclusion is that the cooling degree hours remarkably reduce in summer when the overhang is deeper.

A numerical study on the thermal and wind performance of a residential building showed that the shade on the bedroom window decreases the indoor temperature but the air velocity is unchanged (Elshafei, Negm, Bady, & Suzuki, 2017). Amaral, along with his team found the relationship of three factors: orientation, WFR, and overhang having on the thermal condition in a reference room in Coimbra, Portugal (Amaral, Rodrigues, Gaspar, & Gomes, 2016). Their findings are no contribution to building comfort if the overhangs are in the north, northeast, and northwest orientation. However, when the window size is larger, the overhangs have some effect to decrease cooling degree hours.

3.4 Conclusions

Air movement is useful for physiological and psychological comfort and better indoor air quality of occupants, particularly in hot-humid climates (Olgyay & Olgyay, 1963). As mentioned in discussions in section 2.6, the risk of draught discomfort is low even with higher air velocities in the tropics when compared to moderate or cold climates. Thus, natural ventilation is critical for passive cooling when the temperature difference between indoor and outdoor air is small (Heiselberg, Bjon, & Nielsen, 2016). All-day ventilation is recommended in tropical houses compared to other strategies (night-time or daytime only ventilation) (Liping & Hien, 2007). Olgyay also suggests that ventilation should be optimised in the building over 85% of hours (Olgyay & Olgyay, 1963).

The major principles of natural ventilation including wind-driven and stack-effect should be used to produce air movement in residential buildings in the regions with the high levels of temperature and humidity (Tantasavasdi, Srebic, & Chen, 2001; Aflaki, Mahyuddin, Mahmoud, & Baharum, 2015). However, the efficiency when applying one or both ventilation mechanisms relies on a combination of internal and external factors (Gao & Lee, 2010). The ambient factors are local climate, prevailing wind speed and direction, location, orientation, and urban components of the local neighbourhood. They introduce constraints to the control available and mean consideration of detailed building designs is required by site planners and designers (Gao & Lee, 2010). Meanwhile, architectural design features of the building responding to the surrounding environment may reduce the impacts of solar heat and cooling load on a building, particularly in summer (Givoni B. , 1994).

The façade design is complicated because it involves aspects of architectural styling, as well as, the need to deal with complexities of environmental control. It is therefore important to provide design guidance to help optimise outcomes.

Chapter 4 STUDIES ON ‘SHOP-HOUSE’ DWELLINGS IN HCMC

This chapter describes ‘Shop-house’ dwellings and their intrinsic characteristics in planning and design classified in various styles and periods of history. An important part of this chapter conveys the research results related to ‘Shop-house’ building types and urban spatial structures in HCMC. Those have been identified by the research group of the University of Cottbus, Germany, and provide underlying information for this thesis. They are reported as significant findings of a funded project – “Integrative Urban and Environmental Planning for Adaptation of Ho Chi Minh City to Climate Change” by the German Federal Ministry of Education and Research. Each building type or each urban morphology has respective and particular distinctions of building configurations or urban conditions, which differently shape the indoor and outdoor climate of ‘Shop-house’ dwellings for occupant comfort. The author here will investigate environmental conditions based on a systematic classification of housing and urban types from the German study, and expect to find the relationship between them.

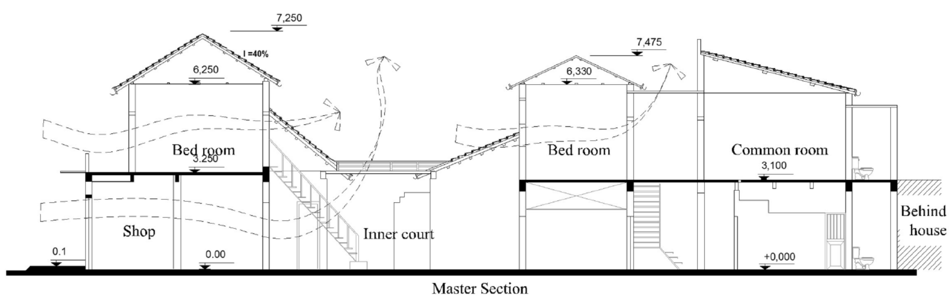
4.1 Definition of ‘Shop-house’ dwellings in Vietnam

The ‘Shop-house’ is a vernacular residential typology repetitively found not only in Vietnam but also in other countries in Southeast Asia such as Malaysia, Thailand, Laos, and Singapore (Aranha, 2013). Yukio Nishimura (1999) found that the Chinese introduced this building typology to Southeast Asia through trading activities. In Japanese, the shop-house is called ‘Ruko’ standing for two words: ‘Rumah’ means house and ‘Toko’ means shop (Le M. T., 1999). Although the Chinese culture has to some extent influenced on the residential architecture in Vietnam, the design characteristics of the Vietnamese shop-house show distinction because of combining with vernacular contextual terms: culture, climate, materials, and traditional architecture (Le M. T., 1999). Shop-houses were originally found in Hanoi as known as Hanoi Old Quarter, and then, in Hoi An and more lately in HCMC.

The shop-house dwelling has a particular settlement pattern including a ‘shop’ for commercial/retail/work purposes normally found on the ground floor, and the ‘house’ providing accommodation on the upper floors (To, 2008; Aranha, 2013). All dwellings are positioned along and perpendicular to streets or alleys, which defines streets and urban blocks (Aranha, 2013). Thus, people can approach the main façade of buildings from road or alley before entering deeper within the building (Dam, 2011). Typically building dimensions are 3-5m in width and 20-25m in-depth, even reaching up to 100m in some older traditional houses. The shop-house can comprise one storey or more up to a normal maximum of five (Le M. T., 1999). An overarching view of the morphologies of shop-houses shows they are diverse in size, configuration, style, and structure.

In general, a ‘shop-house’ is basically a form of terraced house, but its name refers to the commercial function of the house besides residence (To, 2008). Additionally, its principal characteristic is a convoluted building form but often appearing to be like a long and thin tube, so they are also known as ‘Tube house’ or ‘Nhà ống’ in Vietnamese. Consequently, in Vietnam, a terraced house can be called in different names: ‘shop-house’, ‘street house’, or ‘tube house’ (To, 2008).

(a)



(b)

(c)

Figure 4.1 38 Hang Dao – An ancient shop-house built in 1856 in Hanoi Old Quarter: floor plans (a), section (b), exterior and interior (c) (Le, 2011)

According to the studies of To and Le on Vietnamese shop-houses, there may have been two major shop-house typologies divided by historical timeline and urban characteristics (To, 2008; Le H. N., 2011). The shop-houses built before and in the 19th century reflect the responses to surrounding environmental conditions and vernacular features related to human scale, social relationship, use of materials, and spatial composition (To, 2008). Particularly, in traditional shop-houses, for example, 38 Hang Dao in Hanoi Old Quarter as shown in Figure 4.1; in this, the building configuration and horizontally and vertically spatial organisation and its interactions to surroundings allow frequent operation of natural ventilation and penetration of daylight to provide thermal satisfactory conditions and well-being for occupants. In ancient buildings, there are likely more than one family, even up to 10 households owning different spaces within a house (Le H. N., 2011).

Meanwhile, the residences built following the national Economic Reform in 1986, that are commonly known as the modern 'street house', appear in contemporary urban patterns, in particular, in large cities (Figure 4.2) (To, 2008). After that milestone, the shop-house practice has become diverse with no specific directions of architectural style, identical characteristics, aesthetics, and planning controls. To (2008) categorised the types of modern street houses in two ways - morphology and number of open sides (Figure 4.3). Firstly, classification by morphology, he found a total of principal six subdivisions: (1) full plot/full height, (2) one sky well/full height, (3) two sky wells/full height, (4) full plot/single-step façade, (5) one sky-well/multi-step façade, and (6) one front yard/one sky-well/full height. Secondly, three shop-house types classified according to many open sides consist of one-side open (1), two-side open (2), and three-side open (3). Compared to the shop-houses built before 1986, the optimal construction of modern dwellings in terms of building height and land area, along with the compact urban pattern of residential neighbourhoods accounts for difficult conditions to get thermally comfortable environments indoors. The performance of natural ventilation and daylighting is restricted.

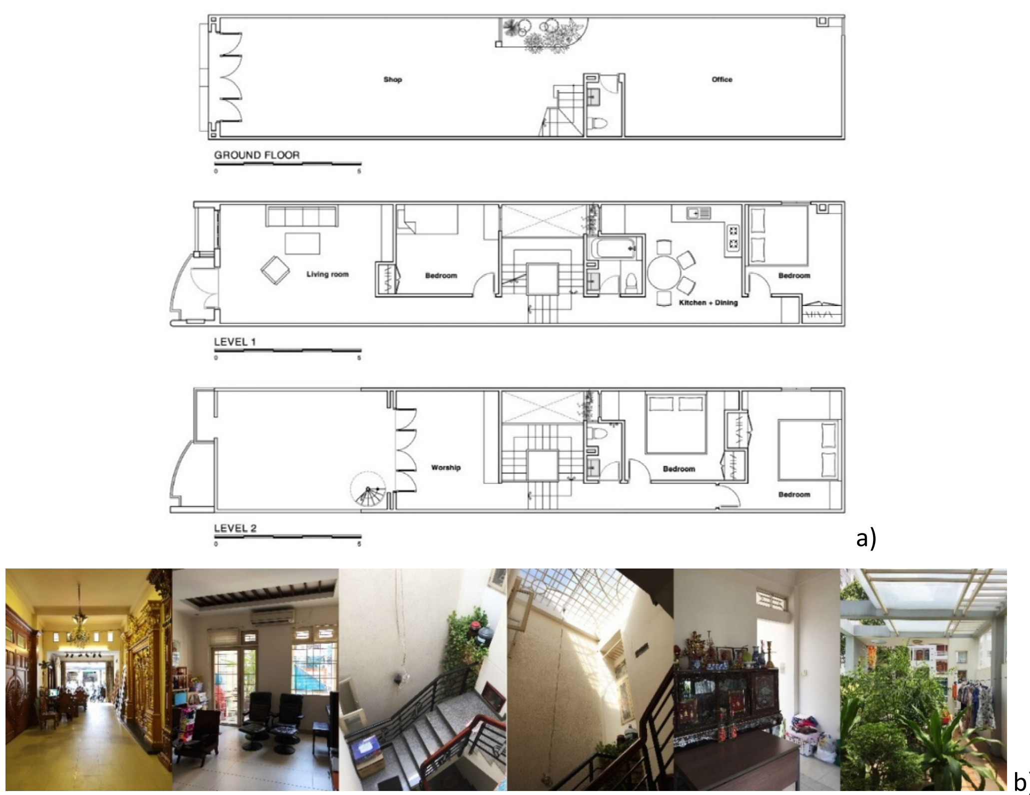


Figure 4.2 A modern shop-house in HCMC after 1975: floor plans (a), and the exterior and interior (b)

The housing market in Vietnam includes three major categories: 'shop-house', detached house (villa), and flat, in which, the 'shop-house' dwelling typology is predominant (98.5%) (CPHSC, 2010) (Parkes & Burrage, 2013). Particularly in HCMC, the total construction coverage of shop-house buildings was approximately 95% of the built-up land area for residential buildings according to the field observations within 2010-2014 (Downes, Rujner, Storch, & Schmidt, 2011). As will be indicated below, the primary characteristics of shop-house dwellings in HCMC are classified into different periods of city history.

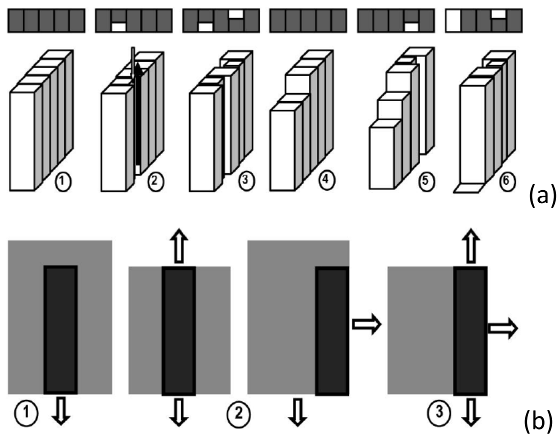


Figure 4.3 Typologies of modern shop-houses by morphology (a) and number of open sides (b) (To, 2008)

4.2 Architectural characteristics of 'shop-house' dwellings in HCMC

A start point is "Gia Định thành thống chí" – a genuine collection of antique historic and geological documents of southern Vietnam recorded by Trinh Hoai Duc in the 1800s, which describes the city's history since 1698 when Nguyen Huu Canh – a Vietnamese General was sent to reclaim and establish an administration in the south of Vietnam by the directive of the Nguyen Dynasty (Trinh, 1972). Initially, the former name of this land was Gia Dinh. Although the current official name of the city is Ho Chi Minh City after 1976, it is also known as another name - Saigon. In general, the history of HCMC is classified into four primary stages corresponding to the four periods of shop-house development in the city as follows: 1698-1859, 1859-1954, 1954-1975, and after 1975 (Le M. T., 1999).

4.2.1 Before 1860 – "Ancient architecture"

After establishing administrative structures of the Vietnamese at the end of the 17th century in southern Vietnam, Saigon became a centre of authority, commerce, and settlement with 20,000 population (Van, 1989). In the 18th century, the citadel system around the city was completed, and within it, residences and towns planned by a grid pattern were located close to rivers and canals to facilitate business and trading, particularly of rice products (Van, 1989). Consequently, Saigon was also known as one of the largest harbours in exporting rice in Southeast Asia. The commercial enhancement attracted the number of migrants from neighbour nations such as China, Cambodia, and India (Tran, et al., 1998).

The primary urban planning before 1860 was characterised by many market towns over the city. The initial shop-houses were mainly built up along market streets, where the local people lived in parallel with making business (Nam, 1997). The architectural principles of the ancient shop-house dwelling are one or two-storey buildings with yin and yang tiled roof and timber structure of most building elements such as columns, walls, beams and slabs, especially unique types of traditional trusses (Figure 4.4c). The Vietnamese ancestors show a master level of the woodwork in traditional houses. The residences well adapt to the warm-humid climate through passive cooling and heating designs (Le M. T., 1999).

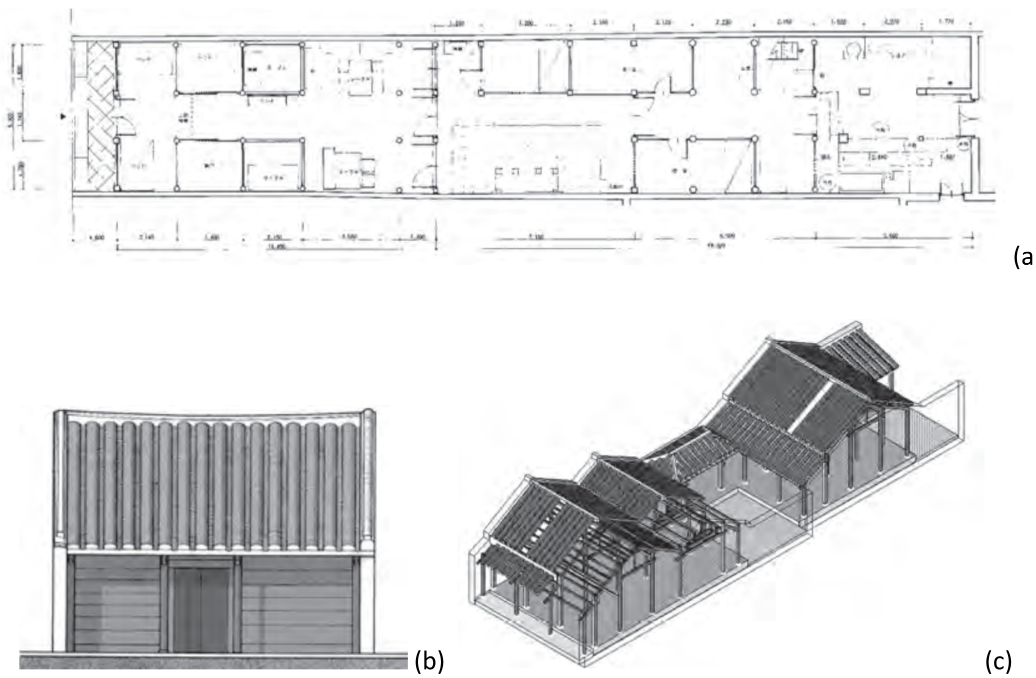


Figure 4.4 Typical architecture of an ancient shop-house before 1860 in Vietnam: (a) floor plan, (b) elevation, (c) sectional perspective (Hoi An Centre for Monuments Management and Preservation, 2008)

The housing dimensions are 4-5m in width and 30m in depth, even up to 100m. Depending on building depth, the interior spaces are variously organised; however, an underlying layout is devised in the order: retail close to the road, worship space + living room, courtyard, bedrooms, courtyard, dining room, courtyard, backup rooms (Figure 4.4a). In between a long building, one or more courtyards are integrated for convective ventilation and daylighting. To connect the different parts of the house, bridge houses are used (Figure 4.4c). The building facade is commonly divided into three compartments, in this, the entrance, as well as the main corridor, is at the middle and two side parts are functional rooms/spaces (Figure 4.4a & b) (Le M. T., 1999). The housing elevation was designed simply without any fancy decoration. The main features on the façade of traditional shop-houses are a deep roof overhang to protect sunlight and rain, additionally, movable wooden shutter panels called as 'Ván lùa' in Vietnamese folk architecture for security, spatial separation and wind permeability (Figure 4.4b). Meanwhile, the internal spaces are separated by the movable wooden partitions with delicately carved patterns (Nguyen Q. H., 1995). They enable the permeability of natural wind and light through spaces.

4.2.2 Within 1860 and 1954 – "Eclectic architecture"

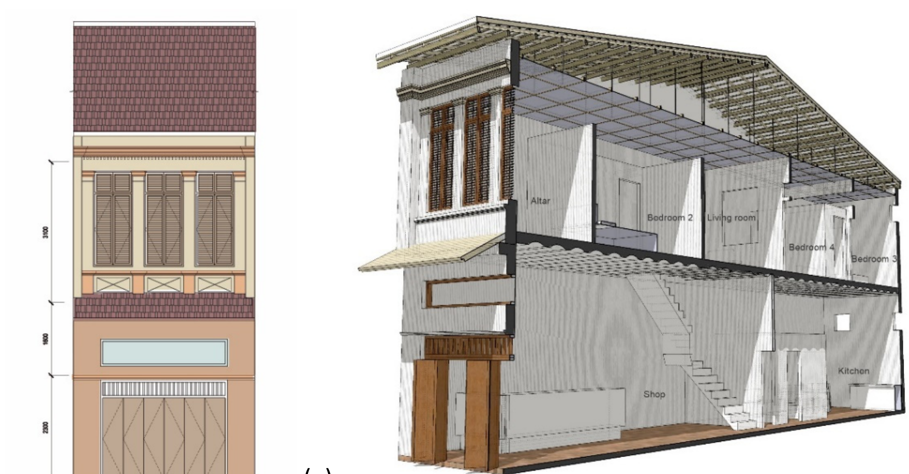
For almost 100 years between 1860 and 1954, Vietnam was a colony of France. Saigon was quickly orientated as a centre of culture, economy, art, and education under the French colonialism in Indochina and Southeast Asia. Saigon was widely known as "Pearl of the Orient" (Tran, et al., 1998). Many new building typologies, for example, office, barrack, church, cultural house, shopping mall, hotel, and factory were presented and built. For the particular built environment of residences, a great number of shop-houses were constructed. Additionally, there was the initial appearance of villas (Dam, 2011).

During that period, more immigrants came to Saigon, especially the Chinese in southern China (Guangzhou) in various positions such as investors, labourers for the French, builders, or traders. Therefore, many multi-scale Chinese communities have been settled across the city until now, in this, the largest Chinese town has been located in Cho Lon, District 5 (Nguyen Q. H., 1995). Under the French regime, considerable economic development took place, along with the motivation of worldwide trading and cultural interference linked to changes in housing design in Saigon. The shop-house architecture in this stage is the harmonic eclecticism of French classic style, Chinese culture, and Vietnamese vernacular tradition (Figure 4.5) (Ton, Tran, Truong, & To, 2010). In accordance with the researchers on the Vietnam architecture and history, the architectural variations of shop-house buildings over the colonial period can be sub-divided into two phases - before and after 1914. The details are shown below.

Figure 4.5 Shop-houses were built between 1860 and 1914 in Cho Lon, District 5 (Uy Huynh, 2017)

Before the First World War, most shop-houses were planned in blocks along and perpendicular to main roads or alleys with the standardised plots of 4m width and 20m depth. The housing height is 2 to 3 floors. The main construction of houses is a brick wall, site-cast concrete slab or brick slab supported by steel beams, and tiled roof. The spatial organisation into the building is simple without courtyards, unlike the shop-houses built before 1860. The land area is optimised for living, business, and storage; the use of front space close to the road like a shop is unchangeable. The façade decorations are followed by the Western classic details, for example as shown in Figure 4.5-6 (Dam, 2011).

A side corridor and a staircase in the middle connect the interior. Moreover, interior spaces are separated by the low walls not touching the ceiling. Additionally, both the front and back walls have openings so that the wind can enter and leave through the house (Figure 4.6b). For opening design, the vernacular configuration of windows and doors was used to facilitate air movement in the building during the whole day (Dang, 2012). Doors are created with two parts: the lower part of folding solid timber panels for security, the upper part of balusters for passive wind flow. Meanwhile, shutter windows were preferable to use for many functions of daylighting, ventilation, and privacy (Le M. T., 1999).



(a) (b)

Figure 4.6 Drawings of shop-houses in Cho Lon between 1860 and 1914: elevation (a), 3D section (b) (Dang, 2012)

After 1914, the French widely expanded the city size in many ways: geographic administration, population and economy to exploit and compensate for the losses of France during the 1st World War (Tran, et al., 1998). As a result, a large movement of immigrants from the provinces around Saigon and other countries occurred in the 1920s. The expansion of urban citizens affected the provision of settlements. Regarding the housing crisis, row houses and low-rise residential quarters were built only for renting (Figure 4.7), along with the increasing number of individual shop-houses. In general, the rental spaces in row houses were divided by floors and households shared one common staircase in the centre of row or two at the sides; therefore, there is a front or back shared corridor to approach households (Le M. T., 1999).

The political situation of France in Indochina following 1914 also contributed to changes in the architectural style of shop-house buildings in Saigon that combined the vernacular architectural identities (‘three-compartment house’, ‘Dinh house’, or yin and yang tiled roof, etc.) with the construction technology, simple layout, materials, and outer decorations of the Western (Le M. T., 1999). Interior furniture, inner decoration, or small landscape was designed following the Vietnamese tradition. The main structure of the house is concrete for columns, beams, and slabs, along with the use of brick walls. Between 1914 and 1945, some new building elements were presented, such as dormers, concrete consoles to support roof overhangs, and concrete balconies with classical steel handrails. In addition, on the main façade, the Renaissance skirting was used to decorate wall/column-top, and windows’ vault, furthermore, the pediment was to cover the roof end and it was carved with many Renaissance details (Figure 4.8).

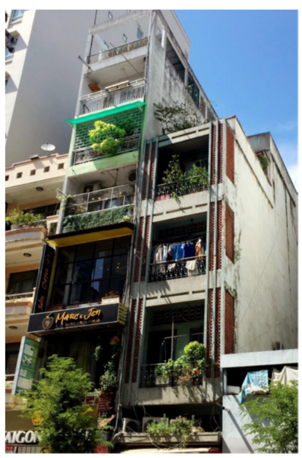
Figure 4.7 Rental row houses on Tran Hung Dao street, district 5

Figure 4.8 Shop-houses in Cho Lon, District 5 after 1914

4.2.3 Between 1954 and 1975 – “Tropical modern architecture”

Following 1954, Vietnam was divided into two different administrative parts: north and south. Southern Vietnam was a colony of America, in this, Saigon took on the role of the capital (Tran, et al., 1998). Then, there was the great immigration of the Vietnamese from north to south in the 1960s, which increased significantly city population in Saigon, evidently, 1.4 million in 1961, and 2.5 million in 1965 (Nguyen T. B., 1997). The enlargement of the city area and urbanisation was thereby an unavoidable response to the growth of population. Many new infrastructure systems were built to serve the expansion of the USA regime in southern Vietnam, for example, the widespread construction of hotels, plazas, entertainment buildings, banks, settlements, and roads around the city. Between 1960 and 1970, the dramatic increase of population was a factor leading to the initial development of high apartments (over five floors) in Saigon (Le M. T., 1999).

Between 1954 and 1975, the Modernism had significant influences on housing design in Vietnam, particularly in Saigon through the introduction of American architects and Vietnamese architects who studied abroad. Furthermore, the first generation of Vietnamese architects, who graduated from the Indochina College of Fine Arts, Vietnam, had the enthusiasm to support Modern Architecture in Vietnam (Tran, et al., 1998). However, the Vietnamese designers delicately integrated the regional identities of climate, tradition, and culture into the austere principles of modern architecture to create a distinct movement in architecture in Vietnam as known as 'Tropical modern architecture' (Nguyen K. , 2012).


(a)

(b)

Figure 4.9 Modern shop-house on Le Thanh Ton str. (a), in Cho Lon (b)

Most shop-houses and row houses over that period were constructed using concrete frames, brick walls, and flat concrete roofs. The utilisation of modern materials such as concrete, steel, and glass was common at that time. The modern construction technology enabled the building of taller houses up to 5 floors (Figure 4.9) (Dam, 2011). Furthermore, the building layout was simple and functional: the shop was always on the ground floor and close to main roads; and then, the staircase, along with the light well was in the middle; and the kitchen + dining + wet court at the rear (the wet court is the washing area of clothes and cooking stuff); living room, bedrooms, and altar are on upper floors; the terrace and drying court are on the top (Le M. T., 1999).

Austerity, strength, and gentleness were the principal criteria in the façade design of modern shop-house dwellings in Saigon before 1975 (Figure 4.9-10) (Dam, 2011; Nguyen K. , 2012). The wash-stone, terrazzo, or mosaic, combining with neutral or light paint colours were household preferences to finish the look of their house (Figure 4.10) (Dam, 2011). To respond to the conditions of tropical climate (warm temperature, humidity, and heavy rainfall), the design strategies for building envelope included: full balconies of building width (Figure 4.10a); ventilation bricks (Figure 4.9a); louvres (Figure 4.9 & 4.10b); projection walls; and concrete depth overhangs (Figure 4.10c). These were commonly found in Vietnamese modern architecture including residential buildings (Nguyen K. , 2012; Schenck, 2018). These elements of building fabric not only create an aesthetic look for the building but contribute to regulating the indoor environment in terms of daylighting, shading, and ventilating. For opening configurations, their geometry was a simple and square shape. In addition, wooden doors and shutter windows were preferable for using on upper floors while the steel or glazing folding doors were utilised on the ground floor (Figure 4.10a & c) (Le M. T., 1999).

(a) (b) (c)

Figure 4.10 Morden shop-houses and row-houses around the city between 1954-1975: (a) (Tran, 2018), (b) (Mel Schenck, 2018), (c) (John Hansen, 1965)

4.2.4 From 1975 to the present – "Chaotic architecture"

Vietnam gained independence in 1975 and after one year (1976), Saigon was officially renamed Ho Chi Minh City (Tran, et al., 1998). Due to losses caused by wars during the previous hundred years, the economic conditions of HCMC and Vietnam after independence were very depressed. Facing the current scenario, the government firstly carried out the Economic Reform plan– 'Đổi Mới' across the country in 1986, from that, the national economy has developed dramatically until now. The rapid growth of the economy links to the enhancement of population and urbanisation, thus, the housing supply is a huge challenge. The governmental management and orientation in settlement planning have underestimated the real performance of the housing market. As a consequence, the architecture of residential buildings including shop-houses in large cities (HCMC) is chaotic without identities, specific styles, and controls (Dam, 2011).

Figure 4.11 Some shop-houses in HCMC after 1975

Figure 4.12 Some examples of contemporary shop-house in HCMC since 2010

The characteristics of vernacular context have not been considered as significant influences on the creativity and practice of housing architecture, as a result, a mix of diverse styles exists (Modernism, Renaissance, Eclecticism, Port-Modernism, etc.), and a variety of volumes, colours, materials, openings, and building configurations (Figure 4.11) (To, 2008). A large number of new shop-houses have been built on streets or alleys and in new and existing residential neighbourhoods across the city. The functions of houses are also various: accommodation only, accommodation + shop, or the entire house as a business. Due to a lack of strict planning management, the buildings' height is diverse up to 9 floors. The building width is 4-6m; however, there are also many houses with 2-3m width. Meanwhile, the depth of houses is from 10-30m (Le M. T., 1999). Recently, more contemporary designs of shop-house in HCMC and Vietnam have shown the studies and regards of designers to create the houses that achieve aesthetic values, creative thinking, contemporary, and the comfortable environment for occupants under considering the influences of local climates and identities (Figure 4.12).

4.3 Classification of 'shop-house' dwelling types

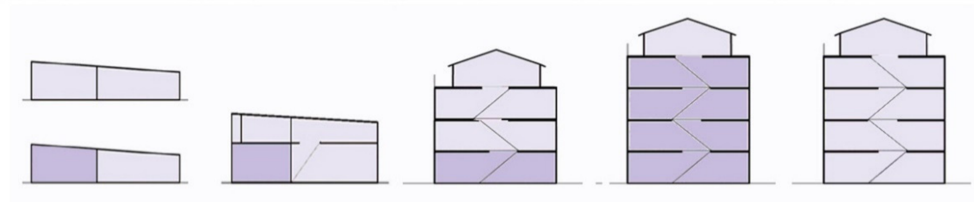
As will be shown below, the classification of 'shop-house' dwelling types is found based on the valuable findings of research on the risks of climate change happening to the HCMC's settlements, that was conducted by a group of researchers of the University of Cottbus, Germany between 2010 and 2014. The project was funded as a part of the research programme "Sustainable development of the Megacities of Tomorrow" by the German Federal Ministry of Education and Research in cooperation with the Department of Nature Resources and Environment in HCMC (Downes & Storch, 2014). To assess the climatic impacts and the adaptation of urban environment for the present and in the future in the city, the researchers approached the issue by considering residential building types and spatial indicators (Moon, Downes, Rujner, & Storch, 2009; Downes, Rujner, Storch, & Schmidt, 2011). The residential typologies across the city were identified by the extensive field studies into three major groups: shop-house, villa, and flat. Particularly, a total of five shop-house building types were found as shown in Figure 4.13: rudimental shop-house (A1), traditional shop-house (A2), new shop-house (A3), commercial shop-house (A4), and row house (A5). The subdivisions are attributed to distinct construction, functionality, and size (Moon, Downes, Rujner, & Storch, 2009).

Figure 4.13 Five shop-house dwelling types in HCMC (1: rudimental house, 2: traditional shop-house, 3: new shop-house, 4: commercial shop-house, 5: row house)

With the shop-house architectural characteristics in such different historical periods, the traditional shop-houses were built before and in the early 20th century. There is no doubt that they are the architectural and municipal heritage of Saigon. However, their preservation has faced the pressures of population and urbanisation growth, though the specific departments of Heritage Management and Conservation in HCMC have had policies and efforts in supports. Nowadays, the traditional shop-house dwellings are scattered around the city districts, especially concentrated in district 5 (Cho Lon), 1, 6 & 8.

Another four shop-house building types have appeared since the Economic Reform in 1986. In detail, the rudimentary houses have been created since the early 21st century as a result of the uncontrollable explosion of population in HCMC. Those houses are mainly located along canals or rivers. In the future with urban spatial orientation in the period 2016-2025, the families living in the approximately 19,254 rudimental units will be resettled in social housings (Pham T. , 2017).

Table 4.1 'Shop-house' building typologies in HCMC (Downes & Storch, 2011)



A-1 Rudimental	A-2 Shop-Traditional	A-3 Shop-New	A-4 Shop-Commercial	A-5 Doppel/Rowhouse
- 1-2 Floors - Residential, (Shop on the road front) - Wood, Brickwork, assortment of materi-als and construction modes - Access: Street, Canal	- 2-3 Floors - Shop on the outside periphery borders to street, residential - Wood, Brickwork, Reinforced concrete -Access: Street and in part back alleyways	- 3-5 Floors - Shop on the ground-floor, Residential - Reinforced concrete, brickwork, glasswork - Access: Street (often from two sides)	- 4-9 Floors - Basically commer-cial use, limited resi-dential use - Reinforced concrete, brickwork, glasswork - Access: Street (often from two sides)	- 3-5 Floors - Residential - Reinforced concrete, brickwork, glasswork -Access: Street

The new shop-house (A3) is the most dominant dwelling type in five housing categories (Moon, Downes, Rujner, & Storch, 2009). Their functions are likely to be retail + housing or housing only. However, around the core city centre, high land cost and crowded inhabitant density result in such new shop-houses mostly to be rented or used for an entirely commercial aim: retail, hotel, restaurant, and office. They have a wide variety of building volumes, heights, design, and architectural style. By the urban spatial planning in HCMC until 2020-2025, apart from the focus on high-rise apartments to solve the pressure of increasing population and land cost, new residential neighbourhoods of row-houses are orientated to develop mostly in the shop-house dwelling market (Vietnamese Government, Resolution 02-2014: Land-use planning of Ho Chi Minh City until 2025, 2014). Row houses commonly contain three to five storeys depending on differently regional planning regulations, and their building design relies on archetypes to retain the architectural homogeneity of a whole street or community.

4.4 Classification of 'shop-house' urban structure types

In respect of the research project undertaken by the University of Cottbus, urban structure types were determined to be a foundation concept to assess vulnerable and adaptive levels to climate change at the urban scale within HCMC. The approach of urban morphologies provides advantages to get insights into the current and future environmental problems of wind flow, flood risk, and thermal stress within settlements in a regional context (Katzschner & Burghardt, 2017). The researchers identified and categorised the urban spatial structures by using the tool as known as Geographic Information Systems (GIS) at a scale of 1:25,000 combining with a city land-use map for the year 2010 and investigations in the field over the entire HCMC area. The results concluded that the total city surface area was 2,114.9km² of 16,292 urban blocks that were classified into 82 discrete urban structural patterns for five main land-use groups: residential use, public and special buildings, industrial and commercial purpose, green and open spaces, and street and water surfaces (Downes, Rujner, Schmidt, & Storch, 2011). Table 4.2 presents a summary of all classifications. Each urban morphology represents many indicators of building types, planning features, population density, environment, and social-economic and bio-physical status. For example, Figure 4.14 indicates various urban patterns found in the central building quarter in district 1 of HCMC.

Table 4.2 Urban structure types found in HCMC 2010 (Downes, Rujner, Schmidt & Storch, 2011)

Utilisation category	No. of sub-division into urban structure types	No. of blocks	Surface Area (km²)	Percentage utilisation category	Percentage of total HCMC surface area
Urban structure types (in total)	82	16.292	2114,9	-	81,7
Residential	25	6717	445,9	100	21,1
Shophouse-based	12	6346	424,8	95,3	20,1
Villa based	4	107	8,4	1,88	0,40
Apartments	5	103	5,0	1,12	0,24
Central Business Dist.	2	160	7,4	1,66	0,35
Public & special use	20	772	52,0	100	2,43
Industrial & commercial use	4	828	56,6	100	2,67
Green & open spaces	33	7995	1173	100	55,5
Remaining street and surface waters	-	-	388,1	-	18,3

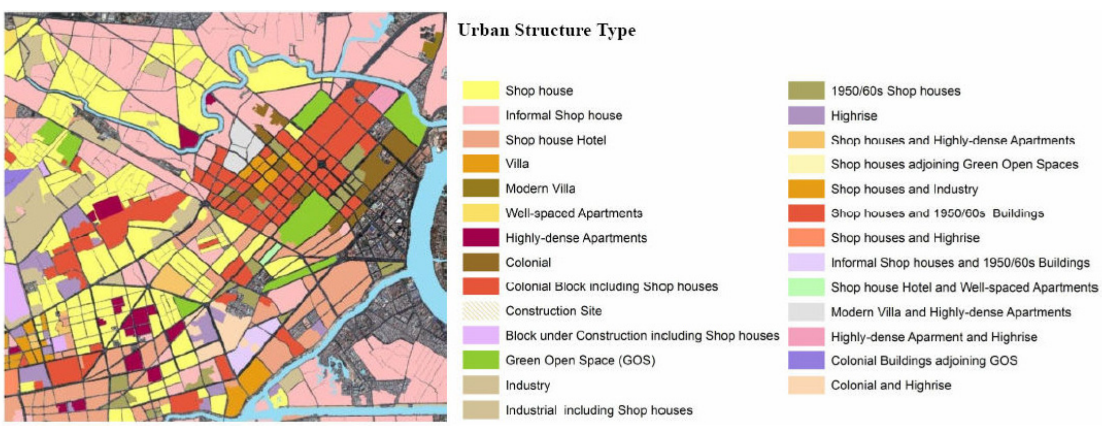


Figure 4.14 Urban structure types in the central business district (district 1) of HCMC (Moon, Downes, Rujner, & Storch, 2009)

In over 16,000 blocks examined, settlement structures were assigned to 6,717 blocks including 12 patterns and with 6,436 blocks categorised as urban low-rise dwellings, which occupied 20.5% of the total HCMC surface area (Table 4.3) (Downes & Storch, 2014). The morphologies of residential blocks are determined by land use, coverage ratio, housing typology, building height, building grouping pattern, road pattern, green and open area, and population density. The density of all dwelling urban structures differs among urban, peri-urban, and rural areas over the city. In relation to the shop-house dwelling types gathered, depending on local planning characteristics every residential neighbourhood contains one or some same shop-house dwelling types. The detailed characteristics of seven common shop-house urban fabrics will be indicated further.

Table 4.3 Summary of urban structure types of 'shop-houses' (Downes & Storch, 2014)

Type	'Shophouse' category	No of blocks	Build. ratio	Surface area (ha)
1	Regular new community	62	60	392
2	Regular new	100	70	450
3	Regular + narrow street	592	75	2,063
4	Irregular high density	425	78	1,602
5	Irregular + yards	794	57	4,444
6	Shophouse irregular & regular	23	69	350
7	Regular + yards	153	44	2,020
8	Irregular clustered	741	30	5,490
9	Irregular scattered	815	28	6,990
10	Irregular +large gardens	2,342	5	17,133
11	Irregular temporary			85
12	Shophouse + industry	222	74	1,292

Type 1 – 'Shop-house regular new community' is characterised by terraced housing archetypes located perpendicular to main or domestic streets in a back-to-back pattern. Within residential groups, there are communal spaces to serve residents such as parks, green pathways, and small-scale public buildings (stores, food shops, and kindergarten). The distribution of pattern type 1 was dominant in new and peripheral districts of HCMC with the surface area of 392ha, for example, the new inner districts of 2, 7 & 9. The maximal ratio of built-up area in Type 1 neighbourhoods is 60% (Figure 4.15) (Downes & Storch, 2014). Dominant shop-house dwelling type is the row-house (A5). Some standardised dimensions of a row-house land plot in new residential blocks are commonly 5x20m, 5x17m, 4x20m, and 4x17m. Due to a particular location, the number of building floors varies from 3 to 5 floors (VIAP, 2012). Referring to the residential planning regulations of TCVN 9411:2012, a 2m rear court in depth is mandatory for ventilation and daylight in all row houses in Type 1 while the front garden is optional depending on planning conditions of specific sites. Thereby, such terraced houses are classified into two subdivisions: the garden row house (with front garden, the construction coverage of 75%, and the main function of habitation) and the urban row house (without a front garden, the coverage ratio of 90%, and building function of habitation or habitation + shop) (VIAP, 2012).

Figure 4.15 Satellite and figure-ground image of pattern type 1 (Downes & Storch, 2014)

Type 2 – 'Shop-house regular new' mainly includes the street row-houses that are located at an angle of 90° toward the main streets and in parallel rows to each other. The planning pattern of houses is back to back (Figure 4.16). An important characteristic of residences in Type 2 neighbourhoods is that they do not have front and rear gardens. As a result, the interior microclimate, particularly at the back of the building may be uncomfortable because of a dark luminous condition and stale air, when the building only connects to surroundings at only one side – the main facade. The building height is likely between three and five stories. Compared to the row houses in Type 1, the construction area of a house is optimal 100%. The building ratio within a neighbourhood is 70%, the landscape facilities of green areas and sidewalks are restricted and inhomogeneous relative to them in Type 1. Type 2 widely distributes in many regions across HCMC, particularly in former inner and new inner districts, for example, Go Vap, Tan Phu, and district 7. Meanwhile, in city centres, the old residential areas are transformed by the blocks of street row houses that provide urban citizens with settlements and commercial benefits. The area of Type 2 found was 450ha of the city administrative area (Downes & Storch, 2014).

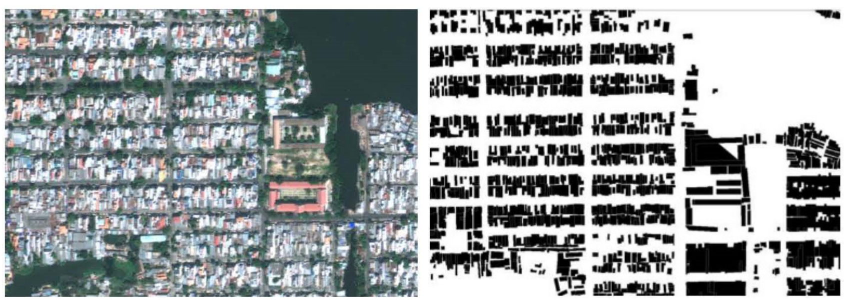


Figure 4.16 Satellite and figure-ground image of pattern type 2 (Downes & Storch, 2014)

Type 3 – 'Shop-house regular with narrow streets/alleys' accounted for the highest density in municipal areas with 2,060ha and mainly distributes in the core, former inner and new inner cities. The spatial structure of type 3 has the regular development of low and high shop-houses facing narrow streets/alleys. The houses along main streets have the advantage to combine two functions of living and business. The spaces within buildings are usually narrow and open to the main streets (Figure 4.17). The conditions of pavements or vegetation are few. The coverage of the constructed surface is 75% around the neighbourhood. The features of high density and narrow spacing within buildings can constrain airflows through the settlement, subsequently not hitting inlets on the building fabric. The building density, volume, and architectural style of shop-houses in pattern type 3 are not homogeneity (Downes & Storch, 2014). Meanwhile, the only factor of maximal building height is commanded by the current national planning regulations depending on particular locations (VIAP, 2012).

Figure 4.17 Satellite and figure-ground image of pattern type 3 (Downes & Storch, 2014)

Type 4 – 'Shop-house irregular with high density' has increased substantially since the national Economic Reform in the 1990s. The major feature of the urban morphology is an irregular and heterogeneous high-density pattern of dwellings with narrow streets or alleys. Buildings are planned along the outer edges of the main streets (Dang & Pitts, 2018b). Due to the unplanned road system and building groups, it is difficult to access and figure the houses' location. Compared to the three above urban types, the widely variable size of land plots, as well as irregular housing arrangement in Type 4, is a result of a very diverse urban pattern (Figure 4.18). The architecture of houses varies with no archetypes. Within Type 4 urban blocks, convoluted groups of different shop-house dwelling types (traditional, new, and rudimental shop-house archetypes) are observed. Additionally, like the new shop-houses in Type 3, the design and total floor area of buildings are diverse in Type 4; however, land use for construction is likely optimal in these areas. Therefore, the empty spaces within settlements are few. This urban pattern was found in the majority of districts in HCMC and covered over 1,600ha in total (Downes & Storch, 2014).

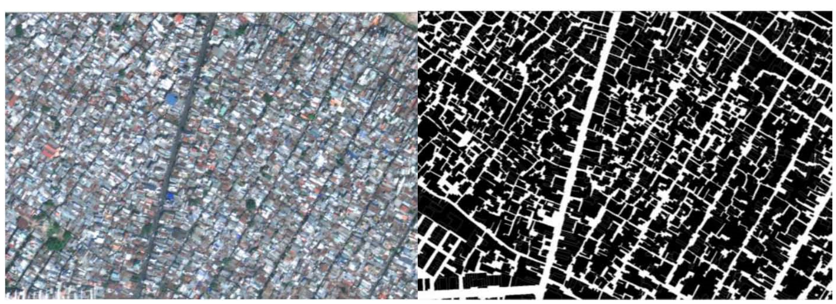


Figure 4.18 Satellite and figure-ground image of pattern type 4 (Downes & Storch, 2014)

Type 5 – 'Shop-house irregular with yards' is similar to pattern type 4; the building ratio over an urban block is less by 20%. This is attributed to the integration of multi-scale yards scattered within the block (Figure 4.19). The use of those yards is tricky to define: usually free for vegetation, vegetable and ornamental gardens, or partly sealed yards. The involvement of yards can bring changes in microclimatic conditions around houses. There is a random arrangement of traditional, temporary, and rudimental shop-houses, even detached houses. The urban fabric covered 4,444ha of total city construction surface area and was observed in all districts, excepting districts 1, 3, 5 and 10 (Downes & Storch, 2014).

Figure 4.19 Satellite and figure-ground image of pattern type 5(Downes & Storch, 2014)

Type 6 – 'Shop-house irregular + regular' is characterised by a medium-density residential block which contains both irregular and regular urban patterns (Figure 4.20). In general, the regular shop-houses orientate to the main roads to form the periphery of the block. However, inside the block, the irregular houses fill in the interior space with a disordered spatial structure. The ratio of irregular and regular layout pattern varies in different residential blocks. The urban type is dispersed in the urban, peri-urban and rural districts of HCMC and covered 350 ha (Downes & Storch, 2014).

Figure 4.20 Satellite and figure-ground image of pattern type 6 (Downes & Storch, 2014)

Type 7 – 'Shop-house regular with yards' was generally found in the new inner and suburban neighbourhoods of HCMC (Figure 4.21). The urban morphology is characterised by a less dense structure and regular arrangement of houses. The housing types found in this group include new, row and rudimentary houses of one to three stories along main streets. Within buildings, many unplanned green spaces can be found, which contributes to regulate the outdoor thermal and wind environment. The urban structure type is allocated predominantly in the suburban and rural districts of HCMC and covered a great area of 2,020 ha (Downes & Storch, 2014).

Figure 4.21 Satellite and figure-ground image of pattern type 7 (Downes & Storch, 2014)

4.5 Conclusions

The chapter collects the primary knowledge related to the architectural and planning characteristics of shop-houses in HCMC over the different historic periods. The distinct values of history, architecture, planning, and culture of shop-houses found have represented the uniqueness of this vernacular housing typology in Vietnam relative to other nations in SE Asia. In HCMC, shop-house dwellings were systematically devised into the various building types (five) and urban spatial structures (twelve).

Returning to the principle of adaptive comfort model (a large correlation between the indoor and outdoor environment in non-air-conditioned buildings) (Humphreys, 1978); additionally, the influences of urban elements on urban environments as discussed in the chapters of research literature above, there is likely sequent relationships between factors: urban conditions and outdoor microclimates, external and internal climates, and the physical building responding to the outdoor climate to create indoor comfortable environments.

Comprehending and improving thermal environments for occupant comfort in naturally ventilated shop-houses of HCMC are two significant objectives of the present research. Although internal thermal conditions for comfort or discomfort are shaped by the physical building, the design of building fabric and interior spaces should be considered concerning interactions with the ambient environment to get satisfactory thermal conditions. The prevailing tropical climate at macro-scale fluctuates within residential neighbourhoods constituted from the different conditions of buildings, roads, trees, and water surfaces. Therefore, the pressure on the physical building and building physics of a shop-house in a settlement can be mitigated if it is regularly exposed to a more pleasant environment described by low temperatures, low radiation, and sufficient wind flows. The twelve shop-house urban morphologies discovered in HCMC are characterised by distinct urban conditions, which can link to the difference in both outdoor and indoor microclimates.

Furthermore, each category of shop-house buildings shows variations in design, volume, size, geometry, and function, that can correlate to divergent environmental performances indoors. For example, in respect of discussions in Sections 4.2 and 4.3, responses of new shop-houses to the surroundings can be wider than other dwelling types owing to a higher degree of passive design strategies applied. As a result, thermal comfort indoors may be advantageous by appropriate design of the dwelling linked to its surroundings.

For the context reported in the current project so far, the influences of either shop-house types or their urban morphologies on comfortable or uncomfortable environments in residences in HCMC is questionable. That hypothesis will be conveyed in the next chapters through field studies on thermal conditions inside and outside shop-houses. Two shop-house types (new shop-house and row house) and seven urban morphologies (Type 1-7 as bolded in Table 4.3) will be used for further examinations due to their prevalence in the city housing stock. Understanding environmental performances in shop-house buildings in respect of a scientific system of their dwelling types and urban geometries can be a potential approach, which contributes to building up the systematic and adaptive design guidance in different contexts of dwelling type and urban environments.

PART 2
RESEARCH MEASUREMENTS

Chapter 5 RESEARCH METHODOLOGY

The chapter depicts the research methodology and procedures used to achieve the defined research objectives. The chapter subsections include research philosophy; research design showing an overall plan of the research to fill the research gaps by suitable research methods and process; the results after absorbing and developing research techniques in the particular context of shop-houses in HCMC, such as time and subject sampling, equipment, and data collection and analysis.

The project primarily uses the quantitative research through numerical data to seek the answers about the interaction of HCMC occupants to the climate and indoor environmental conditions for their comfort; the effect of the building envelope on the indoor environment in relation the outdoor climate; and the approach of design framework to assist practitioners in improving the performance of building envelope for comfort. Understanding thermal perceptions and comfortable environments of occupants in NV shop-house buildings is approached by field surveys, which are a fundamental research method in most comfort studies. Three sample types include subject, building, and settlement. Three field studies were conducted in HCMC in summer 2016 and 2017 and spring 2018.

5.1 Research philosophy

The research philosophical regime is post-positivism known as a traditional philosophy in science research and that is a conception after positivism because the research is relevant to human perceptions and behaviours (Phillips & Burbules, 2000). In theory, the post-positivist research identifies and assesses the causes affecting outcomes (Creswell, 2014). Return to the aim of the project, the outcome is the provision of satisfactory environments for occupant comfort in NV residential buildings in HCMC, particularly shop-houses. Meanwhile, the causes affecting the indoor comfortable environment studied in the thesis include the outdoor microclimate as a result of urban conditions and climate; and the physical building. To approach the outcome, there are various scientific and practical terms to be understood such as occupant comfort perceptions in the given environment and the characteristics of urban and building design in the distinct context of people type (Vietnamese), building type (shop-house), and climate type (warm-humid). That may need to have many on-site data for analysis.

Learning from previous adaptive comfort studies, thermal sensations, preferences, and acceptability of people in shop-houses will be perceived through a positivist lens of empirical studies. The thermal responses of inhabitants are fundamental to assess and refine the application of current comfort models to residential buildings in the tropics such as HCMC. Additionally, from the investigations, the relationship of internal thermal environments and occupant thermal perceptions with various complex variables (the outdoor climate, building and urban types, the building design, occupant adaptation) are then developed.

The final product of opening design guidance is expected to be the result of a large number of numerical studies that are derived from analysis related to the causes of discomfort. This leads to the finding of comfortable environments and required design features of openings found in the naturally ventilated shop-house buildings in HCMC. Figure 5.1 reveals an overall view of the research methodology that this study relied on. It includes a series of sequential layers from the philosophical idea of post-positivism to conduction by the number of detailed techniques.

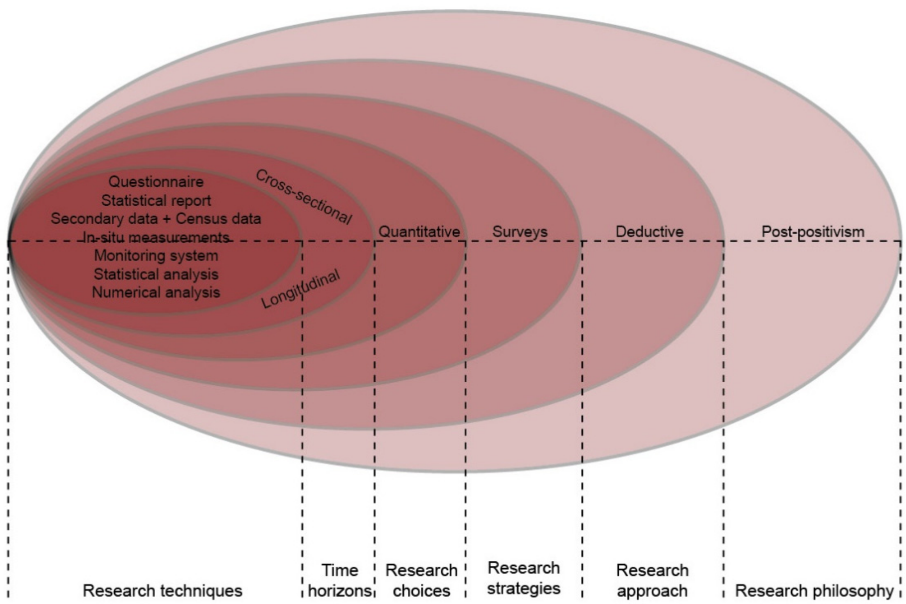


Figure 5.1 A framework for research methodology (adapted from the research onion, Saunders et al., 2007)

5.2 Research design

In order to comply with the philosophical concept in the defined research, the present study is designed using the quantitative method and deductive reasoning to achieve the seven research objectives identified in Chapter 1. The following decisions are taken for the research:

• *The Type of Data.* Understanding occupant thermal sensations and interactions to the given environment in NV shop-house buildings in HCMC, as well as, indoor environmental characteristics and their factors is vital to the project to find real comfort conditions for those buildings and to obtain comfort through the improvement of the building envelope. As previously mentioned, the contextual factors are significant to comfort studies and practice. Furthermore, the sufficiency of the available comfort models and architectural standards is questionable. Hence, the current research will use primary data collected by various methods including questionnaire interviews, measurements, and monitoring in the real environment of shop-houses in HCMC. Quantitative data will be analysed to prove and fill the gaps identified in Chapter 2.

• *Data Collection.* The quantitative research is shown through methods to collect and analyse data. A variety of cross-sectional and longitudinal surveys by questionnaires and measurements will be applied to collect the data of independent variables: subjective comfort votes, environmental parameters in and around buildings, and building characteristics. Then, the data will help explain the complex correlation between urban/building design features and indoor/outdoor environment and occupant comfort. Four main surveys will be planned as follows:

- The first is to collect occupant thermal perceptions. Learning from the experiences of many existing comfort studies, the researcher will carry out field surveys and measurements to take personal parameters, occupant comfort votes, and physical variables (air temperature, air velocity, humidity, and mean radiant temperature) to assess conditions for occupant comfort/discomfort in shop-houses. Analysing occupant comfort votes in given environments will help find comfortable and acceptable thermal conditions for residents in shop-house buildings. Those findings are significant in finding out assessment criteria for environmental performances in houses and the effect of building design on them.

The method of data collection by questionnaire interviews for subjective sensations in the spontaneous environment combined with simultaneous measurements of such an environment has been used popularly in numerous worldwide field studies. Researchers conducted thermal comfort surveys with varying sample sizes in different building typologies and environments, for example, with 118 subjects in free-running offices and residences of Singapore (Ellis, 1953); with the involvement of 818 respondents in similar building types and location (de Dear, Leow, & Foo, 1991); with 1,100 subjects in NV and AC offices in Bangkok (Busch J. , 1992); with 525 subjects in hybrid residences in Indonesia (Henry & Wong, 2004); with 1,200 students in schools of Vietnam (Nguyen A. T., 2013); in the buildings located in different parts of Pakistan with 4,297 questionnaires completed (Nicol & Roaf, 1996), 2,075 questionnaires responded by students in NV universities in Brazil (Candido C. M., 2010).

Three attentions when developing fieldwork are sample size, timescale, and measuring method. Nicol et al. (2012) recommended that the number of respondents involving in comfort surveys should be more than 100 to ensure the reliability of results analysed (Nicol, Humphreys, & Roaf, 2012). In addition, the appropriate sample size also depends on the timescale of surveys: cross-sectional, longitudinal or a combination of both known as repeated transverse because time acts an important role to reflect the dynamic adaptation and responses of subjects to given environmental conditions (Nicol & Humphreys, 2002; Nicol, Humphreys, & Roaf, 2012). The climatic variations induce us to respond to not only the immediate environment but the long-term experience of accumulative conditions. In other words, climate and the immediate thermal feeling of subjects fluctuate over time of the day, month, and year. Returning to the example of comfort surveys above, Ellis and Nicol collected their data over the year while other researchers such as Henry, Bush, and Candido conducted comfort surveys in two typical wet and dry seasons of the tropics. On the other hand, de Dear and Tuan only took data in the wet/hot season. For cross-sectional surveys, the number of subjects should be larger (Nicol, Humphreys, & Roaf, 2012).

Considering the main research subject, which is occupants in shop-houses, their characteristics in terms of anthropometry, social background, occupancy, and family size in a house are very diverse; therefore, the conduction of longitudinal surveys for individual dwellers in shop-houses is difficult. To find an appropriate plan for this project, the repeated transverse method with the same group of respondents in different months/seasons is determined.

The measurement of the spontaneous environment around the subject will comply with the protocols and experiences into ASHRAE 55, TCVN 306:2004, and previous studies (ASHRAE, 2004; MOC, 2004; Nicol, Humphreys, & Roaf, 2012). Referring to them, each variable requires a particular measuring method and equipment with high accuracy.

The second is to collect characteristics of indoor and outdoor environments. The investigation of environmental conditions will occur through cross-sectional and longitudinal measurements in the field. The surveys aim to understand current environmental performances within a building, within a settlement, and from settlement to settlement. The analysis of data interprets the correlation between indoor and outdoor climate and between occupant thermal sensations and indoor environments. These terms are taken into account in relation to the urban structure types.

The measurement of environmental parameters (air temperature, black globe temperature, relative humidity, illuminance, and air velocity) in buildings will be referred to the protocols described in ASHRAE 55 and TCVN 306:2004 (ASHRAE, 2004; MOC, 2004). In the physical variables, measuring internal air movement is more complicated for both the time horizons. The cross-sectional investigation of airflow environment by a 3D grid system in rooms has been validated in previous studies (Moosavi, Mahyuddin, & Ghafar, 2015; Jarzabska, 2015; Hurnik, Blaszczok, & Popiolek, 2015; Peizhe, Liang, Liguo, & Boyuan, 2016). Meanwhile, to monitor air movement, velocity sensors will be installed within the occupied zone for internal airflow and on the building for outdoor winds. Compared to other research methods such as wind tunnels or simulations, on-site monitoring will need time and efforts. That method has shown efficiency in data collection and analysis in some research on urban environments in Singapore and China (Wong & Yu, 2005; Tong, et al., 2017; 2018).

- The third is to report the building data, in particular, opening configurations. Understanding the building characteristics helps the author perceive the application of natural ventilation regimes and opening features in shop-houses. Combined with the investigations of interior and exterior environments, the impact of the building envelope on the internal environment and comfort degree will be explained. The survey techniques are photography, drawing, measurement, and numerical analysis.

- The fourth is to collect feedback of professionals to assess the validity of design guidelines for openings when applied in practice. The main research method is questionnaire interviews. A group of individuals, who are working in the architectural education and industry, will be invited for giving their comments on the approach, framework and method to build up the guidance; its advantages and disadvantages; and its development in future. The validity survey will be organised on-site.

The design manual is towards practical applications and support for the designing profession to achieve comfortable and energy-efficient houses. To ensure those, it will be built up by a combination of scientific research and real knowledge and experience of architects in design. Therefore, before developing the design guidance, a pilot study will be carried out to collect understandings and limitations in the practice of designers related to naturally ventilated houses and the effect of building features, in particular openings, on the level of comfort and energy efficiency inside. The research strategy of the pilot survey will be on-site questionnaires. Finding the potential approach of design guidance and assessing its validity is more reliable when participants involving in both pilot and validity surveys are similar.

- *Data Analysis.* With the database obtained from field studies, they will be analysed by statistical methods to interpret occupant thermal perceptions and expectations in non-air-conditioned shop-houses in HCMC, along with potential relationships between the variables. The quantitative data analysis by statistics has been effective in many existing studies (Humphreys, 1978; Busch J. F., 1990; de Dear & Foutain, 1994; Nicol & Roaf, 1996; Karyono, 2000; Zhang, et al., 2007; Djamila, Chu, & Kumaresan, 2013; Indraganti, Ooka, & Rijal, 2013).

Moreover, the data analysis will also be carried out by parametric studies to develop various design options of design guidance. The environmental impacts of each design case will be tested by numerical thermal and air movement calculations. That method is determined to be effective to find out the environmental profile, particularly the variable of air velocity within a naturally ventilated room/building in many studies (Gao & Lee, 2010; Stavrakakis, Zervas, & Markatos, 2012; Hassan, Shaalan, & El-Shazly, 2004; Hawendi & Gao, 2016; Sacht & Lukiantchuki, 2017; Elshafei, Negm, Bady, & Suzuki, 2017).

The following sections will provide the results of comfort surveys conducted in free-running shop-houses in HCMC.

5.3 Conduction of comfort surveys in HCMC

5.3.1 Regional context

Vietnam is located in Mainland Southeast Asia is a country with an eastern long coastline. It is mainly characterised by a monsoon tropical climate. On the other hand, Vietnam Building Code 02:2009 subdivides the climate in Vietnam into two primary regions including the north and the south with distinct climatic phenomena. In this, due to the geographic location close to the equatorial line, the southern cities are exposed to the typical monsoon tropical climate with two sunny and rainy seasons (IBST, 2009).

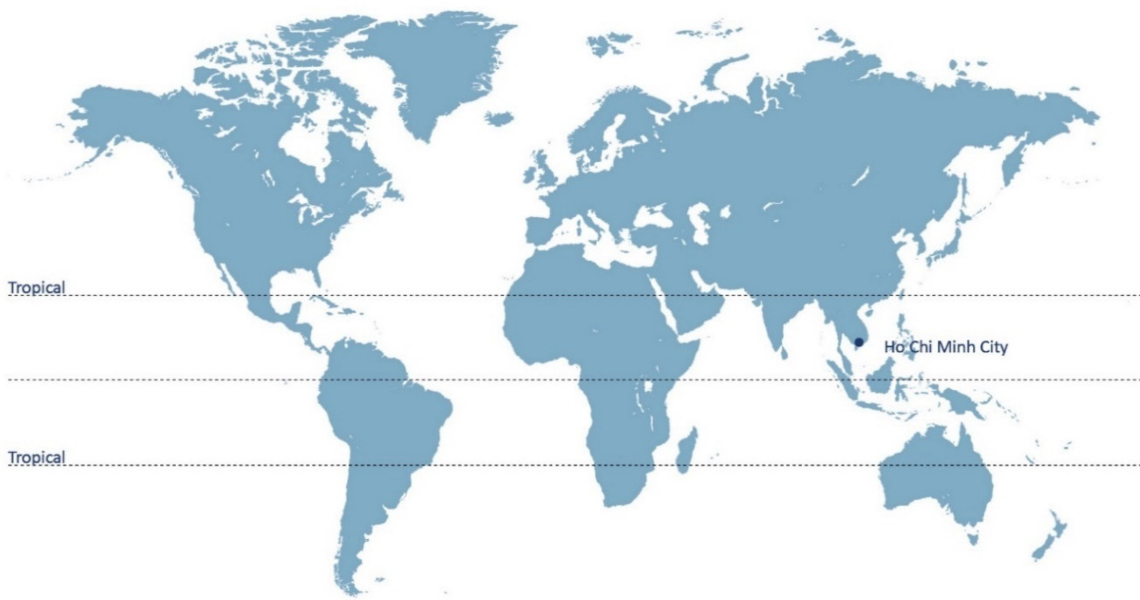


Figure 5.2 Location and climate zone of Ho Chi Minh City

HCMC is the second largest city in Vietnam and is located in the South-Central part of the country. Latitude and Azimuth of HCMC are 10.47°N, 106.4°E, respectively. The height above sea level is 11m. The total of the city area of 2,093 km² is classified into four regions: core-centre (districts 1, 3, 4 & 5), former inner (districts 6, 8, 10, 11, Go Vap, Tan Binh, Binh Thanh, Phu Nhuan, and Tan Phu), new inner (districts 2, 7, 9, 12, and Thu Duc), and suburban (Can Gio, Hoc Mon, Cu Chi, Binh Chanh, Nha Be, and Binh Tan districts). The administrative area, population density, urban spatial structure, and urbanisation progress Among districts and city zones show variations (Figure 5.3) (Gubbry, et al., 2002).

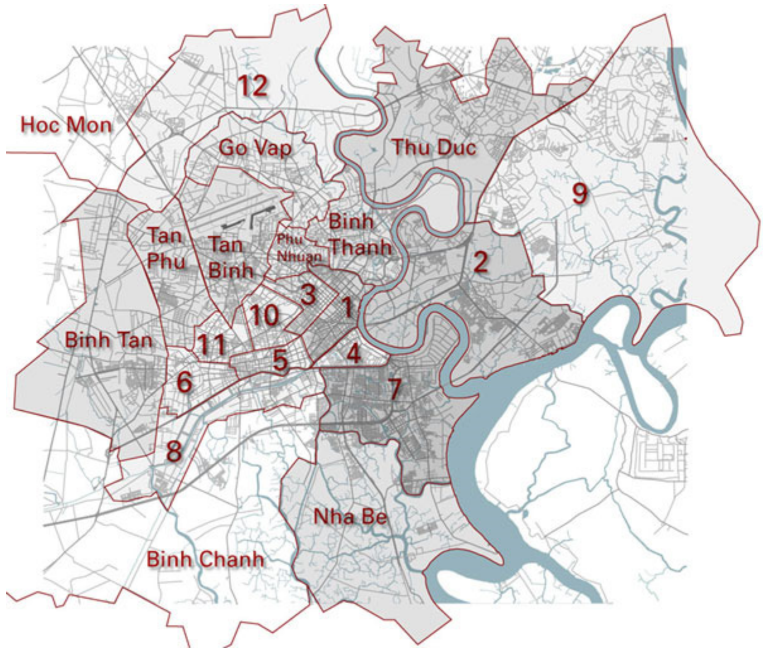


Figure 5.3 The administrative area map of HCMC

HCMC is a typical city of monsoon tropical climate with the principal aspects of warm temperatures, high humidity, and heavy rain across much of the year. Additionally, the local climate is strongly influenced by monsoon winds. In general, two major seasonal mechanisms are operating in HCMC throughout the whole year: the dry season from December to April and the wet season between May and November. Using the meteorological data published in Vietnam Building Code 02:2009, the following will describe the principles of climatic variables in HCMC. It is noticed that the database was collected from the Tan Son Hoa weather station of HCMC during many years and used for construction firstly in 1985, and then, updated in 2008. Consequently, there may have deviations between the analytical results of those data and the current climatic conditions observed.

The annual average temperature is around 28°C, and fluctuation of mean monthly temperatures is not much by approximately 4K (IBST, 2009). Figure 5.4 shows the distribution of maximum, average, and minimum air temperatures for twelve months. The monthly average maximum and minimum temperatures are 35°C in April and 20°C in January and December, respectively. The problem of thermal stress often happens during the warmest months within March and May, particularly April; however, due to the impacts of global warming and climate change, the phenomenon is lengthened until July. After that, the thermal climate becomes more moderate from July until February when temperatures gradually decrease.

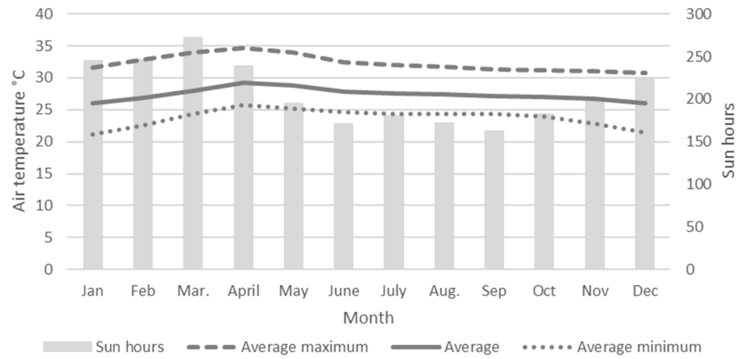


Figure 5.4 Average monthly air temperatures and sun hours in HCMC (IBST, 2009)

In the hot months, along with the impact of intense solar radiation, citizens can tolerate the extreme temperature exceeding 40°C on middays. Despite exposing to warm temperatures, the rainy season usually operates between May and November. Therefore, the atmosphere becomes cooler after raining, especially on heavy rainy days. Nevertheless, discomfort for people is possible when the amount of rainfall is low, that causes higher humidity under warmth simultaneously (Fry & Drew, 1980).

Heat gain in the air is coupled with solar radiation, in particular, for the nations around the equator (Fry & Drew, 1980). A total of annual sun hours are 2,500 in HCMC. Over sunshine periods, there are about 65% of total hours that city surface area is exposed to strong radiation with more than 600W/m2 (IBST, 2009). The greatest number of hours received direct sunlight is up to 270 in March (Figure 5.4) and global radiation is over 170KWh/m2 in this month. In contrast, sun hours are the lowest in September with 170 hours. Between November and March, the sky is fairly clear at 45%; therefore, the total monthly sun hours are higher. Meanwhile, in wet months, the cloud occupies 70-80% of the sky (Fry & Drew, 1980).

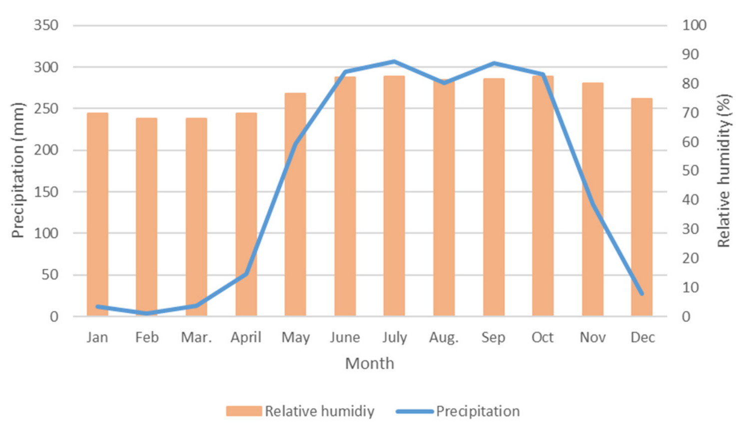


Figure 5.5 Average monthly relative humidity and rainfall in HCMC (IBST, 2009)

According to the climatic database (2008), the rainy season in HCMC likely occurs between May and November. Under the influence of climate change, rainfall in that season increases by 20% (Thuc, et al., 2016). The generous rainfall averages 1,950mm annually, in which, the precipitation reaches a peak in all months from June to October with a monthly average amount of 300mm (IBST, 2009). Meanwhile, the environment is drier due to lower precipitation in the dry season (December to April). In the wet months, air velocity from west to south is remarkably high; therefore, the building should have wide overhangs and large verandas to prevent oblique rainwater at southern or western facades; and slope of the roof also needs to be considered for the best drainage.

The monthly average relative humidity ranges from 70% - 80%. Particularly, during the wet season, the humidity level is above 80% even reaches up to 100% while the air is drier in the first four months. The difference in relative humidity is not much between day and night in the rainy season. Relative humidity during the daytime is lower than at night-time.

In the tropics, the natural wind is an effective means to lower the air temperature and remove the moisture (Olgyay & Olgyay, 1963; Givoni B. , 1976; Szokolay S. V., 1997; Nicol, 2004). The wind operation in HCMC is abundant and frequent over the year. The availability of natural winds has an impact on occupant comfort and promotes the use of natural ventilation to reduce the need for air-conditioning. In HCMC, there are three dominant monsoon winds. The south and southeast trade winds are prevailing in months (March-May) with average and maximal airspeeds of 3.7m/s and 4.5m/s, respectively. The west and southwest monsoon winds operate from June to October (the main rainy season) with an average wind speed of 3.6m/s and the strongest wind reaching 5m/s in August. Additionally, the north and northeast monsoon winds occur between November and February with an average air velocity of 2.4m/s (Pham N. D., 2002).

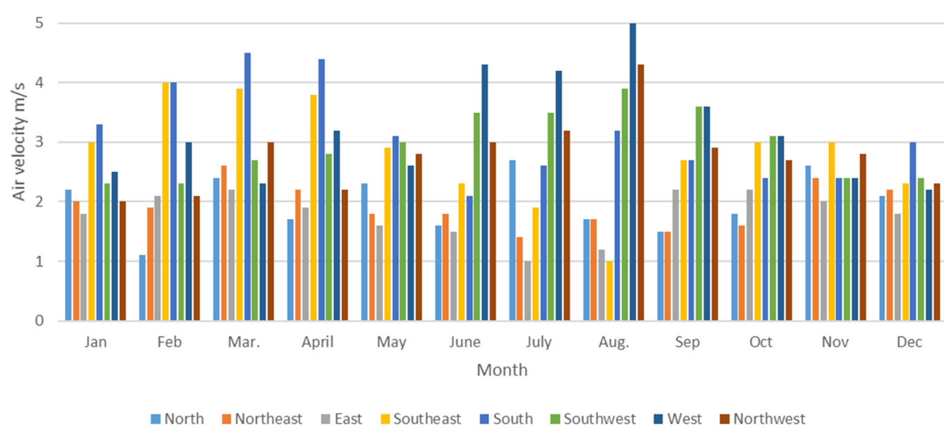


Figure 5.6 Distribution of air velocity by month and direction in HCMC over the year (adapted from IBST, 2009)

5.3.2 Subject sampling

a. Shop-house dwellings

Based on the intrinsically wide diversity of architecture and planning of shop-house buildings as described in Chapter 4, the selection of building samples for investigations did not depend on any strict criterion, excepting rental houses with a small floor area. The diversity of building samples is featured by the floor area, orientation, usage, building height, urban form, and spatial structure. By that way, the author expects the reliability of the data collected and avoidance of bias in results, which are potentially applied to a wider population.

71 shop-houses were visited for thermal comfort and building surveys in HCMC between 2016 and 2018. However, there are only the data of 65 cases used for analyses, among them, 59 houses were revisited in the second time as shown in Figure 5.7. All 65 case studies and building occupants were the main subjects for the surveys.

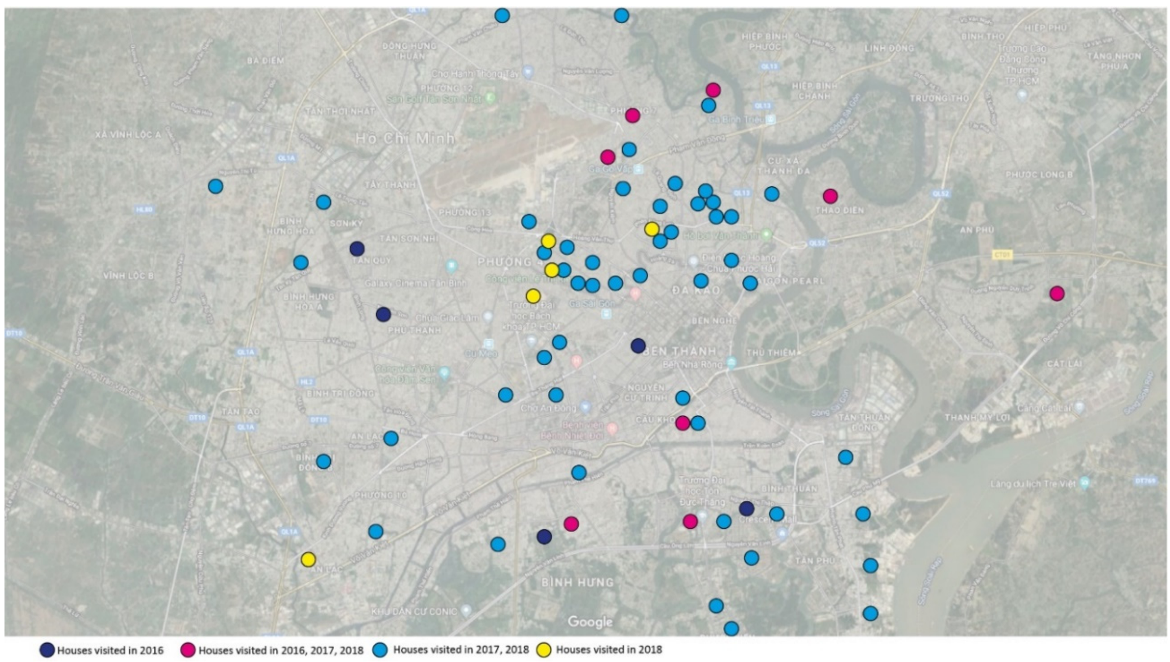


Figure 5.7 Locations of buildings used for the surveys

The increasing thermal stress due to global warming and urbanisation over the city has caused a rise of air-conditioners in residences. In a total of shop-houses examined, 92% of them are operating by two cooling modes (natural ventilation and air-conditioning) while others are entirely naturally ventilated. Additionally, the regulation of human discomfort has been supplemented by various types of fans including low and high standing, ceiling, and wall-mounted. In reality, although current shop-houses have been cooled by various options including operable windows and doors, fans, and air-conditioners, the use of passive building controls and fans is dominant across much of the day and month while air-conditioning machines are only switched on at certain hot periods because of providing low energy cost, thermal satisfaction, naturally environmental delight, and health for occupants. Consequently, understanding thermal perceptions and preferences in naturally ventilated spaces of dwellings is important to this study.

Looking at the whole sample, 92% of 65 houses surveyed with cooling options had the installation of AC, particularly in bedrooms. On the other hand, fans were employed in all residences; however, their application is dissimilar depending on the specific category and room function. In three fan types reported previously, low and high standing fans were the most popular (98% of samples); additionally, they were suitable for many different functional spaces because of their mobility. The use of wall-mounted fans was also preferable (52% of samples). Comparing to those two types, ceiling fans were less dominant, only 37%. They were often present in common spaces with a larger area, such as the living/family room, kitchen, and dining room.

Considering the shop-house types found in the current survey, there are three principal housing types including traditional shop-house (5%), new shop-house (80%), and row house (15%). Despite exposure to a typical climate of monsoon tropical in HCMC, the local microclimate within a settlement and among settlements varies due to the intervention of urban constituents (Moon, Downes, Rujner, & Storch, 2009). Thereby, regarding the spatial structure of residential neighbourhoods, where the single buildings are located, the settlement of 65 houses is classified into 7 urban pattern types, among them, pattern type 4 – Shop-houses in irregular high-density blocks accounts for the majority of 40% and the following is pattern type 3 (22%) – Shop-houses in regular high-density neighbourhoods with narrow streets or alleys (Figure 5.8a). Considering the influence of urban heat island on multiscale climates, the location of residences was widely selected in various residential regions across the city (Figure 5.7). The use of the building cases is diverse with five major functions: only housing (71%), housing + rental (11%), housing + shop (4%), housing + office (8%), and housing + guesthouses (6%) (Figure 5.8b).

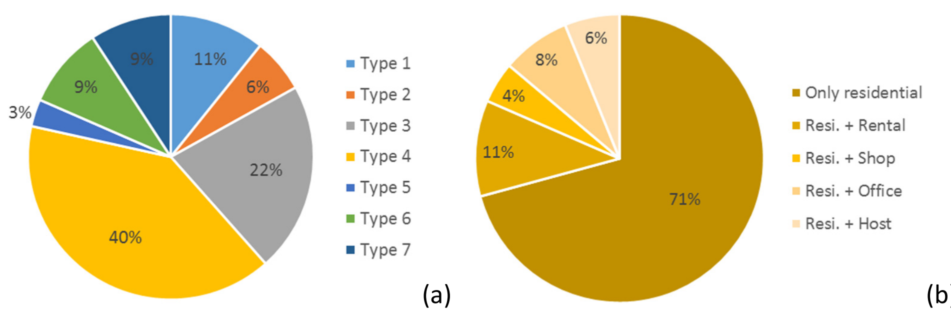


Figure 5.8 Urban types (a) and functions (b) of all housing cases

The building orientation has an impact on passive housing design owing to the relationship with the sun path and prevailing winds. In the culture and built environment of Vietnamese people, defining a good building orientation depends on not only considerations of surrounding site conditions but belief in the Feng Shui philosophy to some extent. The eight common building orientations examined with varying proportions consist of North (9%), Northeast (9%), East (26%), Southeast (17%), South (13%), Southwest (11%), West (9%), and Northwest (6%) (Figure 5.9a). Based on the categorisation, a majority of residences

(76%) face the advantageous direction of prevailing winds but 20% of them are exposed to both effects of prevailing winds and solar heat gain from the direct sunlight during noontime.

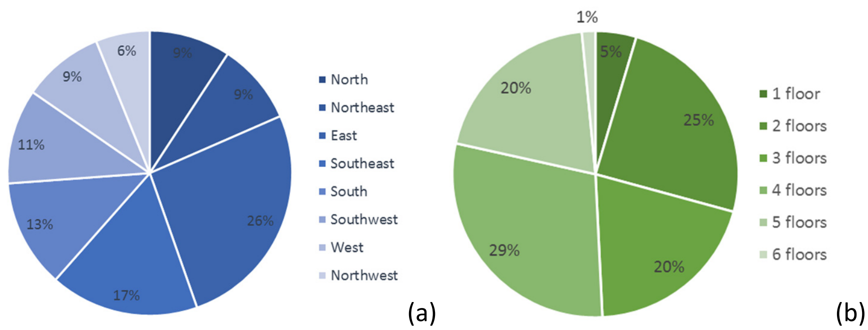


Figure 5.9 Orientation (a) and number of floors (b) of all case studies

The building height is heterogeneous. In all cases examined, the percentage of houses characterised by the lowest height with one floor was 5%. Meanwhile, only 2% of whole buildings reached a maximum height of six floors. The common number of stories of shop-houses ranges between two and five, in these, two and four-story residences were the most dominant (Figure 5.9b). The building height depends upon various reasons, such as household preference, construction budget, and planning regulations of each settlement.

The terms of total floor area and room types of 65 dwellings studied show variations. The size of most cases was between 100-200sqm (46%) whilst many shop-house dwellings having total floor area above 400sqm were fewer with 6%. The percentage of buildings with a total floor area lower than 100sqm, between 200-300sqm and 300-400sqm, was similar (Figure 5.10a). The large volume/floor area of residences may negatively influence the building physics in terms of daylighting and natural ventilation. Energy consumption, therefore, may require more.

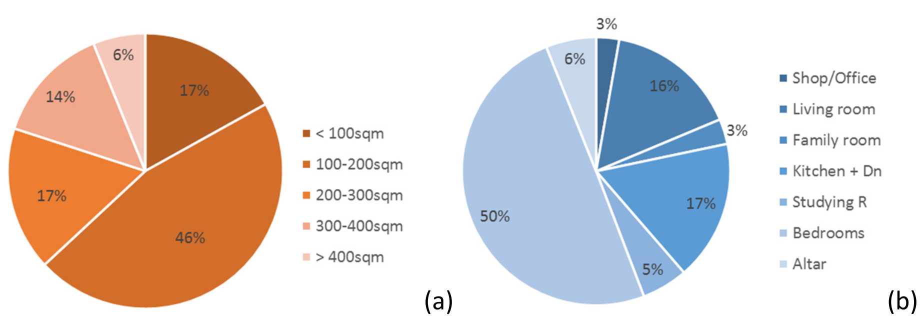


Figure 5.10 Total floor area (a) and percentage of room types (b) in shop-house dwellings in HCMC

The pattern of functional spaces varied between case studies. In a typical shop-house, the main spaces are the living room, kitchen + dining room, and bedroom (Figure 5.10b). 17% of residences had additional functions, for example, the shop or office. Belief in psychic values (Buddhism and ancestors) is a religious culture in most Vietnamese families. Evidently, 6% of buildings investigated organise a formal space for the altar and worship that is commonly placed on the highest floor of the building. Other spaces (family room and studying) are optional depending on the need and preference of households.

The main structure of most shop-house buildings in Vietnam is a combination of brickwork for walls and reinforced concrete for beams, columns, and slabs. In three shop-house types found in the field survey, the thickness of the external walls of row-houses is 200mm complying with the building regulation. Meanwhile, in new shop-houses, external walls are differently thick, popularly 100mm and 200mm. Internal walls are thinner commonly at 100mm. Due to the deficiency of insulation, the quality of thermal resistance of brick walls to outdoor heat is weak with 1.96 W/m^2K and 3.45 W/m^2K corresponding to 200mm and 100mm thickness.

For the predominance of natural ventilation in houses throughout the year, the thermal profile of glazing doors and windows usually performs low. Their panels are a single pane of clear glass installed into wooden, aluminium, steel, or PVC frames. Consequently, the cooling load significantly leaks through glazed panels and door/window frames when the AC system is operative. The roof structure consists of three common forms: single or double pitched roofs covered by tiles or tole sheets and flat concrete roofs. Under roofing, there is usually a layer of gypsum ceiling to prevent heat transfer from the roof down to lower spaces.

b. Occupants

A total of 139 respondents, who are living in 65 shop-houses, took part in two field studies. 117 participants involved in both the 1st and 2nd surveys, moreover, plus 22 new ones in the 2nd observation. Thus, there were a total of 256 datasets collected during the studies. The selection of all the subjects meets the requirements of occupancy: in residence at least 5 years in HCMC and a total of a minimum of 6 hours per day at home (Nicol, Humphreys, & Roaf, 2012). These aspects can ensure a long-term perception and acclimatisation of residents to both indoor and outdoor climates in the city. The following is summaries of basic demographic data of subjects.

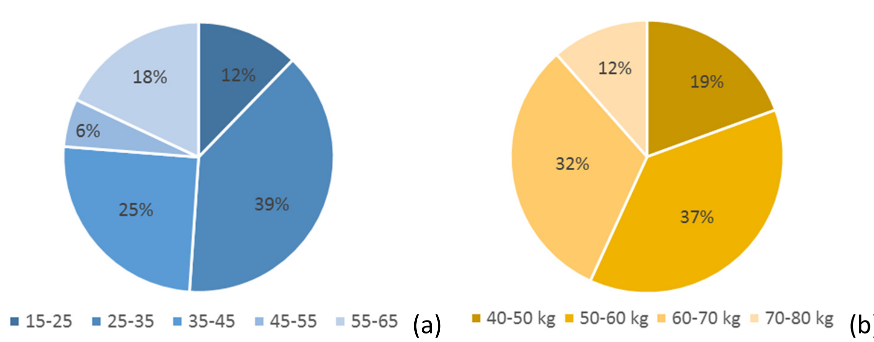


Figure 5.11 Demographic characteristics of occupants

Firstly, a large majority of participants are holding Vietnamese nationality, excepting two Japanese persons. Secondly, the gender of occupants equally shares for female and male. Thirdly, the dwellers were between 15 and 65 years old. The percentage of people at the ages of 25-45 were dominant with 64% while the number of participants in the range of 45-55 years old was the least with 6% (Figure 5.11a). The limit of ages is to avoid some special circumstances who have strong sensitivity of little environmental changes or have not had fully perceptions of the surroundings yet. In addition, people responding to questionnaires had good health and normal comprehension. With those considerations, possible errors or biases among data can be eliminated. Finally, the occupant bodyweight is categorised into 4 groups as follows: 40-50kg (19%), 50-60kg (37%), 60-70kg (32%), 70-80kg (12%). The average weight of the Vietnamese is between 50-70kg with 69% and differs between females and males (Figure 5.11b).

c. Professionals

A total of 57 practitioners, who are working in the professional environments of architectural firms and universities in HCMC, involved in the surveys. They are mainly architects, engineers, and lecturers having 2 to 20 years' experience in the fields of architecture and construction, especially in housing design. Some of the participants were working as a role of environmental designers or consultants of green design. The field studies were organised before and after the design proposal published.

5.3.3 Time sampling

To understand in depth occupant thermal perceptions and environmental conditions in and around the building in HCMC, the cross-sectional surveys were carried out in two typical seasons - the hottest (March-May) and the coolest (December – February) throughout the year. Each field study lasted over a period of 2 months, and questionnaire interviews and measurements started at 8:00 am and ended at 17:00 pm with the management of the researcher and observers.

In addition, before two official fieldworks, a pilot study was conducted to confirm the shop-house building types and urban morphologies found by the researchers of the University of Cottbus. Furthermore, some measurements were taken to test the potential correlation between shop-house building/urban structure types and indoor environments and assume the possible obstacles of official surveys in reality related to selecting participants, getting their permission, identifying variables for measurements, and the response of subjects to a draft questionnaire. Schedule of three field studies is below:

- Pilot study: April – May 2016 (the hottest month of the year)
- First fieldwork: March – April 2017 (the hottest month of the year)
- Second fieldwork: December 2017 – January 2018 (the coolest month)

In parallel to such cross-sectional surveys of environments indoor and outdoor buildings, some shop-house dwellings were selected to monitor environmental conditions for 11 months (April 2017 – February 2018). Monitoring physical variables can describe the long-term environmental pattern indoors in relation to the outdoor climate, occupancy, and occupant controls in the building over that period. Moreover, those cases are located in neighbourhoods with different urban spatial structures; therefore, longitudinal data can help to explain sufficiently the relationship between urban morphology and indoor microclimate and between the physical building and indoor comfortable environment.

5.3.4 Equipment and variables

a. Instruments

The reliability of data also depends on two factors: measurement protocols and the use of appropriate transducers. Thereby, the type of instruments and their specifications should be rigorously considered. In particular, survey methods, the selection and utilisation of instruments had variations, for example, handle meters were used for repeated transverse surveys while loggers were employed to monitor longitudinal environments. In general, the equipment should satisfy some criteria, such as good quality, high resolution, and high accuracy. Table 5.1 and Figure 5.12 summarise all transducers that were used for all surveys. Functions of them are compatible with specific variables in a particular environment. During measuring, the equipment was carefully calibrated before reading results.

Table 5.1 List of instruments used in the survey

No	Meter	Variables	Resolution	Quantity
For spot measurements/Transverse survey				
1	4 in 1 Multifunction environment meter	Illuminance (Lux), Noise (dB)	0.1lux 0.1dB	1
2	Testo 425 - Compact thermal anemometer	Indoor air velocity (m/s)	0.01 m/s	1
3	Temperature Meter PCE-WB 20SD	Black globe temperature (°C), Air temperature (°C), Relative humidity (%)	0.1°C 0.1%	1
For longitudinal measurements (Data recording for long-term)				
1	Netatmo weather station	Indoor/outdoor climate data (air temperature, relative humidity)	0.3°C 3%	3
2	Netatmo wind gauge	Outdoor air velocity (m/s) & orientation (°)	0.5 m/s 5°	3
3	HOBO U12-012 Temp/RH/Light/1 Ext Data Logger	Indoor air temperature (°C), Relative humidity (%)	0.35°C 2.5%	9
4	Air Velocity Sensor T-DCI-F900-S-P (0.15 to 10 m/s) (30 to 1969 fpm) Sensor	Indoor air velocity (m/s)	0.05m/s	4

Figure 5.12 Instruments used for the field studies

b. *Variables*

There were two principal types of variables for investigations including personal and physical. The physical parameters refer to air temperature (°C), relative humidity (%), mean radiant temperature (°C), and air velocity (m/s). In four environmental variables, mean radiant temperature values were converted from the formula (Eq9) in cooperated into temperature, globe temperature, and air velocity. Meanwhile, other indices were measured directly from the meters.

$$TRAV = [(Tg + 273.15)^4 + 1.2x10^8 x d^{-0.4} x V^{0.6} x\ (Tg - Ta)]^{1/4} - 273.15 \quad \text{(Eq9)}$$

Where TRAV = mean radiant temperature (°C)

T_a = air temperature (°C)

T_g = globe temperature (°C)

d = diameter of the globe (m)

V = air velocity (m/s)

The personal variables include metabolic rate (met) and clothing ensemble insulation (clo). The values of activity and clothing level were assumed by means of metabolic rate and garment tables published in ASHRAE Standard 55 (2013) through occupant votes for available options listed in the questionnaire and observation of surveyors. Be different from other building types, for example, school and office, occupants in residential buildings have the freedom to wear their clothes and experience their activities in different spaces over the day. Therefore, there is a wide variability of metabolic rate and clothing insulation values relative to their uniform pattern in working places or educational buildings. In relation to this study, the activity types and preferable garments of occupants were not compulsory during the observations. Figure 5.13 indicates the patterns of activity that the occupants experienced 15 minutes before conducted field studies in two studies. The metabolic rates ranged from 0.8 (light activity) to 1.8 (heavy activity). Over 40% of occupants spent their time relaxing sitting, standing or reading (1met) at home. Some people had medium and heavy gestures, such as cleaning, cooking, or playing.

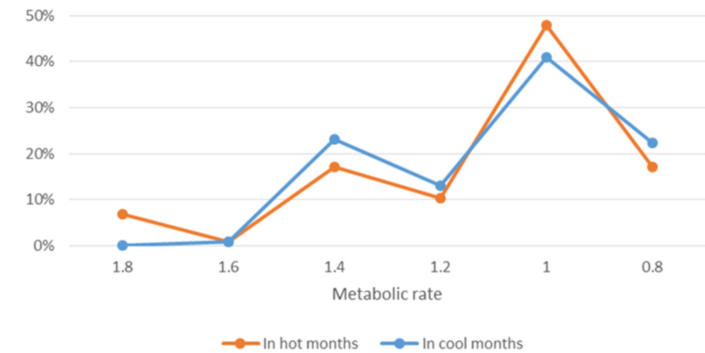


Figure 5.13 Distribution of metabolic rate of occupant activities during two field studies

ISO or ASHRAE standard estimates the range of mean clothing ensemble insulation from 0.3 to 0.5clo in the warm climates (ASHRAE, 2004) (ISO, 2005). Under constant exposure to a hot and humid climate in the southern regions of Vietnam, light clothes are occupant preferences at home to enable convective ventilation and evaporation of sweat on the skin. For instance, the female is preferable to be dressed in light cotton pyjamas, short-sleeved T-shirt and cotton shorts, and light dress. Meanwhile, the male often wears short-sleeved T-shirt or vest for tops, and khaki shorts or light/denim trousers or chinos for bottoms; however, they often keep their tops out to get them cooler on hot days (Figure 5.14). In Vietnam, most people walk on bare feet around their house, which makes them comfortable.

Figure 5.14 Occupants' typical clothes of the Vietnamese in residential buildings in HCMC

Summarising clothing insulation of occupants during both field studies showed large variability and lower values than the standards' recommendation - 0.5clo (Figure 5.15). The clothing data depict high individuality in clothing among people at home and their preference for light and simple clothes. The lowest value of clothing pattern found was 0.08 corresponding to wearing only light shorts. Most occupants selected clothes with insulation values below 0.3clo in summer while in cool months, air temperatures were lower, as a result, the selection of occupant garments changed: 53% of participants (<0.3clo) and 45% (0.3-0.5clo).

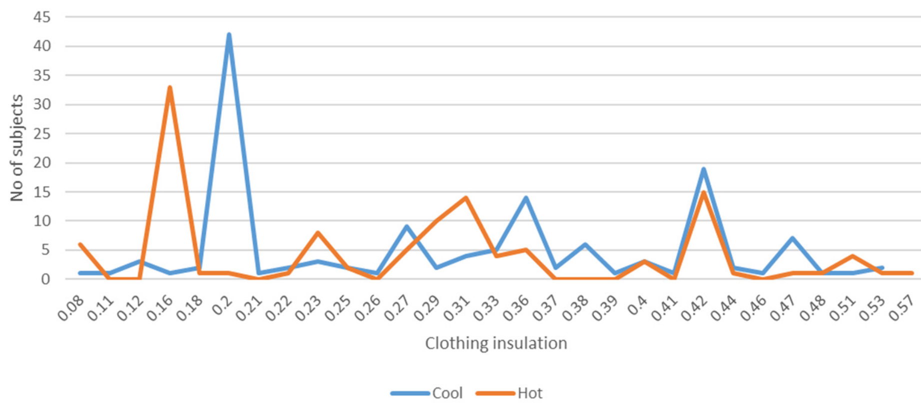


Figure 5.15 Clothing patterns of occupants in two field studies

5.3.5 Collection

a. Comfort surveys

Techniques used for comfort surveys were questionnaire combined with simultaneous measurements of the environment around subjects. For collecting subjective responses, the questionnaire, which was adopted and modified from the samples attached in ASHRAE 55 (2004) and instructions of Nicol, Humphreys, and Roaf (2012), was dispensed to the participants. The form was applied in the native language of Vietnamese and it was also tested during the pilot study, and then, refined for the final empirical studies. Figure 5.16 presents the English version of the questionnaire. Before answering the questionnaire, the researcher explained the purpose of the survey, along with questions to all participants. Then, they had around 10 – 15 minutes to respond to all questions.

The question table is divided into two parts. Part 1 included personal information related to demographics and anthropometrics such as age, weight, and gender. Additionally, checklists of garments and activities were provided for the respondents' choice. Furthermore, the specific location where the occupants replied to the form was also recorded. Part 2 asked for subjective assessments of sensations, preferences, and acceptability in the given thermal and wind environments at that point in time. To examine occupant thermal sensations, a ASHRAE 7-point sensation scale ('cold', 'cool', 'slightly cool', 'neutral', 'slightly warm', 'warm', and 'hot') was applied for voting; however, two warm and hot sensations were modified corresponding to 'hot' and 'too hot' when translated in Vietnamese. The reason is the actual climatic perceptions of occupants and a narrow difference of monthly temperatures in the locality.

The McIntyre 3-point scale of thermal preference was developed by a 7-point scale corresponding to the thermal sensation measure (McIntyre D. , 1980). The airflow questions also concentrated on occupant perceptions of the wind environment around them. The occupants voted for their air movement sensations related to airspeed by a scale of 5 points ('too still', 'still', 'just right', 'windy', and 'too windy') and their airflow preferences by a 3-point scale ('more air movement', 'no change', and 'less air movement'). Besides, the subjects registered their 'acceptable' or 'unacceptable' and 'satisfied' or dissatisfied' with the thermal conditions where they were presented. Simultaneously, they were also asked for the reasons affecting their votes.

University of Huddersfield, Huddersfield, UK
School of Art, Design & Architecture

SURVEY FORM

Project title: **Optimisation of Natural Ventilation to Balance Thermal Comfort and Energy Efficiency in The 'Shophouses' of Ho Chi Minh City, Vietnam**
Researcher: **Thanh Hung Dang** Supervisor: **Prof. Adrian Pitts**
Contact: Thanh.Dang@hud.ac.uk, thanhhung84mt@yahoo.com

This survey has been produced by Thanh Hung DANG at the University of Huddersfield, UK. The results of this survey will be used to predict and analyse comfort and ways in which occupants use 'shophouses', and to investigate the performance and energy consumption of shophouse dwellings in Ho Chi Minh City, Vietnam.

INFORMATION

1. Occupant's number:

2. Gender ☐ Female ☐ Male

3. Age: ☐ 15-25 ☐ 25-35 ☐ 35-45 ☐ 45-55 ☐ 55-65

4. Weight ☐ 40-50 ☐ 50-60 ☐ 60-70 ☐ 70-80

5. Occupant's current clothing

☐ Pyjamas ☐ Sleepwear dress ☐ T-shirt ☐ Shorts	☐ Shirt/blouse short sleeves ☐ Shirt/blouse long sleeves ☐ Hoodie ☐ Sweater ☐ Jacket	☐ Trousers (thick) ☐ Trousers (thin) ☐ Sweatpants ☐ Thin skirt ☐ Thick skirt	☐ Short sleeve dress ☐ Long sleeve dress ☐ Slippers ☐ Shoes/sandals/socks ☐ Chair(fabric, cushions)

6. Occupant's activity in the last 15 minutes
☐ Reclining ☐ Seated quietly ☐ Standing relaxed ☐ Light activity standing ☐ Medium activity standing

7. Occupant's location (which room)
☐ Living R ☐ Family R ☐ Kitchen + dining ☐ Bedroom ☐ Working/learning R ☐ Worshipping R

QUESTIONNAIRE

8. How do you feel about the indoor air temperature at the moment? (ASHRAE Scale)

Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

9. Is this environment acceptable to you? ☐ Acceptable ☐ Unacceptable

10. If you are unacceptable, which below reasons impact on of your choice? *(you can pick many answers)*
☐ Too much air movement ☐ Not enough air movement ☐ Hot surrounding surfaces
☐ Too dry ☐ Too wet ☐ Too hot ☐ Too cold

11. You would prefer to be:

Much warmer	Warmer	A bit warmer	No change	A bit cooler	Cooler	Much cooler

12. How do you feel about the air movement in your room at the moment?

Too still	Still	Just right	Windy	Too windy

13. Are you satisfied with the current air movement condition? ☐ Satisfied ☐ Dissatisfied

14. For the air movement in your room, you would like:

More air movement	No change	Less air movement

Figure 5.16 The question table for thermal comfort surveys

While subjects were giving their answers, the surveyor instantaneously measured the physical variables (air temperature, air velocity, humidity, and globe temperature) by the manual equipment. The meters were positioned in a radius of 1m around such occupants. Depending on a personal posture such as sedentary, standing or lying, the environmental data were read at three different levels of height above floor – 0.1m (low), 0.6m (medium), 1.1m for sitting and 1.7m for standing (high). Time to read the values was 30 seconds after the meters' calibration. An airspeed value was averaged of all numbers recorded by a hot wire anemometer within 30 seconds at each measurement. All data were recorded and numbered in separate sheets with a similar code of every respondent.

During measurements, the internal environmental conditions were kept entirely natural with no operation of mechanically cooling systems such as fans and air-conditioners. They were switched off to ensure true sensations and reliable responses of occupants in NV environments. The measurement of environmental parameters in comfort surveys complied with the rules mentioned in ASHRAE Standard 55-2004.

Compared to previous field studies on subjective thermal perceptions in offices or schools (de Dear & Foutain, 1994; Karyono, 2000; Rangsiraksa, 2006), even in residences in SE Asia (de Dear, Leow, & Foo, 1991; Feriadi & Wong, 2004; Wong, et al., 2002; Hussein, Rahman, & Maria, 2009; Djamila, Chu, & Kumaresan, 2013), subjects were often gathered in the same room for replying to questionnaires and taking measurements. Besides, the subjective metabolic rate was assumed at the same level of 1met. However, the distinctions of building type and human occupancy in shop-houses observed during the pilot study in HCMC were considered to suggest another survey method. To ensure reliability and reality of data, the fieldwork was carried out in various spaces of the building which the subjects expected to spend their time instead of grouping them in a specific room. They were also free to wear their clothes and to spend their activity. This method sounds plausible because the daily activities of residents and their occupancy merely vary around the house over time. Additionally, the indoor climate among rooms within a house may have variations, that can link to differently subjective sensations and interactions with the thermal environment which occupants are presented.

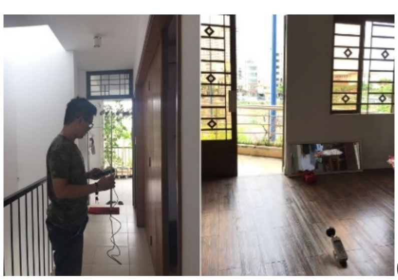
b. Environmental performances

Environmental conditions in and around the dwelling were assessed by two techniques – repeated spot measurements and longitudinal recording. In 65 shop-houses visited, there were 22 cases selected for the cross-sectional studies in both hot and cool seasons. They were grouped into three shop-house building types (traditional shop-house, new shop-house, and row house) and seven urban structures from pattern type 1 to 7 as shown in Table 4.3. The environmental studies were conducted room by room in each building and for both indoor and outdoor climates. During taking measurements, electrical cooling machines were turned off while windows and doors were open to ensure NV environments in the building. The information on measuring day and time was also reported.

The environmental profile of a building was constituted by five physical parameters including air temperature, globe temperature, relative humidity, luminous level, and airspeed. They were collected by the handle instruments. To collect the data of temperature and relative humidity, the digital thermometers were located at the centre of each room and numbers were read after meters completed their calibration.

Meanwhile, the measurement of airspeeds was more complicated through a 3D mesh system established for individual rooms/spaces within a building. The size of mesh depends upon room dimension and its boundary is set back at least 500mm from internal walls of a room. At an intersection, a hot wire anemometer measured air velocity at three different heights above floor level: 0.1m (low), 1.1m (medium), and 1.7m (high) within the occupied zone. The final airspeed value of every measurement was a mean of all numbers extracted automatically over 30 seconds. Airflow through inlets and outlets on the building fabric was also examined by assessing air velocity. For wall apertures and windows, an anemometer was located at the centre of opening for reading. Meanwhile, wind flowing through doors was collected at three arrays of the effective opening above the floor. The distribution of daylight in a building was measured on a 2D mesh of working plane at 0.8m above floor. The grid system was similarly designed to wind measurement.

In the above 22 houses, 3 cases of them containing one row-house in pattern type 1, 2 new shop-houses in pattern types 3 & 4 were installed the data loggers for monitoring the environment in and around the building for 11 months. Because of a limited number of loggers, their installation was within the occupied zone in some major rooms, such as living room, kitchen and dining, and bedrooms of each sample. The transducers recorded the physical data indoors (air temperature, humidity, and air velocity) with the intervals of 30 minutes whilst the outdoor sensors were set to save data every 5 minutes. In all environmental parameters, measuring wind velocity was tricky because of inconsistency. For outdoor winds, the Netatmo wind gauges were installed at the balcony of building façade and recorded wind velocity data and its direction through connection with the units of Netatmo weather station (Figure 5.17b). On the other hand, indoor airspeeds were monitored through a combination of a HOBO air velocity sensor and a HOBO logger. The sensor worked as a meter while the logger was a storage device besides a function of recording air temperatures and humidity values indoors.


(a)

(b)

Figure 5.17 Taking measurements of the indoor environment in the shop-houses of HCMC: (a) cross-sectional, (b) longitudinal

c. Building characteristics

When visiting the subjects and taking the measurements, surveyors concurrently reported the principal characteristics of houses related to building/urban type, building size, building elements, and several rooms and floors in separate statistical sheets. Collecting building information of all case studies, particularly opening configurations, was conducted by tools: photography, sketching, on-site measurements, and redrawing. Then, data of building openings were classified into different variables described above in Section 3.3, for example, size, orientation, material, operation, and type. That action will be beneficial for further analysis.

d. Feedback of professionals

The validity of research's outcome - a proposal of opening design guidelines, was tested by two questionnaire forms with the professionals, who are working on the construction industry in HCMC. The first form was distributed to the participants before the proposal published. That survey aimed to perceive the shortcomings, which designers are facing to achieve a comfortable shop-house in Vietnam and to find proper reasons and initial ideas for building an effective design tool kit in further.

The second questionnaire was provided to a group of previous participants after the draft of opening design guidance had been issued. That survey was to examine its possibility and applicability in practice. Based on the database of investigations of occupant thermal sensations and building environments and building features, a demonstration of design guidelines for opening configurations was suggested. To collect feedback from professionals, many seminars were organised in firms. The participants had time to experiencing and discussing after the researcher's presentation. Finally, they responded to the questions' form. Their comments are significant for the author to revise and advance guidance further.

5.3.6 Data analysis

Two major analytical methods used in the research are statistical analysis and computational simulation. The data of questionnaire interviews and measurements were analysed by a common statistical software program known as IBM SPSS Statistics version 24. For the current work, different calculations of SPSS were carried out corresponding to particular analyses. For instance, descriptive statistics showed the distribution of variables examined through the values of mean, maximum, minimum, standard deviation, and frequency. Furthermore, the regressions of linear, probit and logistic were used to identify the correlation between environmental variables and between them and subjective votes. The comfort conditions were identified based on those regressions. To gain the reliability of results, all raw data were tested for the problems of error or bias before operating official analyses. The details of statistical analyses, as well as their results, will be shown more in Chapter 6.

The proposal of opening design guidance is a result of a wealth of parametric studies operated by a simulation software program in architecture and construction known as licensed DesignBuilder version 5.5. The thermal and wind calculations integrated into that computational tool were operated to investigate the environmental condition of a generic 3D building model when different opening variables and their variations were applied. The environmental calculations were designed in the worst climatic period across the year (summer months). Apart from thermal investigations indoors, the airflow environment in the building was studied by using the CFD module (Computational Fluid Dynamics) of the DesignBuilder program. More details of parametric studies will be indicated in Chapter 9.

5.3.7 Ethical issue

The surveys were carried out with the occupants' voluntary participation. The agreement of participants is shown by the consent form. Therefore, the confidentiality of the subjects' personal information is mandatory. All responses of subjects are confidential and unallowable to pass to another party. For each visit, the researcher contacted occupants and got their permission before visiting with the detailed explanations of purpose and activities related to the on-site survey.

5.4 Conclusions

Table 5.2 summarises all research methods deliberated to use for this study on thermal comfort conditions in NV residential buildings of HCMC. Those methods concentrated on both objective and subjective assessments. In spite of the fact that the surveys' conduction learned experiences from previous studies and complied with the protocols in standards, measurement techniques had adaptation and modification to match to the local contextual factors of distinctive vernacular shop-house building type and its inhabitants.

In free-running shop-houses, both indoor and outdoor climates exchange over time through building surfaces and openings on them. Under a warm humid climate in HCMC, though the air temperature is the main determinant influencing the indoor comfort, its daily or yearly difference is not much compared to in other climate zones. The availability of sufficient airflows can retain occupant thermal satisfaction in the building in warm conditions. However, wind dynamic characteristics in and around the building are convoluted to control because of the outdoor climate and the influence of urban and building design. Consequently, studying airflow characteristics is usually carried out in the laboratory and computational simulation. However, despite the advantages of these methods, they cannot entirely present real urban and building conditions and the complex interplay between them on the environmental condition. For the current work, the internal and external environment of shop-house dwellings, particularly air movement was investigated by a combination of three methods: spot measurements, long-term monitor, and numerical analysis by CFD. They aim to understand in depth real climates inside and outside the building and to evaluate precisely contributions of internal factors (physical building) and external factors (urban context) to environmental performances in the long-term.

Table 5.2 Summary of research methods used in the research

No	Survey type	Sample type	Number of samples	Time horizons	Variable type	Research techniques		
						Questionnaire	Measurements	Statistical form
1	Thermal comfort	Occupants	117 respondent in hot months 139 respodents in cool months	Repeated transverse	Physical parameters Subjective votes	●	●	
2	Environmental conditions	Buildings	22 houses	Repeated transverse	Physical parameters		●	
			3 houses	Longitudinal				
3	Building characteristics	Buildings	65 houses	Cross-sectional	Opening configuration			●
4	Outcomes' testing	Practitioners	55 participants	Repeated transverse	Subjective votes	●		

In respect of the aim of the project shown in Chapter 1, design guidance for openings is produced to apply to the design of shop-house dwellings in Vietnam to improve indoor comfort in those buildings. Obtaining that point was designed by a comprehensive plan of 3 Steps with the participation of apposite research techniques of collection and analysis (Figure 5.18).

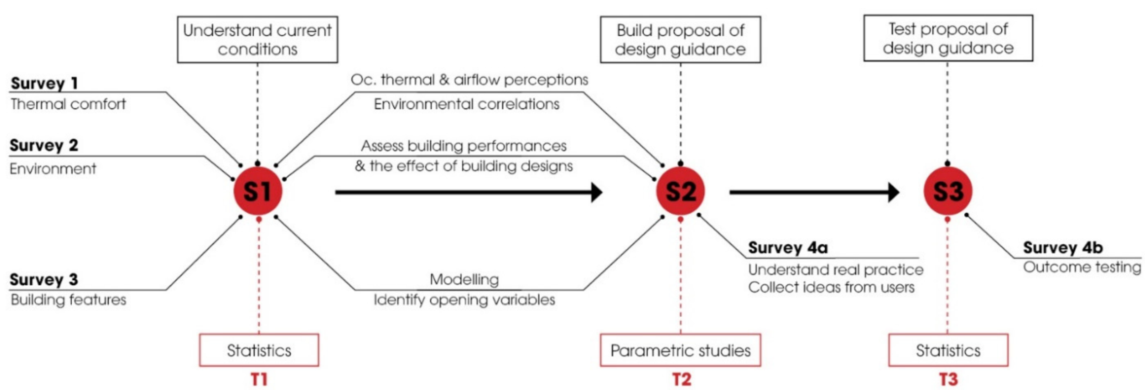


Figure 5.18 3 Steps of research methodology

Step 1 is to understand the current conditions of the building and urban characteristics of shop-houses, thermal environments, occupant thermal perceptions in those environments. Field surveys were carried out by many questionnaire interviews with residents and measurements around their house. Data were mainly analysed by the statistical method. Step 1 happens at the early stage of the project. The findings extracted from that step are the research foundation for building a frame of assessments of indoor thermal conditions and criteria for modelling in the further stage of parametric studies.

Step 2 aims to produce a proposal for design guidance. The major research method to study the methodology of the guidance is parametric simulations. Meanwhile, the idea and structure of design guidelines were derived from the measurements in Step 1 and questionnaire surveys with designers for asking for their experience in housing design in HCMC.

Finally, Step 3 is to validate the outcome. Testing the validity and applicability of the design guidelines in a real practical environment was conducted through interviews with the practitioners, who are working in studios, offices, universities in HCMC.

A 3-Step scheme is like a 'spine' of the research that designs and connects the research actions and their conduction with appropriate methods. That plan also reflects the research objectives identified in Chapter 1 and ensures sufficiency and comprehension of the project. The next chapters will go details in data analysis and findings.

Chapter 6 THERMAL COMFORT FOR THE SHOP-HOUSE

In the research literature, the conditions which occupants find comfortable in free-running residences in the tropics, have been a gap because of the influence of various contextual factors. Consequently, this chapter mainly analyses occupant thermal sensations, preferences, and acceptability to the environment in NV shop-house buildings in HCMC. Then, conditions for occupant comfort and discomfort in given building environments will be identified. Obtaining comfortable conditions for shop-houses contributes to building the assessment framework of potential design guidance to evaluate the effect of building envelope design of shop-houses. The analyses are supported by data from comfort surveys conducted in shop-houses in warm and cool seasons.

The findings will be compared to previous research in regions with similar climatic patterns and the recommendations of standards disseminated in practice. The comparisons will fill the gap of their validity when used in the built environment of Vietnam, particularly in the design of shop-houses.

Based on the comfort theory in free-running buildings, another gap identified is the influence of urban morphologies on the outdoor climate, and therefore linking to human comfort in shop-houses in HCMC. The chapter will partly analyse that correlation through investigating the basic outdoor climatic characteristics and indoor conditions within the building considered in the systematic classification of urban morphologies identified in HCMC by the research team of the University of Cottbus, Germany. Understanding that relationship is significant in considering the impact of urban forms on the building design to create comfort in shop-houses and their incorporation in the design guidance.

6.1 Outdoor climates

Summarising cross-sectional data from the multiple environmental measuring points around the city at levels under 10m in summer and spring shows significant differences in outdoor climatic conditions within settlements between both seasons (Table 6.1).

Table 6.1 Outdoor climate of shop-house dwellings in hot and cool months

Variable	**Hot (n=59)**				**Cool (n=65)**			
	Mean	Max	Min	SD	Mean	Max	Min	SD
Air temperature (°C)	32.6	37.8	29.5	1.63	30.1	32.8	26.5	1.45
Relative humidity (%)	60.5	79	41	8.06	60	73	43	6.51
Air velocity (m/s)	0.32	0.9	0.07	0.19	0.37	1.03	0.09	0.25

During hot months (April and May), average temperature, relative humidity, and air velocity were as follows: 32.6°C (SD 1.63), 61% (SD 8.06), and 0.32m/s (SD 0.19). The outdoor temperature and airspeed reached a peak at 38°C and 0.9m/s in summer. In HCMC, the rainy season concurrently occurs in summer; therefore, uncomfortable warmth can partly be mitigated during and after rain. However, the rainfall is often lower in the early season, for example, in April and May; therefore, it was not too wet with a maximum humidity of 79%. Meanwhile, the climate was cooler in the dry months with the average temperature decreased by 2.5°C. The maximum air temperature recorded was 32.8°C, which is 5°C lower compared to on hot days. The average humidity between both measurements was similar; however, the lower deviation shows higher consistency of the humid environment in the dry season. Average, minimal, and maximal wind velocities over spring were higher with values of 0.37, 0.09, and 1.03m/s, respectively.

To make comparisons with the meteorological data of HCMC from the Tan Son Hoa weather station published by Ministry of Construction in 2009, the city macroclimate was changing so more recent years were examined for this study. Depending on that document, the maximum, minimum, and average temperatures were 34.3°C, 25.5°C, and 29°C in summer and 31.2°C, 21.3°C, and 26°C in spring, respectively (IBST, 2009). These figures are 2-4°C lower than the actual thermal performances, that can explain the current issue of thermal stress for citizens around the city. Furthermore, the outdoor air movement dramatically differs between the two resources. The average wind speed recorded from the official weather stations, which are located in open areas and a greater height (>10m), was 2.5m/s over two seasons whilst that number was very low (0.35m/s) in reality at the lower level within urban dwelling blocks. Therefore, the actual climatic observations can precisely reflect the real environments surrounding buildings instead of only using meteorological station records in the analysis. This unexpected difference found between climatic data and real measurements is significant for both dwelling planning and design, but it is important to be able to understand the impact.

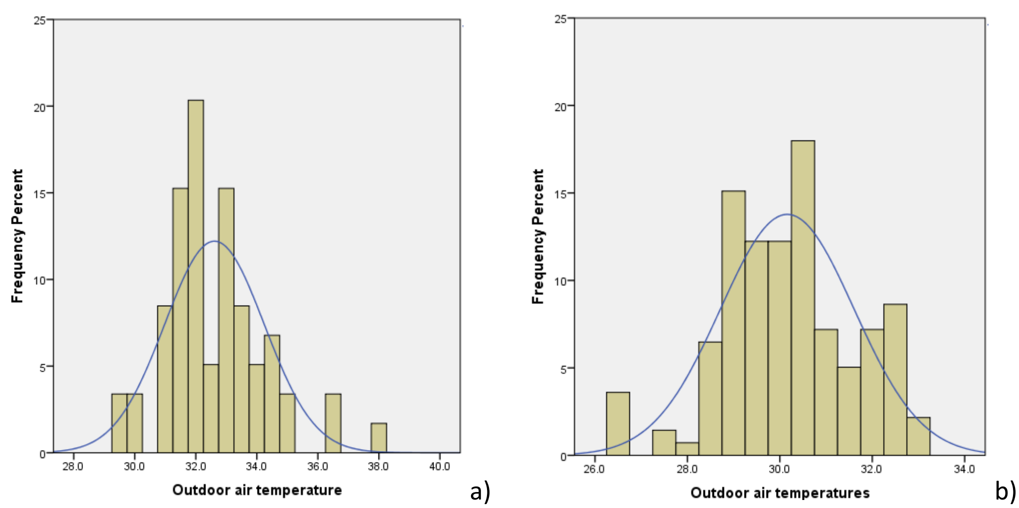


Figure 6.1 Distribution of outdoor air temperature in hot (a) and cool (b) months

The histograms indicate the distribution of outdoor thermal and wind environment in two seasons. The range of ambient temperatures observed was 29-38°C in the wet season and 26-33°C in the dry season, in this, the majority of temperature data lied within 31-35°C and 28.5-33°C (Figure 6.1).

The research literature on urban environments and outdoor comfort has identified the variations of neutral temperature and acceptable thermal bandwidth in different geographic locations in the tropics: 29.3°C and 26-31°C in Taiwan (Lin, 2009; Lin, de Dear, Hwang, & Matzarak, 2009; Lin, de Dear, & Hwang, 2011), 27.9°C in Hong Kong (Ng & Cheng, 2012), 23.1-31°C in Chiang Mai, Thailand (Srivanit & Auttarat, 2015), 27.9°C and 25-31°C in Barranquilla, Colombia (Villadiego & Velay-Dabat, 2014) and 27.5-33.5°C in Kuala Lumpur, Malaysia (Bakar & Gadi, 2016). From the context of the research reported here, the comfort predictions gathered from studies in the humid tropics show that the conditions of subjective thermal neutrality in outdoor spaces fall into a typical range of 23-31°C. Referring to that acceptable range, 85% and 23% of measurements were outside the limits meaning people would experience uncomfortable warmth in the wet and dry season, respectively.

Unlike the meteorological data recorded by the official weather stations, which are located in open areas and at a greater height, the on-site observations of air movement at the occupied level within the dwelling blocks showed the majority of airspeeds were low and typically less than 0.3m/s across two field studies. Measured airflow in the city ranged from 0.1-1.0m/s over two measuring periods (Figure 6.2).

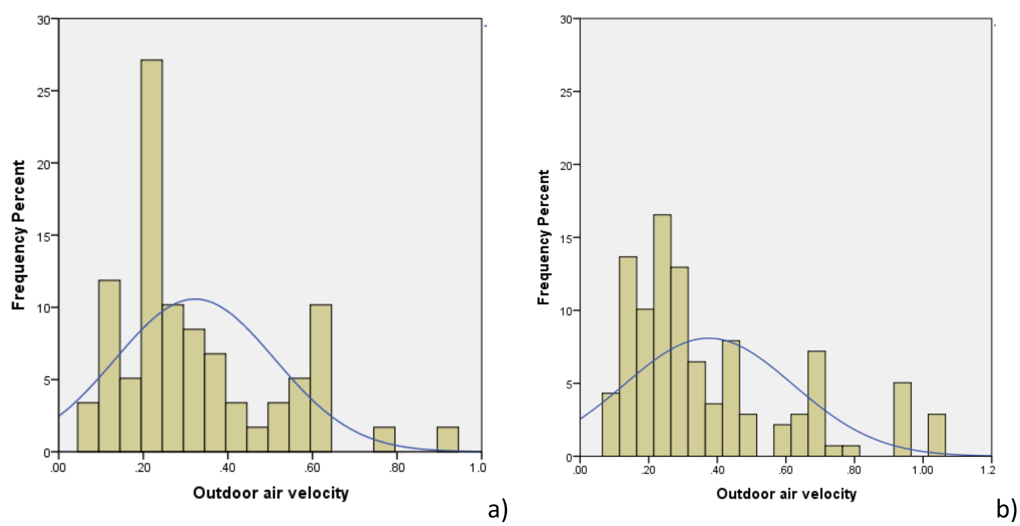


Figure 6.2 Distribution of outdoor air velocity in hot (a) and cool (b) months

The microclimatic conditions surrounding the dwellings of HCMC may confirm urban discomfort for residents because of warm air temperatures. Under warm thermal conditions in the tropics, people can find comfortable at high air temperature under the intervention of increased air velocity (Nicol, 2004). Nevertheless, real outdoor air movement is certain insufficiency over 75% and 93% of residential neighbourhoods examined referring to the acceptable ranges: 0.5-1m/s (Szokolay S. V., 1997; MOC, 2004) and 0.9-1.3m/s (Ng & Cheng, 2012) for occupants in the tropics. The uncomfortable condition of urban spaces can influence thermal environments and comfort inside the co-located naturally ventilated shop-houses.

Apart from the impact of prevailing patterns of tropical climate in HCMC, the terms of urban context (planning and urban constituents) can partly contribute to thermal and wind distribution around buildings. Therefore, considering the microclimate of settlements characterised by different urban conditions, this is significant in helping quantify comfort/discomfort of the individual urban morphologies and thus can support the assessment of appropriate design recommendations or changes to respective spatial structures of settlements. The following sections find the relationship of urban conditions with indoor and outdoor climates.

6.2 Indoor climate

Table 6.2 provides statistical summaries for 256 data sets of indoor environmental measurements inside the free-running shop-house dwellings in the rainy and sunny seasons. The data averaged across three heights taken around the subjects in the immediate environment. There was a similarity between the three parameters of air temperature, mean radiant temperature, and operative temperature in both field studies. The mean air temperature was 32°C (SD 1.18) in hot months and 29.5°C (SD 1.46) in cool months. The mean and minimum temperatures in summer were 2.5°C and 3.5°C more than in spring, respectively. The maximum indoor air temperature exceeded 33.8°C, even up to 34.6°C on hot days in rooms on the upper floors where are more vulnerable to solar radiation from the roof. Interestingly, in cool spring the interior thermal environment may be warmer than the outside. The maximum indoor air temperature recorded in that season was higher by 1°C relative to the outdoor figure. That can be attributed to internal heat sources. Meanwhile, this event was opposite during summer.

Table 6.2 Indoor environment of shop-houses in hot and cool months during surveys

Variable	**Hot (n=117)**				**Cool (n=139)**			
	Mean	Max	Min	SD	Mean	Max	Min	SD
Air temperature (°C)	32.0	34.6	29.1	1.18	29.5	33.8	25.4	1.46
Mean radiant temperature (°C)	32.0	35.5	29.0	1.35	29.6	34.4	25.5	1.50
Operative temperature (°C)	32.0	34.8	29.1	1.25	29.5	34.1	25.4	1.48
Relative humidity (%)	62.0	77.0	45.0	7.29	62.5	77	45.5	6.51
Air velocity (m/s)	0.22	0.8	0.01	0.15	0.18	0.7	0.00	0.13

In comparison with previous studies on indoor thermal environments in SE Asia, the range of temperatures between 25.5-34.5°C inside residential buildings of HCMC was slightly warmer than the climate found in other neighbour nations, for example, in Jakarta (23-32°C) (Karyono, 2000); in Jogjakarta

(26-32.6°C) (Henry & Wong, 2004) in Indonesia; in Singapore (26-32°C) (de Dear, Leow, & Foo, 1991); and relatively similar to the limits found in Malaysian residences (Djamila, Chu, & Kumaresan, 2013).

From the table, the characteristics of relative humidity taken in two seasonal measurements were similar within the range of 45%-77%. 86% of RH values fell into the acceptable zone (30%-80%) for occupants recommended in TCVN 7438-2004 (VSQI, 2005). Interior air velocities were low and fluctuated in naturally ventilated rooms with limits of 0.0 and 0.8m/s and a mean lower than 0.15m/s (SD 0.1). The light wind condition with a mean air velocity of below 0.2m/s is common in non-air-conditioned dwellings of the tropics (de Dear, Leow, & Foo, 1991; Wong, et al., 2002; Henry & Wong, 2004; Djamila, Chu, & Kumaresan, 2013). However, the range of airspeeds obtained in other fieldwork in SE Asia is much wider than the current study, for example, 0–1.5m/s in Malaysia (Djamila, Chu, & Kumaresan, 2013), and 0–1.2m/s in Indonesia (Henry & Wong, 2004). Whereas, De Dear et al. found a band of real air velocities between 0.05–0.58m/s in public housings of Singapore, which is similar to the finding of the present study (de Dear, Leow, & Foo, 1991).

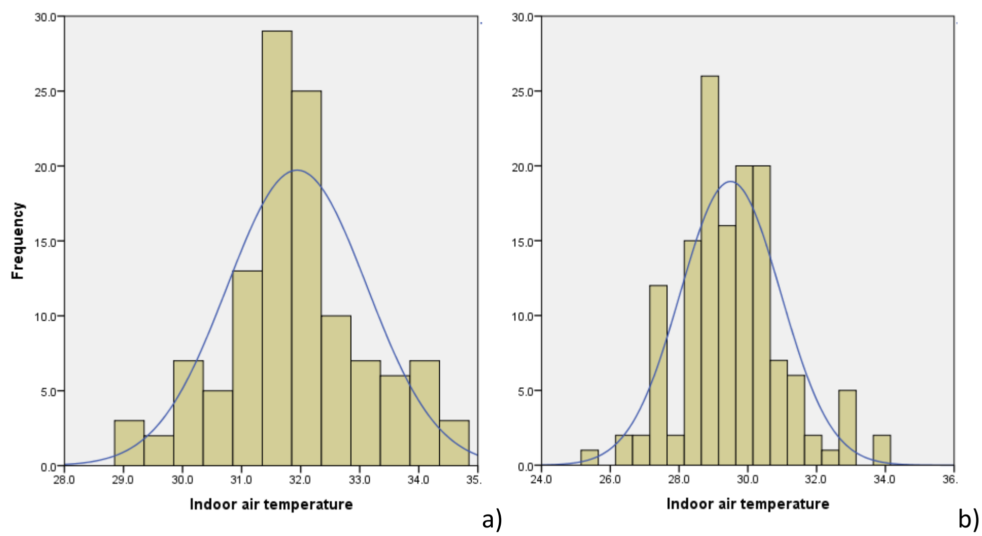


Figure 6.3 Distribution of air temperature in shop-houses surveyed in hot (a) and cool (b) months

Figure 6.3 illustrates a nearly normal distribution of air temperatures in shop-house samples in hot and cool months. The major pattern of thermal climate fell within 31-33°C and 28.5-32°C across summer and spring, respectively. Referring to the comfort conditions implemented in the international and national standards, discomfort for occupants due to a warm condition was calculated. The temperature range recorded was warmer than the threshold recommended in TCVN 9411:2012 (29°C) by 2-4°C and in ASHRAE 55 (27.5°C) by 3.5-5.5°C (ASHRAE, 2004; VIAP, 2012). Furthermore, compared to the acceptable environments in buildings defined in the existing national (21.5-29.5°C) and international (21.5-28.5) standards, the majority of measurements were out of the zones, particularly under hot summer.

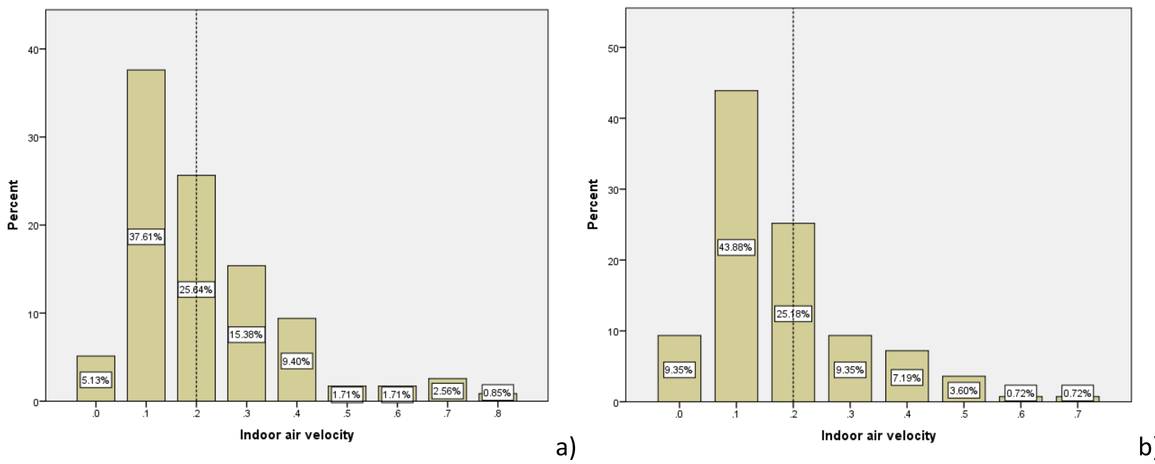


Figure 6.4 Distribution of air velocity in shop-houses surveyed in hot (a) and cool (b) months

ASHRAE Standard 55 identifies 0.2m/s and 0.8m/s to be the threshold of local discomfort in close and open spaces, respectively (ASHRAE, 2013a). Also, the present national standards recommend the comfortable zone of air velocities between 0.5-1m/s is used for residential buildings (NIA, 2004; VIAP, 2012). In the tropics, some researchers carried out experimental and empirical studies on the limits of air movement acceptability in free-running buildings, for example, 0.3-0.9m/s (Gong, et al., 2006) and 0.4—0.9m/s (Candido, deDear, Lamberts, & Bittencourt, 2010). Considering the airspeeds taken in shop-house buildings in HCMC, they certainly showed insufficiency for inhabitant comfort under warm conditions. Most data were below 0.2m/s, even in a great number of circumstances, the airspeeds were below 0.05m/s (Figure 6.4). If considering the typical range of 0.3-0.9m/s to be air movement acceptability in tropical climates, a few measurements (30% in summer and 20% in spring) with a better airflow condition were found in naturally ventilated shop-houses.

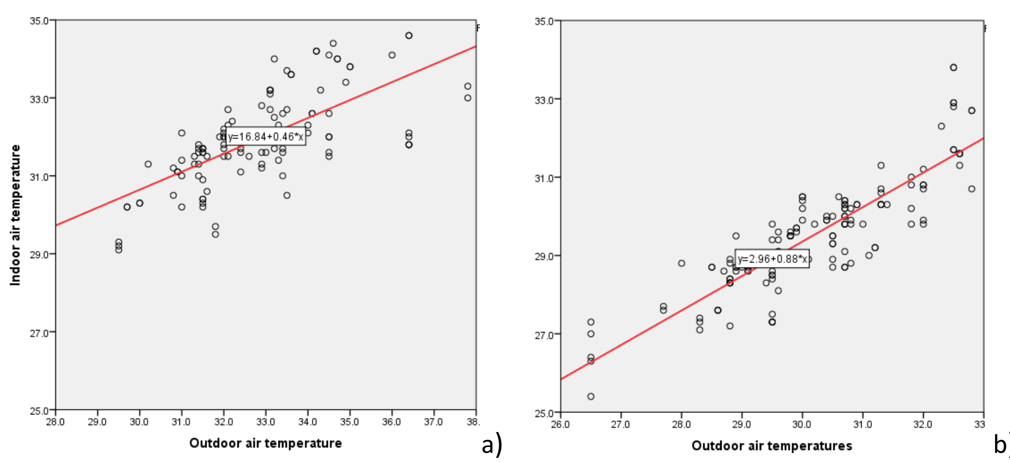


Figure 6.5 Correlation between indoor and outdoor air temperature in hot (a) and cool (b) months

Returning to the theory of adaptive thermal comfort, there is a large correlation between the internal and external climate in free-running buildings. This is also found throughout the field studies in naturally ventilated shop-houses in HCMC. The analysis of linear regression showed a close relationship between two variables: indoor and outdoor air temperatures in both seasons (Figure 6.5).

The statistical significance was characterised by a high R-square value: 0.68 in hot months and 0.87 in cool months. Exchange of two thermal climates is an intrinsic characteristic in open buildings, especially in tropical housing architecture (Tantasavasdi, Srebic, & Chen, 2001). Unlike temperature variable, interior and exterior air movement did not correlate. Two scatter plots shown in Figure 6.6 present a complex pattern of indoor and outdoor air velocities.

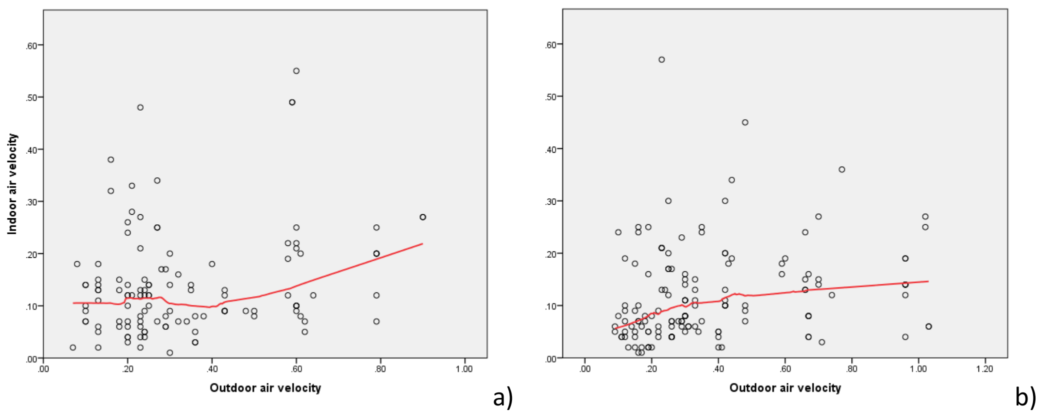


Figure 6.6 Correlation between indoor and outdoor wind environment in hot (a) and cool (b) months

Based on the above analyses of actual environmental performances in naturally conditioned shop-houses in HCMC, people are certainly exposed to uncomfortable warmth and low airflow. Additionally, there is a strong correlation between the internal and external thermal climate in houses. This is linked to the unsatisfactory thermal conditions of urban environments within settlements across much of the year found above, and possibly contribute to dissatisfaction inside. Furthermore, the negative relationship of two wind environments may be interpreted as the inefficiency of natural ventilation design strategies applied in shop-house dwellings. Therefore, the indoor thermal satisfactory environment and comfort can benefit from a combination of mitigating uncomfortable outdoor environments and applying to correctly building design, such as shading, passive solar and natural ventilation designs, and material usage, to reduce the impact of heat and accelerate airflows in the building.

6.3 Influences of urban geometries on indoor and outdoor microclimate

Sections 4.4 and 5.3.2 identified seven categories of urban morphology, which provide a good selection of commonly found dwelling urban structures. Each of these was visited and measurements of a set of environmental parameters (air temperature, relative humidity, and air velocity) were taken during two field studies. Each urban type is a distinctive spatial morphology; however, for some similar factors between some urban types (density, housing types, road pattern, and dominant landscape conditions), four groups of urban types were devised: Group 1 (pattern types 1 & 2), Group 2 (pattern type 3), Group 3 (pattern types 4, 5 & 6), and finally, Group 4 (pattern type 7).

This section finds differences in urban microclimate between settlements formed by urban shop-house geometries. The distinct physical conditions of each urban form differently govern the exterior microclimate under the common influence of tropical climate. The mean temperature calculated in Group 3 was the highest, which means the most urban discomfort. Meanwhile, the mean temperature within Group 4 was the coolest due to the shadowing effect within high dense buildings. The outdoor climate was more satisfactory for people with lower temperatures and higher wind flows in the neighbourhoods such as Groups 1 and 7 planned with low density, regular building pattern, green spaces and vegetation.

The air exchange with the outside affects the comfortable environment in naturally ventilated shop-houses; therefore, there is a consequent correlation between urban morphologies and indoor thermal environments. Comparisons of indoor and outdoor climatic characteristics between groups of urban patterns proved that relationship. In the three physical variables, the performance of air velocity was more complicated. Although the urban structure affects wind flows within settlements, the difference in airflow inside shop-houses was negligible. Furthermore, both indoor and outdoor wind environments were low for occupant satisfaction. The following subsections provide details of measurement results.

a. Air temperature

Two boxplots in Figure 6.7 indicate the variant distribution of air temperature surrounding residential neighbourhoods grouped into different urban forms. Be different from the outdoor thermal pattern of all urban types found in spring, the warm microclimate distributed normally in summer, particularly in the settlements of spatial morphologies 1-6 through the fairly same length of box-whiskers. There are some outliers and extreme scores, which may result from the cross-sectional measuring method and a partly influence of distinct temporal features between urban blocks of a pattern type.

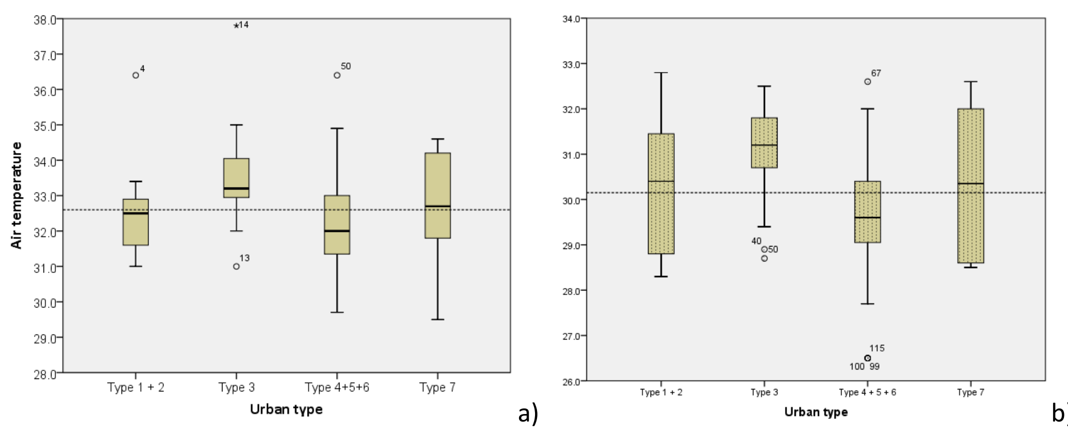


Figure 6.7 Distribution of air temperature in hot (a) and cool (b) months by urban structure types

The warmest thermal condition was found in pattern type 3, which was characterised by the highest median air temperature over two seasonal investigations: 33.6°C (SD 1.67) in summer and 31.1°C (SD 0.98) in spring. Those figures are higher than the respective average line of the whole data collected across 7 urban forms; additionally, the extremely warm climate was nearly 38°C in summer. Meanwhile, the median outdoor temperature is close to the line within pattern types 1+2 and 7. The hot environment around buildings in pattern type 3 may be a result of solar radiation due to reflection from buildings around and the absorption of asphalt roads. Meanwhile, the on-site observations around settlements of pattern type 3 found two typical conditions of vegetation: the paucity of trees to shade street surfaces and unsuitable type of plants for urban conditions (spacing, building height, and density). Those shortcomings of vegetation can be disadvantageous for comfort at the level of pedestrians because the radiant and convective heat from high surface temperatures of unshaded roads is added. Considering the issue, appropriate solutions of vegetation can be useful to minimise impacts by providing shadows and to lower air temperature in urban environments (Golany, 1996; Tong, et al., 2017).

The average air temperature in Group 1 and 4 areas was similar and close to the average of 32.6°C in the wet months and 30.2°C in the dry months. However, the variability of thermal conditions during hot days was different between those urban types. In Group 1, 95% confidence interval of air temperatures was narrower at 2.5°C (31-33.5°C) and with SD (1.49) and standard error (0.47) compared to the wider range of 5°C (29.5-34.5°C), higher SD (1.92) and higher standard error (0.78) in Group 4 – see Figure 6.10a. In addition, although the grouping pattern of buildings in Group 1, 2 & 4 is regular, the presence of green areas around those Groups 1 and 4 is a result of a cooler thermal condition, particularly, in Group 4 with the lowest temperature of 29.5°C found in summer. The unplanned large green areas in Group 4 probably play a significant role in moderating the microclimatic conditions around residential neighbourhoods.

In Group 3, the mean of air temperature outdoors was the lowest of all seven urban patterns – 32.1°C (SD 1.52) in hot summer and 29.6°C (SD 1.28) in cool spring. Under the urban morphology depicted by the irregularity and high dwelling density in Group 3, overshadowing between buildings appears to reduce the impact of solar heat, producing a cooler thermal condition in these types. However, the compact urban pattern may provide an obstruction for airflow and comfort convective cooling.

b. Relative humidity

Relative humidity varied between 48% and 80% across all urban types observed during two dissimilar seasons, excepting some unusual cases close to the humid level of 40% found in the dwelling areas of pattern types 4+5+6 in summer and 3 in spring. Some details are shown in Figure 6.8. In summer, the range of outdoor humidities was wider in all city spatial structures due to the impact of seasonal precipitation mechanism in the tropics. Among 71 shop-house settlements examined in HCMC, distinct urban physical elements and their planning within the neighbourhoods of types 4+5+6 contribute to the consistency of outdoor humid environment over two measuring times.

The hot air temperature caused the drier environment over summer months in pattern type 3, while the air condition was more humid in all other patterns. However, referring to the acceptable relative humidities as defined by TCVN 7438:2004 shows that almost 100% (pattern type 3) and 75% (all other pattern types) of RH values recorded comply with the standard at a range of 30% to 70%. Data collated for the lowest density neighbourhoods (pattern types 1+2) and the highest density blocks (pattern types 4+5+6) show the humid condition of the air in those locations; the supplement of air breezes is thus significant in improving occupant thermal comfort by dissipating moisture in the hot condition.

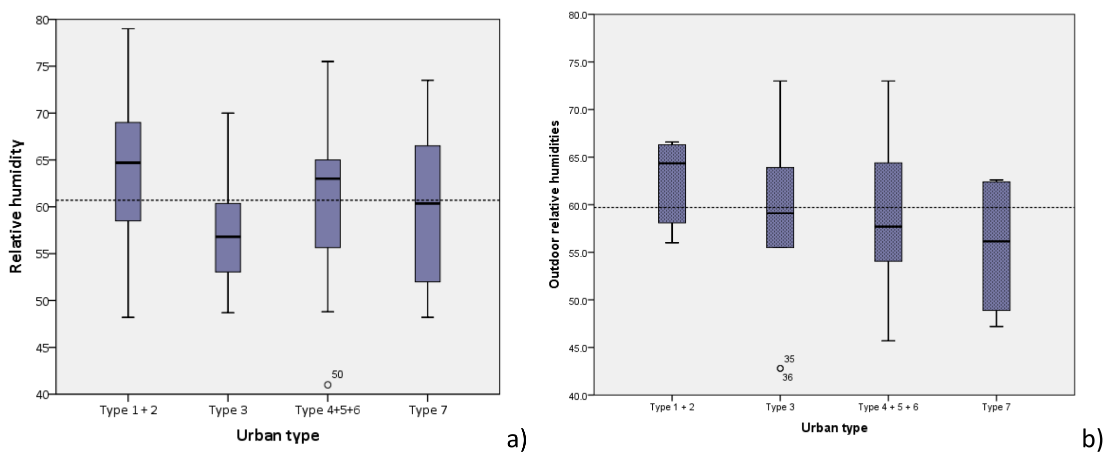


Figure 6.8 Distribution of relative humidity in hot (a) and cool (b) months by urban structure types

Although the above analyses simply compare the humidity levels between urban types and between real condition and recommendation implemented in the national standard, it is noticed that this variable is coupled with air temperature primarily and a range of various factors; therefore, it is more difficult to measure and explain the influence of humidity precisely (Nicol, 2004). Humidity is confirmed to be an important factor influencing human comfort and health in warm-humid climates (Tanabe & Kimura, 1994; Nicol, 2004). Under those climatic conditions, the involvement of sufficient air velocity for ventilative cooling is a great advantage for indoor and outdoor environments and air quality (Olgyay & Olgyay, 1963).

c. Air velocity

As shown in Figure 6.9, the different spatial structure between urban types causes variations in the air movement environment. In observations, the wind pattern of the two graphs is quite similar. The condition of airflow in pattern types 1+2 & 7 was determined to be more sufficient because of certain beneficial urban characteristics, for example, the low population density, regular road pattern, and simple road system. Furthermore, other potential factors of green sidewalks and large open spaces around those settlements not only alleviate the warm environment by the evapotranspiration process of plants and shaded areas but encourage wind convection (Johansson & Emmanuel, 2006; Ng & Cheng, 2012; Tong, et al., 2017). Those urban constituents can contribute to regulating the warm air, balancing humidity, and enhancing airflow around buildings; and subsequently improving the probability of outdoor comfort. Meanwhile, the irregular building pattern, along with high density is a result of the lowest wind environment in Group 3 with the mean airspeeds around 0.2m/s and a lower degree of air turbulence.

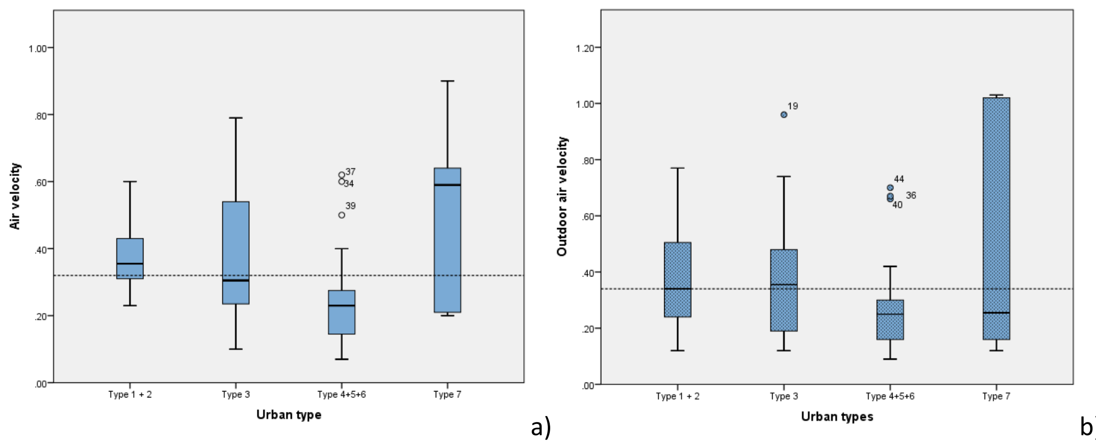


Figure 6.9 Distribution of outdoor air velocities by urban types in hot (a) and cool (b) season

The mean airspeeds within settlements of Group 1 and 4 were 0.4 and 0.55m/s, respectively. The maximum air velocity in Group 4 recorded was at 0.9m/s in summer and 1.0m/s in spring. Referring to the acceptable zone of air velocities (0.5-1m/s) recommended into TCVN 9411:2012 for shop-house building design, approximate 50% of airspeed values observed fell into that range in those urban patterns during two measurements. On the other hand, the performance of wind flows in Group 3 was poor with 90% of airspeeds were lower than 0.5m/s, particularly in summer, and as such can cause summer thermal discomfort. The irregular pattern of houses within the area of Group 3 may affect tricky wind performance outdoors, evidently, there were unusual higher airspeeds taken in some neighbourhoods. In Type 3, the amplitude of wind speed was from 0.1 to 1.0m/s, with approximately 40% and 30% of the values above 0.5m/s in the hot and cool months, respectively.

d. Correlation between indoor and outdoor environments by urban forms

The variations of outdoor climates within shop-house settlements classified under a system of urban types are confirmed. Additionally, a correlation between the outdoor microclimate and the urban condition is also found. This chapter part will study on the complex relationship among three categories: indoor environment, outdoor climate, and urban spatial structure.

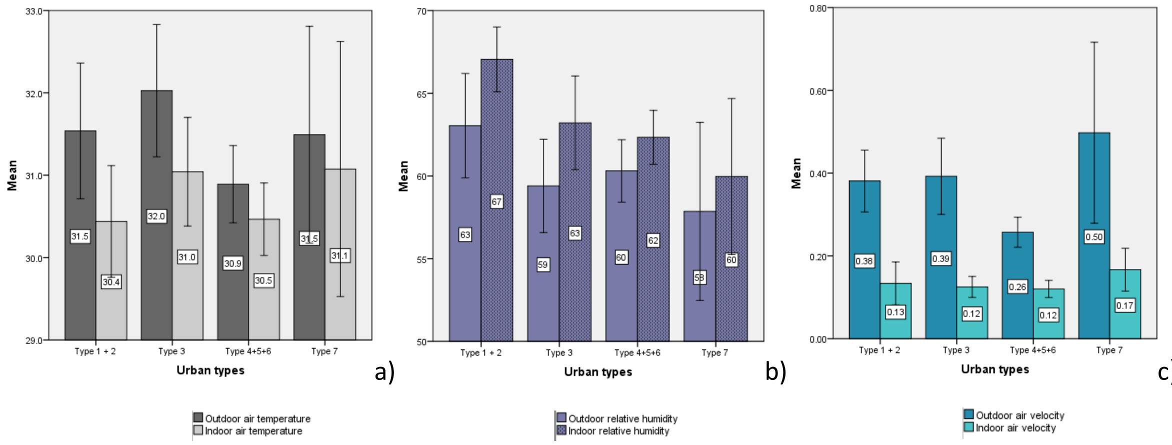


Figure 6.10 Indoor and outdoor climates over two studies by urban types: temperature (a), RH (b), and velocity (c)

Figure 6.10 represents the profile of interior and exterior climates according to groups of urban types; and a comparison of thermal characteristics between them. All graphs were drawn by all the seasonal data measured. The left graph (a) emphasises indoor and outdoor air temperatures distributed within different urban types. The hottest thermal condition inside and outside residences was found in pattern type 3. Thermal regulation by urban elements in the new residential communities of Groups 1 and 4 results in the potential for a more satisfactory and delightful environment surrounding for pedestrians because of lower temperatures and more sufficient airflows. That consequence links to improve the indoor comfortable environment. Meanwhile, compact building grouping patterns are a function of a cooler condition at the occupied zone around buildings in Group 3. Thereby, the indoor temperatures of shop-houses in those urban morphologies were also lower.

Moreover, the common shop-house dwelling type in residential blocks of Groups 1 and 2 is the row house whilst the new shop-house dominantly appears in Group 3 and a mix is in Group 4. Considering the deviation of indoor and outdoor temperature between urban types shows a higher variation in Group 1 and 2, which may explain the effective response of the physical building of row houses to the outdoor climate.

The urban geometry of a settlement also affects the humid and wind condition outdoors. All humid data inside and outside the shop-house within seven urban morphologies were between the acceptable range (30-80%). In this, the most humid environment was in the housing in Group 1. Two graphs (a) and (b) show a positive correlation between two climates in terms of temperature and humidity in four groups of urban types.

In four urban structural groups, the wind condition around Group 4 was the most sufficient and this has been inferred as being due to much low construction coverage and larger open areas integrated within a settlement. However, in neighbourhoods of Group 3, winds usually tend to be deflected and dispersed when flowing through a tricky unplanned building block. As a result, the wind environment around buildings was lower. Despite the available variation in the wind flows within settlements between urban patterns, Figure 6.10c likely presents a disconnect between interior and exterior wind environments. Despite sufficiency of outdoor natural wind, the average airspeed in the building within seven urban geometries was similarly low. This reports the less efficient performance of shop-house building fabric to induce wind outdoors and to produce air movement through the interior. Moreover, the calm airflow indoors can be interpreted by the embodied exterior wind condition intervened by urban constituents. The cross-sectional wind data showed not high mean airspeeds in most urban forms. Therefore, the consideration of appropriate urban design to create sufficient wind flows around residences is worth indoor airflow satisfaction and comfort.

Taken together the findings above confirms a strong correlation between temporal and spatial factors within a settlement and the outdoor microclimate and the thermal environment in open shop-house buildings based upon a systematic categorisation of urban morphologies found in HCMC. Additionally, the insights of environmental characteristics within settlements gathered from the research presented show that the current design and planning of those urban patterns so far categorised do not properly provide outdoor environmental satisfaction for occupants, particularly wind conditions. Even in new residential areas formally planned with lower densities, appropriate building archetypes, and integrated public facilities compared to the highly compact settlements existing in central districts, still, fail to provide comfort.

In order to address these deficiencies, the principles of urban design, for example, road pattern, spacing, building height and density, building grouping, vegetation, ratio and location of open spaces should be considered carefully in relationship with the ambient environment to create an outdoor satisfactory climate for pedestrians. That also creates the benefit of the associated indoor climate in housing planning in HCMC and Vietnam more generally. Moreover, another consideration is a good responsive design of the building to the outdoor climate. In three physical parameters analysed, the wind is the trickiest to control at the urban scale and the single building. Therefore, a thermally comfortable environment indoors will require a combination of correct designs of settlement planning and individual building. Nevertheless, the solutions to urban design are out of the scope of this study. The influence of urban structures on the indoor environment will be considered in approaching effective design guidance for the building envelope of shop-houses.

6.4 Thermal comfort responses

This subsection researches real occupant thermal perceptions and preferences in warm environments in free-running shop-houses in HCMC. The thermal acceptability and tolerance of Vietnamese people in shop-houses were higher than the assumptions in international and regional standards and previous studies in residential buildings and other types in the tropics. The comfortable and preferred and acceptable temperatures were found for shop-house dwellings. In a building, occupant comfort perceptions differed between rooms. The following sections show detailed analyses.

6.4.1 Thermal sensation votes

Figure 6.11 represents the percentage of subjects responding to their thermal sensation to the given thermal environments inside naturally ventilated shop-houses through two field studies. The subjective votes were based on the ASHRAE 7-point scale: cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (1), warm (2), hot (3).

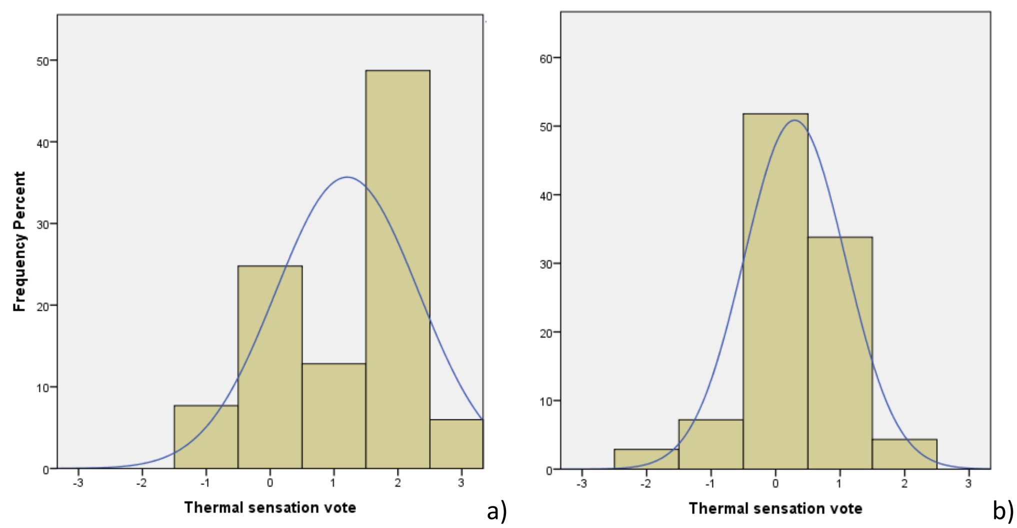


Figure 6.11 Distribution of thermal sensation votes in hot (a) and cool (b) months

The range of thermal sensation vote (TSV) between both seasons has a deviation of 1 unit. Under warm summer, approximate 55% of occupants felt 'warm' and 'hot'. Meanwhile, 45% of subjective votes fell into a thermally acceptable range from (-1) to (+1), in which, 25% of them found thermal neutrality (Figure 6.11a). On the other hand, human thermal perceptions considerably changed in the cool spring. More than 50% and 90% of subjects reported that they comprehended 'neutral' and the thermal sensations ranged from 'slightly warm' to 'slightly cool', respectively (Figure 6.11b). However, a few people (3%) supposed that the immediate environments where they occupied were cool in the same season. The difference in seasonal thermal sensations shows that indoor environments were more comfortable for inhabitants in the cool months in HCMC.

6.4.2 Thermal acceptability

The distribution of occupant thermal acceptability and unacceptability dramatically shifted between hot and cool climate (Figure 6.12). The left chart presents less discrepancy (10%) between the responses for two categories: ’acceptable’ and ‘unacceptable’ to the immediate thermal environment indoors during summer. Uncomfortable warmth influenced over 45% of occupant registrations for thermal unacceptability. Meanwhile, approximate 55% of ‘acceptable’ votes accounted for subjects’ thermal satisfaction and expectation for hot climates through their higher degrees of adaptation in the tropical house without air-conditioning than in other building types and moderate or cool climates. The finding in HCMC is consistent with previous field studies over warm-humid climates (Karyono, 2000; Nicol, 2004; Candido, deDear, Lamberts, & Bittencourt, 2010; Djamila, Chu, & Kumaresan, 2013).

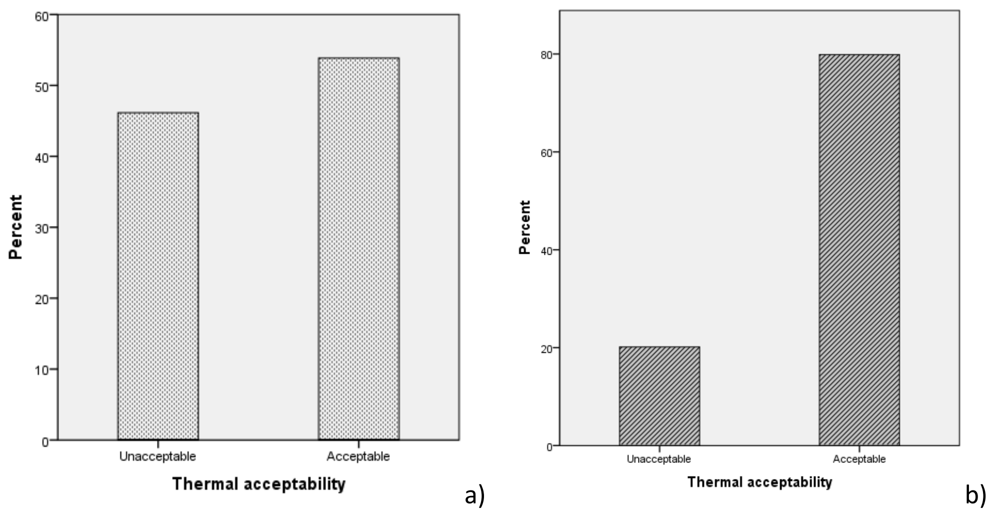


Figure 6.12 Distribution of thermal acceptability in hot (a) and cool (b) climate

In the dry season which thermal conditions indoors and outdoors were more pleasant, the ratio of ‘acceptable’ to ‘unacceptable’ votes was 4 times and the number of subjects satisfying the environment was 25% greater than the votes for the same category in warm months. Various sources seasonally governed people’s discomfort and they will be analysed in further.

The histogram analysis of thermal acceptability against TSV shows an increase in subjective thermal tolerance under warmer conditions, particularly in summer. That is proved by a high distribution of ‘acceptable’ responses at the scale of ‘warm’ sensation (above 22%), though the majority of subjects voted for ‘unacceptability’ at the same point (Figure 6.13a). More than 30% of dwellers were acceptable found the internal environmental acceptability. However, some of them found the dissatisfaction with the internal environment, although their sensational votes fell into the acceptable thermal zone. Nobody found acceptability when they registered for the ‘hot’ cognition. On the contrary, the thermal acceptability was concentrated within the margin from 'slightly cool' to 'slightly warm' during cool months, in particular, a large majority of 'acceptable' responses at the 'neutral' point (Figure 6.13b). Nevertheless, a few people did not find satisfaction with the interior thermal condition even though they felt comfortable.

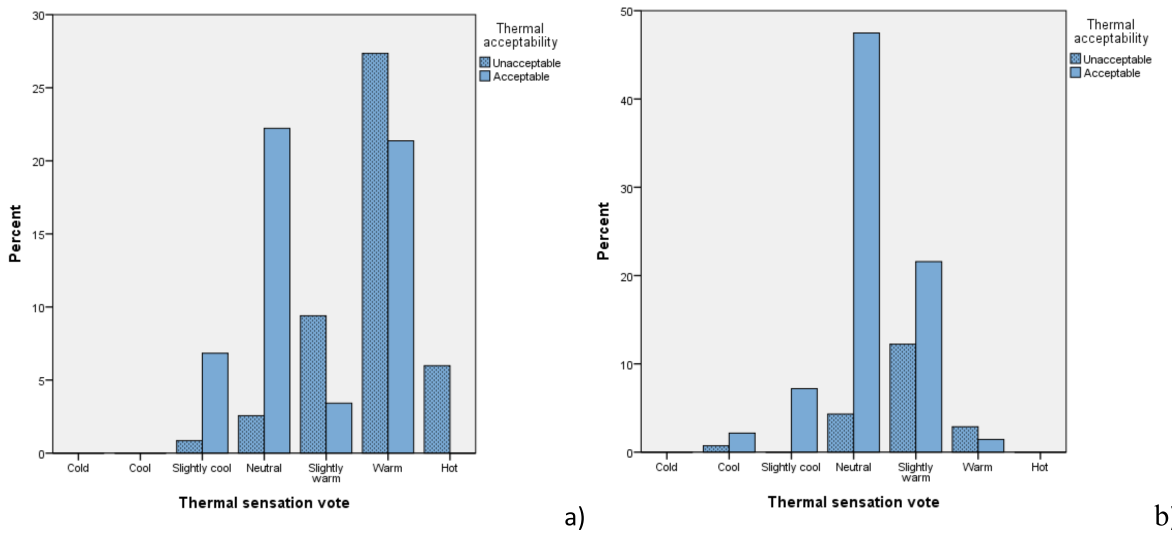


Figure 6.13 Distribution of thermal acceptability in TSV scale

6.4.3 Prediction of neutral temperature and comfort range

Occupant neutral temperatures for free-running shop-house dwellings were predicted by the linear regression of T_{op} and TSV and the limits of that line within the thermal sensation categories from 'slightly cool' - (-1) to 'slightly warm' - (+1).

Table 6.3 summarises three models of comfort votes against indoor operative temperatures, along with their statistical outputs. The outcomes were seasonally reported via analysing 117 and 139 data sets collected in HCMC in hot and cool months, respectively. Besides, a linear model of the whole population (n=256) was studied. Certainly, a strong correlation between the two variables (T_{op} and TSV) is found in all models. The sub-sections below provide more details of findings and their discussions.

Table 6.3 Regression lines of comfort found in the wet and dry season and whole population

	Wet season n=117	Dry season n=139	Whole population n=256
Neutral temperature (Top) °C	28.5	28.5	28.5
Comfort range	N/A	24.5-32.3	25.5-31.5
Regression equation	TSV = 0.36.Top - 10.23	TSV = 0.26.Top - 7.28	TSV = 0.33.Top - 9.34
Coefficient determination (R^2)	0.159	0.235	0.329
R-value	0.4	0.49	0.57
Significance	0.000	0.000	0.000

6.4.3.1 In wet/hot months

The graph below shows the pattern of all the scattered plots on the right side of the reference line at 29°C. The linear regression analysis between two parameters - indoor operative temperature and subjective vote found a moderate relationship:

$$TSV = 0.36xT_{op} - 10.23 \qquad \text{(Eq10)}$$

($R = 0.398$, $R^2 = 0.159$, Sig. =0.000, BCa 95% CI = [.190, .519])

Where TSV = thermal sensation vote

T_{op} = operative temperature (°C)

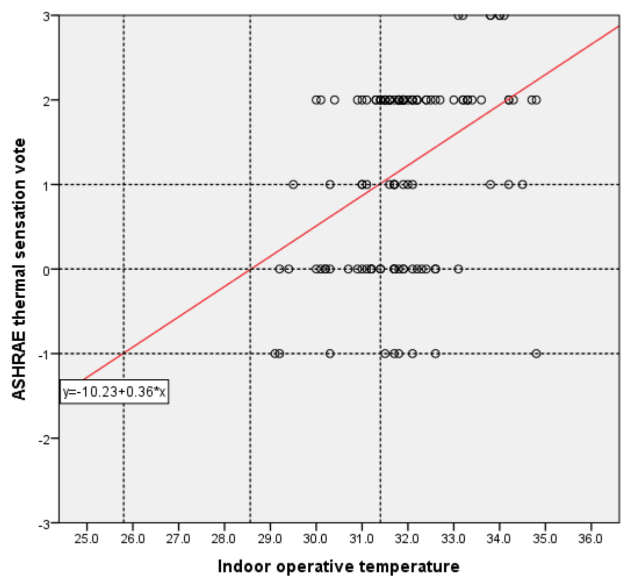


Figure 6.14 Neutral temperature for the hot season (n=117)

The neutral temperature was 28.5°C and the comfort range was from 25.8 to 31.5°C in warm months (Figure 6.14). However, the air temperatures taken in the field were not found to go below 29°C during the daytime in summer. Therefore, under the current distribution of available data, it is likely that identifying the lower limit of comfort can lack reliability. The statistical value of R squared (0.398) is explained by a medium link to indoor operative temperature for the occupants' responses. In hot humid climates, for example, in HCMC, people normally appear to tolerate warmer conditions than others at high and medium altitudes. The long-term acclimatisation and flexible behavioural adjustments of people to the regional climate could provide a reason for a higher level of acceptability. And perhaps, these explain why subjects sensed neutral in spite of the observed temperatures of over 31.5°C (Dang & Pitts, 2018a).

Although the zone of acceptable temperatures for the naturally ventilated residences in warm months lies between approximately 25.8°C and 31.5°C, the environmental condition indoors cannot be considered as offering true thermal comfort. Approximate 65% of observed data show indoor operative temperatures higher than the upper limit of the comfort zone (Dang & Pitts, 2018a).

6.4.3.2 In dry/cool months

Unlike the scattered chart in summer, all plots of T_{op} against TSV distribute from 25°C to 34°C in the dry season. The linear regression was made up of two variables as below:

$$TSV = 0.26xT_{op} - 7.28 \qquad \text{(Eq11)}$$

(R=0.49, R^2=0.235, Sig.=0.000, BCa 95% CI = [.071, .284]

Where TSV = thermal sensation vote

T_{op} = operative temperature (°C)

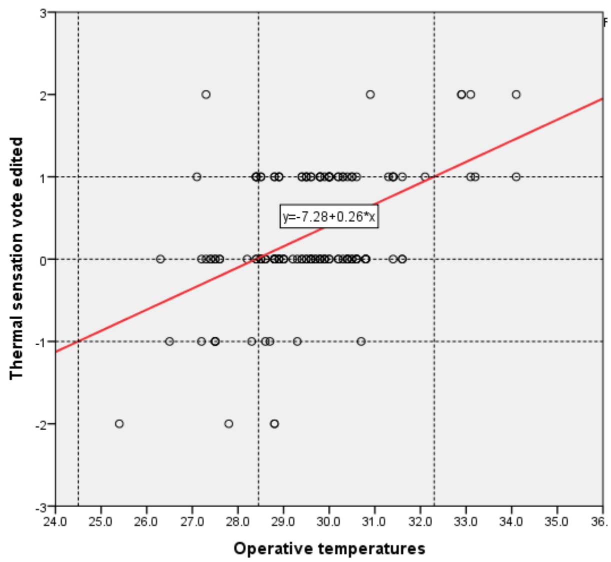


Figure 6.15 Neutral temperature for the cool season (n=139)

The analytical outputs of linear model show significance in statistics with the correlation coefficient (R=0.49), which depicts a larger effect between T_{op} and TSV than that relationship found in summer. The neutral temperature for free-running shop-houses in cool months was 28.4°C (Figure 6.15). There is likely no difference in the comfortable temperature between the two seasons. However, the lower regression coefficient of the model (Eq11) links to a higher threshold of acceptable temperature at 32.3°C compared to the upper limit of 31.5°C identified by the equation (Eq10). A wider bandwidth of comfort under cooler conditions was found within 24.5°C and 32.3°C. The interval of 8K may be plausible because of the following reasons: a cooler thermal condition indoors and outdoors, and occupants' thermal acceptability against a wider range of indoor temperatures in the dry months.

6.4.3.3 For the whole population

Combining all 256 responses of two field studies made up of the algorithm:

$$TSV = 0.33xT_{op} - 9.43 \qquad \text{(Eq12)}$$

Where TSV = thermal sensation vote

T_{op} = operative temperature (°C)

The line interception at TSV of '0' is equal to the neutral operative temperature (28.5°C) predicted for non-air-conditioned shop-house dwellings in HCMC. That number is the same as the results found in hot and cool months. The statistical model performs a large relationship between independent and dependent variables with R-value of 0.57, Sig.=0.000, and BCa 95% CI = [.237, .389]. Moreover, the gradient slope of the regression line (0.33) indicates occupant thermal sensitivity within a 1 unit change of thermal sensation scale. Limiting the regression model between two reference lines of (-1) and (+1) identifies a range of the acceptable interior thermal environment within 25.5-31.5°C (Figure 6.16). Additionally, 90% and 80% of occupants were acceptable to the magnitude of temperatures as follows: 27 to 30°C and 26.3 to 30.8°C.

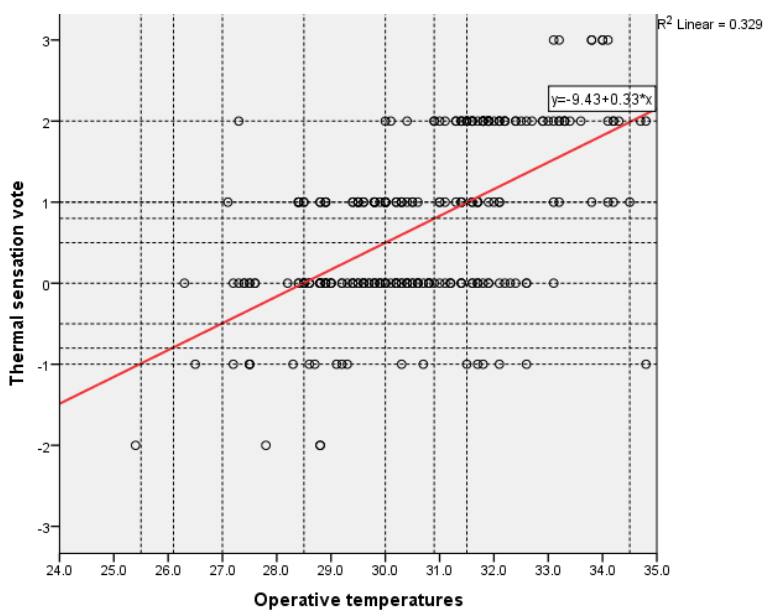


Figure 6.16 Neutral temperature and comfort range for the whole population (n=256)

Comparisons of the internal comfortable thermal environments investigated between the current research and previous work are shown in Table 6.4. The values presented in the table were assumed by numerous field surveys carried out in NV buildings in wet and dry seasons and the whole year across the wider tropics, particularly in SE Asia. Initially, the neutral thermal sensations of residents vary significantly in residential buildings in different tropical countries. The thermal neutrality predicted by the present study is similar to the assumption of de Dear for public housings in Singapore (de Dear, Leow, & Foo, 1991) and warmer by 1.0-3°C compared to the studies by Ellis, Webb, and Wong in Singapore (Ellis, 1953; Webb, 1959; Wong, et al., 2002); the research of Ballantyne in Port Moresby (Ballantyne, Hill, & Spencer, 1977); the work of Preechaya in Bangkok (Rangsiraksa, 2006). However, when compared with other studies in residences in Kota Kinabalu by Harimi and in Jogjakarta by Henry, the comfortable temperature in HCMC is determined to be cooler.

Table 6.4 Comparison of neutral temperatures and comfort ranges studied in the tropics

	Building type	Location	Months included	Neutral temperature (°C)	Comfort range (°C)	Regression equation
Ellis	Residential & office	Singapore	All year	26.4 Ta	N/A	N/A
Webb	Residential & office	Singapore	All year	27.3 ET	N/A	N/A
Ballantyne	Residential	Port Moresby	All year	25.4-27.2 Ta	N/A	N/A
Harimi Djamila	Residential	Kota Kinabalu Malayisa	Wet and dry seasons	30 Ta	27-32.5 Ta	TSV = 0.395Ta - 11.875
Henry Feriadi	Residential	Jogjakarta Indonesia	Wet and dry seasons	29.2 Top	27.5-31 Top	TSV = 0.59Top - 17.21
Nuyk Hien Wong	Residential	Singapore	Wet season	27.5 Ta	25.9-29.1 Ta	N/A
Preechaya Rangsiraksa	Residential & office	Bangkok Thailand	All year	26.7 Ta	23.4-30 Ta	TSV = 0.308Ta - 8.215
Richard de Dear	Residential	Singapore	Wet season	28.5 Top	N/A	N/A
The present study	Residential	Ho Chi Minh Vietnam	Wet and dry seasons	28.5 Top	25.5-31.5 Top	TSV = 0.33Top - 9.43
John F. Busch	Office	Bangkok Thailand	Wet and dry seasons	25 ET	22-30.5 ET	TSV = 0.289ET - 8.247
Tri Harso Karyono	Office	Jarkata Indonesia	All year	26.7 Top	23-8-30.3 Top	TSV = 0.31Top - 8.38
Richard de Dear	Office	Townsville Australia	Wet and dry seasons	24.3 Top	22.3-26.2 Top	TSV = 0.522 Top - 12.67
Christhina Candido	School	Maceio Brazil	Wet and dry seasons	N/A	26-31 Top	N/A
Madhavi Indraganti	Office	Chennai Hyderabad India	All year	26.2 Tg 28.8 Tg	N/A	TSV = 0.313 Tg - 8.1708 TSV = 0.215 Tg - 5.682
Top: Operative temperature; Ta: air temperature; ET: effective temperature; TSV: thermal sensation vote; Tg: Indoor globe temperature						

In addition, the comfort bandwidth and the upper comfort limit found across warm humid climates also have some divergences. The following descending band of acceptable temperatures is sorted: Preechaya's research in Bangkok (6.5K), the present study (6K), Harimi's work (5.5K), and Henry's study (4.5K) (Henry & Wong, 2004; Rangsiraksa, 2006; Djamila, Chu, & Kumaresan, 2013). The highest threshold of thermal acceptability was determined at 32.5°C in open tropical residences in Malaysia (Djamila, Chu, & Kumaresan, 2013). Despite the fact that those example studies were conducted for the similar building typology – residential, the similar cooling system – natural ventilation, and the similar environment – tropical, the differences in thermally comfortable cognition of occupants result from the factors associated with distinct regional climate, ethnical background, culture, housing sub-types (shop-house, detached house, and flat), vernacular building design, and thermal history.

The neutral and acceptable temperatures found in the present study are higher when collated to previous comfort studies in offices with and without HVAC in Bangkok, Thailand (Busch J. F., 1990); Jakarta, Indonesia (Karyono, 2000); Townsville, Australia (de Dear & Foutain, 1994); and Chennai, India (Indraganti, Ooka, & Rijal, 2013) which reported the neutral temperatures as the following: 25ET, 26.7 T_{op}, 24.3 T_{op}, and 26.2 T_g. A difference of thermal neutrality (1.8 to 4.2°C) between those studies can be attributed to two reasons: building type (office and residence) and cooling mechanism (natural ventilation and HVAC). The distinction between thermal responses in air-conditioning and NV buildings have been arisen by the varying context of the environment, thermal experiences, and expectations of future thermal desire (Brager & de Dear, 1998). In AC buildings, inhabitants' adaptability is narrower in constant thermal conditions controlled by HVAC while they have more opportunities for accessing available building controls and operating personal adjustments in non-air-conditioned buildings (Szokolay S. V., 1997) (de Dear & Brager, 2002). The higher comfortable temperature and acclimatisation of occupants in free-running shop-houses show the ability to save significant energy for cooling systems.

The author has attempted to measure occupant thermal sensations and acceptability in the given environment of free-running shop-houses in HCMC in warm and cool climates. Their thermal perceptions differed seasonally. Gathering all data of TSV and T_{op} over typical seasons in HCMC, the range of comfort conditions for residents was assumed. That range directly affects the housing design. Architects will properly evaluate human thermal satisfaction in real environments, and then propose appropriate design strategies for buildings to adapt to seasonal climates and to provide the acceptable thermal conditions for residents in shop-houses.

Additionally, the author reconciles some variations in data and analysis with other studies in the tropics. The discrepancies are consistent with the hypothesis addressed in Section 2.2 about the influence of contextual terms on human thermal perceptions and expectations in open environments in warm-humid regions; and can help explain the significance of primary data taken from field surveys to obtain the comfort conditions for shop-houses, which will be used as the criteria to assess the comfort degree and the performance of building design in houses.

Such differences could also prove significant. Many researchers stated that finding the limits of acceptable temperatures is significant for the practice because of assuming how much energy can be reduced (Arens, Humphreys, Zhang, & de Dear, 2010; Nicol, Humphreys, & Roaf, 2012). The acceptable temperatures obtained in the current study show higher thermal tolerance of the Vietnamese people in naturally cooled shop-houses than they found in studies with similar/different building types and of similar environments. It is important in Vietnam to conduct studies to understand clearly what occupant sensations and expectations in residential buildings and shop-houses as this has impacts on demand for and use of air-conditioning systems and rise of energy use.

6.4.4 Comfortable conditions by rooms

Reviewing the distinct research method used for the current project, the collection of subjective sensational votes and environmental measurements in shop-houses was conducted in various rooms of buildings, instead of grouping all participants in a specific room in previous comfort studies. The reason behind is identical characteristics of daily human occupancy in their house. Data collection by this way intrinsically reflects occupant thermal sensations and reactions to the environment of different spaces within the house, in which, they daily occupy and expect to spend their time during surveys. Consequently, interior environments and ASHRAE sensation votes were collected under the classification of various common room types in a shop-house building: living room, family room, kitchen + dining, bedroom, and studying room/office/shop.

Table 6.5 Mean TSV and T_{op} in different room types within a shop-house

Room type	Mean thermal comfort vote	Mean indoor operative temperature (°C)	Mean relative humidity (%)
Living room	0.64	30.5	63
Family room	1.33	31.6	62
Kitchen + dining	0.57	30.5	62
Bedroom	0.66	30.8	60
Studying room + office + shop	1.03	30.6	63

Table 6.5 presents the mean values of subjective comfort vote and internal operative temperature categorised in the different functional spaces. The average thermal environment in the family room was the hottest, as a result, the mean TSV in these rooms was out of the acceptable zone between -1 and +1. Meanwhile, the mean operative temperatures were similar and occupant thermal cognition seemed to be acceptability in other rooms. Another analysis is interesting to find a variation of 2.3°C neutral temperature among 5 room types (Figure 6.17). The lowest and highest neutral temperatures were 26.9°C in study rooms/offices/shops and 29.2°C in bedrooms, respectively. The subjective thermal neutrality was in family rooms, living rooms, kitchen + dining rooms as follows: 27.8°C, 28.6°C, and 28.8°C. Inhabitants certainly felt warmer than mean thermal neutrality (28.5°C) for the whole population in bedrooms. Whereas, they found a cooler sensation as their comfort in the studying room/office/shop and family room. This confirms that different environmental conditions between interior spaces, which are featured by distinct function, room geometry, spatial design, and room fabric, influence desired thermal perceptions of occupants.

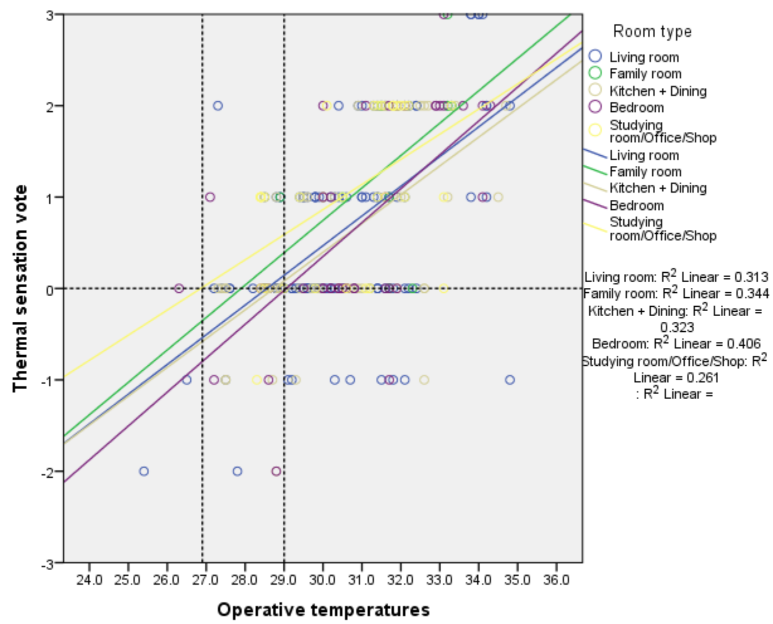


Figure 6.17 Neutral temperature analysis in different functional rooms of the shop-house

Table 6.6 shows detailed analysis. The variation of comfortable temperatures in those rooms can be explained by some reasons. Firstly, in most houses of Vietnam, particularly shop-houses, the living, family, cooking, and dining rooms are commonly communicative spaces of a family. The geometry of those rooms is usually designed as an open plan. Secondly, as the larger area of the whole space, natural ventilation and lighting are usually optimised; therefore, that implicates the optimum concentration of operable windows and doors. Thirdly, considering the spatial layout of a shop-house, the rooms are normally positioned on the lower floors, for example, ground or first floor. As a result, the impact of intense solar energy from the roof or surrounding is less. Meanwhile, the bedroom is usually on the upper floors and possibly receives more solar radiation through roof and openings in exposed walls. Therefore, the thermal environment in the bedrooms is usually more unpleasant than other room types. The demand and use of air-conditioners and fans are more in those rooms.

Table 6.6 Neutral temperature and statistical model by room types

Room type	Neutral temperature (°C)	Regression equation	R²	R-Value	Gradient slope	p-value
Living room (A)	28.6	TSV = 0.32Top - 9.28	0.313	0.56	0.32	0.000
Family room (B)	27.8	TSV = 0.35Top - 9.89	0.344	0.59	0.35	0.045
Kitchen + dining (C)	28.8	TSV = 0.31Top - 9.05	0.323	0.57	0.31	0.000
Bedroom (D)	29.2	TSV = 0.37Top - 10.77	0.406	0.64	0.37	0.000
Studying room + office + shop (E)	26.9	TSV = 0.27Top - 7.38	0.261	0.51	0.27	0.002

The correlation coefficient of five statistical models above 0.5 concludes a large effect between T_{op} and TSV, especially, the significant R-value of 0.64 calculated for the bedroom. Moreover, the regression gradient value of models (A, B, C, D) slightly differs from 0.33 of the equation predicted for the whole population. Thereby, the zone of acceptable temperatures for those rooms still lies within the common range (25.5-31.5°C) estimated above. Meanwhile, the neutral thermal condition for the studying room/shop/office changes and is more sensitive because of the lower gradient slope.

Going through the above analyses indicates different environmental characteristics for occupant comfort between rooms within the house. That is a result of the spatial and fabric design of the building, its response to the outdoor climate, and distinct activities in varying rooms. The discovery is significant in comfort research and practice. Firstly, the different occupant thermal sensation in rooms of free-running shop-houses potentially shows that the common method of comfort field surveys, which usually gathers participants in a specific room of building for collecting their votes and measurements, should be thoroughly reconsidered when conducted in NV buildings in the tropics, especially residences, in which, human occupancy and adaptation, environmental conditions, and design features are diverse between spaces within a dwelling. In addition, some variations analysed by a sample group of shop-houses in the present study show the plausible modification of available surveying methods when used in the particular context of people (Vietnamese), building (non-air-conditioned shop-house), and climate (monsoon tropical) type in Vietnam.

Secondly, the findings potentially have impacts on the design of shop-house and saving energy. Architects may propose appropriate responsive design strategies for each space of a house to create comfortable and acceptable environments for residents in different rooms. By that way, the efficiency and adaptation of building performance are higher, and subsequently linking to saving more energy for cooling. That potential diversity of design should be considered to be incorporated in the design guidance, which shows its adaptation for design when applied for different rooms within a building.

6.4.5 Comparison of TSV and PMV

Histogram analyses of thermally sensational predictions were carried out by computing the PMV index using the CBE Thermal Comfort Tool. For comparison between the distribution of TSV and PMV, it should be noted that most calculations related to warm conditions lie outside of the acceptable thermal environment for comfort (-0.5 < PMV < +0.5) with 10% PPD (predicted percentage of dissatisfied). However, if predicted mean votes are normalised into a seven-point scale of TSV (-0.5 < PMV < +0.5 set as 0/neutral, +0.5 ≤ PMV ≤ +1 set as +1/slightly warm, and +1 < PMV < +2 set as +2/warm), 94% and 48% of the results produced by the heat balance model are in 'warmer than neutral' region (> +1) under warm summer and cool spring as shown in Figure 6.18, respectively. Only 2% of the PMV values are distributed in 'cooler than neutral' region when the climate is cooler. In addition, the mean numbers of computed PMV and actual TSV over two seasons are as follows: 1.42 and 0.71. There seems to be a considerable discrepancy between the predicted comfort votes and what might be otherwise expected from subjects located in a hot tropical climate. More analyses will be displayed further.

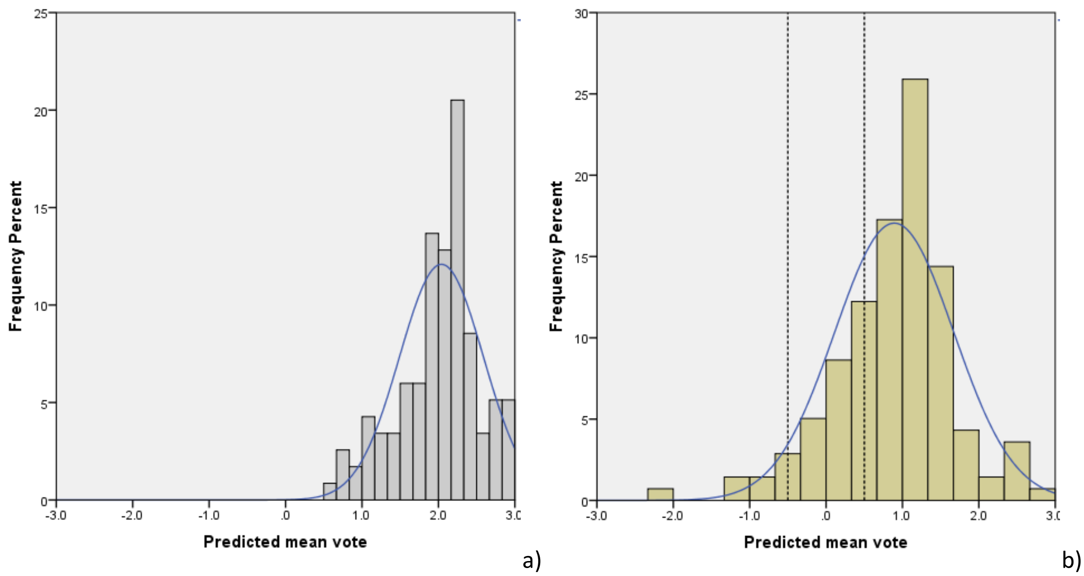


Figure 6.18 Correlation of effective temperature and thermal sensation vote in summer (a) and spring (b)

Two patterns emerge from these graphs analysing the correlation between PMV and TSV as shown in Figure 6.19. The simple equations are below:

In the rainy season:

$$TSV = 0.77xPMV - 0.58 \qquad \text{(Eq13)}$$

(R^2=0.185, R-value=0.43, Sig.=0.000, BCa 95% CI = [.524, 1.206])

In the dry season:

$$TSV = 0.37xPMV - 0.04 \qquad \text{(Eq14)}$$

(R^2=0.138, R-value=0.37, Sig.=0.000, BCa 95% CI = [.216, .532])

Where TSV = thermal sensation vote

PMV = predicted mean vote

A moderate relationship between two variables was found in both measurements with the correlation coefficient between 0.3-0.5. That explains the discrepancy of occupant thermal sensations predicted by two comfort models, particularly assumptions in cool months for the lower R-value. In Figure 6.19a, the pattern of 90% scattered plots is placed in the warmer region (PMV > +1). The outputs of the statistical model (Eq13) illustrate an imbalance between the actual subjective vote and predicted vote. Applying the algorithm Eq13, when TSV is equal to 0 and +1, PMV has respective values of +0.7 and +1.8. In other words, it is probably that the Fanger model predicts the warmer comfort temperature than the real occupant neutrality. Furthermore, in the lower part of the chart (at the level of -1), the significant deviation in comfort predictions between two approaches can also be seen. Some subjects indicated that they felt 'slightly cool' in field surveys, but the PMV-based calculations are the 'slightly warm' to 'hot' condition.

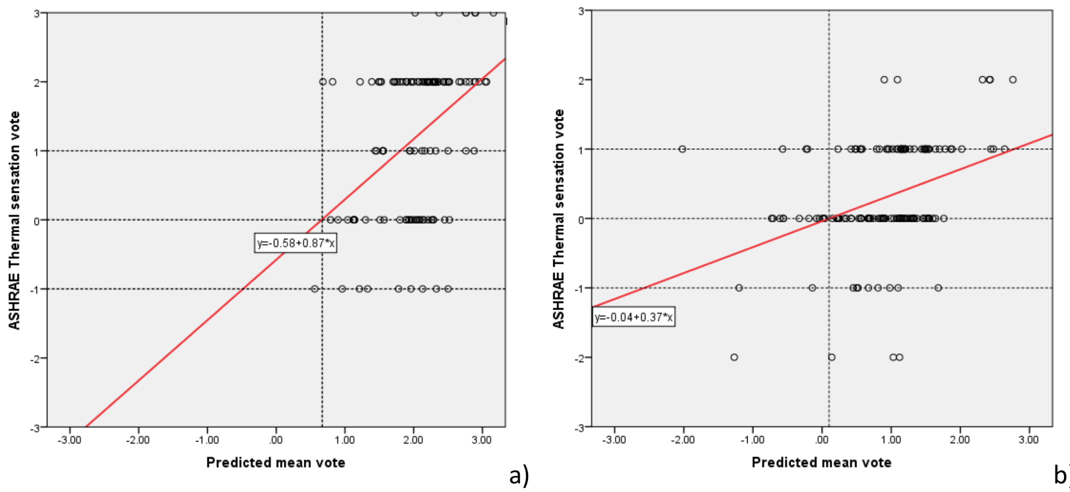


Figure 6.19 Regression analyses for PMV and TSV: in hot (a) and cool (b) months

The linear regression (Eq14) presented in Figure 6.19b is characterised by a lower gradient, that results in a greater discrepancy in predicting human thermal sensations by the heat balance model in the dry months. The equation shows that when applying the TSV values of -1 and +1, the PMV is equal to -2.6 and +2.8. However, the thermal neutralities at 0 are similarly assumed by the two models.

As previously mentioned in the literature, the PMV model has shown limitations when assuming occupant thermal sensations in warm climates (Fountain, Brager, & de Dear, 1996; Humphreys & Nicol, 2002; Wong, et al., 2002; Feriadi & Wong, 2004; Busch J. , 1992; Nicol, 2004; Nguyen, Singh, & Reiter, 2012). The invalidity of that model results from assumptions of personal factors (clothing and activity patterns) without accounting for the influence of climatic differences and environmental temperatures (Nicol, 2004). In the current research, the variations of thermal neutrality predicted by the heat balance model and the adaptive comfort model acknowledge that the PMV formula overestimates occupant sensations at high temperatures and underestimates at low temperatures in naturally ventilated shop-houses in HCMC. The inaccuracy of the heat balance model means that the adaptive comfort model is more adequate to use in the built environment of naturally conditioned shop-houses. Thereby, the international and national standards, which include that model, applied in Vietnam, for example, ISO 7730 and TCVN 7438:2004 possibly show inadequacy in practice. That has impacts on the building design and the size of building service systems and energy use.

6.4.6 Comparison of the adaptive models and standards

The previous section concluded that the thermally comfortable environments predicted by the adaptive approach are more suitable in the housing design in HCMC and Vietnam. This section compares the findings for naturally conditioned shop-houses identified in the current study with the existing adaptive comfort models determined to be appropriate to use in residential buildings in the tropics such as Vietnam and with the recommendations suggested in TCVN 9411:2012 and TCVN 306:2004 – Vietnamese construction codes for shop-house design. These analyses aim to evaluate their validity in applications in the built environment of Vietnam.

There are four adaptive models used for analysing. Returning to the research literature of thermal comfort studies discussed in Chapter 2, Humphreys (1976) established one formula by using the extensive database of world-wide fieldworks (Humphreys, 1978). Additionally, de Dear et al. (1997) found another based on a thousand data sets collected across four climatic zones (de Dear, Brager, & Cooper, 1997). That model has been embodied in ASHRAE 55. Tuan Nguyen (2012) and Toe and Kubota (2013) applied the meta-analysis for data collected in NV buildings in warm-humid climates to discover the algorithms to estimate thermal comfort (Nguyen, Singh, & Reiter, 2012; Toe & Kubota, 2013). All adaptive models are made up of the monthly mean outdoor temperature (Tout) and the indoor comfort temperature (Tc). More details of all models and the calculation of thermal neutrality are presented in Table 6.7.

Table 6.7 Adaptive comfort models and their results for free-running buildings

Authors	Comfort model	Comfort range	Mean neutral temperature (°C)	Tc in hot season (°C)	Tc in cool season (°C)
Humphreys (i)	Tc = 0.534Tout + 11.9	22.3-30	26.5	27.4	25.8
De Dear and Brager (ii)	Tc = 0.31Tout + 17.8	22.4-30.4	26.3	26.8	25.9
Tuan Nguyen (iii)	Tc = 0.341Tout + 18.83	24.2-32.3	28.2	28.7	27.7
Doris and Tetsu (iv)	Tc = 0.53Tout + 14.5	24.8-33.5	29	29.9	28.3

Before analysing, referring to ASHRAE 55, Tout was firstly defined as the monthly mean outdoor temperature; however, it is currently changed by the prevailing mean outdoor temperature (Tpm) (Nicol, Humphreys, & Roaf, 2012). There is not much difference found in calculating the neutral and acceptable temperatures between two variables in the equations (ii) and (iii). Subsequently, Tout was used for all the models shown in the table. Three patterns emerge from four adaptive formulas and those numbers predicted. Firstly, the gradient coefficient and constant of regression models vary owing to the difference raw database used for assumptions.

Secondly, the neutral temperatures over a whole year and the wet/dry seasons were assumed by applying the monthly mean outdoor temperature of meteorological data of HCMC issued by Vietnam

Building Code 02:2009. The comfort temperatures predicted by the models (i) and (ii) are lower than the actual value (28.5°C) found by the present study. Meanwhile, the equation (iv) overestimates real occupant thermal neutrality in free-running shop-houses in HCMC. In four models compared, the predictions of indoor thermal comfort by the model (iii) are close to the findings of the current research.

Thirdly, the bandwidth of acceptable temperatures inferred from three equations: ASHRAE, Humphreys, and Tuan Nguyen, is 8K while the range is nearly 9K by the assumption of the model (iv). Those limits are wider than the real ones found in shop-houses (25.5-31.5°C). Furthermore, the comfort band of equations (i) and (ii) are lower than that of the current study. Meanwhile, two models (iii) and (iv) show that the lower limit is cooler while the upper limit is warmer than the real comfort zone assumed.

Another comparison is with the existing Vietnamese standards for thermal comfort conditions in residential buildings in Vietnam including TCVN 9411:2012 and 306:2004. Into them, the acceptable thermal range recommended is 21.5-29.5°C and the neutral point is 25.5°C (NIA, 2004; VIAP, 2012). These suggestions are closer to the predictions of ASHRAE 55 and Humphreys. With the adoption of ASHRAE 55 but the lack of thermal comfort database obtained by surveys in residences in Vietnam, the comfort temperatures in the standards are inequivalent the real thermal acceptability.

The variations of the neutral and acceptable temperatures assumed between the current research and the existing adaptive comfort models show that the validity of those models should be reviewed to apply in free-running shop-houses in Vietnam and HCMC, although they have been researched to use in naturally ventilated residences in the tropics. The model of de Dear et al. and Humphreys is a result of database collected in naturally ventilated and HVAC office buildings over the world (Humphreys, 1978; de Dear, Brager, & Cooper, 1997). Meanwhile, two others used the method of meta-analysis. The database of these models does not partly reflect the influence of contextual terms on thermal perceptions of the Vietnamese in shop-house buildings.

Furthermore, to assist architects, the national standards have been implemented; however, their recommendations have shown insufficiency in the practice of housing design in Vietnam, particularly of or shop-houses. That likely impacts on the whole procedure of building design, as a result, houses having lower environmental performances than the real comfortable sensation of residents are proposed. Therefore, the need for cooling energy can be increased. The variations of comfort findings between the current research and the standards will ask for the review of standards in implementations and widespread comfort studies to build the database further, which qualifies to issue a practical comfort model applied in the design of shop-houses in Vietnam and HCMC.

6.4.7 Thermal preference

The thermal preference votes utilised a seven-point scale (+3 – 'hotter', +2 – 'warmer', +1 – 'little warmer', 0 – 'no change', -1 – 'little cooler', -2 – 'cooler', and -3 – 'colder') corresponding to thermal sensation scale to identify the preferred temperature of the subjects. The asymmetrical result showed over 95% and 77% of occupants preferred a cooler condition during summer and spring. Most of them voted for preferences of 'little cooler' and 'cooler' – see Figure 6.20. The number of these votes was approximately equivalent to the number of subjects who felt warm and hot under observed environmental condition. In a comparison of inhabitants' thermal preference between two seasons, there are some variations in tendency. Under warm summer, a few people (4%) were satisfied with the indoor thermal condition while more dwellers (20%) found conditions to be thermally neutral in cool months - even they preferred the warmer environment. In contrast, on the hottest summer days, some occupants preferred a 'colder' state to retain their comfort.

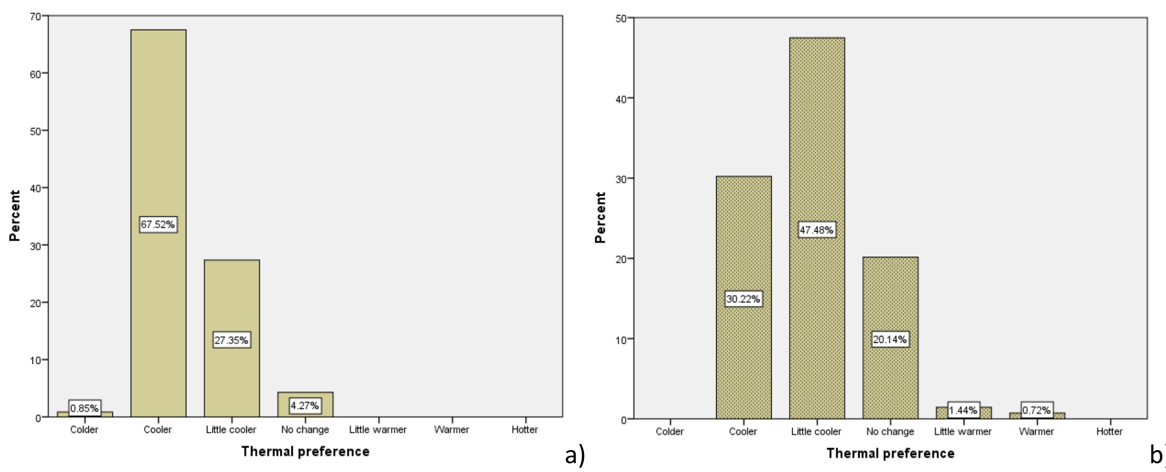


Figure 6.20 Occupant thermal preference in hot (a) and cool (b) months

Binary logistic analyses were operated separately for the two groups of preference votes – 'want to be cooler' (<0) and 'no change' (=0) in the two seasons – wet (the red curve) and dry (the blue curve) (Figure 6.21). The preferred temperature was determined at the intersection of the regression and reference line at the probability of 50% as a neutral percentage of people who want to be cooler. Although the real data do not show completely on the lower part of the exponential line, outputs after analysing are significant in statistical terms (R square values = 0.999 and Sig. < 0.05).

The logistic analysis between preference vote of 'want to be cooler' and operative temperature shows the subjects desire the cooler condition rather than the neutral temperature found. The preferred temperature is 27.5°C for the hot months and 26.9°C for the cool months, which is 1°C and 1.5°C lower than comfort temperature, respectively. In reality, the desirable environment for people is not easy to achieve in the current environment in Vietnam as the internal ambient temperatures experienced during the survey were much higher than what might be predicted as desirable.

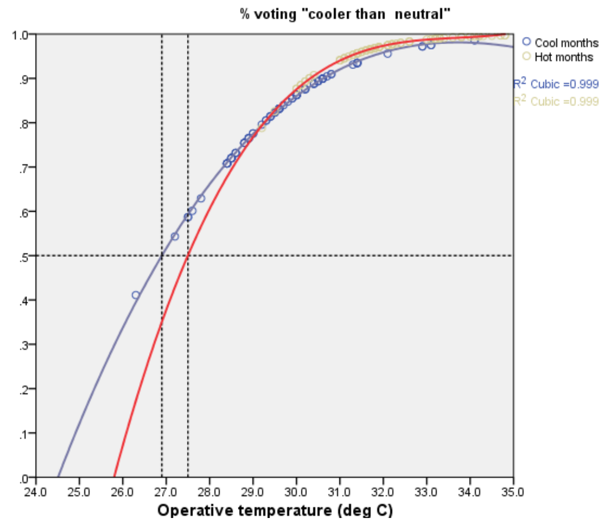


Figure 6.21 Probit analysis to thermal sensation percentage

Reviewing the work of Henry Feriadi (2004) and de Dear (1994) one finds that the preferred temperatures for the occupants were found at the intersection of two probit lines for two trends – 'want to be cooler' and 'want to be warmer'. However, the observed data in HCMC show a slight variation; for instance, the subjects did not find conditions in which their preference would be 'want to be warmer' in summer and few people preferred that condition in spring. Thus, the identification of the preferred temperature in HCMC has to use a modification shown in Figure 6.21. The temperature preferred by occupants in the hot months is 27.5°C which is 1.5°C and 3.8°C higher than which is found in naturally ventilated houses in Jogjakarta, Indonesia (Feriadi & Wong, 2004) and air-controlled office buildings in Townsville, Australia (de Dear & Foutain, 1994), respectively. Meanwhile, in comparison with the preferred temperatures between the current study and the de Dear and Fountain's work, there is a difference of 3.7°C in the cool months. To explain these rational variations, the method of collection of samples (building type, ventilated principle, and social background) and regional climate analysed are contributing factors.

6.5 Conclusions

Chapter 6 is one important segment of the whole thesis. Climates inside and outside naturally ventilated shop-house dwellings were investigated in HCMC during the wet and dry seasons. Besides, thermally comfortable environments for occupants were identified through questionnaire interviews and on-site measurements. Key summary points are:

• Environments in and around shop-houses were systematically analysed concerning urban spatial structures. The gap, which is the effect of urban morphologies on comfortable environments in shop-houses, is filled. There is a close correlation between urban compositions and the outdoor microclimate within a settlement characterised by different urban patterns and between the outdoor and indoor climate of shop-houses. That relationship will be incorporated later into the potential design guidance to consider the impact of urban conditions on the building envelope and indoor comfort.

• Internal and external thermal conditions of shop-houses are likely to be unsatisfactory for occupants. The environmental performance is characterised warm temperatures and low airflow for human satisfaction. In basic parameters (air temperature, humidity, and air velocity) affecting human comfort in shop-houses, the airflow condition should be paid more attention because of the calm performance and the low correlation with the outdoor wind. The improvement of indoor comfort (low temperatures and sufficient airflow) should result from appropriate urban and building designs. The actual urban environments show that the current urban design of all urban patterns studied does not properly provide satisfactory exterior environments for occupants. This consequence can be disadvantageous for creating indoor comfort while the physical building does not certainly respond well to the outdoor climate. Therefore, the availability of design guidance means to the practice.

• Using statistics, the raw data sets over two field studies were analysed to identify the neutral and acceptable temperatures for non-air-conditioned shop-houses in HCMC as follows: 28.5°C and between 25.5 and 31.5°C. Additionally, subjects tend to desire a cooler environment of 27.5 and 26.9°C in the wet and dry seasons, respectively. However, getting the desired temperatures is difficult because of the prevailing warmth in naturally ventilated shop-houses in HCMC. Despite that, finding desirable thermal conditions may be significant in estimating changed comfortable thermal sensations in future, that may implicate the acceptable temperature range and subsequently the building design and the performance of building energy. A new comfort zone discovered in the current study will be a criterion of the design guidance to assess the comfort or discomfort of the thermal environment in buildings and then the effect of building design.

• Thermal responses of residents differ in different rooms within a free-running shop-house building due to the effect of occupancy, physical and spatial characteristics of rooms, and their interaction to the surrounding climate. This finding assists to confirm the efficiency of the surveying method conducted in shop-houses of HCMC. It is a combination of previous research experiences and protocols and understandings of the real context of people, building, and climate. Therefore, the field questionnaire interviews and measurements were carried out in various rooms of shop-houses instead of gathering subjects in a specific room for investigations, which is the common way used in previous research in both

HVAC and naturally conditioned buildings. The different neutral thermal sensations in spaces of a shop-house would affect the building design to consider the diversity and appropriateness of passive design strategies applied for single spaces/rooms. By this manner in design, the building performance may be higher, which means that energy consumption may be saved more. Consequently, the finding is potential to be considered in the design guidance, which shows its adaptation in applications for different rooms.

- The invalidity of the heat balance model, even the existing adaptive comfort models acknowledged to be proper in the non-air-conditioned building in warm-humid climates is found when applied to predict the thermal comfort environments in shop-houses in HCMC. Their assumption is underestimation or overestimation of the real thermal sensations. Furthermore, the current data and analysis are consistent with the gap, which draws the insufficiency of the existing international and national standards applied for the shop-house design in Vietnam. The available lower neutral and acceptable temperature set-points into such standards will encourage the need and use of more mechanical cooling systems and subsequently increase the amount of energy consumption in residences. Therefore, the implementation of the standards should be reviewed and updated to reflect the reality of the built environment. This will require an enlarged database in the future.

Chapter 7 AIR MOVEMENT PERCEPTIONS

The unsatisfactory environment in shop-houses in HCMC is likely caused by warm temperatures and calm airspeeds. The correlation of temperature variable against occupant comfort and discomfort is found. Returning to the gap addressed in Chapter 2, which is the role of airflow in restoring overall thermal comfort of people in tropical houses (Nicol, 2004; Candido C. M., 2010), Chapter 7 will, therefore, analyse the relationship between thermal and airflow acceptability. Air movement perceptions and acceptability of people will be understood in relation to thermal sensations. Corresponding to the comfortable thermal conditions found in Chapter 6, desired and acceptable airspeeds inside naturally ventilated shop-houses will be discovered. The combination of thermal and airflow acceptable range is the assessment criteria of building design to achieve overall human comfort in non-air-conditioned shop-house dwellings in HCMC. The principal research method is field questionnaire surveys and simultaneous measurements. During comfort studies, subjects responded to the questions associated with their air movement sensations in presented immediate environments.

7.1 Reasons for discomfort

For the group of subjects feeling unacceptable to the environment in shop-houses, they personally found discomfort causes. There were eight suggestions for their votes including ‘too windy’, ‘less windy’, intensive radiation’, ‘too dry’, ‘too moist’, ‘too hot’, ‘too cool’, and ‘less windy + too hot’. Two main factors causing occupant discomfort were low airflow and warm conditions in both measuring periods of warm and cool climates. However, occupants differently perceived the discomfort sources when the climate was shifted. The changed air temperature in cool months had an impact on unacceptability by airflow.

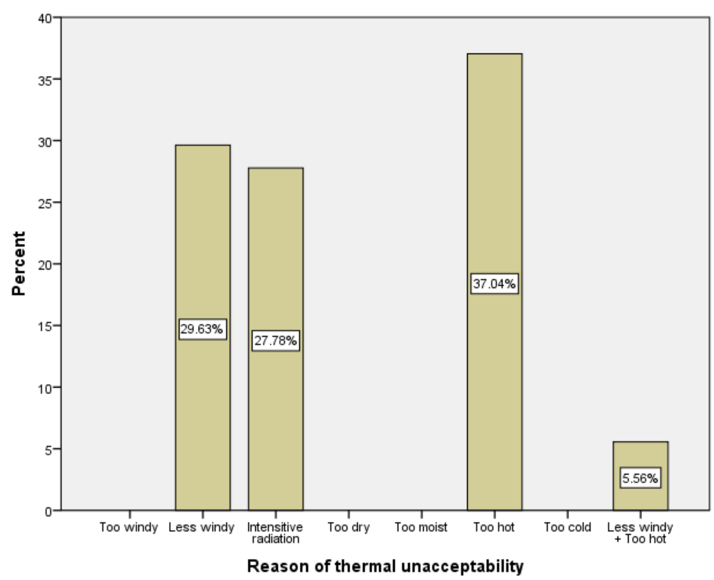


Figure 7.1 Reasons for discomfort found in summer

In the hot summer, 46% of subjects did not accept the immediate environment which they exposed. Figure 7.1 represents that heat gain and poor air movement were the main factors of discomfort. 5.5% of occupants were uncomfortable due to the impact of both factors. Additionally, 37% and 30% of people responded to their dissatisfaction by too hot and still airflow environments, respectively. Moreover, 28% of voters agreed that 'intensive solar radiation' was also a reason if discomfort. However, the impact of radiation also links to heating the indoor environment. Thereby, in summer, the source causing thermal dissatisfaction for residents was mainly the high temperature and partly the low natural wind.

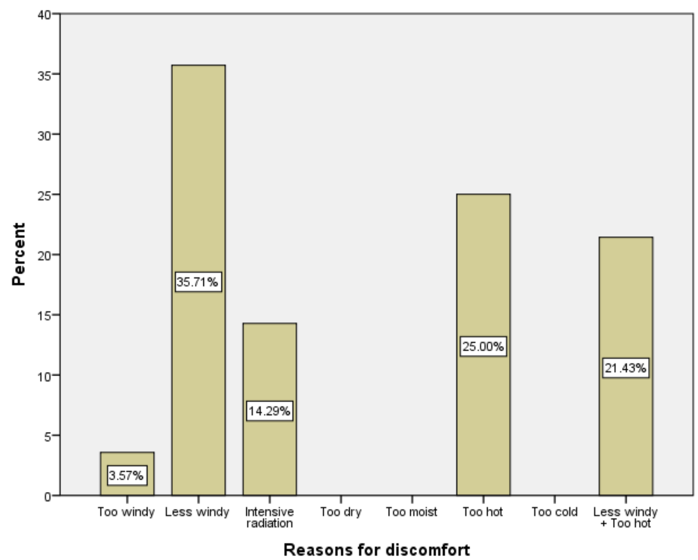


Figure 7.2 Reasons for discomfort found in spring

In spring, the distribution of similar discomfort causes found in summer varied. The cooler outdoor climate linked to the reduction of indoor temperatures, and subsequently, the number of residents being unsatisfactory by warm air decreased (Figure 7.2). Meanwhile, the occupant thermal dissatisfaction was significantly caused by enduring less windy environments (57%). In the cool season, some occupants responded to the too windy condition as their discomfort; however, the real indoor airflow measured was low. That issue can explain the impact of cool air temperature on occupant airflow perceptions; and therefore, subjects could find dissatisfaction by draught discomfort even low airspeeds.

The analysis above acknowledges the two basic factors (high temperatures and low airflow) influencing human discomfort in free-running shop-houses. That partly explains the close relationship of two variables of temperature and air velocity with overall comfort and discomfort of residents. Excepting the dominant cause of warmth, the airflow of low velocities has also significant impacts, especially in summer because poor air movement cannot maintain occupant thermal tolerance in warm environments. Meanwhile, when the climate is cool, low airflow can also cause draught discomfort. Thus, a question is: What are the air velocities which occupants find comfortable and acceptable in given thermal environments of naturally ventilated shop-houses in HCMC? The following sections will discover those things.

7.2 Air movement perceptions

This section will cover the correlation between thermal and air movement sensations, preferences, and acceptability of occupants in free-running shop-houses in HCMC. There is likely a simultaneous effect of both variables on satisfactory and unsatisfactory perceptions of people. That is significant in finding the comfortable and acceptable airspeeds influencing overall human comfort in parallel to the satisfactory thermal conditions. However, the contribution of air movement to comfort is more difficult to understand than the air temperature.

7.2.1 Air movement sensations

After answering the questions related to thermal perceptions, the subjects continued to report their sensations to the airflow environment in the location they occupied. A 5-point sensational scale was suggested: 'too still', 'still', 'just right', 'windy', and 'too windy'. Air movement sensations depend on not only airspeed but air temperature and personal variables (Nicol, 2004). Two graphs below show seasonal variations of occupant airflow cognition, which may result from changed thermal conditions between two periods.

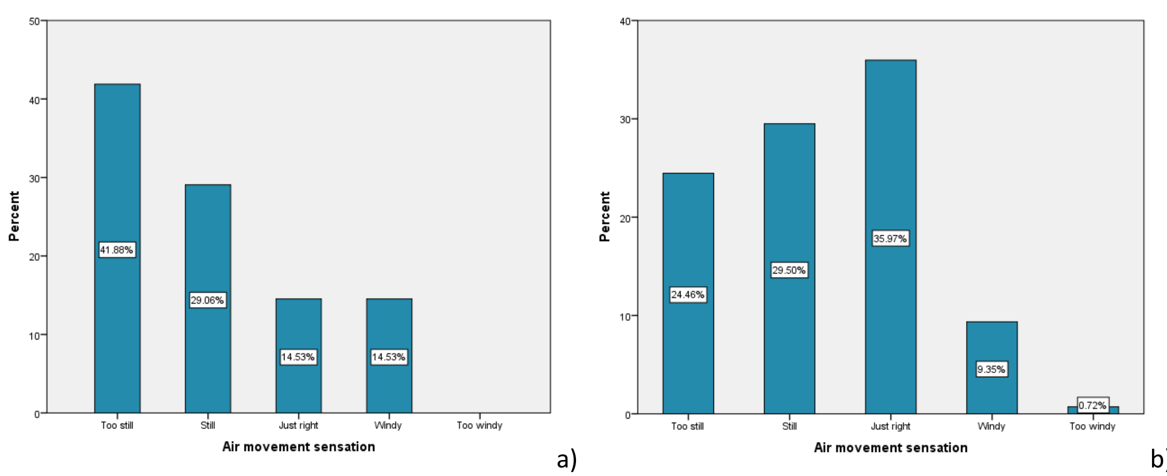
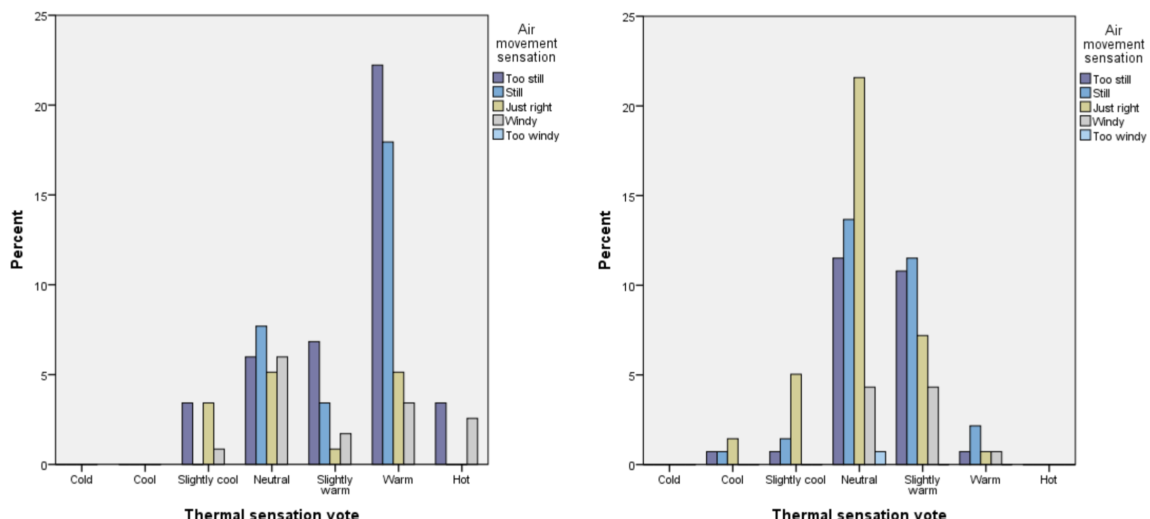


Figure 7.3 Air movement sensations in hot (a) and cool (b) months

Many existing studies have confirmed the effect of sufficient wind on the comfort restoration or extension in tropical buildings, particularly in warm periods (Tanabe & Kimura, 1989; 1994; Szokolay S. V., 1997; Nicol, 2004); however, the airflow was likely calm for residents' satisfaction in shop-house dwellings. The air movement below 0.3m/s measured in summer might cause the 'too still' and 'still' sensations of most people (71%) in dwellings (Figure 7.3a). The percentage of occupants found air movement neutrality was low (14.5%) while the remaining samples were exposed to windy conditions.

Meanwhile, in spring, the total of votes for ‘still’ and ‘too still’ sensations reduced by 17% (Figure 7.3b). The number of subjects who found comfortable airflow rose by 21%. 10% of respondents voted for the ‘windy’ and ‘too windy’ air movement.

The current data of subjective responses and physical measurements showed the influence of thermal environment on air movement sensations because a large number of subjects accepted low airspeeds in shop-houses in the cool climate, even lower velocities than data taken in summer. Additionally, a part of the subjects found the draught discomfort in cool environments with light or medium airflows. Whereas, higher air velocities indoors should be required in warm environments of summer. The variations in air movement sensations between seasons present the concurrent effect of both temperature and natural wind on human comfort perceptions in shop-house buildings.



a) b)

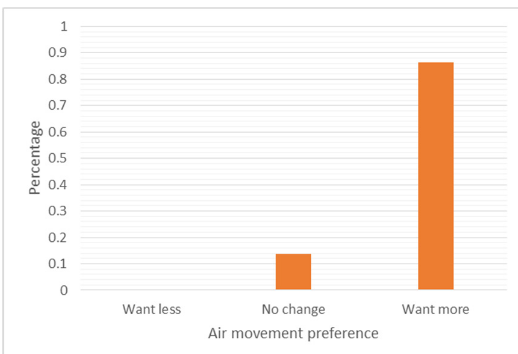
Figure 7.4 Relationship of air movement and thermal sensation in hot (a) and cool (b) months

Figure 7.4 explains further the relationship between thermal and air movement sensations through a combination of two voting data collected over two measuring periods. For each thermal sensational statement, various air movement responses were distributed. That implies complexity in that relationship and subjectivity in neutral and acceptable cognition. The statement of warm discomfort nearly matched to the complaint of subjects about the ‘too still’ and ‘still’ air movement with the highest votes of over 40% (Figure 7.4a). Therefore, there was likely a positive correlation of warm temperature and poor natural ventilation, which caused thermal dissatisfaction of many occupants in summer. However, 30% of subjects accepted warmth (from ‘slightly cool’ to ‘slightly warm’) under conditions of low airspeeds. Whereas some occupants were unacceptable to the warm to the hot environment, but even as they sensed ‘just right’ and ‘windy’ air movement indoors.

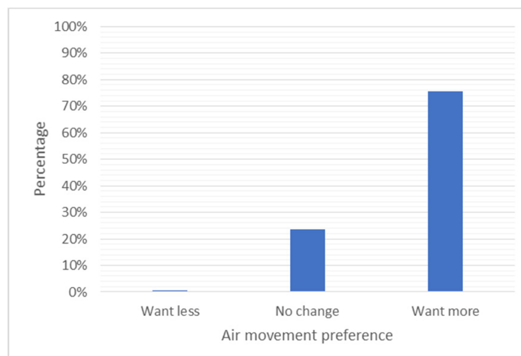
In the dry season, the majority of subjects found thermally comfortable under various airflow conditions in their house. The highest percentage of occupants (34%) got both thermal and air movement acceptability, in this, 22% of them found neutrality (Figure 7.4b). In addition, more than 50% of subjects accepted the interior thermal condition, though they registered the still airflow. This may present a negative relationship between two variables. The reduced temperature in the cool season has significant influences on subjective comfort perceptions.

7.2.2 Air movement preference

The subjects were asked for their preference for the given wind environment in two seasons through three options: 'want less', 'no change', and 'want more'. Most subjects certainly wanted satisfactory air movement indoors during surveys (Figure 7.5).



a)



b)

Figure 7.5 Distribution of air movement preference in the hot (a) and cool (b) season

There is a 10% difference in the percentage of people wanting more airflow between the two seasons. As previously mentioned, the lower temperature in cool periods had an impact on the air movement sensation and preference of occupants. Therefore, many votes for 'no change' preference rose by 10% while 'want more' preferences decreased by 10%. That also showed that more people satisfied the airflow environment which they experienced at the same time of their interviews. In warm summer, the subjects reported two conditions: no change and dominance of more air movement (Figure 7.5a). However, in cooler climates of spring, apart from most votes for 'no change' and 'want more', some people wanted less wind because of their cool discomfort (Figure 7.5b).

Occupant expectations for satisfactory air movement correlate with their thermal sensations, particularly in warm climates. The two figures below represent simultaneous evaluations of overall thermal sensation and air movement preference in summer and spring. The distribution of air movement preference varied in the thermal sensation between two seasons.

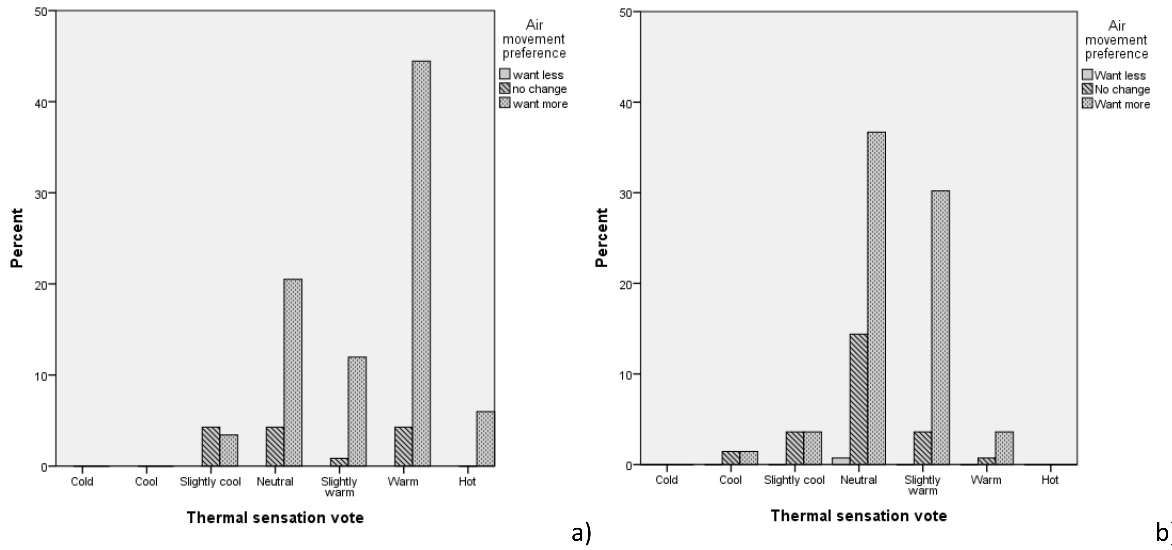


Figure 7.6 Thermal sensation and air movement preference: hot months (a) and cool months (b)

In summer, in over 85% of subjects asking for more airflow, more than half of people sensed warmth, and the availability of adequate natural wind could, therefore, restore their comfort (Figure 7.6a). The remaining data shared with four thermally sensational scales: 'slightly cool', 'neutral', 'slightly warm', and 'hot'. Although 35% of occupants found acceptability in the thermal environment where they were exposed, they desired more air movement for their satisfaction. However, a few inhabitants (10%) also accepted warm conditions in summer with the unchanged preference of airflow.

On the other hand, in cool spring, 70% of subjects required more natural wind for their satisfaction. In this, larger percentages of votes were distributed in the sensations of 'neutral' (38%) and 'slightly warm' (30%). Meanwhile, almost 25% of people preferred no changes in the wind condition when they currently found comfortable. However, some occupants felt neutral, although they expected less air movement.

There was also a significant relationship between thermal and air movement preference. Assessing air movement preferences by the seven-point scale of thermal preference showed a direct correspondence between 'want be cooler' and 'want more wind'. In summer, 85% of people preferred a cooler thermal environment by providing more airflow, especially at the sensation point of 'cooler' (60%). Meanwhile, such a correlation between two variables had some differences in cool months because of the outdoor cooler climate. Approximate 65% of personal preferences were 'more air movement' to get a cooler thermal condition. Due to a reduction of exterior temperatures, the percentage of people simultaneously preferring thermally cooler and more airflow decreased in the dry season. In addition, the majority preferred the 'little cooler' condition rather than the 'cooler'.

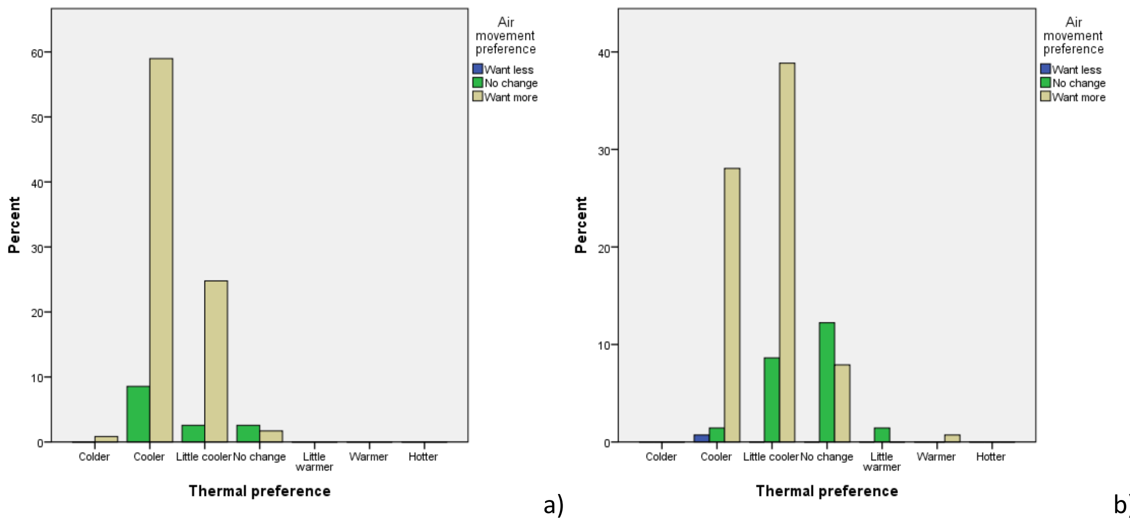


Figure 7.7 Cross-tabulated percentages for thermal and air movement preferences in hot (a) and cool (b) months

Between two seasons, more occupants desired unchanged thermal conditions in spring. Most of them preferred the current natural wind environment while others expected a 'no change' thermal condition with more wind provision. Furthermore, a few residents wanted less air movement although they preferred a cooler environment indoors. 25% of dwellers who found neutral and preferred cooler under the unchanged or less airflow condition demonstrated the influence of air temperature on occupant air movement preferences in the cool climate.

The investigation of occupant air movement perceptions in free-running shop-houses in HCMC confirms insufficient wind condition to maintaining human comfort. Consequently, inhabitants almost preferred 'more air movement' to balance the warm environment indoors. Additionally, air movement sensations of occupants depended on both air velocity and temperature in the given environment. Therefore, there was a close relationship between thermal and air movement sensations and preferences. In summer, the supply of airflow with higher velocities is a preference of most people. However, in cool spring, although a large number of occupants prefer more air movement, people sensing cool and quite cool can be uncomfortable when airspeeds are accelerated more than their expectation. As a result, to retain the acceptable thermal conditions for people found in shop-houses, the availability of airflow will be required how. The next section will identify the neutral and acceptable airflow in buildings.

7.3 Prediction of comfortable and acceptable air movement

Previous studies on air movement acceptability have focused on the maximum airspeeds which extend the upper comfort limits in warm climates. Meanwhile, overall human comfort in naturally conditioned buildings in those climates is also affected by sufficient air movement, although the indoor temperature falls within the acceptable thermal range. The previous section has found a close relationship between both airflow and thermal perceptions and preferences and their effect on human comfort in free-running shop-houses. Thus, determining acceptable airspeeds incorporated into thermal acceptability is significant for building requisite conditions of human comfort in those buildings. The section will address that issue.

7.3.1 Air velocity and air preference

The occupant air movement preference and acceptability were assessed in relation to air velocities in the presented environment in order to find out the condition of air movement which people found satisfactory. The overall air velocities indoors were binned by an interval of 0.1m/s. The analyses were devised into two measuring periods - hot and cool months (Figure 7.8).

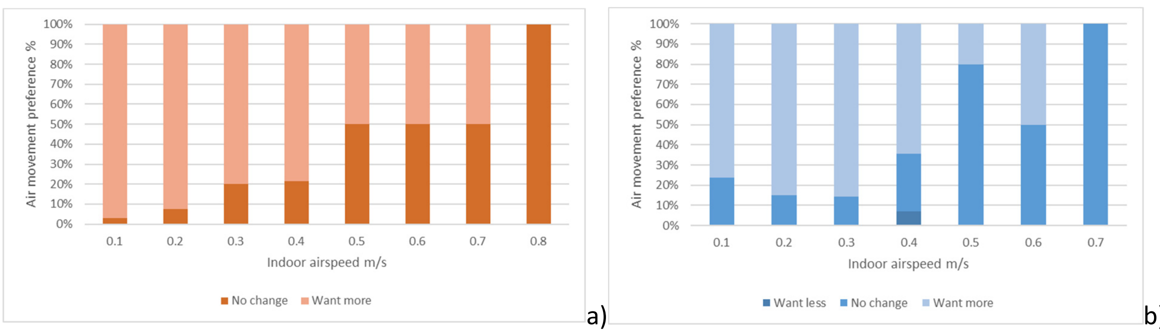


Figure 7.8 Air movement preference and air velocity range in hot (a) and cool (b) months

Under warm summer conditions, the majority of occupants desired more windy environments. The percentage requesting 'no change' in airspeed gradually increased when wind velocities were greater. At low airspeeds of 0.1 and 0.2m/s, below 10% of 'no change' responses were observed. However, the percentage of subjects voting for 'no change' in airspeed rose to 50% when they were exposed to stronger airspeeds within 0.5–0.7m/s. No people responded to more air movement at the value of 0.8m/s air velocity (Figure 7.8a).

Meanwhile, the distribution of air movement preference against wind velocities was characterised by a different pattern in cool months (Figure 7.8b). During that season, indoor airspeeds ranged between 0.1-0.7m/s. A total of 139 participants registered three air movement preferences: 'want less', 'no change', and 'want more'. Most respondents (around 80%) preferred more air movement when they experienced airspeeds below 0.4m/s. Nevertheless, the number of voters for such preference significantly reduced as taken air velocities increased from 0.4 to 0.6m/s, particularly 80% of subjects were satisfied by wind environments of 0.5m/s. The occupants entirely got airflow satisfaction when enduring the wind velocity of 0.7m/s. In cool climates, some people preferred the consistent airflow of 0.4m/s.

Combining wind data grouped into the categories of air movement preference over two measurements, the number of votes for ‘no change’ and ‘want more’ preferences equally shared at air velocity scales of 0.5, 0.6, and 0.7m/s in warm months. Meanwhile, although that pattern was found when inhabitants were exposed to an airspeed of 0.6m/s, people dominantly started to find their satisfactory with air movement of 0.5m/s in cool periods. Based on the observations, the overall airspeed of 0.5m/s can be determined to be the minimum limit of occupant satisfaction in naturally ventilated shop-house dwellings. The figure is much more than the threshold of draught discomfort (0.2m/s) in air-controlled buildings or cool/temperate climates recommended in the ASHRAE and ISO standards (ISO, 2005; ASHRAE, 2013a). Consequently, in free-running residential buildings in the tropical climate, Vietnamese people will accept and desire higher air velocities to retain their thermal comfort. In addition, occupant satisfaction with the airflow environment seasonally varied. People were completely satisfied with the air movement of 0.8m/s and 0.7m/s in the wet and dry season, respectively. Those values are equal to the maximum limit suggested for NV buildings in warm climates by ASHRAE 55 (ASHRAE, 2013a).

7.3.2 Air velocity and air movement acceptability

This section analyses the relationship between the immediate wind environment in which the subjects spontaneously gave their ‘acceptable’ and ‘unacceptable’ assessments and preferences in different surveying periods.

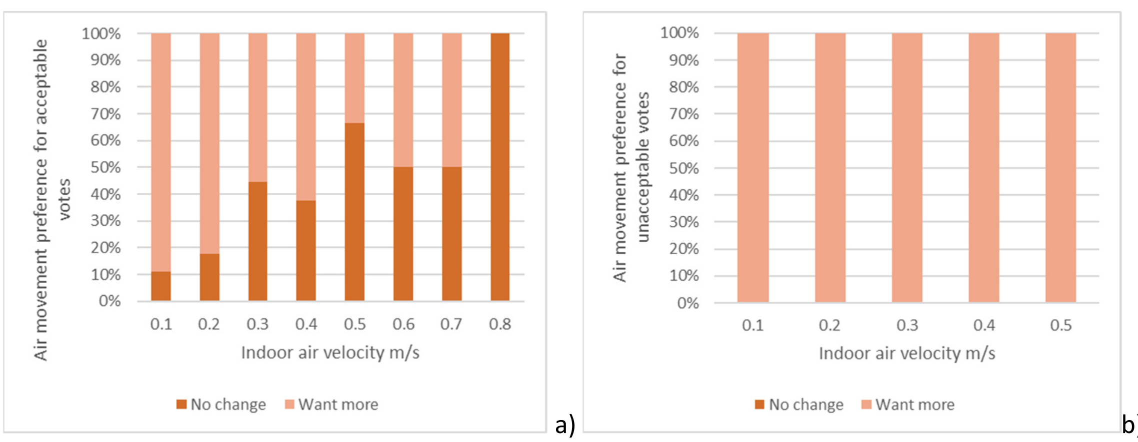


Figure 7.9 Airflow preference of subjects for whom the air movement was acceptable (a) and unacceptable (b) in warm months

Figure 7.9a emphasises the registration of ‘air movement acceptable’ in warm climates. The percentage of subjects preferring ‘no change’ in natural wind fluctuated over airspeeds taken between 0.1 and 0.8m/s; however, the number of votes for this preference was more in thermal conditions with higher airspeeds in the range 0.3 – 0.7m/s. Over 80% of respondents confirmed both air movement acceptability and ‘want more’ preference when they occupied a poor wind environment of 0.1 and 0.2m/s. On the other hand, when the indoor air velocity elevated to 0.5-0.7m/s, the proportion of subjects accepting the immediate wind environment with no changes increased over 50%. Occupants found airflow comfort at airspeeds of 0.8m/s. On the other hand, Figure 7.9b presents another analysis of air movement preferences and unacceptability combined in the wet season. 55% of occupants, who found unacceptable to the current airflow which they were presented, preferred 'more air movement' across all air velocity scales (0.1-0.5m/s).

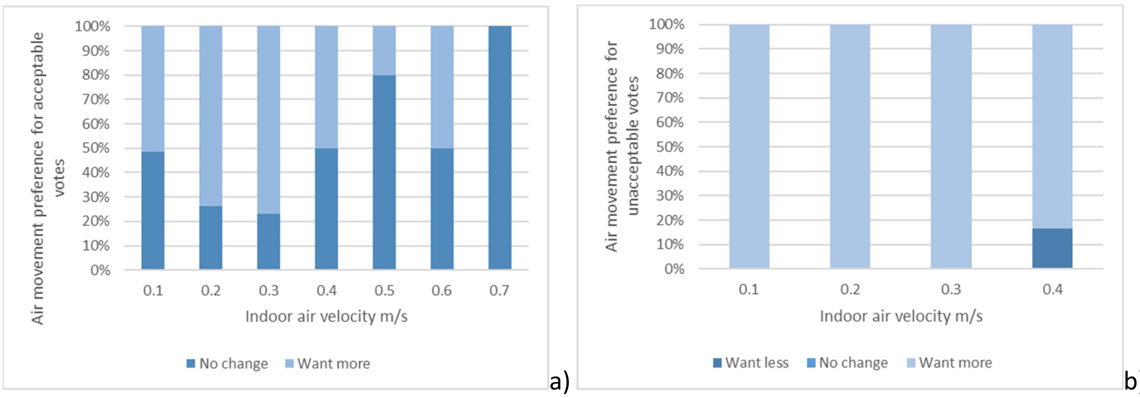


Figure 7.10 Airflow preference of subjects for whom the air movement was acceptable (a) and unacceptable (b) in cool months

The next discussion aims to find out air movement environments which occupants found unacceptable and acceptable in the dry season. Considering the votes for acceptability (Figure 7.10a), reduced indoor temperatures in that season changed the air movement preference and acceptability of occupants to the given wind condition. For example, they accepted low airspeeds. 50% of subjects were satisfied with low/static air movement of 0.1m/s. However, a large percentage of occupants (over 70%) desired to increase their current airflow when they experienced an air velocity of 0.2 and 0.3m/s. The number of subjects asking for 'more air movement' decreased when air velocity increased. At the velocities of 0.4, 0.5, and 0.6m/s, the percentage were 50%, 80%, and 50%, respectively. Inhabitants were neutral in the wind environment of 0.7m/s.

Figure 7.10b evaluates air movement preferences versus wind velocity scales in the group of 'unacceptable' votes. Almost 43% of respondents voting for airflow unacceptability in the survey wanted 'more air movement' over the range of 0.1-0.4m/s. In warm summer, occupants primarily wanted wind velocities above 0.4m/s to get satisfactory whilst 15% of subjects were uncomfortable and preferred 'less air movement' at the same airspeed because of the potential risk of draught in cool climates.

The analyses of current data in terms of the air movement preference and acceptability of subjects and airspeed measurements in shop-houses confirm a difference in comfortable and acceptable air velocities between two measurement periods. The changed thermal characteristics of the indoor environment can influence air movement expectations of occupants. Residents were neutral when they experienced airspeeds of 0.8m/s (in warm climates) and 0.7m/s (in cool climates).

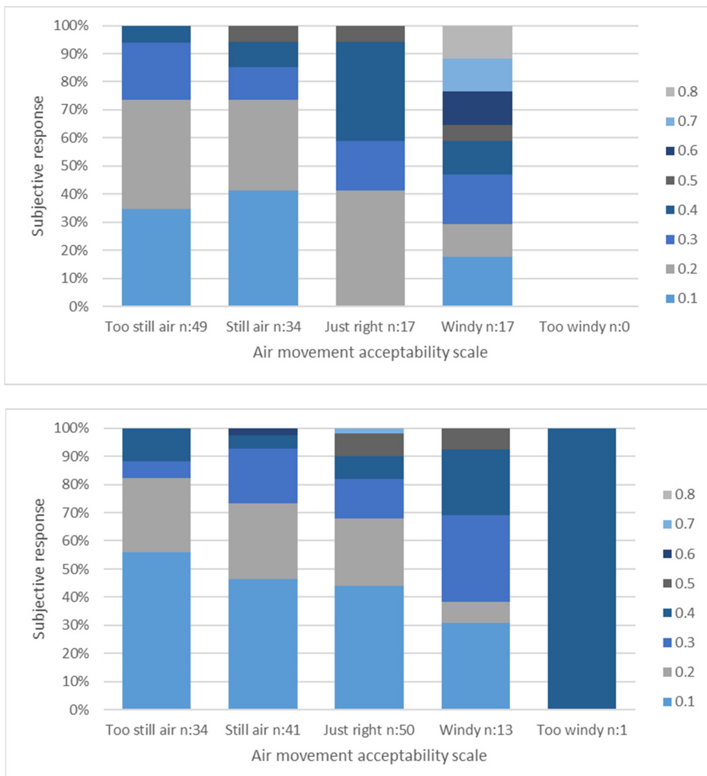
Referring to recommendations of air movement by ASHRAE Standard 55-2013 for naturally ventilated buildings, the indoor airspeed may not exceed 0.8m/s to avoid draught discomfort under conditions of light clothing insulation (0.5-0.7clo) and pattern of metabolic rates between 1.0 and 1.3 met (ASHRAE, 2013a). Returning to Chapter 5, the on-site observations of personal factors showed that the clothing and activity patterns of residents were much lower with the range of 0.1-0.5clo and the metabolic rates of 0.8-1met in non-air-conditioned shop-house dwellings, respectively. Compared to the recommendation of ASHRAE 55, the comfortable air movement in shop-house buildings exceeds that figure, particularly in warm climates.

Using the limit of 50% votes between 'no change' and 'want more' preference to identify the minimum acceptable air velocity for occupants, there is also a variation of that figure between two seasons. In hot months, the acceptable wind environment was within 0.5 and 0.7m/s. At an airspeed of 0.5m/s, although the number of occupants found satisfactory reached up to 70%, some others were uncomfortable and wanted higher airspeeds. Consequently, the airspeed of 0.5m/s can be defined to be the minimum limit of air movement acceptability in summer. Whereas, in cool months, at a velocity of 0.4m/s, an equal percentage of occupants preferred 'more air movement' and 'no change'. Thereby, that figure was determined to be the lower acceptable air movement in the cool climate. Between two seasons, air movement of occupant acceptability deviates 0.1m/s.

7.3.3 Distribution of airspeed by air movement sensation

This section explores the correlation between air velocity and air movement sensation but focusing on respondents voting for 'acceptable', and then finds a range of air movement which occupants accept in different seasons. For the subjects accepting the given wind environment, they also gave their sensation feedback on such environment by using a five-point scale: - 2 (too still), -1 (still), 0 (just right), +1 (windy), and +2 (too windy) while airspeeds were taken simultaneously. Two different patterns likely emerge from two graphs (Figure 7.11).

Reviewing the distribution of air movement sensations shown in Figure 7.3, 60% of data fell into the acceptable range from -1 to +1 in warm months, whereas, the majority of samples (75%) concentrated into that zone in cool months. Over summer, for the subjects finding airflow acceptability in 'still air' conditions, 41% of samples were acceptable at 0.1m/s and the percentage decreased for 32% at 0.2m/s, 12% at 0.3m/s, 9% at 0.4m/s, and 6% at 0.5m/s (Figure 7.11a). The occupants were exposed to a wide range of air velocities from 0.1-0.8m/s in windy environments with comfort votes as follows: 17% of votes at 0.1m/s, 12% at 0.2m/s, 17% at 0.3m/s, 12% at 0.4m/s, 6% at 0.5m/s, and 36% equally shared with three values of 0.6, 0.7, and 0.8m/s. The air movement acceptability of occupants covering a wide range of air movement explains that sensitivity to airflow depends on various dynamic factors, such as air velocity, air temperature, and personal factors (Toftum, 2004). On the other hand, at the sensation scale – 'just right' of air movement, most inhabitants were satisfied with airspeeds of 0.2 and 0.4m/s. A minority of people felt neutral in the airflow condition of 0.5m/s (6%). In the typical warm climate in summer, the supply of natural wind is significant for occupant satisfaction; therefore, it is likely that occupants were satisfied with greater air movement reaching up to 0.8m/s that was also the highest value taken during field measurements in summer. No subjects complained about the wind environment to be 'too windy'.



a)

b)

Figure 7.11 Air movement acceptability to different prevailing wind velocities in hot (a) and cool (b) months

Meanwhile, in the dry/cool season, the percentage of votes for acceptable sensations falling in the range of -1 to +1 mostly concentrated into the range of 0.1-0.3m/s with the total votes of each velocity as follows: 121% at 0.1m/s, 58% at 0.2m/s, and 64% at 0.3m/s compared to 58% (0.1m/s), 85% (0.2m/s), and 47% (0.3m/s) calculated from summer data. In the airflow environment of 0.4m/s, subjects registered different sensations: 5% of 'still air', 8% of 'just right', and 23% of 'windy' while the pattern of three sensation scales at the similar airspeed respectively were 8%, 35%, and 12% in summer. A minority of occupants found air movement acceptability with stronger wind velocities of 0.5-0.7m/s.

The discussions reported here show the varying acceptable ranges of air movement (-1 to +1) for occupants in naturally ventilated shop-house buildings in the wet and dry season. They were acceptable to the zone of 0.1-0.8m/s in the warm climate and 0.1-0.7m/s in the cool climate. However, depending on the thermal characteristic of a given environment and personal factors, a larger percentage of inhabitants found air movement acceptability at low air velocities of 0.1-0.3m/s when the outdoor climate was cooler relative to in warm summer. Furthermore, the number of samples accepting higher airspeeds of 0.6 and 0.7m/s were negligible.

By comparison with the natural airflow conditions which occupants perceived acceptability between two seasons, occupants vary in their responses. Residents certainly satisfied air movement environments of lower air velocities in dry months. Elevated airspeeds can cause draught discomfort. Meanwhile, in hot months, residents prefer higher air velocities up to 0.8m/s. The real limits of human airflow acceptability (0.1-0.8m/s) are quite wide in naturally ventilated shop-houses. However, the finding of the close relationship between thermal and airflow sensations, preferences, and acceptability emerges that within a wide range of acceptable temperatures identified in shop-houses, which airspeed values of the acceptable range will be recommended to be available to restore overall human comfort. The following section will address those.

7.3.4 Correlation of air movement and operative temperatures

Based on the band of acceptable airspeeds (0.1-0.8m/s) found inside free-running shop-houses, the next analysis determines minimum acceptable airflows corresponding to the comfortable temperature limits (25.5-31.5°C) identified in Chapter 6.

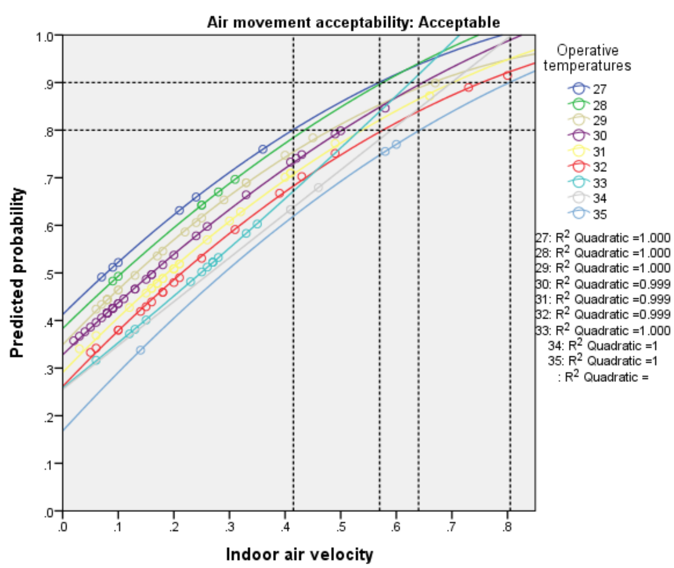


Figure 7.12 Correlation between air movement and operative temperature

During comfort studies, environmental data of air temperature and wind velocity were taken while subjects were responding to the questionnaire tables related to their thermal and air movement sensations. All raw 256 data sets collected in both wet and dry seasons were used for analysis. Subjective sensation votes for the immediate environment were grouped into two 'acceptable' and 'unacceptable' categories. The operative temperatures measured between 25.5-35°C were binned by intervals of 1°C and air velocities from 0.1 to 0.8m/s were also binned into intervals of 0.1m/s. The probit analysis was applied to identify minimum air velocity values which 80% and 90% occupants reported acceptability. The probability within each bin has been calculated by probit analyses. Some details of the analysis are presented by curves in Figure 7.12.

The quadratic models of most temperature values are significant in statistical terms, apart from the curves of 26, 33, and 34°C have not been concluded because of the skewed distribution of the votes. Based on the pattern of the graph, the respective minimum air movement for 80% and 90% occupant acceptability were determined to be 0.42-0.57m/s and 0.57-75m/s corresponding to the range of temperatures between 27-32°C.

Table 7.1 summarises the minimum airspeeds respectively binned to the individual operative temperatures for thermal acceptability found in Chapter 6. The results were divided into two categories – 80% and 90% acceptability. The following minimum and maximum airspeeds identified were 0.4 and 0.7m/s. There was a difference of 0.15m/s between two groups of acceptability examined.

Table 7.1 Minimum air velocities for 80% and 90% acceptability in relation to operative temperature

Operative temperature (°C)		**Air movement acceptability**	
		V,m/s (80%)	V,m/s (90%)
Comfort zone	25.5 - < 27	0.2 < V < 0.4	
	27	0.4	0.55
	28	0.45	0.55
	29	0.5	0.65
	30	0.5	0.65
	31	0.55	0.7
	31.5	0.55	0.7
Outside the comfort zone	32-34.5	0.55 < V ≤ 0.65	0.7 < V ≤ 0.85

Making some assumptions about data at the temperature value of 26°C, and combining the results of air movement perceptions and acceptability found in the above sections, the range of 0.2-0.4m/s can be used as the minimum level of airflow that should be provided in thermal conditions of 25.5°C to lower than 27°C. At 32°C, which mostly is on the edge of the upper comfort limit, the acceptable air movement to 80% and 90% occupants is 0.55 and 0.7m/s, respectively. Greater airspeeds than those would be required in warmer environments. From the probit analysis, in the higher airflow environment of 0.65 and 0.85m/s, respective 80% and 90% of occupants can tolerate the warm temperature at 34.5°C.

In the review of the research literature of acceptable wind velocities found in the tropics, Candido (2010) identified the range of 0.4—0.9m/s corresponding to operative temperatures within 26-31°C in free-running school buildings in Brazil (Candido C. M., 2010). Additionally, Gong et al. (2006) carried out experiments in a climate chamber and concluded the band of indoor comfortable airspeeds was between 0.3—0.9m/s without a correlation with thermal conditions (Gong, et al., 2006). The zone of minimum air velocities found in residential buildings in HCMC is narrower in comparison to those studies. The acceptable thermal conditions determined in the present study is quite similar to Candido's work. However, the minimum airspeeds for 80% and 90% acceptability required are different at similar temperature values. For example, in a warm comfortable environment of 30°C, 80% of occupants will retain their overall comfort sensation if the available airflow is 0.5m/s and 0.7m/s referring to the findings of the current study and the work in Brazil, respectively. The difference indicates that the tolerance of the occupants is higher in the warm climates of Vietnam and occupant expectations for air movement comfort are easier to achieve because of the lower requirements of air movement. Variations in factors related to building type, social background, and regional climatic characteristics can be attributed to differences between studies in Vietnam and Brazil.

Another comparison is with the suggested comfortable wind velocities of 0.5-1m/s advised in the local standard – TCVN 9411:2012 that has been used for the design of shop-houses in Vietnam. For the current research, the minimum range of air movement which occupants find comfortable in reality is lower than the theoretical suggestions. A difference in the findings of airflow assumed by TCVN 9411:2012 and the current study opens insights. The present and previous research in the tropics has acknowledged the effect of airflow on restoring and extending the overall human comfort in free-running buildings. However, achieving sufficient airflows indoors is very important. The real performance of natural ventilation in shop-house buildings in HCMC was generally found to be insufficient to provide thermal satisfaction. The majority of in-situ wind data taken were lower than 0.5m/s. In Chapter 6, the issue of poor air movement in residences can be attributed by inappropriate urban and building designs. Based on the higher recommendations of internal airspeeds in TCVN, the current design has been failed to meet the standard. Additionally, the pressure on design strategies for settlement planning and the building fabric is higher. Therefore, the suggestions in the national standard show insufficient in implementations due to lacking field database. Meanwhile, the lower acceptable airflow requirements in real environments may be more appropriate in practice.

7.4 Conclusions

- Reviewing the research literature, which confirms the contribution of natural wind to the overall comfort of occupants in naturally ventilated buildings in the tropics. The analytical results of field data taken in shop-house dwellings in HCMC have clarified the significance of natural ventilation for occupant comfort in their house.

- Chapter 2 identifies the research gap of the close relationship between two environmental parameters: air temperature and air movement and their simultaneous effect on the restoration of overall human comfort in non-air-conditioned shop-house buildings. Through the analysis of current data, the gap is proved. Occupant air movement sensations, preferences, acceptability are affected by their thermal perceptions in the given environment.

- Using the statistical analysis of air movement comfort votes and measurements of the immediate environment, the present research determines the airspeed which residents find comfortable is 0.8m/s in warm climates and 0.7m/s in cool climates. The minimum acceptable airflow is respectively 0.5m/s and 0.4m/s.

- The correlation between thermal and airflow perceptions shows that the achievement of overall comfort sensation is required a combination of acceptable temperatures and airflows. From that hypothesis, through the combined analysis of temperature and airspeed data taken in the environments which occupants voted for their acceptability over two seasons, the minimum air velocities for 80% and 90% occupant acceptability are respectively within the bands of 0.4-0.55m/s and 0.55-0.7m/s in relation to acceptable temperatures of 27-31.5°C. However, the comfortable thermal conditions for shop-houses are between 25.5-31.5°C; therefore, in thermal environments of 25.5- below 27°C, indoor wind velocities should be in the range of 0.2-0.4m/s.

- The minimum levels of indoor air movement that people find comfort in relation to air temperatures are important for the practical work of designers. Taking the comfort temperatures found in Chapter 6 and combining them with the range of minimum air velocities found here produces a comfort zone linking the interaction of these variables. This finding will be used later to build up an assessment framework for the environmental consequence of various options in the design guidelines.

- The significant variation in the acceptable air movement suggested between the current project and the national standard TCVN 9411:2012 for NV shop-house buildings shows the necessity to review the sufficiency of that standard and to propose an appropriate range of acceptable air velocities in future practice. The higher range of comfortable air movement can cause pressures on the practice of architects and the possibility of design strategies to meet the standard. Additionally, despite the valid acceptable airflow limits, to achieve them by optimising the building design is questionable. Therefore, the availability of the design manual will be significant in improving the building performance and create the possibility of research findings or standards in practice.

The following chapters will focus on the design of real shop-house buildings, particularly opening characteristics to understand how they affect indoor environmental performances and the level of comfort through using the assessment framework of comfortable temperatures and airflows discovered.

PART 3
RESEARCH ANALYSES

Chapter 8 ENVIRONMENTAL CONDITIONS IN THE SHOP-HOUSE

Chapters 6 & 7 have found a close correlation between thermal and air movement acceptability for the overall human comfort in free-running shop-house buildings in HCMC. Those chapters have determined the neutral and acceptable temperatures and airspeeds. In Chapter 3, which reviews the effect of urban and building design on the indoor environment, a question is: How does the building envelope of shop-houses, particularly opening elements respond to the outdoor climate and affect the indoor environment and comfort? Consequently, Chapter 8 mainly focuses on understanding the short and long-term building physics in shop-houses for occupant comfort and discomfort through using the outcomes deduced in Chapters 6 & 7 to assess indoor environmental performances. Additionally, the interplay of the building design and urban environments on the indoor climate and occupant thermal comfort will be shown. These analyses are significant in considering that complex relationship in the design of shop-house to get comfort. That will be also considered when building a proposal of design guidelines applied to build comfortable shop-houses in HCMC and Vietnam. To support those analyses, the chapter will use cross-sectional environmental measurements in 22 housing samples and the monitored data in three houses for both indoor and outdoor climates in different seasons.

8.1 Cross-sectional measurements

Table 8.1 summarises information about the measuring process in 22 shop-house buildings in HCMC. All those houses were categorised into urban pattern types: 7 houses in Group 1 (pattern types 1+2), 7 houses in Group 2 (pattern type 3), and 8 buildings in Group 3 (pattern types 4, 5 and 6), along with three common housing types (traditional shop-house, new shop-house, and row house). Figure 8.1-3 shows a general view of single buildings and their urban spatial structure taken by Google maps.

In all case studies, there are 5 samples visited three times (pilot study in 2016 and two official field studies in 2017 and 2018) while others were measured in physical variables in warm and cool climates. Data loggers were installed in three houses (A2, B3, and C5) for long-term monitor over 11 months. The author also considered the effect of building orientation on interior thermal conditions; therefore, eight major orientations were selected. For each visit, information of timing, date and cloud coverage was reported. Measurements proceeded between 10:0-17:00. Sky conditions were commonly mixed and overcast during surveys.

The measuring results are summarised in Table 8.2. There was a thermal variation in indoor and outdoor climates between surveying seasons. The outdoor thermal climate ranged between 33-34°C and 29.5-30.5°C in warm and cool months, respectively. In summer, the temperature difference between the two environments was by typically 1.5°C compared to the average figure of 0.7°C in cool spring.

Table 8.1 List of 22 shop-houses conducted with cross-sectional measurements

No	Housing type	Orientation	Warm 2016			Warm 2017			Cool 2018		
			Time	Date	Sky	Time	Date	Sky	Time	Date	Sky
TYPE 1 + 2											
A1	Row house	East	10:30	134	Clear	10:00	127	Overcast	10:30	23	Overcast
A2	Row house	South				16:00	106	Mixed	12:30	4	Overcast
A3	Row house	South				10:00	98	Mixed	10:00	21	Overcast
A4	Row house	North				10:00	118	Mixed	10:00	18	Overcast
A5	New shophouse	West				10:30	113	Overcast	10:45	14	Overcast
A6	Traditional	South				10:30	130	Overcast	10:00	17	Overcast
A7	New shophouse	Southwest	10:00	130	Mixed	10:00	130	Overcast	10:00	26	Overcast
TYPE 3											
B1	Row house	South				16:00	98	Clear	14:00	27	Overcast
B2	Traditional	Southeast				11:00	123	Miixed	11:45	15	Overcast
B3	New shophouse	Northwest	15:00	127	Mixed	15:00	127	Overcast	14:30	9	Overcast
B4	New shophouse	East				11:30	107	Mixed	14:00	12	Clear
B5	New shophouse	West				15:30	107	Mixed	15:00	7	Mixed
B6	New shophouse	North	15:00	133	Mixed	11:00	107	Mixed	14:00	30	Overcast
B7	New shophouse	Northwest				10:00	101	Mixed	11:00	24	Overcast
TYPE 4 + 5 + 6											
C1	Traditional	South				16:30	111	Mixed	11:30	12	Clear
C2	New shophouse	West				15:30	103	Mixed	15:30	13	Overcast
C3	New shophouse	North				10:30	111	Mixed	11:30	13	Mixed
C4	New shophouse	Southeast				11:00	126	Mixed	10:30	20	Mixed
C5	New shophouse	East	10:30	127	Mixed	10:15	92	Mixed	12:00	6	Mixed
C6	New shophouse	Southeast				16:00	106	Clear	16:00	21	Overcast
C7	New shophouse	Northeast				10:00	129	Overcast	11:30	33	Overcast
C8	New shophouse	Southwest							15:00	36	Mixed

In addition, external microclimates differed between urban types. The discrepancy from 0.5 to 1°C was found. In three groups of urban forms researched, thermal conditions around residences in the pattern type 3 showed the most dissatisfaction with the average warm air temperature of 34°C (SD 1.95) in summer and 30.6°C (SD 0.74) in spring. Meanwhile, the lowest average temperature around pattern types 1+2 linked to the more humid condition outdoors than in neighbourhoods of other urban structures, particularly in summer. Exterior average wind environments also varied between urban morphologies: 0.4m/s in Group 1 & 2 and 0.3m/s in Group 3.

The difference in urban environments between settlements influenced indoor environments. The air temperature inside houses planned in neighbourhoods of Group 2 averaged at 32.6°C (SD 1.22) in summer, which was warmer by 1.1°C and 0.7°C relative to the climate in buildings in Group 1 and 3. A similar pattern was found in cooler months with a narrower variation of 1°C. The difference in temperature also affected the humidity environment inside buildings. The average RH value in shop-houses of Group 1 was 67% in both measuring periods while that figure was lower by 5% in buildings located in other urban pattern types.

Figure 8.1 Urban patterns and architecture of buildings in Type 1+2

Figure 8.2 Urban patterns and architecture of buildings in Type 3

Figure 8.3 Urban patterns and architecture of buildings in Type 4+5+6

Through the comfort studies analysed in Chapters 6 & 7, insufficient air movement in shop-house dwellings to restore human comfort in warm conditions were observed. The investigations of airflow conditions within all rooms of 22 houses confirmed a similarity. Average wind velocities: 0.2m/s in summer and 0.1m/s in spring were much lighter than the acceptable airflow limits found in Chapter 7. That issue was common in all 22 cases even the available impact of urban types.

Moreover, the factor of building orientation also has impacts on the indoor thermal climate. Averaging interior air temperatures in the shop-house buildings grouped into various orientations presented a warmer environment (33.2°C) in buildings facing west while cooler thermal conditions at 32°C were observed in the houses oriented at other directions, for instance, east and south. Especially, ambient temperatures in buildings on the north side were the lowest.

Table 8.2 Indoor and outdoor thermal conditions

	OUTDOOR CONDITIONS						**INDOOR CONDITIONS**							
No	**Air temperature °C**		**Relative humidity %**		**Air velocity m/s**		**Air temperature °C**		**Relative humidity %**		**Air velocity m/s**			
	2017	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**	**2018**	**2017**		**2018**	
TYPE 1 + 2												Min - Max		Min - Max
A1	31	31.1	68	61.9	0.34	0.2	31	29.3	69	70	0.1	0.07 - 0.1	0.05	0.03 - 0.07
A2	32.9	31.8	58.5	58.3	0.59	0.59	32.1	30.6	58	62	0.3	0.14 - 0.43	0.18	0.1 - 0.31
A3	33.4	30.7	54.3	65.6	0.36	0.22	31.3	29.9	64	68	0.12	0.08 - 0.23	0.08	0.04 - 0.19
A4	36.4	28.8	48.2	66.3	0.43	0.26	31.9	28.3	64	69	0.11	0.04 - 0.3	0.1	0.07 - 0.16
A5	32.4	27.2	79	59.7	0.23	0.35	30.9	26.6	79	62	0.09	0.07 - 0.11	0.08	0.03 - 0.09
A6	32.8	29.9	64.4	64.2	0.31	0.77	31.5	29.4	70	68	0.14	0.1 - 0.18	0.11	0.03 - 0.18
A7	31.5	30.1	69	64.5	0.35	0.12	31.8	29.2	66	69	0.19	0.16 - 0.27	0.07	0.05 - 0.13
AVERAGE	**32.9**	**29.9**	**63.1**	**62.9**	**0.4**	**0.4**	**31.5**	**29.0**	**67**	**67**	**0.2**		**0.1**	
SD	**1.75**	**1.54**	**10.28**	**3.04**	**0.11**	**0.24**	**0.46**	**1.28**	**7**	**3**	**0.07**		**0.04**	
TYPE 3														
B1	33.2	30.7	56.8	67	0.29	0.19	32.3	29.9	59	70	0.2	0.1 - 0.21	0.05	0.04 - 0.07
B2	34	29.7	55.4	62.4	0.48	0.43	33.8	30	57	61	0.2	0.07 - 0.37	0.14	0.04 - 0.2
B3	31	30.8	70	63.8	0.24	0.48	30.7	30.3	71	67	0.1	0.06 - 0.17	0.2	0.04 - 0.49
B4	37.8	30.4	48.7	43.4	0.24	0.44	33.3	30	59	46	0.12	0.03 - 0.22	0.16	0.08 - 0.31
B5	34.1	31.3	50.1	59.1	0.32	0.3	33.8	30.9	53	62	0.12	0.06 - 0.17	0.08	0.04 - 0.14
B6	33.2	31.4	56.8	60.9	0.5	0.71	33.5	30.5	57	64	0.07	0.05 - 0.12	0.06	0.02 - 0.13
B7	35	31.2	53	62.2	0.61	0.29	32.4	29.8	63	67	0.11	0.04 - 0.2	0.08	0.02 - 0.2
	33	29.4	63	64.1	0.2	0.23	31	28.6	70	69	0.1	0.06 - 0.17	0.1	0.05 - 0.2
AVERAGE	**33.9**	**30.6**	**56.7**	**60.4**	**0.4**	**0.4**	**32.6**	**30.0**	**61**	**63**	**0.1**		**0.1**	
SD	**1.95**	**0.74**	**6.96**	**7.24**	**0.15**	**0.17**	**1.22**	**0.67**	**7**	**8**	**0.05**		**0.05**	
TYPE 4 + 5 + 6														
C1	34.7	28.3	52.5	50.1	0.1	0.18	34.1	28.4	53	53	0.09	0.05 - 0.14	0.1	0.04 - 0.29
C2	34.5	29.5	53.2	52.8	0.6	0.67	33.6	29.1	51	56	0.3	0.1 - 0.61	0.11	0.06 - 0.19
C3	32.1	28.8	60.2	50.6	0.3	0.3	31.5	27.9	63	57	0.09	0.04 - 0.17	0.09	0.04 - 0.12
C4	32.2	30.5	61.3	61.7	0.23	0.23	31.1	28.2	64	71	0.12	0.05 - 0.15	0.08	0.04 - 0.15
C5	31.4	32	64.5	56.7	0.2	0.42	30.2	29.8	66	66	0.12	0.06 - 0.24	0.24	0.11 - 0.35
C6	36.4	30.4	41	69	0.16	0.15	30.9	29.6	70	71	0.09	0.05 - 0.13	0.04	0.03 - 0.06
C7	32.4	28	60.2	67.3	0.35	0.14	31.7	28.3	67	65	0.26	0.15 - 0.35	0.15	0.05 - 0.23
C8		29.6		45.7		0.25		29.3		49			0.1	0.06 - 0.15
AVERAGE	**33.4**	**29.6**	**56.1**	**56.7**	**0.3**	**0.3**	**31.9**	**28.8**	**62**	**61**	**0.2**		**0.1**	
SD	**1.83**	**1.31**	**7.96**	**8.50**	**0.16**	**0.18**	**1.44**	**0.71**	**7**	**9**	**0.09**		**0.06**	

The real thermal environment in 22 typical buildings generally showed dissatisfaction for occupants due to warmth and calm airflow indoors. Seasonally climatic changes also intervened to mitigate indoor temperatures, particularly in the dry season. Additionally, urban elements forming various urban spatial structures had relation to varying outdoor microclimates between settlements, subsequently causing differences in interior environments and comfort degrees between shop-houses in different settlements. Moreover, the indoor thermal condition was also governed by the building orientation.

The next section aims to understand environmental performances and the effect of the building and urban design on indoor microclimates and comfort through environmental, architectural, and urban surveys of three typical buildings classified into three urban forms and two shop-house types.

8.2 Longitudinal assessments

This section analyses environmental performances in terms of air temperature, relative humidity and air velocity in three shop-house examples, which are located at three different urban morphologies: case 1 – A2 in pattern type 1, case 2 – B3 in pattern type 3, and case 3 – C5 in pattern type 4. Comfort conditions for occupants differed between rooms/spaces within a building, between case studies, between urban patterns, and between seasons owing to the influence of various internal and external factors. The internal factors are related to the building design: building/room orientation, spatial layout, room geometry, building fabric, and opening configurations. Meanwhile, the external factors include the outdoor climate and the urban constituents of settlement which the building is presented. Assessing physical environments for human comfort in those typical cases is based on the research outcomes of acceptable thermal and air movement zones discovered in previous chapters. Through analyses, the relationship among the building design (focusing on openings), the urban design (focusing on urban forms), indoor environments, and human comfort will be understood. The next three subsections will discuss in depth the results of on-site measurements in three housing samples.

8.2.1 Case study 1 (A2)

8.2.1.1 Description

a. Urban Context

A first case study is a row house positioned in Type 1 residential neighbourhood characterised by a regular building pattern with low density and available public spaces around the area. All houses are planned adjacently and perpendicularly to domestic streets in a back-to-back pattern. Construction of residences within such neighbourhood has complied with some regulations. The standardised site dimension is 5m (width) by 20m (length); however, construction coverage allows to be 75% to encourage comfortable microclimatic conditions in the dwelling. Thus, the main and rear building façades are set back 3m and 2m, respectively. The building envelope complies with an archetype for all houses despite some allowable changes in openings, finishing materials, and colours. The number of stories and the total height of all buildings is homogeneous.

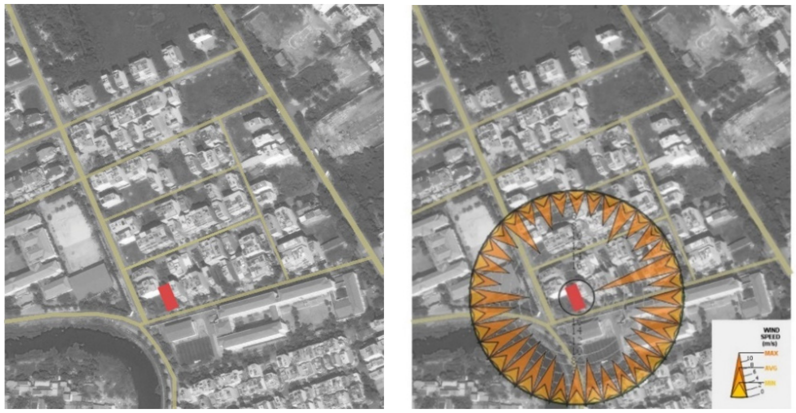


Figure 8.4 Urban morphology and wind pattern in case A2

The major building orientation is almost south. A 4-story secondary school is opposite the current house. The east side of the house is another building while neighbouring land plots at north and west have been under construction. The housing orientation has the potential to absorb seasonal winds from southeast-southwest directions, even monsoon winds from the north.

Figure 8.5 Urban context around case A2

Internal roads are shaded by vegetation along sidewalks (Figure 8.5); additionally, each house also has front and back gardens. An evergreen condition in and surrounding buildings is potential to mitigate outdoor environments, subsequently positively influencing the indoor thermal comfort when exchanging with the outdoor climate.

b. Architecture

The building was built in 2015. Site building coverage is 75sqm. Within the settlement, one typical house contains five stories: ground floor, mezzanine, two upper floors, and rooftop as described in Figure 8.6. The building function is a combination of household office and housing for occupancy of three adults and two children.

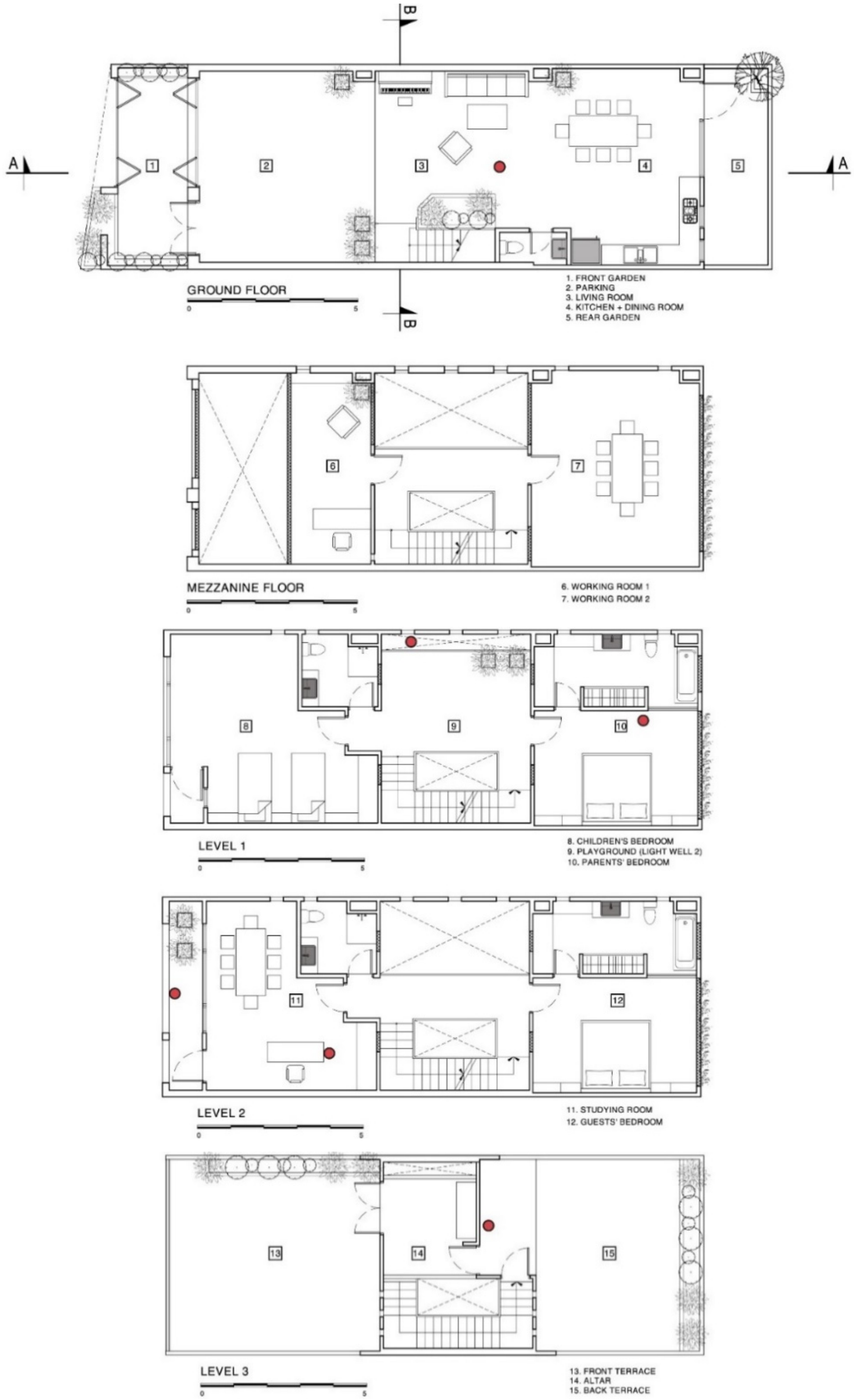


Figure 8.6 Floor plans and placements of instruments (red dots)

On the ground floor, common spaces (parking, living room, kitchen, and dining room) are organised as an open plan connected with two front (3m) and back (2m) gardens that enable daylighting and air movement through the whole space. Within the house, a staircase attached with a green area is integrated. Besides, the front garden is utilised for planting and parking at daytime. The garden is surrounded by a perforated fence that is permeable to outdoor winds. A smaller shaded garden at the back may create pressure differences resulting in the effect of air movement between two gardens. Additionally, it works like a buffer zone for natural lighting and ventilation in the back rooms through openings installed in the rear wall.

The whole mezzanine is used for offices of an architectural firm. Two voids are alternately integrated with two working rooms to make the volume of parking and living room larger (Figure 8.7). The working rooms are separated by ventilation brick walls which allow the secondary daylight source and air movement crossing the spaces.

On levels 1 and 2, bedrooms overall face two potential orientations of predominant winds (south and north); and they also connect with internal open spaces such as the staircase and light wells through openings in the partition wall. On level 3, a rooftop is constituted by a front vegetable garden, a worship space, and a back terrace for drying.

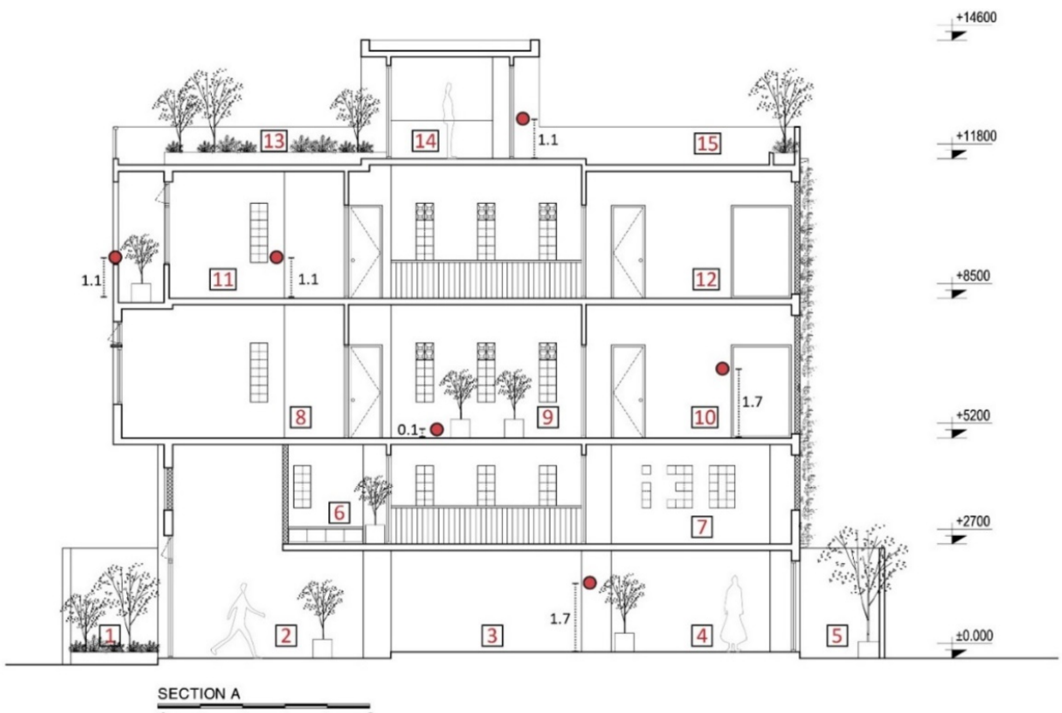


Figure 8.7 Building section and locations of instruments

The red points in Figures 8.6-7 represent the position of monitoring instruments. They were placed to record data of air temperature, air velocity, and humidity from April 2017 until February 2018. Additionally, a set of instruments was simultaneously used to collect outdoor data. All loggers were installed within the living space; however, depending on the function and condition of each room is that their position above the floor was different: 0.1m, 1.1m, or 1.7m.

c. *Environmental design strategies*

At the early stage of construction, owners considered the optimisation of environmental responsive designs to achieve indoor comfortable and healthy environments and reduce the size of cooling and lighting systems, subsequently saving more energy use. Thus, interior spaces are entirely or partly open through horizontal and sectional spatial layout and utilisation of various opening types on the building fabric. Ventilation bricks are an identical design feature of this house. They not only optimise the performance of building physics, particularly natural ventilation but contribute to homogenous aesthetics for the building. In the house A2, a number of passive daylighting and cooling design strategies are applied as shown in Figures 8.8-13:

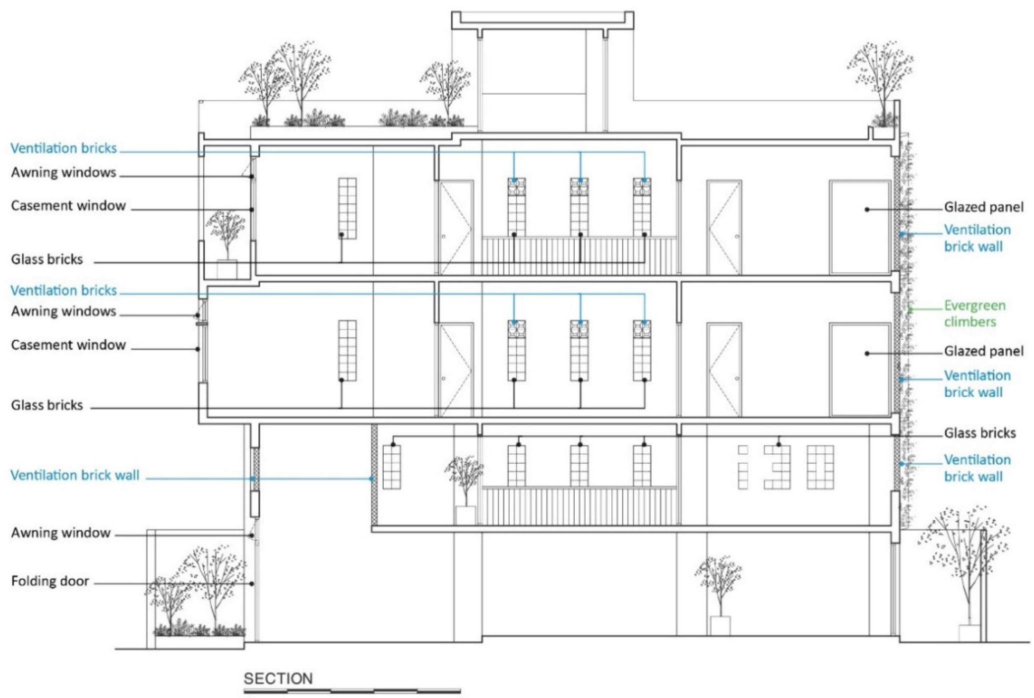


Figure 8.8 Building elements for passive designs in the house A2 (Section A)

The southern elevation has the potential for catching natural winds from southern directions. The perforated area occupies over 50% of the external wall with various opening types used: folding door, side-hinged door, casement window, awning window, and ventilation brick (Figure 8.9 Elevation). An advantage of ventilation bricks and high awning windows is constantly wind permeability during the day, even when main doors and windows are closed. Although the indoor airflow pattern benefits from the large inlets, the overheating risk is possible. Therefore, elements, such as the balcony, overhang, and internal fabric curtain are employed to reduce solar impacts.

Meanwhile, all rooms facing north are entirely designed with ventilation bricks for natural ventilation, daylighting and shading (Figure 8.8 & 10). Northern winds can enter in those spaces between November and February through the ventilation brick walls. Additionally, to prevent the access of sunlight in equinox, the outer layer of northern facade is covered by Rangoon creepers. They also create a natural and friendly feeling for users (Figure 8.8).

A mandatory requirement in the design of row houses within the settlement of pattern type 1 is the integration of central courtyards, light wells, or voids with the minimum size of 6m² (VIAP, 2012). They not only are the main elements of social/environmental connection within a building but encourage air change within indoor spaces and remove the interior hot air by stack and wind effects.

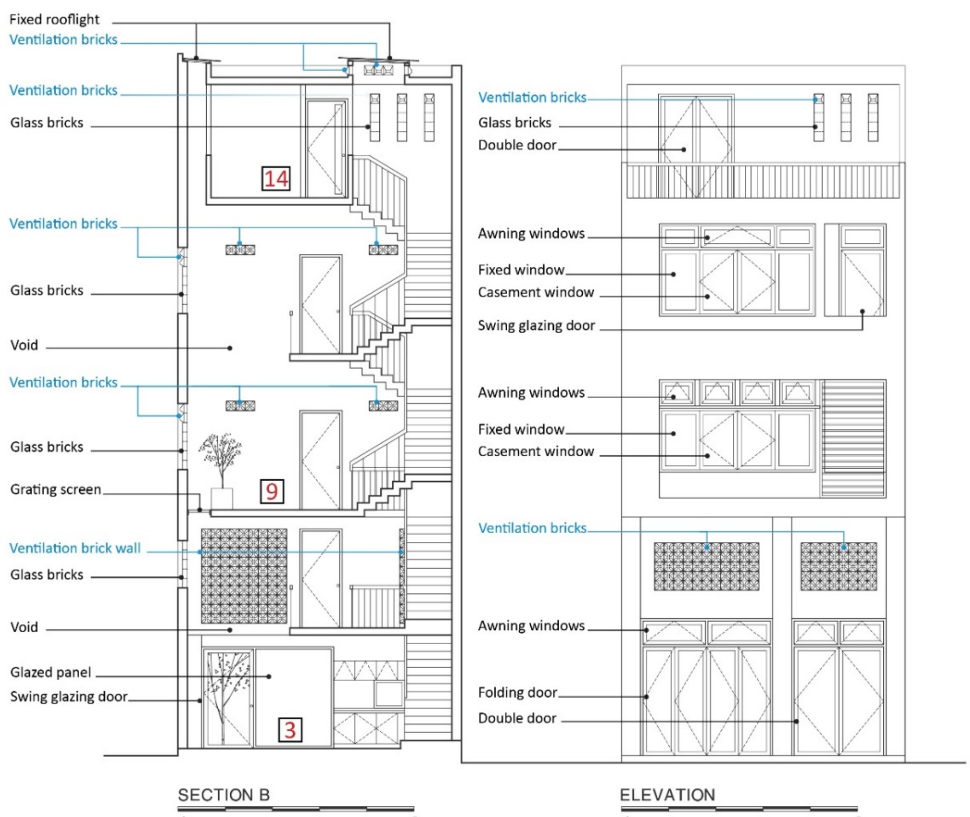


Figure 8.9 Building elements for passive designs in the house A2 (section B and elevation)

To optimise the wind effect, openings are organised in both external and internal walls (Figure 8.8-9). As shown in two longitudinal (A) and cross (B) sections, ventilation bricks installed in internal walls play a role of leeward openings, even when room doors are closed. Furthermore, ventilation bricks are also positioned at the staircase (in the western wall and around skylights) to encourage warm air removal.

Alongside the passive cooling design, the reduction of lighting energy consumption is concerned in this house. Natural light in the building is optimised by the openings installed on most building facades (south, north, and west) (Figure 8.8-10). Additionally, in the circulation area, natural light penetrates inside through skylights and glass bricks positioned in external walls and then daylighting lower spaces.

Figure 8.10 Elevation, architectural features and internal spaces of the house A2

Two primary natural ventilation principles used include stack and cross-ventilation. In windward facing south and north, the availability of openings enables to maximise the enter of predominant winds around the year. Opening features are diverse in type, operation, size, and fenestration for inlets and outlets on the building envelope to create various ventilation effects (Figure 8.11-12).

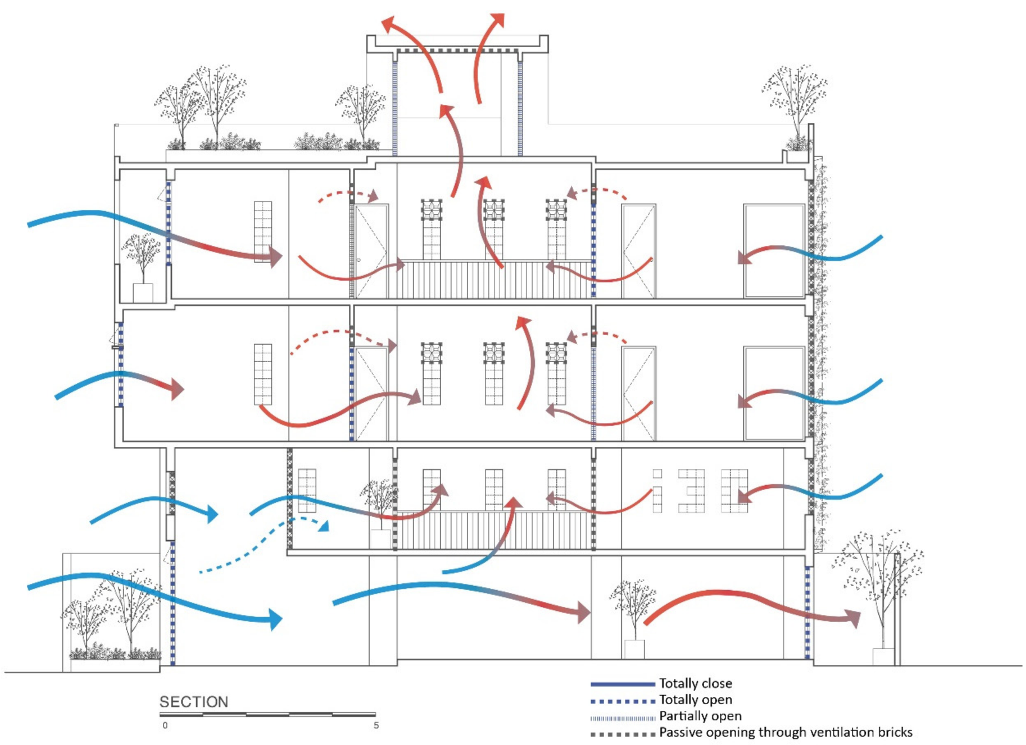


Figure 8.11 Operation of natural ventilation in the morning

Figure 8.11 depicts natural wind driving operations during the daytime. Most windows/doors are open in diurnal, excepting doors in the altar room while ventilation brick walls are passively open. The windward apertures capture prevailing winds from south and north; hot air in rooms then moves into the staircase through openings in internal walls and escapes outside through outlets. Depth of most rooms is satisfactory to cross-ventilation. The placement and ratio between inlets and outlets influence the path and velocity of air stream within the room.

On the ground floor, all the spaces are wholly open and connective with the staircase. When outdoor winds blow in, they exchange with indoor air and escape by two directions: crossing the kitchen door to the rear garden and through openings on the top floor due to the stack effect into the staircase as shown in Figure 8.12. Consequently, there is a combination of two natural driving forces. Such combined ventilation systems are also found in most interior spaces due to non-aligned placement of openings in opposite walls and a spatial connect between rooms and the light well.

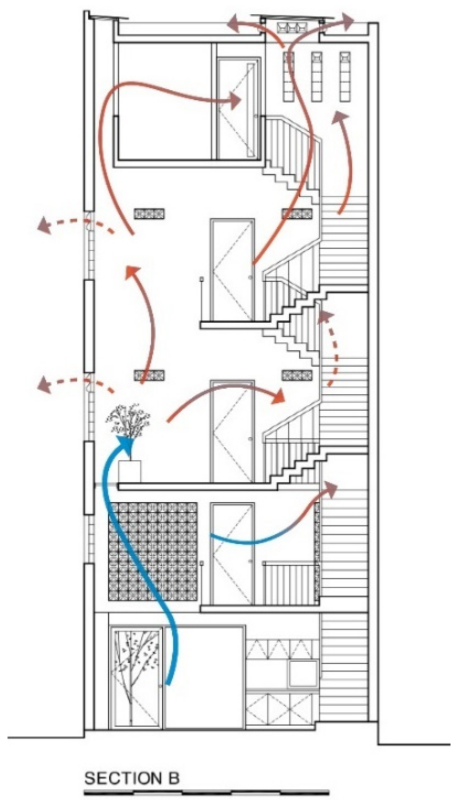


Figure 8.12 Stack ventilation through the staircase

At night, most external windows/doors and internal room doors are closed while awning windows and ventilation bricks are still operative. Figure 8.13 shows the operation of night ventilation. Night air temperatures decrease significantly; therefore, the outdoor cool air is permeable to the interior through those means to provide an amount of fresh air, ventilation, and coolness around the house during the sleeping time. Although the effect of natural ventilation at bedtime is less powerful than that at daytime due to closed openings partly, a combination of low air temperatures and consistent air movement can also bring thermal satisfaction for occupants.

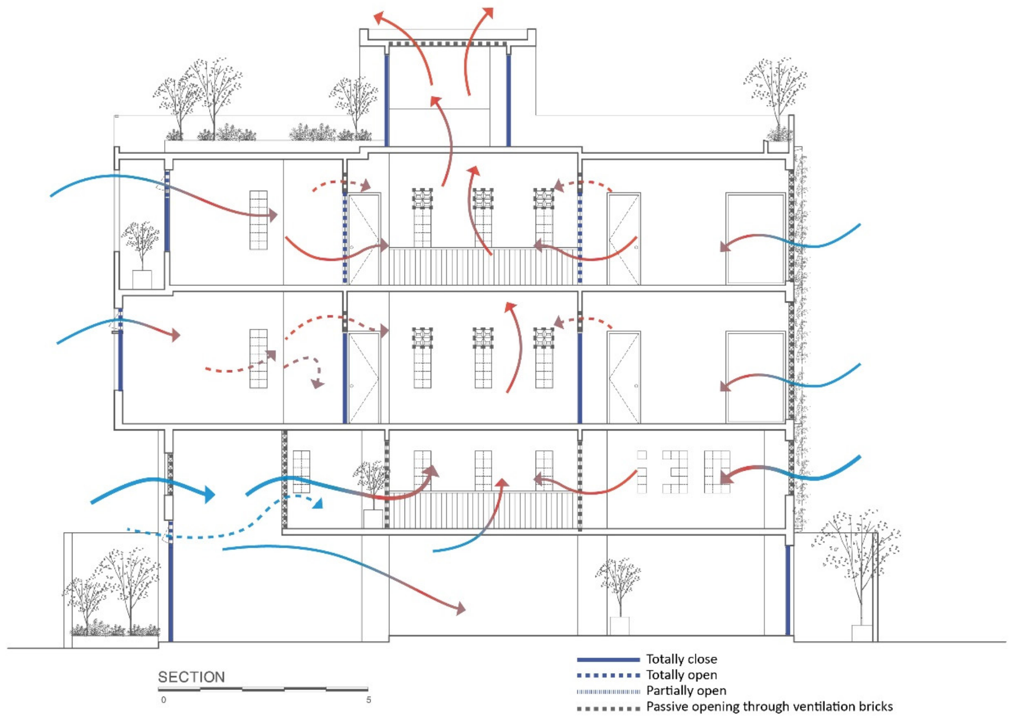


Figure 8.13 Operation of natural ventilation during sleeping time

In short, internal thermal environments were quite pleasant during visits to the building A2 in warm and cool seasons. For row houses in settlements of pattern type 1 as this case, the basic regulations in planning and architecture potentially provide advantages to obtain a satisfactory microclimate in the building, in terms of daylighting and ventilation. The remaining important responsibility is of architects. Thus, the users, who are also the architects of this house, properly considered the correlation between indoor and outdoor environments, the effect of interior microclimate on health, well-being, and the reduction of energy for cooling and lighting. Then, a series of various responsive design strategies were applied to reduce heat gain and to enhance air movement and natural light around the house.

8.2.1.2 Outdoor climate

Data of exterior climate were gathered by a set of instruments installed in the building A2 from April 2017 until February 2018. All data are devised into varying periods: hot months (April and May), mid-season (from June to October), and cool months (from November to February).

Figure 8.14 shows the distribution of daily mean outdoor air temperature with the blue dash line representing the gradual temperature decrease across those seasons. The variation of average air temperature found was 3°C. The maximum discrepancy between the hottest and coolest day was 11°C. The current observation of in-situ outdoor climate may show a wider difference than the common meteorological characteristic reported in tropical monsoon climates. Climate change may have impacts on such a difference.

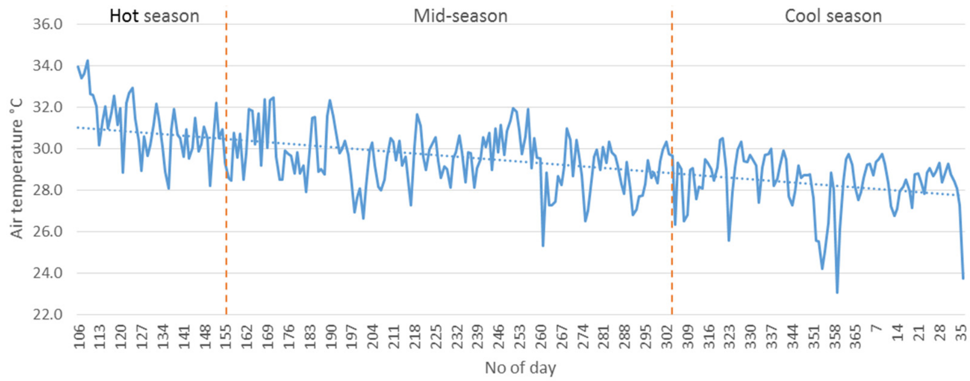


Figure 8.14 Distribution of daily mean outdoor air temperature

Over the monitoring period, some technical interruptions happened with the wind gauge; thus, some data were lost. As shown in Figure 8.15, daily mean outdoor wind velocities fluctuated for 11 months. The settlement planning design contributes to the sufficiency of external wind environments with a mean value of 6.0 m/s (SD 4.7). The intensity of wind was stronger over 10m/s in the mid-season when rainy months mainly occur, even the additional operation of typhoons coupled with gales. Besides, the building orientation at the south, the housing location at the corner and the availability of a canal nearby may be grounds for high incident winds to this house. Meanwhile, airspeeds were relatively constant at 2 to 4m/s in other seasons, particularly in cool months. The large divergence of outdoor winds recorded between seasons resulted from the seasonal wind mechanism and turbulent effect. An abundance of external winds is potential for obtaining satisfactory air movement and comfort indoors.

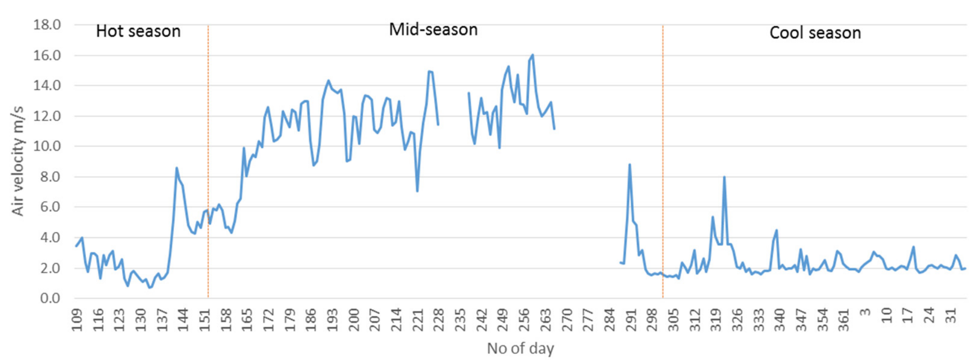


Figure 8.15 Distribution of daily mean outdoor air velocity

Table 8.3 summarises the hourly climate data around the house. The variability of hourly outdoor temperatures seasonally varied: 26-42°C in summer, 24-42.5°C in the mid-season, and 20—36.5°C in spring. The thermal climate in the hot season was averagely 1.5°C and 2.5°C warmer than in the mid and cool season, respectively.

The outdoor RH reached the maximum 100%, particularly on raining days. The tropical rains and storms principally operate between June and October in HCMC; therefore, average RH over that period was higher than in other months. Wind conditions over the whole year showed large variability. Under the influence of rainfalls and storms, airspeeds in the mid-season were very strong with a mean wind velocity of 10m/s (SD 4.5), even reaching up to 39.6m/s. Meanwhile, the average air velocity in hot and cool months was as follows: 3m/s (SD 2.4) and 2.3m/s (SD 1.4), which are more pleasant for people.

Table 8.3 Outdoor climatic characteristics over the year

Seasons	Variables	Maximum	Mean	Minimum	SD
Hot season (March, April, May)	Air temp. (°C)	41.9	31.0	25.9	3.4
	RH (%)	100	76	44	12
	Air speed (m/s)	12.9	3.0	0.0	2.4
Mid season (June, July, August, Sep., Oct.)	Air temp. (°C)	42.4	29.6	23.9	3.1
	RH (%)	100	81	44	12
	Air speed (m/s)	39.6	10.0	1.0	4.5
Cool season (Nov, Dec, Jan., Feb.)	Air temp. (°C)	36.4	28.4	20.1	2.9
	RH (%)	100	78	50	11
	Air speed (m/s)	14.8	2.3	0.8	1.4

In conclusion, the outdoor climate over the monitoring period indicated a wide thermal variation between day and night time and between seasons. Exterior hot conditions within March and October can negatively affect thermal satisfaction and behaviours of inhabitants when enduring discomfort indoors. Meanwhile, it was much cooler within November and February, which was beneficial for getting human comfort but also possibly causing cool discomfort when temperatures decreased. Between the three seasons, the mean humidity distribution was quite similar (a difference of 5%). Wind velocities surrounding the building widely fluctuated under the influence of seasonal mechanism. In given outdoor dynamic environments, the response of the physical building to their characteristics means to mitigate and retain indoor satisfactory microclimates for occupants over the year. With the availability of passive designs of this building, how indoor environments performed. The next sections will discuss more.

8.2.1.3 Indoor thermal climate

a. Air temperature

The building was visited at 16:00, 106th date (summer) and 11:00, 4th date (spring) for conducting snap-shot measurements of variables. Comfortable environments by rooms are found in Figure 8.16. With the passive cooling designs optimised in the case, the climatic correlation between the indoor and outdoor was close, evidently, a slight variation of two environments was below 2°C, especially a narrower difference of 0.7°C in warm summer. Furthermore, the thermal data showed a seasonal change in both interior and exterior climates. A divergence in the outdoor environment was 0.7°C while the average indoor temperature of all rooms investigated differed 1.5°C between two seasons.

Moreover, the thermal condition varied between rooms with a warmer tendency according to building height. That event was similarly found in the outdoor climate. The vertically internal temperature difference was 2.5°C in summer and 1.2°C in spring. In lower spaces, which overheating by solar radiation is partly obstructed; the thermal environment was more comfortable for inhabitants. In summer, the average temperature was 31°C and 31.5°C on the ground and mezzanine floors, respectively. These figures were lower by 1-2°C compared to room temperatures on the upper floors. Differences in temperature between the indoor and outdoor, between floors, and between inlets and outlets are potential for operation of buoyancy-driven ventilation besides the wind effect, particularly in summer. Whereas, the wind effect may be more useful in cool months because of a narrower thermal difference between rooms.

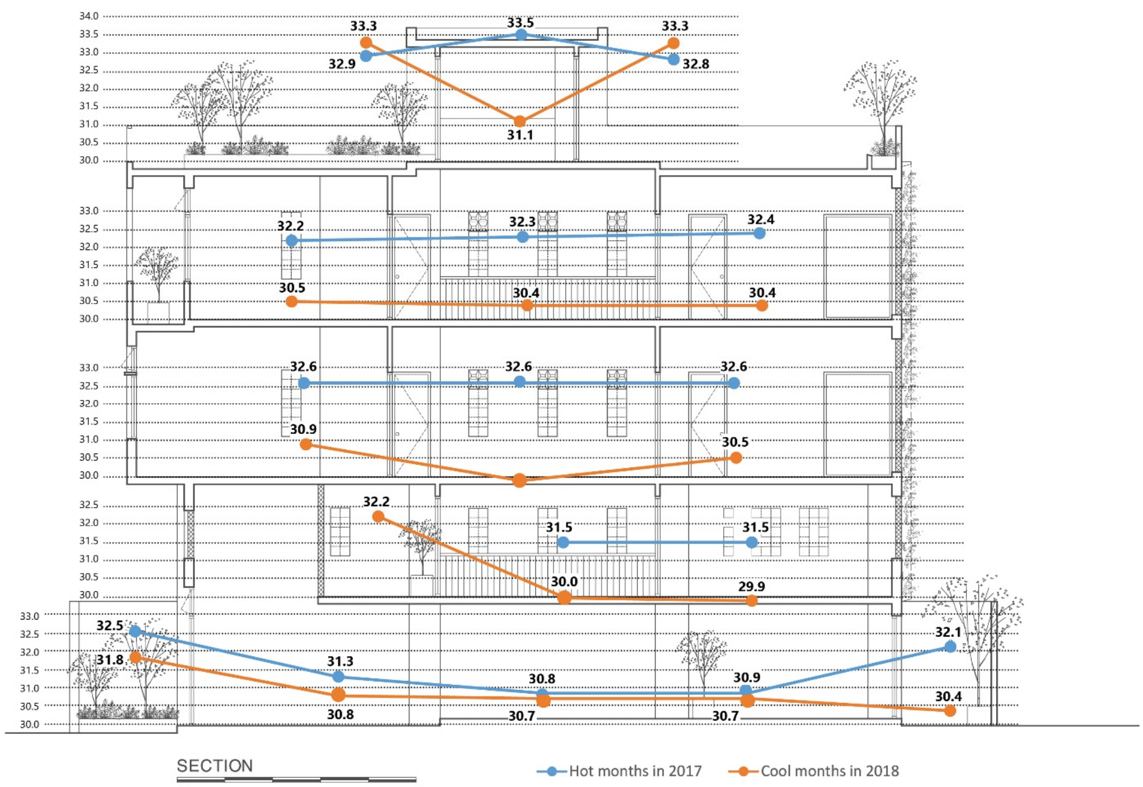


Figure 8.16 Distribution of air temperature within the house in hot and cool months

The further analysis is longitudinal thermal performances in four spaces: an open space (living room + kitchen + dining room), staircase, parent bedroom, and studying room through monitored data by HOBO instruments. Figure 8.17 describes the pattern of daily mean air temperatures in those rooms in relation to the outdoor climate.

Room temperatures positively fluctuated to outdoor temperatures, which presented a close relationship between two climates in free-running buildings. Internal thermal environments were cooler when the external temperature reduced. The deviation between the interior and exterior environment was wider when it was hotter. A greater variation of two climates in summer may show the effective responses of building envelope to outside warm environments.

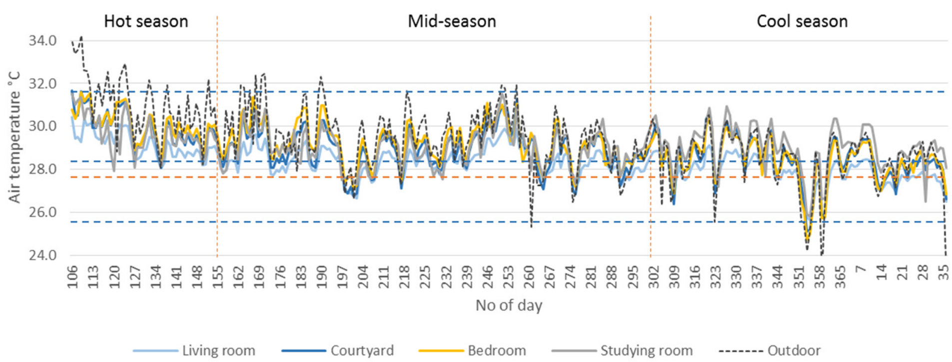


Figure 8.17 Distribution of daily mean indoor air temperature by room

The lines of daily mean room temperatures were mostly within the acceptable thermal limits (25.5-31.5°C), excepting some days in December. Data are categorised into three seasons. In summer and the mid-season, environments in those rooms were warmer than neutral temperatures of 28.5°C. Although the thermal patterns lie between the comfort zone, provision of air breezes should be required to restore thermal satisfaction when air temperatures are more than 27°C (referring to the acceptable airflow range found in Chapter 7).

Table 8.4 Hourly indoor thermal conditions of 4 rooms by season

Seasons	Values	Living room	Courtyard	Bedroom	Studying room
Hot season (March, April, May)	Maximum	33	34	34	33
	Mean	29	30	30	29.5
	Minimum	27.5	27	27.5	23
	SD	0.7	1.3	1.2	1.4
Mid season (June, July, August, Sep., Oct.)	Maximum	30.5	33	34	33
	Mean	28	29	29	29
	Minimum	26	25	25.5	24
	SD	0.7	1.4	1.4	1.3
Cool season (Nov, Dec, Jan., Feb.)	Maximum	30	34	33	33
	Mean	28	28	28	29
	Minimum	24.5	23.5	23.5	21
	SD	0.8	1.6	1.4	1.6

There were similar thermal conditions measured by snap-shot and monitoring methods. The environment in ground-floor spaces was the coolest in four rooms throughout the year. The spatial organisation of such rooms accounts for their lower temperatures than in other rooms. The less satisfactory thermal climate observed in the parent bedroom and studying room was because of the impact of the surrounding environment at higher levels above the ground and the effect of solar radiation from the roof. The more comfortable thermal environment in rooms on the ground floor is robustly confirmed by the report of hourly temperatures in the spaces surveyed shown in Table 8.4. The mean and maximum temperatures inside the living room were 29°C and 33°C, 28°C and 30.5°C, and 28°C and 30°C in the hot, mid, and cool season, respectively (Table 8.4). Those figures were 1-4°C lower relative to in other spaces over three periods. Furthermore, the environment on the ground floor was more consistency with lower SD numbers during monitoring.

Table 8.5 grouped hourly temperatures of those rooms into five variations: <25.5°C and >31.5°C (out of the comfort zone), 25.5-27°C and 30-31.5°C (75% acceptability), and 27-30°C (90% acceptability) within April 2017 and February 2018. Thermal environments in the living room were the most satisfactory with 94% of hours accepted by 90% of occupants. Meanwhile, that percentage reduced by 20% in other spaces; additionally, the number of unacceptable temperature hours in those was more by 5-6%. Thermal conditions performed quite similar among the staircase, bedroom, and studying room.

Table 8.5 Percentage of uncomfortable and comfortable temperatures

Room type	T < 25.5	25.5 ≤ T < 27	27 ≤ T ≤ 30	30 < T ≤ 31.5	T > 31.5
Living room	0.5%	3.7%	94.3%	1.4%	0.0%
Courtyard	1.1%	5.2%	74.4%	15.8%	3.5%
Bedroom	1.2%	3.3%	74.8%	16.3%	4.4%
Studying room	0.8%	3.5%	73.8%	18.5%	3.4%

It is certain that thermal environments surveyed in and around the sample A2 present the intrinsic characteristic of tropical monsoon climate – warmth across much of the year, evidently a short period of temperatures under 25.5°C. Around 1% of hours showed cool discomfort in most spaces investigated. When experiencing cool temperatures, occupants usually adapted by putting on light warm clothes, in addition, they partly closed openings to reduce the air exchange between two climates.

In acceptable thermal conditions between 25.5-31.5°C, despite the majority of temperatures (≥94%) within the comfortable range in rooms, a greater percentage of them were more than 28.5°C. Considering the comfort zone for free-running shop-houses discovered in Chapters 6 & 7, the availability of minimum airflow of 0.4m/s is significant in restoring occupant thermal satisfaction, especially in the studying room where the proportion of warm acceptable temperatures (30-31.5°C) were greater (18.5%). Under warmer conditions, a combination of natural and mechanical cooling systems was used to maintain comfort. While most rooms were naturally ventilated or fanned during the year, the studying room was cooled by the air-conditioner at certain times in summer, evidently, room temperatures dropped deeper than common thermal performances in other rooms (Figure 8.18).

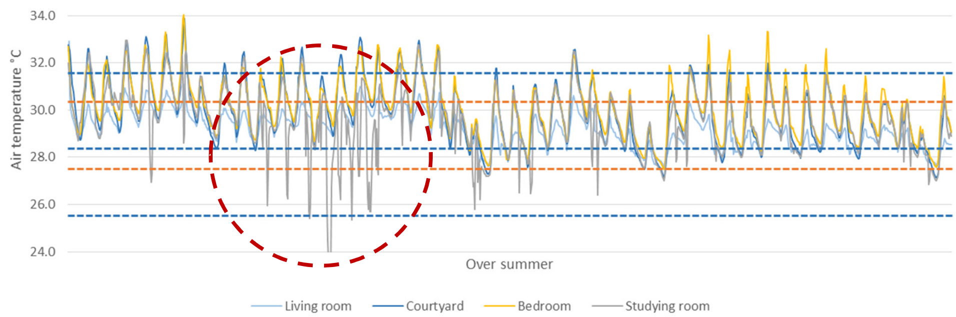


Figure 8.18 Distribution of hourly air temperature in 4 spaces over summer

b. Relative humidity

The continuous lines of the chart below present daily mean relative humidities in four spaces studied over the year. The humid environment in those rooms varied in the relationship of thermal performances. The apparent discrepancy was observed in warm months: 10% in summer and 5% in the mid-season. The cooler condition in spaces on the ground floor linked to higher humidities than in other rooms over three seasons. In summer, warmer temperatures inside both bedroom and staircase resulted in drier conditions indoors. The use of air-conditioner in the studying room affected the indoor humidity distribution, particularly in summer; thereby, the daily mean humidities were greater than in other spaces. Nevertheless, warmer temperatures in further months correlated to the reduction of humidity in that space.

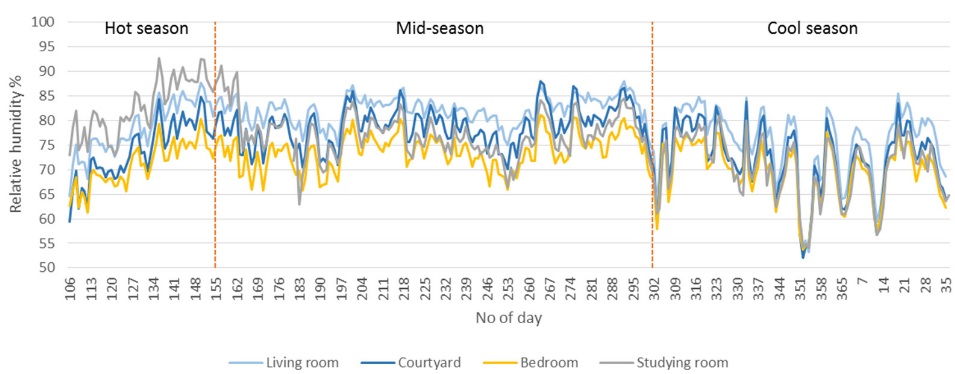


Figure 8.19 Distribution of daily mean indoor relative humidity over the year by room

On the other hand, in the cool season, humidity considerably reduced and fluctuated over that period. Within 351st – 358th dates, daily mean RH values of all rooms nearly dropped at 53%. Those changes were respective to the fluctuation of indoor and outdoor temperatures. The humidity variation between rooms was slightly in that season due to a thermal balance between rooms.

Table 8.6 presents the seasonal humidity condition in four rooms based on hourly recorded values. The ambient environment in the dwelling was likely humid over the year. The mean RH within the living spaces was more than 70%, especially in the rainy months (April-October) with average values between 70-82%. The indoor humidity reached up to a maximum of 99%, for instance, in the studying room. According to the national standards, the recommended humidity range is between 30%-70% and up to a maximum of 80% in warm months in buildings of the tropics (VSQI, 2005; VIAP, 2012). A great number of humidity values were higher than the threshold between April and October, particularly in the rainy season. Consequently, in warm months, high temperatures coupled with high humidities possibly cause human discomfort due to the constraint of evaporation on the body skin. Adequate natural ventilation is significant to accommodate the indoor microclimate and to retain comfortable statements.

Table 8.6 Hourly relative humidity conditions in 4 rooms by season

Seasons	Values	Living room	Courtyard	Bedroom	Studying room
Hot season (March, April, May)	Maximum	91	91	84	99
	Mean	79	74	71	83
	Minimum	52	51	51	54
	SD	6.1	7.7	6.0	7.4
Mid season (June, July, August, Sep., Oct.)	Maximum	91	91	84	97
	Mean	82	78	73	77
	Minimum	54	48	49	50
	SD	4.4	6.2	5.7	6.6
Cool season (Nov, Dec, Jan., Feb.)	Maximum	91	93	85	87
	Mean	76	72	70	71
	Minimum	45	45	47	46
	SD	8.0	8.4	7.0	7.5

c. Airflow distribution

This section discusses air movement in the building. Besides right-now airspeed measurements in two field studies, two wind sensors were placed in the living room and staircase to record airspeeds between April 2017 and February 2018. Variations in air movement were found between rooms and between surveying periods for the effect of building design (opening design features, room geometries, orientation and floor position) and outdoor microclimates. Opening configurations differently featured in each space result in the variation of natural ventilation principles, along with the distribution and intensity of airflow within the room. The wind effect was stronger on the upper floors with less obstruction of surrounding urban elements. In summer, prevailing winds from the south and southeast majorly operate with an average speed of 4m/s while the wind power is lighter in spring. Excepting the physical influences, human occupancy and the use of openings by occupants partly govern indoor airflow conditions. Further analyses indicate wind dynamic characteristics (velocity, pattern, and flow rate) inside rooms of the house in different seasons through short and long-term data collection.

Air velocity at intersections on the 2D grid was averaged from values read at three different heights (0.1m, 1.1m, and 1.7m) and was represented by contour colour maps. Furthermore, the respective standard deviation is shown at each point. The horizontal flow pattern within rooms was compared in a couple of warm and cool climates.

On the ground floor, the natural wind was more satisfactory, particularly in hot months with higher airspeeds and more uniform distribution of them. Airspeeds ranged from 0.05-1.2m/s with many values greater than 0.4m/s (Figure 8.20). Additionally, the zones of sufficient airspeeds mostly occupied a whole area of the floor. Building conditions, such as an open plan, simple furniture, a large opening area positioned in opposite walls, enhance cross-ventilation within the space, along with partly the stack effect through the connectivity of air between the ground floor and light wells at the staircase.

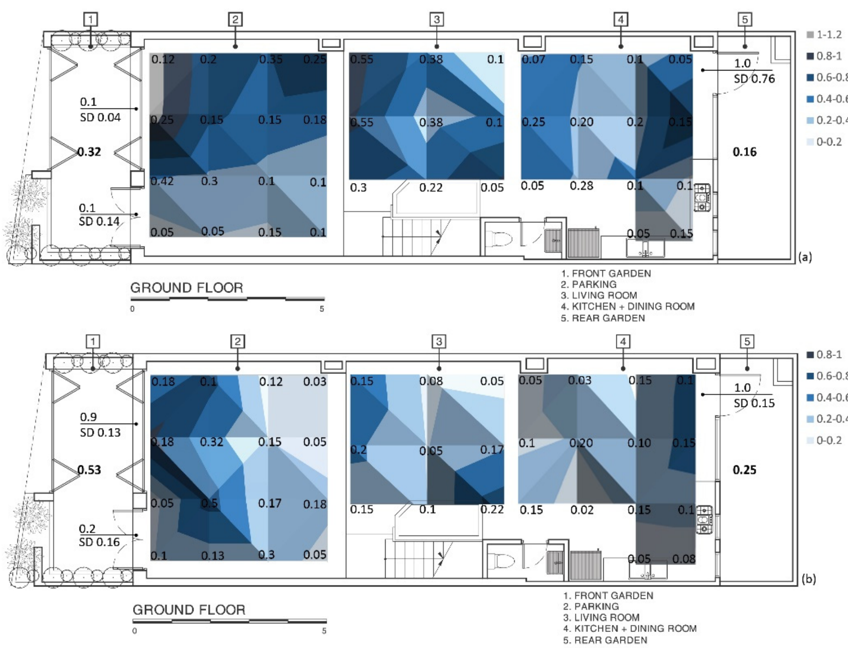


Figure 8.20 Airflow pattern on the ground floor in hot (a) and cool (b) season

Meanwhile, with similar physical building conditions, a reduction in outdoor wind velocities in cool periods influenced less uniformity of airflow indoors, especially in middle zones of the floor. Air turbulence was higher around inlets or outlets relative to a larger zone of lower airspeeds than 0.4m/s. Those observations showed less sufficiency of airflow to balance warm temperatures in the dry season.

On the mezzanine floor, natural ventilation poorly performed with most airspeeds lower than 0.2m/s in both seasons (Figure 8.21). Despite the optimisation of the opening area in internal and external walls by ventilation bricks for air movement in working rooms, the real effect was unexpected. However, a great opening area also results in a high ventilation degree.

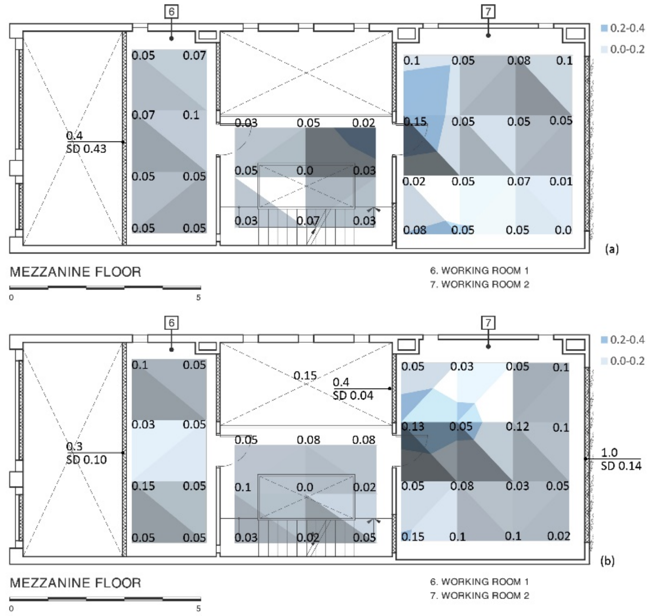


Figure 8.21 Airflow pattern on the mezzanine in hot (a) and cool (b) season

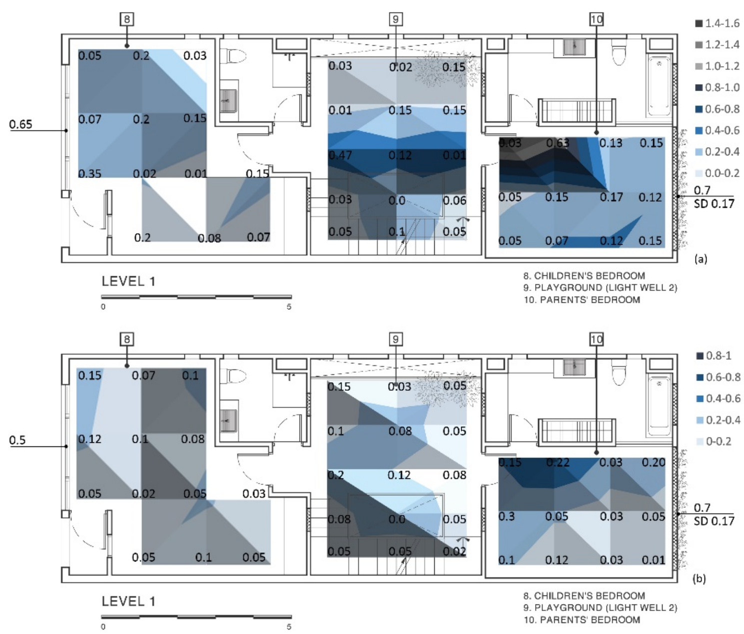


Figure 8.22 Airflow pattern on level 1 in hot (a) and cool (b) season

Air movement on the upper floors was greater than on the mezzanine. The performance of natural wind also varied in different rooms (children and parent bedrooms, and staircase) under the operation of seasonal winds. In the summertime, most areas of the occupied zone inside such spaces were cooled by airspeeds between 0.2-0.6m/s whilst ventilation quality decreased by 50% in springtime (Figure 8.22). Among three spaces, the natural wind was driven more sufficiently in the master bedroom, although its location is at the back of the building and faces north. Contour maps within the room are formed by higher and wider wind velocities of 0.1-1.6m/s in summer and 0.1-0.65m/s in spring compared to 0.05-0.4m/s and 0.05-0.25m/s in the children bedroom; and 0.1-0.6m/s and 0.05-0.3m/s in the staircase, respectively.

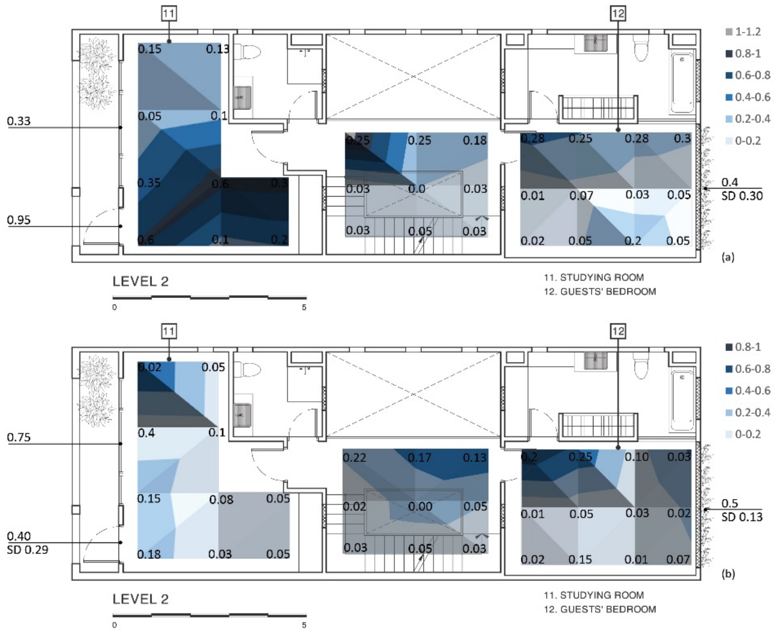


Figure 8.23 Airflow pattern on level 2 in hot (a) and cool (b) season

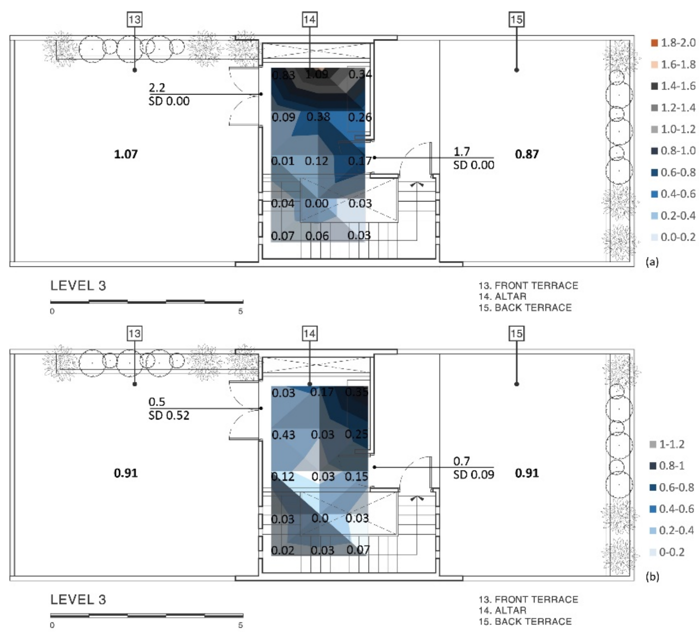


Figure 8.24 Airflow pattern on level 3 in hot (a) and cool (b) season

Indoor and outdoor air movement was stronger on level 2 & 3 (Figure 8.23-24). Different indoor airflow patterns between two seasons were also found. In the wet season, the studying room facing south was characterised by a more comfortable wind environment with high airspeeds (0.4-1.2m/s) almost occupying the room area. Nevertheless, in spring, airflow performance was reversible with a non-uniform pattern and a larger zone of lower velocities. In the guest room, the range of air movement was 0.1-0.5m/s and 0-0.8m/s in summer and spring, respectively. The airflow pattern was uneven with light airspeeds (0-0.2m/s) operating mostly the occupied zone.

Using the same wind data collected over two fieldworks, air movement around the building is evaluated on the section. They are indicated by line graphs computed at three different levels within the occupied zone (low – 0.1m, medium – 1.1m, and high – 1.7m). Some conclusions are as follows:

The wind distribution fluctuated along room depth depending on the intervention of building means (openings, light wells, and voids). Over summer, occupants on the ground floor, parent bedroom, and studying room experienced more sufficient airspeeds averagely between 0.3-0.6m/s at three levels measured (Figure 8.25). Especially, the upper part of the human body sensed more pleasant air breezes than other levels with airspeeds over 0.6m/s, even up to 1.0 m/s. Wind distributions were relatively uniform within those rooms. On the open ground floor, despite greater room depth, the organisation of windward and leeward openings, along with a distinctive spatial geometry connected with voids and the staircase contributes to a more consistency airflow environment indoors. However, the larger inlet area than outlets caused a gradual decrease in air movement in further zones of the floor.

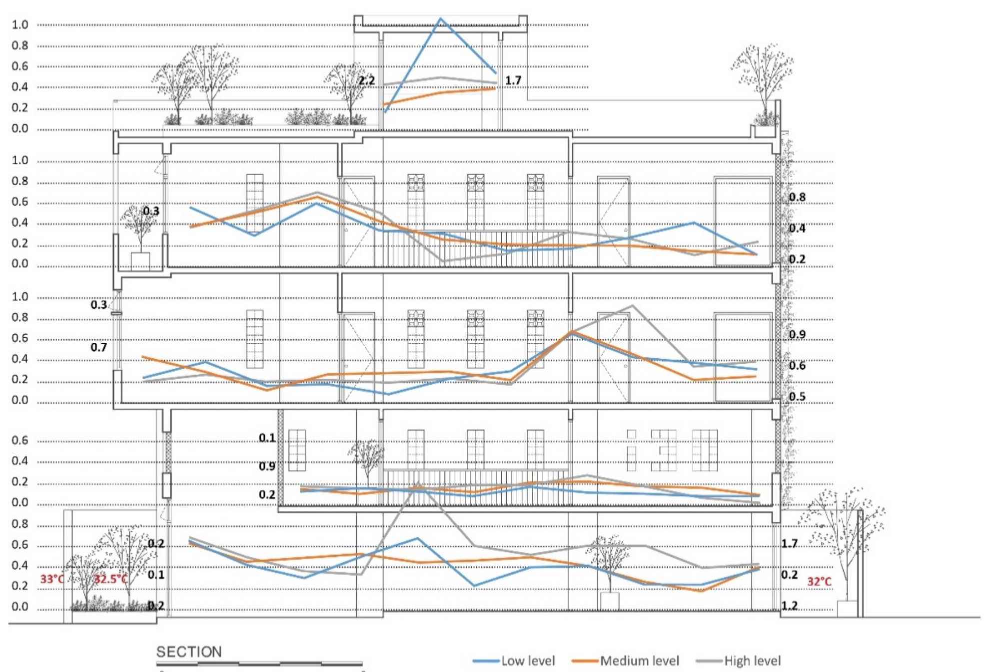


Figure 8.25 Distribution of indoor air movement in the hot season

Whereas, air movement was calmer in other rooms with vertical airspeeds under 0.2m/s at three heights of the human body that influenced occupant thermal satisfaction. Despite large openings in walls, inducement of natural wind into those spaces was negligible. Under changes in seasonal winds, airflow conditions were mostly lighter inside most rooms in the cool season with three airspeed lines fluctuating within 0-0.4m/s (Figure 8.26). Therefore, overall human comfort would be difficult to obtain.

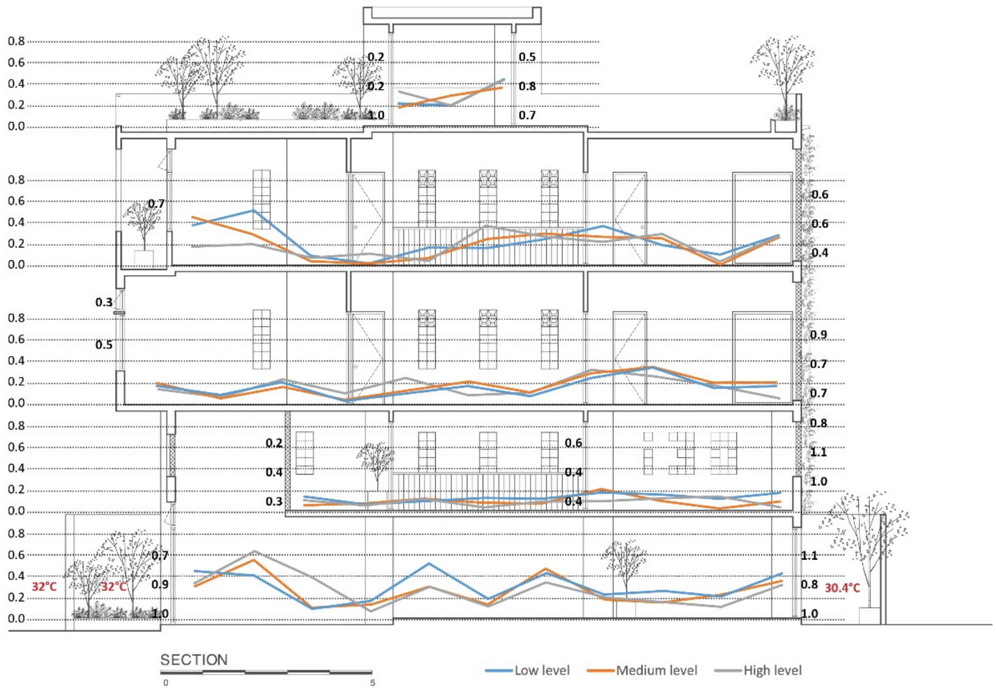


Figure 8.26 Distribution of indoor air movement in the cool season

Based on the line charts, the assessment may be imprecise because of no continuity of data collected by spot measurements. This can require other research methods by monitoring, wind tunnels, or numerical simulations.

Two velocity sensors were installed to understand longitudinal air movement in the living room and staircase. Wind data were recorded every 30 minutes. The major ventilation mechanism on the ground floor is the wind effect while the stack effect may operate within the staircase through light wells/voids. Using monitored data for analysis can reduce errors in research relative to cross-sectional surveys.

Table 8.7 presents a constant fluctuation of airflow in two spaces surveyed. All wind data are devised into three seasons. The presence of air movement in the staircase confirmed the effect of stack ventilation, even with higher velocities than in the living room. Airflow in the living room was assessed by maximum, mean, and minimum air velocities as follows: 0.7m/s, 0.11m/s, 0.03m/s in hot summer; 0.57m/s, 0.09m/s, 0.0m/s in mid-season; and 0.59m/s, 0.09m/s, and 0.05m/s in cool spring. Meanwhile, in the staircase, respective figures were 0.91m/s, 0.21m/s, and 0.04m/s between April and May; 1.27m/s, 0.18m/s, and 0.02m/s between June and October; 0.58m/s, 0.18m/s, and 0.04m/s between November and February. Although the mean airspeeds in two given environments were low in all three seasons, airflow conditions were more sufficient for comfort with higher velocities at certain times.

Table 8.7 Characteristics of air environment in the living room and courtyard by season

Seasons	Values	Living room	Staircase
Hot season (March, April, May)	Maximum	0.70	0.91
	Mean	0.11	0.21
	Minimum	0.03	0.04
	SD	0.09	0.12
Mid season (June, July, August, Sep., Oct.)	Maximum	0.57	1.27
	Mean	0.09	0.18
	Minimum	0.00	0.02
	SD	0.06	0.11
Cool season (Nov, Dec, Jan., Feb.)	Maximum	0.59	0.58
	Mean	0.09	0.18
	Minimum	0.05	0.04
	SD	0.06	0.08

Table 8.8 groups air velocities into variations according to recommendations of ASHRAE Standard 55 (ASHRAE, 2013a) and subjective reactions against air movement found by (Szokolay S. V., 1997). 0.2m/s is the limit of draught discomfort suggested by ASHRAE in air-controlled buildings; airspeeds under 0.25m/s are unnoticed; 0.25-0.5m/s is pleasant; 0.5–1m/s is awareness of air movement; draughty may be possible when airflow is above 1.0m/s. Among variations, referring to TCVN 306:2004, the range of comfortable air movement in dwellings in Vietnam is 0.5-1m/s, even acceptability at 1.5m/s in hot climatic conditions (MOC, 2004).

Table 8.8 Airflows in the living room and staircase assessed by Szokolay scale (1997) and Table 7.1

Room	Szokolay scale (Szokolay, 1997)				
	V < 0.2 (draught limit by ASHRAE)	**0.2 ≤ V < 0.25 (unnoticed)**	**0.25 ≤ V ≤ 0.5 (pleasant)**	**0.5 < V ≤ 1.0 (awareness)**	**V > 1.0 (draughty)**
Living room	89.1%	6.0%	4.8%	0.2%	0%
Staircase	54.2%	21.6%	23.1%	1.1%	0.01%
	Air movement acceptability (shown in Table 7.1)				
	V < 0.2	**0.2 ≤ V < 0.4 (25.5 - <27°C)**	**0.4 ≤ V ≤ 0.55 (27 - 31.5°C)**		**V > 0.55**
Living room	89.1%	10.0%	0.8%		0.1%
Staircase	54.2%	40.9%	4.3%		0.6%

Airspeeds monitored over the year indicate that most values were below 0.25m/s corresponding to unnoticed sensations in the living room (95%) and in the staircase (76%). Wind environments were more acceptable for inhabitants into the staircase with 23% of air velocities in the range of 0.25-0.5m/s compared to 5% in the living room. Within the staircase, 1% of wind data fell into the comfort zone (0.5-1m/s). Few airspeeds were over 1.0m/s in those spaces.

The current airspeed data are evaluated by the air movement and thermal acceptability for 80% occupants discovered in Chapter 6 and 7. In the living room, people experienced 10% of hours in comfortable environments constituted by airflows of 0.2-<0.4m/s and temperatures of 25.5-<27°C. For acceptable temperatures within 27-31.5°C, the corresponding acceptable air velocities (0.4-0.55m/s) were 0.8%. The more satisfactory condition of airflow was found in the staircase with 41% and 4.3% of airspeeds ranged between 0.2-<0.4m/s and 0.4-0.55m/s, respectively. Furthermore, 0.6% of wind velocities were more than 0.55m/s that could provide sufficient airflow for occupant warm tolerance.

Compare to stronger wind environments outdoors, indoor airflow conditions were calm over the year. The availability of passive cooling strategies partly provided the positive effect of natural ventilation on thermal environments and human comfort in the building. Some spaces were ventilated by sufficient airspeeds at certain times of the day and year, for example, in spaces of the ground floor, the studying room, and the master bedroom. However, overall airflow patterns in most rooms showed inadequacy to restore thermal satisfaction of occupants in prevailing warm conditions because of a larger percentage of air velocities lower than 0.4m/s. That implicated the frequent use of fans to cool the body. Therefore, the effect of building design including opening features should also be reviewed.

8.2.1.3 Discussions

Table 8.9 summarises the spatial and opening configurations of rooms influencing thermal and wind performances in rooms. Basic characteristics include dimension, volume, floor and wall area, the area of inlets and outlets, and the opening ratio. Some discussions are as follows:

- The planning and architectural regulations of row houses in areas of pattern type 1 partly bring advantages to organise openings on different facades of a building, which regulates indoor microclimates by catching seasonal winds from different directions over the year. For example, in the house A2, all rooms are open toward south or north through openings in external walls. Among them, the rooms orientated south take more advantages of the southeast to southwest prevailing winds with stronger velocities.

- The effect of cross-ventilation remains if room depth is five times less than room height (Rennie & Parand, 1998). Considering the present case, the distance between opposite walls satisfies the recommendation to drive air movement within most rooms. However, the real airflow inside most spaces was inadequate across much of the year. The result can be explained by the influence of other factors related to opening configuration and fenestration.

In rooms, the ground floor is an interesting case when designed as an open plan with large openings in windward and leeward walls. Although the ratio of length to height is above five, the distinctive spatial geometry of that whole space with a connect to voids at parking and living room and the staircase results in a more complicated distribution of airflow with higher air velocities within the space.

Table 8.9 Physical characteristics of rooms in the house A2

Parameters	Zones						
	2+3+4 (Living room, kitchen, parking)	**6 (Working room 1)**	**7 (Working room 2)**	**8 (Childern bedroom)**	**10 (Parents'bed room)**	**11 (Studying room)**	**12 (Guests' bedroom)**
Orientation	South & North		North	South	North	South	North
Floor dimensions	5.6x14.7x2.4	5.6x2.35x2.35	5.75x4.93x2.35		3.45x4.93x3		3.45x4.93x3
Volume (m³)	234.5	30.9	66.2	80.1	51	66.8	51
Floor area (m²)	82.3	23.2	28.2	26.7	17	22.25	17
Wall area (m²)	102.5	37.4	50.3	72.8	52.8	64.9	52.8
Exterior wall area (m²)	28.3		13.5	12.75	10.9	17.04	10.4
Total of exterior OA (m²)	15.6		3.2	5.5	4.5	8.2	4.5
Inlet area (m²)	13.8	6.2	3.2	3.0	4.5	4.4	4.5
Outlet area (m²)	2.0	3.8	4.6	1.8	1.8	1.8	1.8
Ratio of inlet to outlet area	6.9	1.6	0.7	1.7	2.4	2.4	2.4
Total of EOA (m²)	15.7	9.9	7.8	4.9	6.3	6.2	6.3
Ratio of effective opening to windward wall area (%)	49%	47%	24%	24%	41%	26%	43%
Ratio of effective opening to leeward wall area (%)	15%	29%	34%	17%	17%	17%	17%
Ratio of effective opening to exterior wall area (%) (EOWR)	49%		24%	24%	41%	26%	43%
Ratio of effective opening to floor area (%) (EOFR)	19%	43%	28%	18%	37%	28%	37%
Ratio of outdoor opening to exterior wall area (%) (OWR)	55%		24%	43%	41%	48%	43%

- In the initial design phase, an appropriate ratio of opening to floor area (EOFR) can be effective in air movement in the room/building. According to ASHRAE 55 and TCVN 5687:2010, that ratio should be more than 4% for minimal ventilation (ASHRAE, 2004; NUCE, 2010), additionally, a range of 20-30% EOFR suggested for creating the ventilation efficiency (Givoni B. , 1976; Chand, 1976). In Table 8.9, the EOFR of rooms surveyed is between 18-43%. Three zones (2+3+4, 7, and 11) have a ratio between 20-30% that may result in beneficial wind environments. However, in reality, airflow was low in zone 7 because of the disadvantageous room orientation in respect of incident wind directions. That result was similar to zone 6 despite the largest EOFR (43%). Two zones 11 and 12 with a greater EOFR than 30% were ventilated by more sufficient airspeeds. However, larger openings can cause thermal discomfort by heat gain; thereby, the control of solar access is considered by a combination of ventilation bricks and creeping plants.

- Another concern is the effective opening to exterior wall ratio (EOWR) that influences air movement in living spaces. Reviewing previous studies, the ratio recommended is between 30-50% (Givoni B. , 1976; Chand, 1976). The building has the main façade in the south and another in the north. Excepting the working room 1 with no external walls, in other rooms, the ratio of spaces (2+3+4, 10, and 12) is in the limits, which means more sufficient air movement found during the surveys.

- The similarity between EWOR and OWR indicates the occupant preference for natural ventilation through the maximum of the operable area of openings, for example, in zones 2+3+4, 7, 10 & 12. Whereas, in the children bedroom and studying room, the total area of openings almost doubles the operable area. A greater OWR value can cause overheating by solar access from the south between October and February. Thus, horizontal shading devices are added to reduce the impact. Analysing the building fabric, the shading designs are different in such rooms.

• The wind effect is applied in most spaces of the building through the availability of openings in opposite walls. The inlet to outlet ratio significantly intervenes the velocity of air paths within a space (Tang, Viet, & Nguyen, 2007). In most spaces examined, that ratio ranges from 1.7 to 6.9, which means the larger area of windward openings than the area of leeward openings. Therefore, indoor air velocities significantly reduced after outdoor winds blow through inlets.

8.2.2 Case study 2 (B3)

8.2.2.1 Description

a. Urban context

The building B3 is located in a busy commercial residential neighbourhood. Due to the potential location for business, most households have used lower floors for renting or opening self-business. The urban structure of the settlement is type 3 represented by the rows of new shop-houses regularly planned with a high density and back-to-back pattern. Unlike row houses in pattern type 1, shop-house dwellings in pattern type 3 are close to main streets to facilitate business, and subsequently having no front and back gardens (Figure 8.27-28). Considering planning regulations for urban shop-houses along commercial streets, the building coverage allows a maximum of 100%; and the building height can reach up to 5 floors.

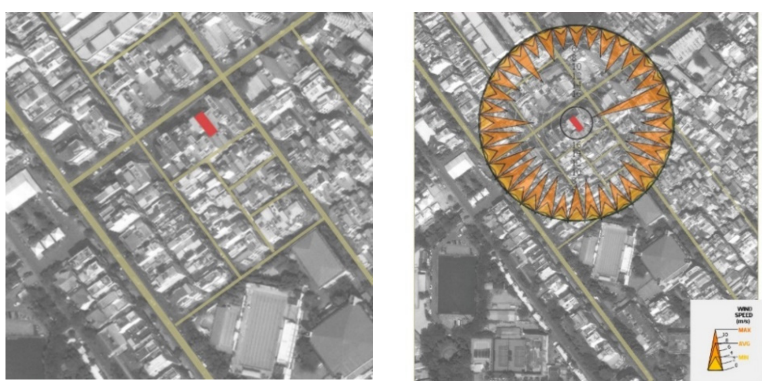


Figure 8.27 The urban context of the house B3

The building is open toward the only orientation of northwest while other sides are obstructed by neighbours (Figure 8.27). Thereby, the building environment usually communicates the surroundings on the northwest façade and rooftop. The meteorological data show that the incident wind to the building is majorly from minor direction (north) with an average velocity of 2m/s (IBST, 2009). The wind is more consistent in the dry season (November to February).

Figure 8.28 Surrounding environment of the house B3

Additionally, the sun is usually behind or over the building during the morning hours while the intense solar impact operates in the late afternoon. That requires protection against external heat gain. The coupled disadvantages of outdoor climate and urban planning conditions can result in restrictions to provide thermal satisfactory environments inside the building, especially air movement. Consequently, passive cooling strategies should be applied in careful considerations.

b. Architecture

The housing type of B3 is the new street shop-house. In comparison with row houses as the A2, the land size of the B3 is smaller with a dimension of 4 by 17m and the construction density gets 100%. The five-story building has a simple spatial layout indoors.

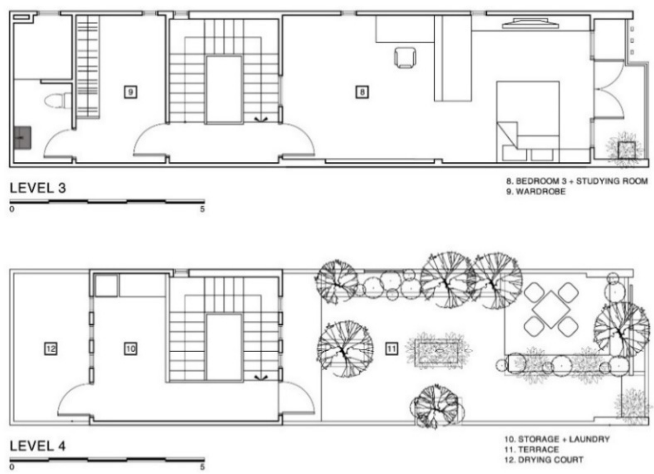


Figure 8.29 Floor plans and placements of instruments (red dots)

The whole ground floor is used for a shop and parking while occupants are living on the upper floors. The living room, kitchen, and parent bedroom are positioned on level 1. Levels 2 & 3 contain children bedrooms, wardrobes, and bathrooms. Due to a common planning feature of settlements of pattern type 3 (residences have the only façade), the bedrooms are prior to be open outside to absorb daylight and winds while other rooms are at the back with poorer environmental conditions. The laundry and drying courts are organised on the top floor, along with a nice terrace, which is a green social space for whole families. The roof garden may be effective to prevent the absorption of solar radiation from the top – see Figure 8.29-30. The spatial design in the B3 is quite popular in most 'new shop-houses' built in commercial areas in HCMC in the early 2000s. Real conditions of the building are described more in Figure 8.31.

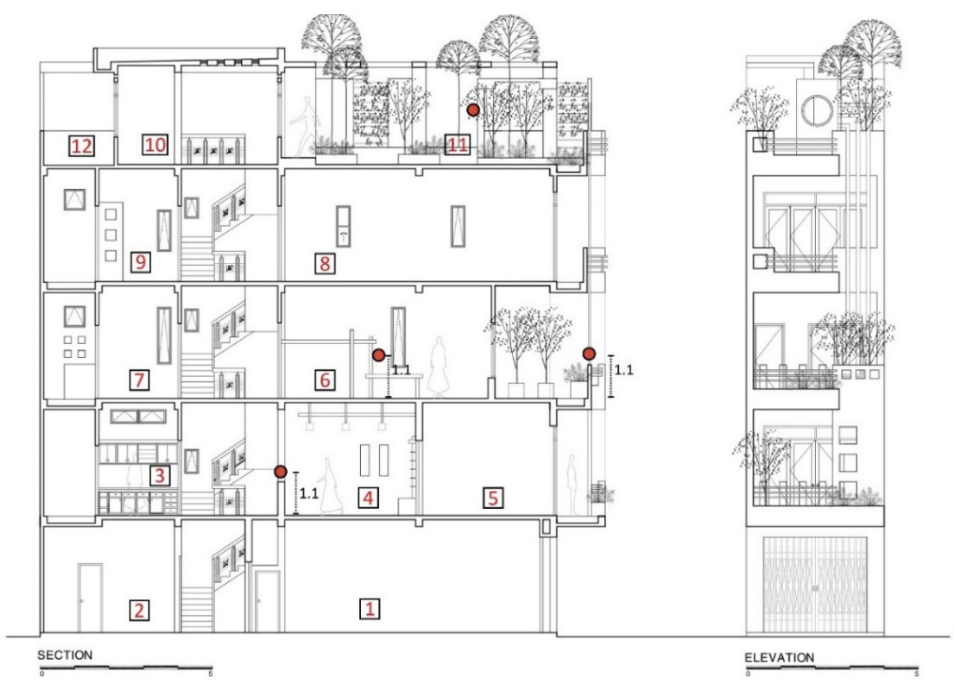


Figure 8.30 Section and elevation of the house

HOBO loggers were installed at a height of 1.1m above the floor in bedroom 2 (6) and living room (4) to collect temperature and humidity data over 11 months. Besides, a set of Netatmo instruments was also placed in the balcony of the third floor to record the outdoor climates (Figure 8.30).

Figure 8.31 Architecture and interior spaces around the house

c. *Environmental design strategies*

Alongside the distinctive regulations of urban planning in neighbourhoods of pattern type 3 mentioned above, great economic interests of the housing estate in commercial residential areas also affect the maximum construction of shop-house buildings commonly here in terms of land coverage and building height. That consequently restrains the application of passive design strategies for the building to provide comfortable microclimates for dwellers in the house. The building B3 is a typical example. It is difficult for architects to optimise living and commercial spaces and to improve indoor environments.

Glazed windows and doors are mainly maximised on the only building façade in the northwest, which bedrooms are attached to. Therefore, these rooms may be daylit and naturally ventilated more sufficiently than other deeper spaces of the building. Windows consist of fixed and casement types. Two main door types used are folding door and single door (Figure 8.32). To reduce the impact of sunlight around noon, full balconies on the main façade are available. However, it is likely that their effect is not significant to cut off the access of low west solar angles.

The house was built in 2005. Before renovation in lately 2017, due to the great building depth, to improve the airflow and luminous distribution in the living room, kitchen, and service spaces, awning and single-hung windows were installed in the southwest wall of the building. However, most of them were sealed later for the presence of the neighbour house. Consequently, the environmental performance in those rooms become worse by dull illuminance and stale air.

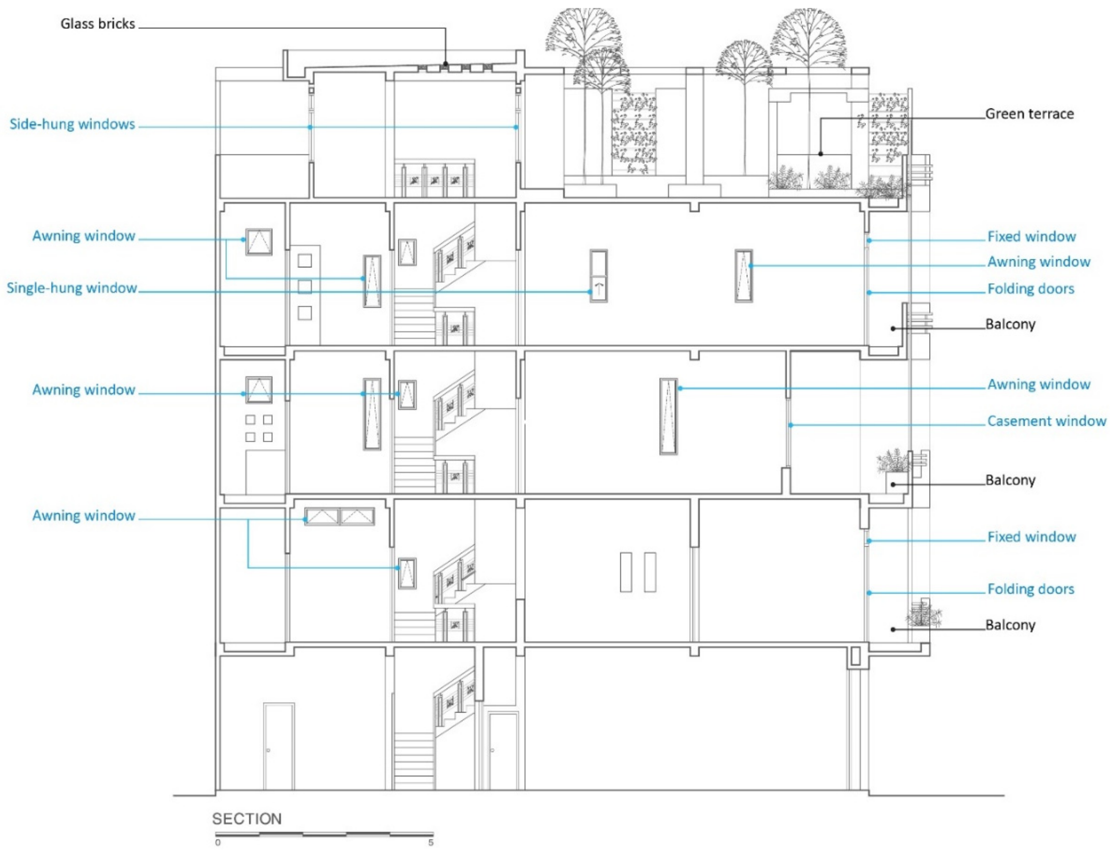


Figure 8.32 Building elements of climatic responsive design

All bedrooms are primarily ventilated and daylit at a single side. In bedrooms on level 1 and 3, four-panel folding doors almost occupies the whole external wall area. Additionally, above the doors, fixed windows are integrated to enlarge the area of full opening and enhance daylight access. Meanwhile, on level 2, the exterior bedroom wall is punctured by a glazed single door and double casement window.

During the daytime, internal room doors are usually open; therefore, airflows may cross within bedrooms. After moving through outlets in internal walls, they may rise into the staircase and escape through single-hung windows on the top floor. On the other hand, the principle of sing-sided ventilation is primary when the room doors are closed. Two scenarios of natural ventilation inside the building depending on the operation of room doors are presented in Figure 8.33-34.

The appearance of the staircase in the centre may be effective for ventilating and daylighting in the living room, kitchen, and other spaces, which openly connect to the staircase. In the staircase, glass bricks on the roof partly bring diffused sunlight for the staircase and lower spaces while the wall holes and side-hung windows positioned in external walls may encourage ventilation (Figure 8.32). However, the effect may be negligible because the large area of stair structure obstructs air movement vertically and therefore reduces the penetration of daylight to lower floors. Consequently, environmental conditions in the cooking and living rooms are usually opaque and stale during the day.

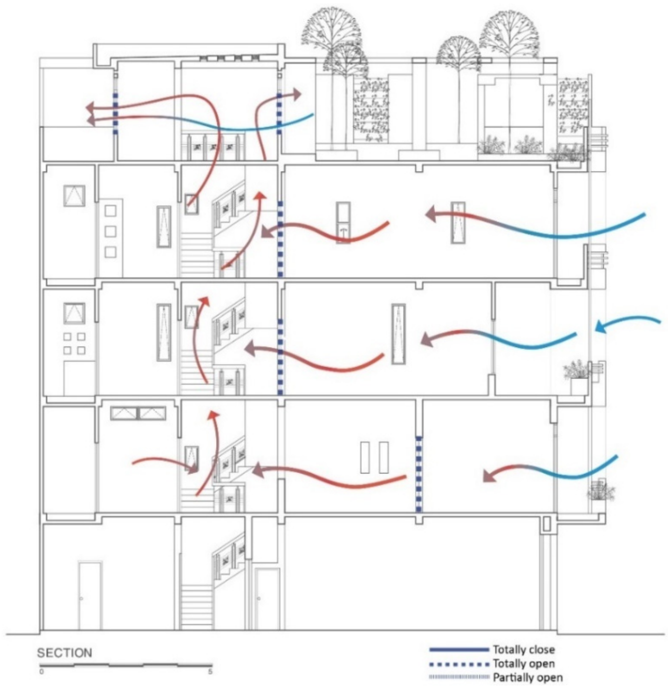


Figure 8.33 Operation of natural ventilation when room doors are open

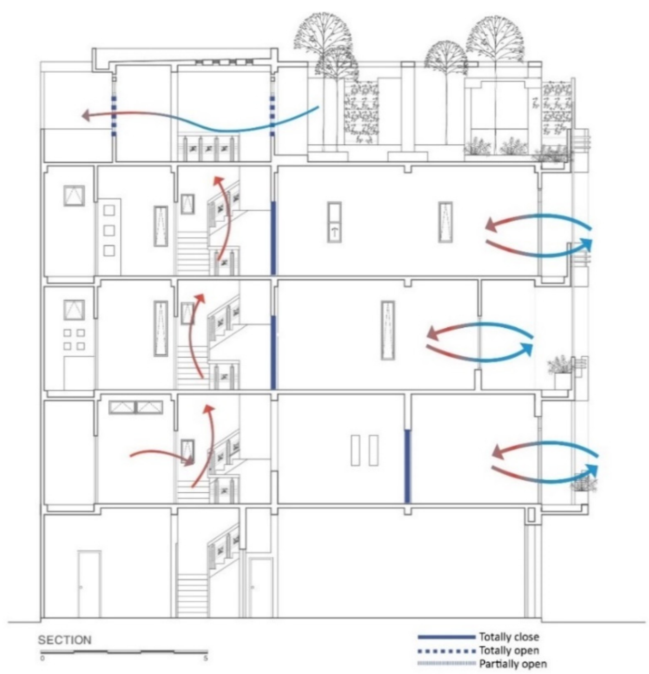


Figure 8.34 Operation of natural ventilation when room doors are closed

In two field studies, indoor environments performed dissatisfaction because of warmth, calm air movement, and darkness in many spaces of the building. It is certain that the available passive design solutions may not create indoor comfortable environments, subsequently causing the frequent use of mechanical cooling systems such as fans and air-conditioners. The next sections will present detailed analyses of indoor and outdoor climates through on-site measurements.

8.2.2.2 Outdoor climate

The climatic data around the house B3 were recorded by the Netatmo sensors and are grouped into three different periods: hot season – March to May, mid-season – June to October (mainly rainy season), and cool season – November to February (Table 8.10).

Table 8.10 Seasonal outdoor climatic characteristics

Seasons	Variables	Maximum	Mean	Minimum	SD
Hot season (March, April, May)	Air temp. (°C)	47.5	31.3	27.4	2.7
	RH (%)	100	77	42	10.7
	Air speed (m/s)	2.5	1.0	0.0	0.2
Mid season (June, July, August, Sep., Oct.)	Air temp. (°C)	40.8	29.6	25.4	2.1
	RH (%)	100	81	55	8.2
	Air speed (m/s)	9.0	1.3	0.0	0.7
Cool season (Nov, Dec, Jan., Feb.)	Air temp. (°C)	40.0	28.5	23.5	1.7
	RH (%)	100	78	50	7
	Air speed (m/s)	3.5	1.0	0.0	0.3

Mean air temperature decreased by 3°C across three seasons. The outdoor thermal climate was described by average air temperature of 31.3°C (SD 2.7) in hot months, 29.6°C (SD 2.1) in rainy months and 28.5°C (SD 1.7) in cool months. In summer, the climate was extremely hot for human tolerance when temperatures got a maximum at 47.5°C. That figure was 7°C warmer than it in other seasons. Meanwhile, the temperature dropped at the lowest point of 23.5°C in spring. The too hot or cool thermal pattern of external environments in summer or spring possibly influences human comfort in the house B3.

In HCMC, the heavy rainy months are commonly from June to October (IBST, 2009). Consequently, the mean and minimum relative humidities were higher – 81% (SD 8.2) and 55% over that period, respectively. Whereas, in the hottest months (March-May), the ambient environment was drier and widely fluctuated due to the effect of summer rainfalls at certain times.

In comparison with outdoor winds in the case A2, the wind around the house B3 was much lower. The mean air velocity in three seasons was more similar about 1m/s. Probably, low airflows were consistently static, evidently small SD figures in the whole year. In three seasons, the tropical rains in the mid-season caused more powerful outdoor winds, even reaching up to 9m/s.

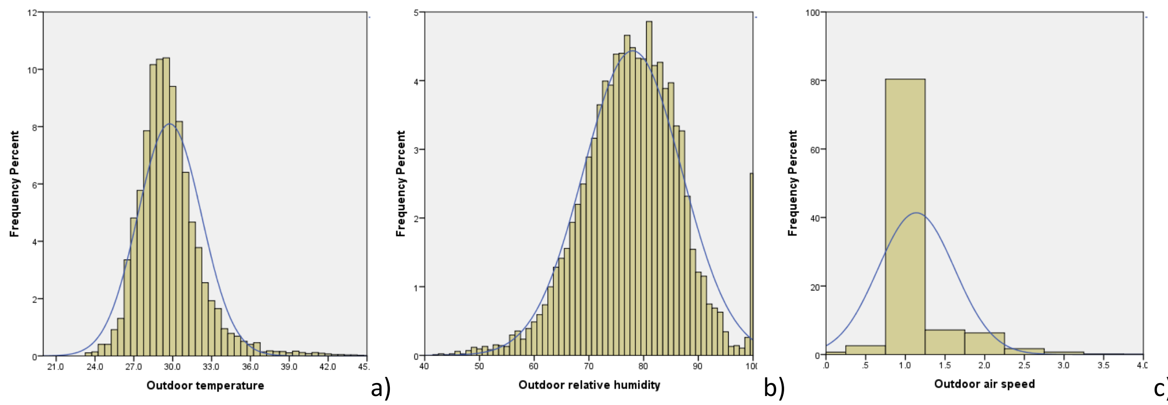


Figure 8.35 Distribution of hourly outdoor temperature (a), relative humidity (b), and airspeed (c) over the year

Figure 8.35 shows the distribution of outdoor environmental parameters over the monitoring period. The thermal and humidity distributions were normal with 17% of temperatures warmer than the threshold (31.5°C) and 40% of humidities greater than the maximum limit (80%) (NIA, 2004). Those conditions explained the identical characteristics of tropical climates.

Meanwhile, the pattern of outdoor winds was skewed toward rather low velocities. The compact building grouping form in blocks of pattern type 3 significantly restricts the power of wind flows. Furthermore, the building orientation on the northwest shows disadvantages to capture predominant winds that certainly operate from southeast to west. A larger number of airspeeds were around 1m/s across much of the year.

The climate surrounding the building overall performed few advantages to get pleasant microclimates and occupant comfort indoors for the influence of warm temperatures and high humidities. Meanwhile, the indoor air movement may be insufficient to restore occupant satisfaction under prevailing low wind environments observed outdoors.

8.2.2.3 Indoor thermal climate

a. Air temperature

Thermal environments inside the dwelling are analysed by distribution lines of temperatures cross-sectionally measured in summer 2017 and spring 2018 as shown in Figure 8.36. Both measuring times were similar at 3:00 pm. Between the two periods, the pattern of thermal climate in the building negligibly differed (0.5°C). The mean temperature was 30.7°C in summer and 30.2°C in spring.

Room temperatures ranged between 30.4-31°C in summer and between 29.6-30.9°C in spring. Those figures are assessed to be the 'slightly warm' acceptability. In addition, no thermal differences between rooms, particularly in hot months showed a warm consistency within the building. However, in spring, temperatures in the kitchen and living rooms were lower by 1°C than in bedrooms.

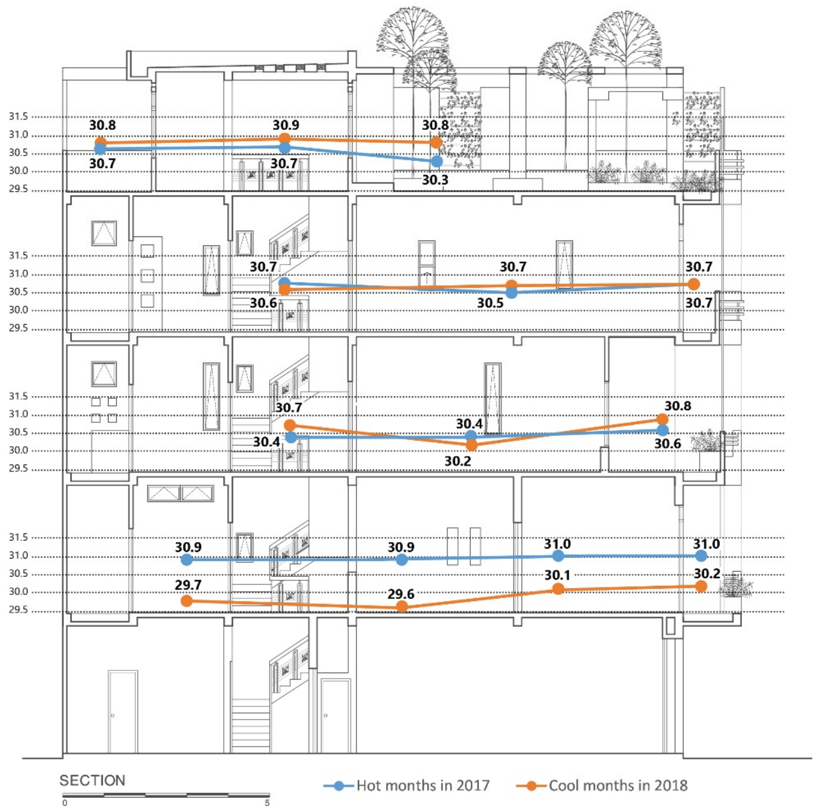


Figure 8.36 Air temperature distribution within the house in hot and cool months

Data loggers were installed to investigate longitudinal environmental distributions in the living room and bedroom (6). Figure 8.37 represents the pattern of daily mean air temperatures in those rooms in comparison with the outdoor climate for 11 months. There was a similarity between results deduced by snap-shot and long-term measurements.

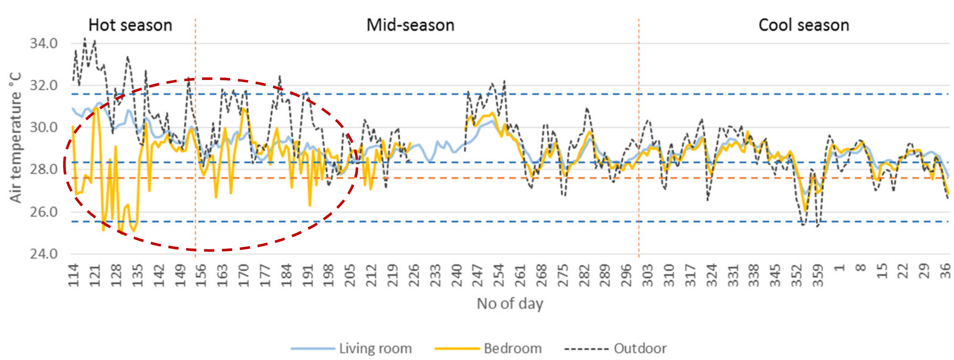


Figure 8.37 Distribution of daily mean indoor air temperature by season and room

The spatial connectivity between rooms and the outdoor climate results in variant environmental performances between two spaces surveyed. Both cooking/dining and living rooms are designed as an open space in the middle of the building without a connect from the outdoor for natural lighting and ventilating. Therefore, temperatures in those rooms were much cooler up to 3°C than external temperatures, particularly in hot periods – see the red circle in Figure 8.37. Meanwhile, the environment in the bedroom closely fluctuated to the external climate over the year.

Daily mean air temperatures in two rooms are within the limits of 25.5-31.5°C but mainly distributing the upper half of comfort one. Despite experiencing the warm comfortable condition in both living room and bedroom, occupant thermal sensations and adaptive behaviours varied in reality, particularly in hot months. Steep fluctuations of temperature pattern in the bedroom between 114th-212th dates interpreted occupant discomfort, and subsequently affecting their adaptation by switching on the air-conditioner to cool the room and restore their thermal satisfaction. Between October and February, the outdoor cooler climate influenced occupant thermal perceptions and their adaptive behaviours to retain comfort by using primarily natural ventilation and fans in the room.

Table 8.11 groups hourly temperatures recorded in the living room and bedroom into three seasonal periods. The thermal environment in two spaces was more similar and mostly acceptable for occupants referring to the limits of 25.5-31.5°C found in shop-houses, although slightly warmer climates were found in the bedroom. Hourly temperatures in the living room ranged from 26.5-31.5°C during three seasons. Less deviation of temperatures between seasons performed a higher consistency of thermal environment in the room. That consequence is partly for the environmental separation between the living room and the outdoor.

Table 8.11 Hourly indoor air temperature by room and season

Seasons	Values	Living room	Bedroom
Hot season (March, April, May)	Maximum	31.5	32
	Mean	30	28
	Minimum	29	19.5
	SD	0.6	2.8
Mid season (June, July, August, Sep., Oct.)	Maximum	31	32.5
	Mean	29	29
	Minimum	27.5	22.5
	SD	0.5	1.2
Cool season (Nov, Dec, Jan., Feb.)	Maximum	31	30
	Mean	28.5	28.5
	Minimum	26.5	25
	SD	0.6	0.8

In the bedroom, the minimum temperature dropped at 19.5°C in summer and 22.5°C in the mid-season relative to 29°C and 27.5°C respectively in the living room. The wide thermal difference confirmed the operation of air-conditioner in the bedroom over those periods. Besides, that explains that occupant thermal acceptability, preferences, and behaviours are different and subjective in a similar thermal condition between rooms.

Table 8.12 Percentage of uncomfortable and comfortable hours by room

Room type	T < 25.5	25.5 ≤ T < 27	27 ≤ T ≤ 30	30 < T ≤ 31.5	T > 31.5
Living room	0%	0.1%	91.2%	8.6%	0%
Bedroom	3.4%	2.5%	85%	6.5%	2.6%

Considering the comfort conditions for free-running shop-houses, 100% of temperatures recorded in the living room were within the acceptable range including 91.2% values between 27-30°C, which 90% occupants find acceptability (Table 8.12). Meanwhile, environments in the bedroom were less satisfactory due to the lower percentage of temperatures falling into the limits of 90% occupant acceptability, along with 6% of temperatures out of the acceptable zone. However, air-conditioning in the bedroom at certain times affected the real thermal performance; therefore, if considering the situation of entirely naturally ventilated room over the whole investigated period, a number of unacceptable hours might be more.

b. Relative humidity

Humid environments in two rooms surveyed positively fluctuated according to outdoor humidities (Figure 8.38). However, in the bedroom, the operation of air-conditioners between April and July affected the strange distribution of humidity. Thereby, RH values over that period were higher than in the living room, even the exterior environment. Meanwhile, the ambient environment in the living room tended to be drier than the outdoor. Ignoring air-conditioned periods in the bedroom, daily mean relative humidity inside two rooms varied between 65-85% in hot months and between 55-80% in cool months. Wider variations of outdoor climates in the cool season dramatically affected humidity fluctuation indoors.

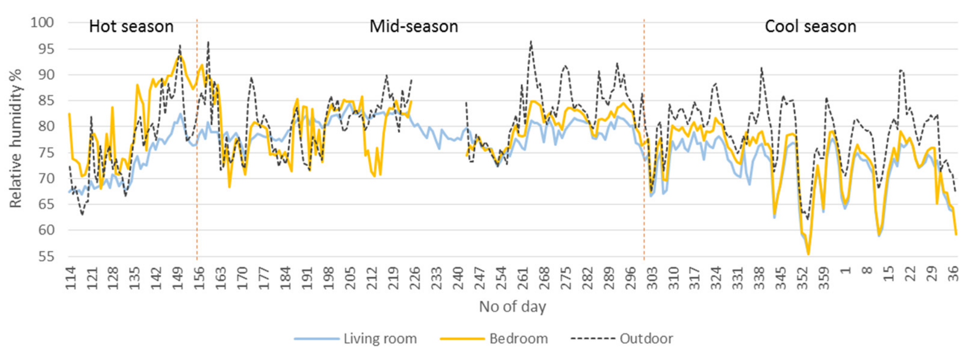


Figure 8.38 Distribution of daily mean indoor relative humidity over the year by room

Furthermore, the environmental disconnect between the living room and the urban climate also linked to greater differences in humidity between two environments compared to a closer correlation found in the bedroom.

The mean relative humidity in the living room was 72% (SD 5), 79% (SD 3.2), and 72% (SD 6) in the hot, mid, and cool seasons, respectively. Meanwhile, the following values were 80% (SD 9.5), 80% (SD

6.2), and 73% (SD 6.5) in the bedroom (Table 8.13). Referring to the maximum humidity limit of 80% in TCVN 9411:2012 regulated for shop-houses, the air in the bedroom conditioned by mixed-mode systems performed more humid with 40% of hourly RH data greater than that threshold. That issue requires an increase of airflow to improve natural ventilation and regulate air quality. Meanwhile, in the naturally ventilated living room, the percentage of unacceptable humidities were lower by 50%.

Table 8.13 Characteristics of hourly relative humidity by room and season

Seasons	Values	Living room	Bedroom
Hot season (March, April, May)	Maximum	84	95
	Mean	72	80
	Minimum	63	61
	SD	5.0	9.5
Mid season (June, July, August, Sep., Oct.)	Maximum	86	96
	Mean	79	80
	Minimum	59	53
	SD	3.2	6.2
Cool season (Nov, Dec, Jan., Feb.)	Maximum	82	84
	Mean	72	73
	Minimum	51	53
	SD	6.0	6.5

d. Airflow distribution

Air movement within the building was examined in the measuring condition, which all doors and windows were open. Gathering the outdoor climatic data from Netatmo sensors, the mean velocity of incident winds was 2.5m/s and 3.5m/s in the respective hot and cool seasons.

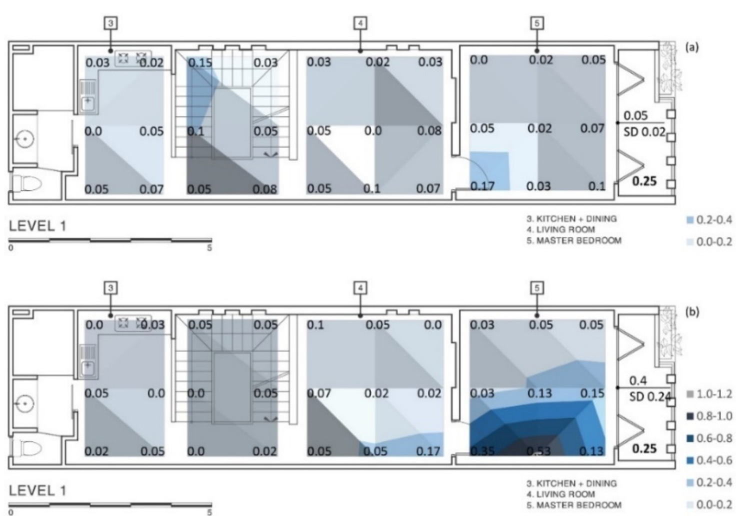


Figure 8.39 Air pattern on level 1 in hot (a) and cool (b) season

The above investigations of comfortable environments showed warm acceptable conditions in the building and high humidity in bedrooms with mixed-mode ventilation. Reviewing the acceptable air movement limits incorporated into thermal comfort found in Chapter 7, the minimum airspeed required is 0.45m/s to restore thermal acceptability for residents. However, the real airflow in most living spaces was much calm with air velocities below 0.25m/s, although all windows and doors were open during the surveys (Figure 8.39-42). Furthermore, the pattern of low airspeeds was uniform within rooms. Hence, under calm airflow conditions indoors, occupant thermal satisfaction might not remain, even when indoor temperatures were within the acceptable band.

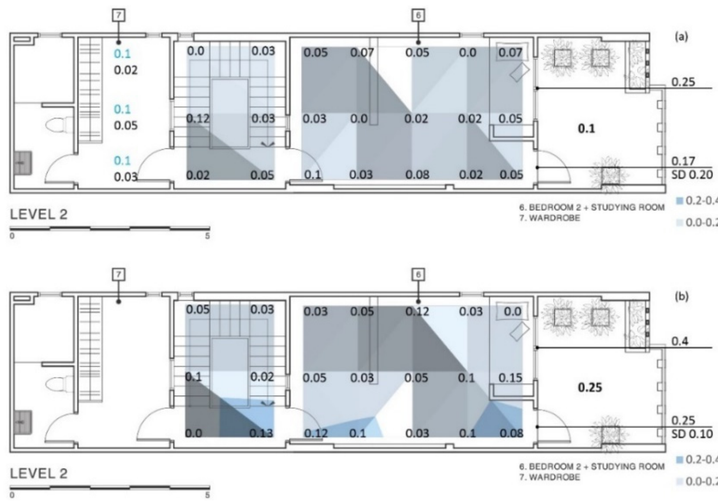


Figure 8.40 Air pattern on level 2 in hot (a) and cool (b) season

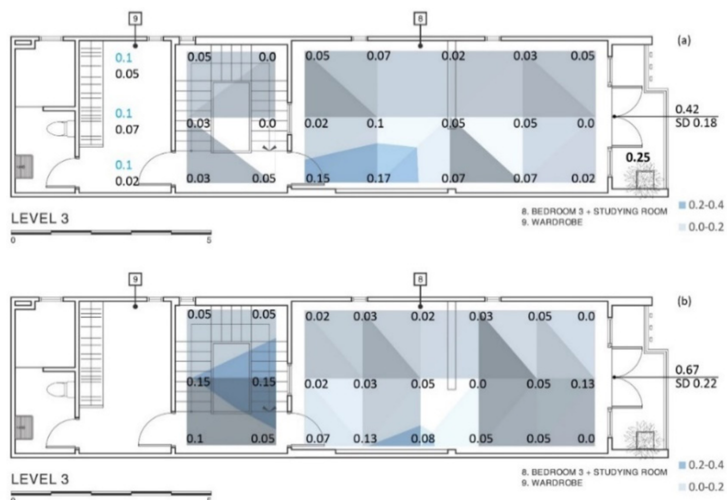


Figure 8.41 Air pattern on level 3 in hot (a) and cool (b) season

There are some explanations for low air movement in the building. Considering the building fabric, internal room doors act as outlets while glazed doors and windows on the main façade are inlets for outdoor incident winds. However, the building orientation of northwest does not receive advantages of predominant winds between southeast and southwest across much of the year while winds from north and northeast mainly operate between November and February with lower velocities. Besides, the nearly similarity of temperatures between interior spaces and between the indoor and outdoor caused a negligible pressure difference between inlets and outlets, and subsequently, airflow driven the space was weak. Furthermore, due to the limited planning factors, no openings are positioned in spaces behind bedrooms, which partly restricts the effect of airflow between the outdoor and the staircase. Another reason is the larger area of inlets to outlets reducing the velocity of airflow within the room. Taking those reasons together, the current spatial layout and opening design features are not beneficial to the natural ventilation efficiency in the building.

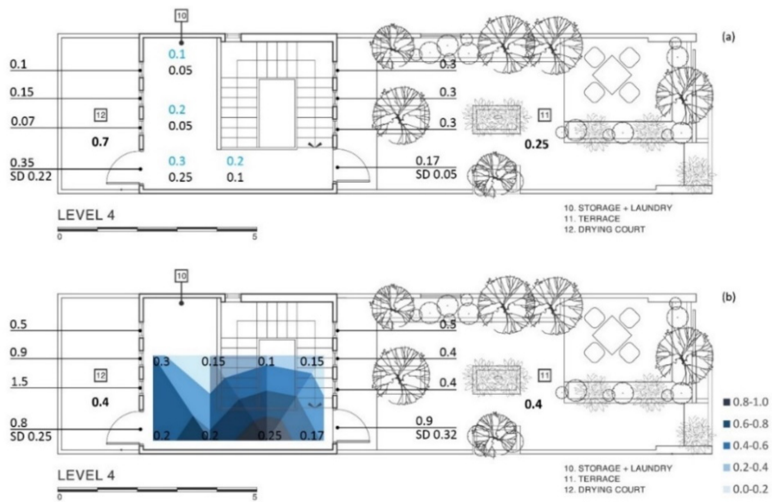


Figure 8.42 Air pattern on level 4 in hot (a) and cool (b) season

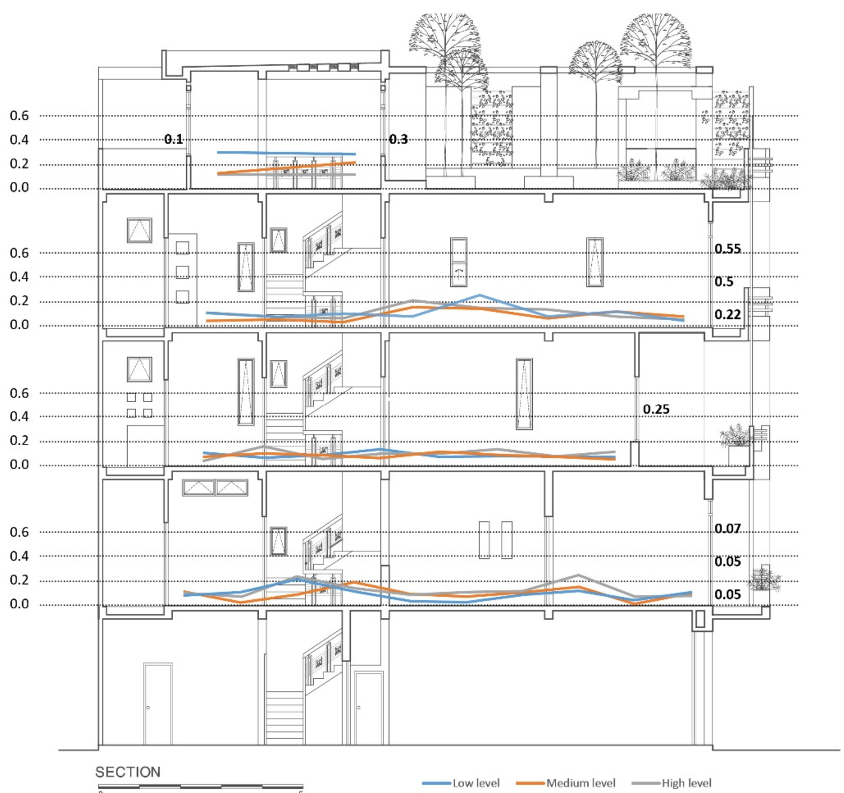


Figure 8.43 Distribution of indoor air movement in the hot season

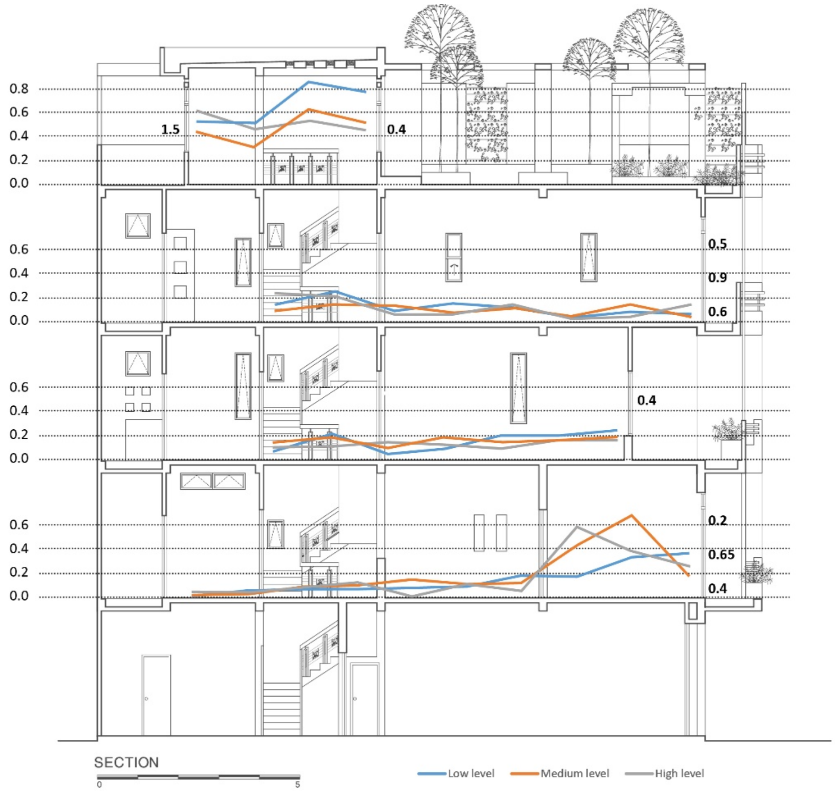


Figure 8.44 Distribution of indoor air movement in the cool season

Figures 8.43-44 present the sectional airflow pattern within the building at three different heights of the human body during two surveys. The distribution of air velocities in most rooms was lower than 0.2m/s at all three high levels above the floor in both seasons. Between two measuring periods, the indoor wind environment in the cool season showed more satisfactory, in particular, in bedrooms because of the effect of monsoon winds from north directions over that period. However, airflow was overall insufficient to restore human thermal neutrality throughout the whole year.

8.2.2.4 Discussions

In reality, the permitted largescale construction of urban shop-houses in high dense settlements of pattern type 3 potentially causes disadvantages to optimise passive design strategies; therefore, the building physics performs less effectively. For example, the building B3 has the main façade facing a busy commercial street. Daylighting and natural ventilation are likely applied at a single side through openings positioned on that façade. Consequently, the indoor thermal microclimate was unsatisfactory for inhabitants in most living spaces, even in bedrooms, which are open toward outside. Poor microclimatic conditions with low ventilation, warmth, and gloominess also cause another risk for human health, especially in the kitchen and living room with the poor air quality due to the still air and the stagnation of pollutants emitted when used.

Designers attempted to employ some passive design solutions to get the high environmental performance, such as integrating the light well + staircase, opening spaces behind bedrooms toward the staircase, optimising windward openings in external walls and windows in internal walls for encouraging ventilation and daylighting. However, their real effect is unexpected due to external contextual factors (urban conditions and outdoor climates) and the inappropriacy of embodied strategies.

As previously discussed, the living room and kitchen have no exterior walls and openings. Meanwhile, three bedrooms have doors and windows in the windward wall and room doors in the leeward wall. Table 8.14 indicates characteristics of spatial geometry and openings in those bedrooms. The area of exposed walls is similar (12.2m²) in all rooms while the floor area and volume of zone 8 are the largest – 30m² and 93m³, respectively.

Table 8.14 Opening characteristics of rooms 5, 6 & 8

Parameters	5 Parent bedroom	6 Children bedroom 1	8 Children bedroom 2
Orientation	Northwest		
Floor dimensions	3.8x3.8x3.2	3.8x6.1x3.2	3.8x7.9x3.2
Volume (m³)	46.2	74.2	96
Floor area (m²)	14.4	23.2	30
Exterior wall area (m²)	12.2	12.2	12.2
Total of exterior OA (m²)	7.8	4.5	7.8
Inlet area (m²)	6.1	4.1	3.2
Outlet area (m²)	1.8	1.9	2.0
Ratio of inlet to outlet area	3.4	2.1	1.5
Total of EOA (m²)	7.9	6.0	5.2
Ratio of effective opening to windward wall area (%)	50%	31%	26%
Ratio of effective opening to leeward wall area (%)	15%	16%	17%
Ratio of effective opening to exterior wall area (%) (EOWR)	50%	33%	26%
Ratio of effective opening to floor area (%) (EOFR)	55%	26%	17%
Ratio of outdoor opening to exterior wall area (%) (OWR)	64%	37%	64%

Due to the building orientation, the building potentially receives sunlight from the west in the late afternoon in warm months and winds from north-northeast in the cool season. Trimarianto (2003) suggested that the glass area in east or west walls should be a maximum of 30% to avoid heat gain indoors. Whereas, the OWR index in all three zones studied is greater than that limit. The larger area of openings in the exterior wall (64%) in rooms 5 and 8 is advantageous for the access of natural light and winds. However, that is also the issue of overheating risk if shading designs are inappropriate. In reality, although the full balcony is attached in every room, it shows low efficiency to prevent sunlight with low angles around noon. When building controls are not effective to retain comfort, most doors and windows are usually closed for operating air-conditioners, particularly during the afternoon in hot months.

Chand and Givoni (1976) recommended two indices for getting satisfactory microclimatic conditions in rooms including the ratio of effective opening to exposed wall area (EOWR) between 30-50% and the ratio of free opening to floor area (EOFR) between 20-30%. In three bedrooms, the EOWR and EOFR in room 8 are lower than the limits, which may explain calm air movement. Meanwhile, the value of those parameters meets the suggestions of Chand and Givoni in bedrooms 5 and 6. Although airflow in those rooms was higher than in bedroom 8, the overall performance was insufficient for occupant acceptability. That consequence possibly results from a large deviation between inlets and outlets. Thus, the wind effect is negligible. Another reason is the calmer winds from the north-northeast, additionally, they can be obstructed partly before hitting the building for urban conditions surrounding.

8.2.3 Case study 3 (C5)

8.2.3.1 Description

a. Urban context

The building C5 is planned in a residential neighbourhood of pattern type 4, which is designed informally with an irregular road and building pattern and much high density. Approaching houses in the area is by an interlace system of multi-wide alleys (Figure 8.45). Unlike shop-house dwellings in regular residential areas, physical and architectural features of all buildings are heterogeneous in pattern type 4.

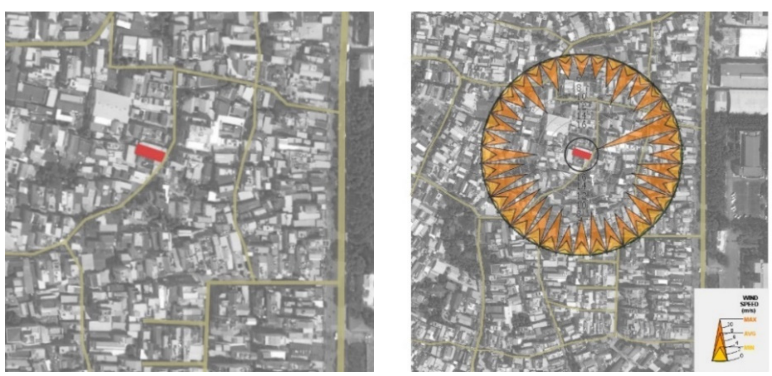


Figure 8.45 Site conditions around the building C5

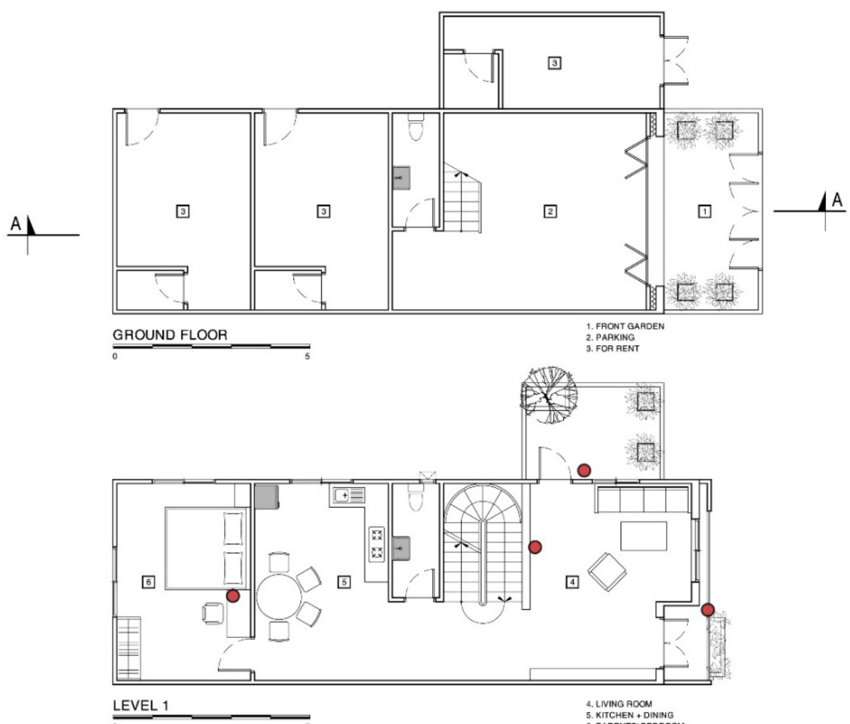
The building mainly faces east; therefore, it may catch winds from southeast-south between March-May. On the ground floor, the building is surrounded by neighbour constructions and subsequently only opens toward the east. However, on the upper floors, the building can be open in three directions (east, west, and north). Thereby, predominant winds from west-southwest and north-northeast can also hit the building around the year. However, for the western direction, overheating risks around noon is potential that affects thermal comfort indoors.

Figure 8.46 Urban context around the house C5

b. Architecture

The building type of C5 is ‘new shop-house’ with the dimensions of 5.2m(W) x 14m(L). The whole building contains three stories and a rooftop (Figure 8.47). Excepting the main usage of housing, owners are using rooms on the ground floor for renting. Three shelters for rent have private access. For the priority of most floor area for business, the remaining smaller area of the main house is used for parking and a garden.

The living room, kitchen + dining room, and parent bedroom are positioned on level 1 while three bedrooms for children and guests are on level 2. Most living spaces on those floors are open toward the outside for absorbing natural light and winds. The cooking + dining room and bedroom 8 have an exposed wall on the north while other suites exchange with the outdoor climate on two different orientations: the living room and bedroom 7 (east and north) and bedrooms 6 and 9 (north and west).



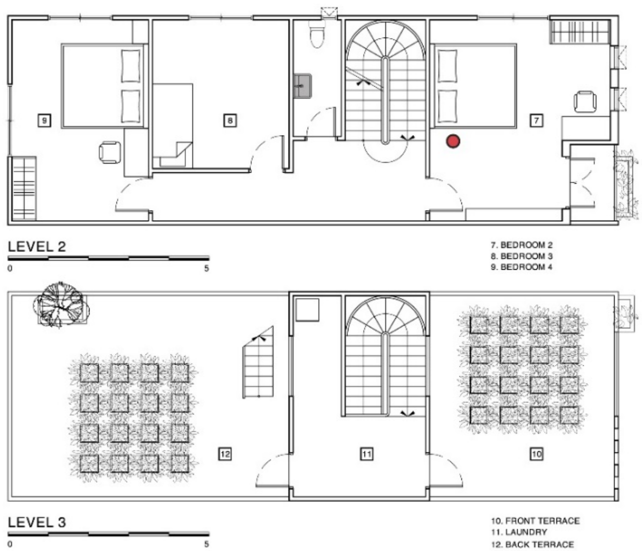


Figure 8.47 Floor plans and placements of instruments (red dots)

The whole space for living, cooking, and dining on level 1 is designed as an open plan to encourage the environmental exchange between the indoor and outdoor. Furthermore, the living room has a green terrace with decorative bushes and water, which is reused from the roof of the lower renting house. Alike most shop-houses in Vietnam, the staircase is positioned in the centre of the building to connect other spaces together. On the rooftop, the whole area is used for growing orchid gardens. A small area close to the staircase on level 3 is for residents to wash and dry their clothes.

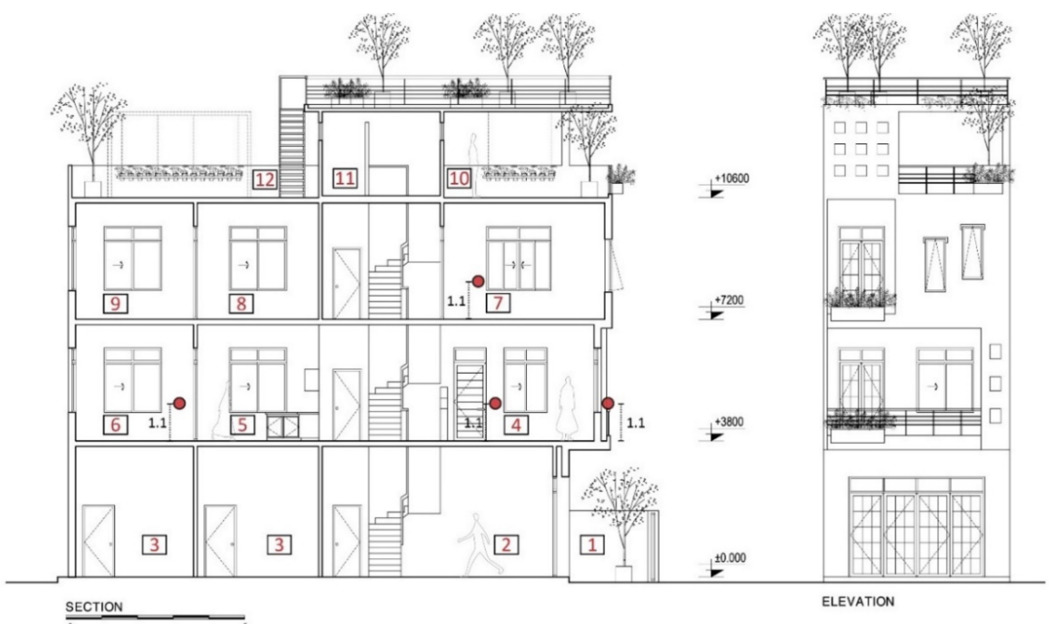


Figure 8.48 Building section and elevation

The photos below show the interior and exterior conditions of the building during visits (Figure 8.49). There were two HOBO loggers and a set of Netatmo equipment installed at the height of 1.1m above the floor in the living room, parent bedroom, and children bedroom to collect indoor environmental data – see Figure 8.47-48. Meanwhile, another Netatmo set was positioned in the outdoor for recording surrounding climates between April 2017 and February 2018. The instrument measuring temperature and humidity was installed on the north building side while the wind meter was on the main façade.

Figure 8.49 Architecture and interior spaces of the house

c. Environmental design strategies

Most interior spaces are naturally daylit and ventilated across much of the year by a glazed window and door system designed in west, north, and east building elevations. In external walls, there are primarily three door types: a 4-panel folding door used for the main entrance door on the ground floor; double and single doors installed on the upper floors. The external doors are formed from the glass panel assembled in steel door frames. In internal walls, single-hinged glazed doors with aluminium stiles and rails are utilised. The structure of interior and exterior doors similarly has two parts: the lower part is movable door leaves of 2.4m high and the upper part is fixed windows of 0.4m high (Figure 8.48).

Apart from doors, sliding windows are used in all rooms. The composition of windows also includes two parts: upper fixed panels and lower sliding panels (Figure 8.50). With the advantage of three elevations, most rooms connect to the surroundings through at least one window. In bedroom 7, two awning windows on the main facade were blocked for replacement of a wardrobe after the renovation in 2018 (Figure 8.49).

Besides the intervention of physical building, orchid gardens on the rooftop can be effective to reduce the solar energy transferred from the roof to lower spaces (Figure 8.50). Moreover, the long rectangular holes positioned at the high level of walls around the staircase not only provide daylight for the interior but play a role of outlets for ventilation.

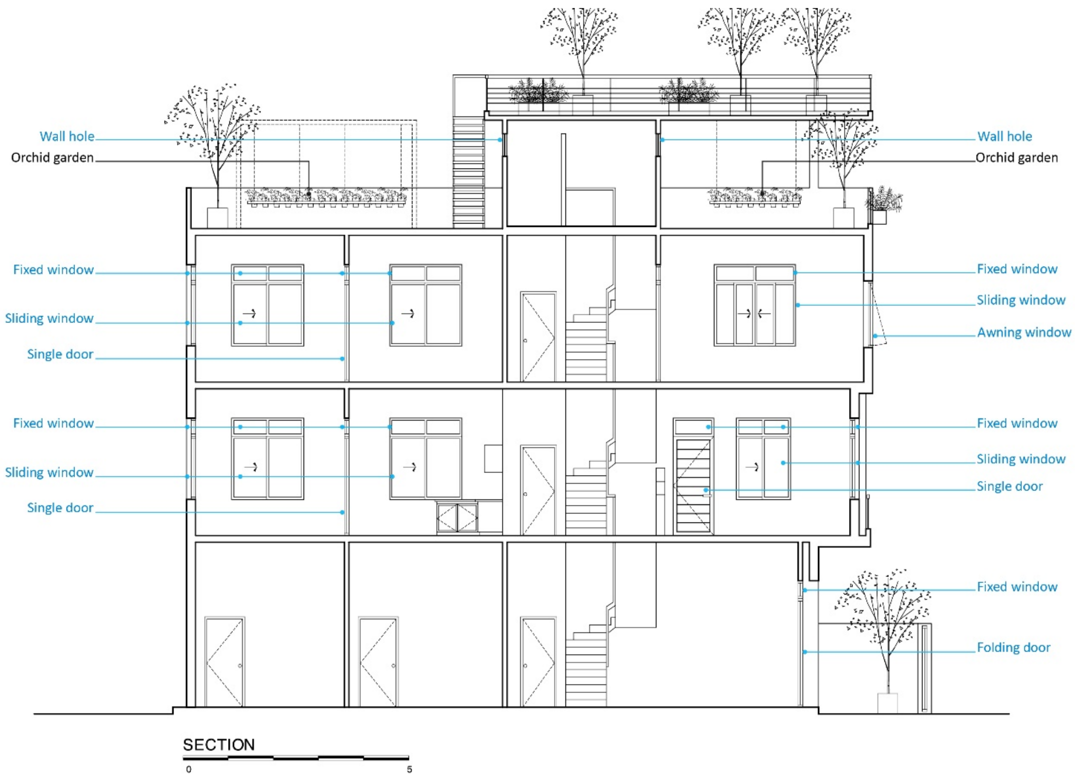


Figure 8.50 Building elements for passive designs used in the house

In each room, the availability of openings in opposite walls is potential to encourage air movement crossing the space (Figure 8.51). Occupants prefer to use natural winds for cooling and getting thermal satisfaction because of their delight and health, and energy savings for the building. Consequently, during the day, all doors and windows are open. Meanwhile, during the night-time, windows are usually open for wind permeability in bedrooms. Windows are designed with double layers - the outer glazing sash and the inner steel frame; thereby, they satisfy two aims of security and ventilation.

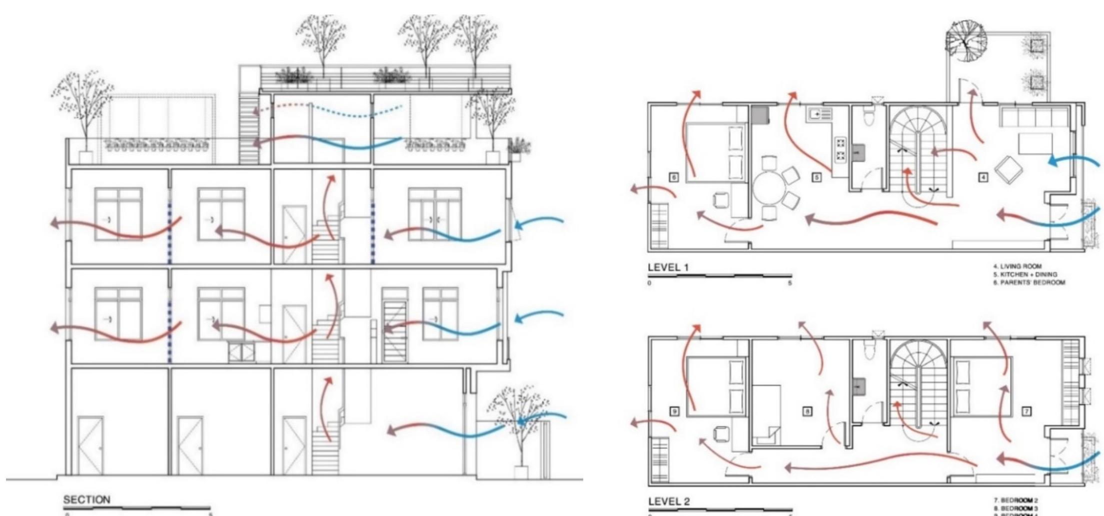


Figure 8.51 Cross-ventilation operated in the house

The main principle of natural ventilation in the building is cross-ventilation. Figures 8.51 presents the wind pattern within the house under the effect of outdoor winds from east-southeast. However, the role of opening inlets and outlets will be shifted if the direction of incident winds changes. When outdoor winds hit the windward openings, airflow paths within spaces are present between inlets and outlets.

8.2.3.2 Outdoor climate

The climate surrounding the building was investigated by environmental sensors for 11 months. The range of outdoor temperatures widely changed from 21.4 to 40.3°C (Table 8.15).

Table 8.15 Outdoor climatic characteristics over the year

Seasons	Variables	Maximum	Mean	Minimum	SD
Hot season (March, April, May)	Air temp. (°C)	40.3	30.6	25.2	3.1
	RH (%)	93	73	40	11.3
	Air speed (m/s)	18.0	1.8	0.0	2.5
Mid season (June, July, August, Sep., Oct.)	Air temp. (°C)	38.9	29.5	24.3	3.1
	RH (%)	100	80	48	10.4
	Air speed (m/s)	23.5	2.1	0.0	3.1
Cool season (Nov, Dec, Jan., Feb.)	Air temp. (°C)	35.1	28.1	21.4	2.7
	RH (%)	100	76	48	9.8
	Air speed (m/s)	21.5	2.9	0.0	3.8

The following outdoor temperature variation in the hot, cool and mid-season was 25.2-40.3°C; 24.3-38.9°C; and 21.4-35.1°C. The thermal environment in hot climates averaged at 30.6°C (SD 1.2) that was 1°C and 2.5°C warmer than the mean temperature between June-October and November-February, respectively. The urban contextual aspects (narrow spacing, irregular pattern, and dense construction coverage) affect overshadowing among buildings and subsequently partly reducing solar impacts on the urban environment. Therefore, the outdoor climate was not usually too hot, even in summer. That could bring benefits for the satisfaction of the indoor thermal condition.

As shown in Table 8.15, exterior humid environments fluctuated between 40-100%. The environment was wetter in the rainy and cool seasons. The average RH in hot months was 73% (SD 5.8) while the value was 80% (SD 5.4) in the mid-season and 76% (SD 6.2) in cool months. Discussing wind conditions surrounding the house in the east, air velocities were more powerful in the wet months with a wider range of 0.0-23.5m/s and extreme winds compared to the maximum value up to 7m/s recorded in other seasons. In three monitoring periods, the mean airspeed was the highest (3.0m/s, SD 1.5) between November and February while winds were the lowest with the average of 1.8m/s (SD 1.4) in the hottest months. The calmer wind flows in warmer climates of summer could impact indoor and outdoor comfort of residents.

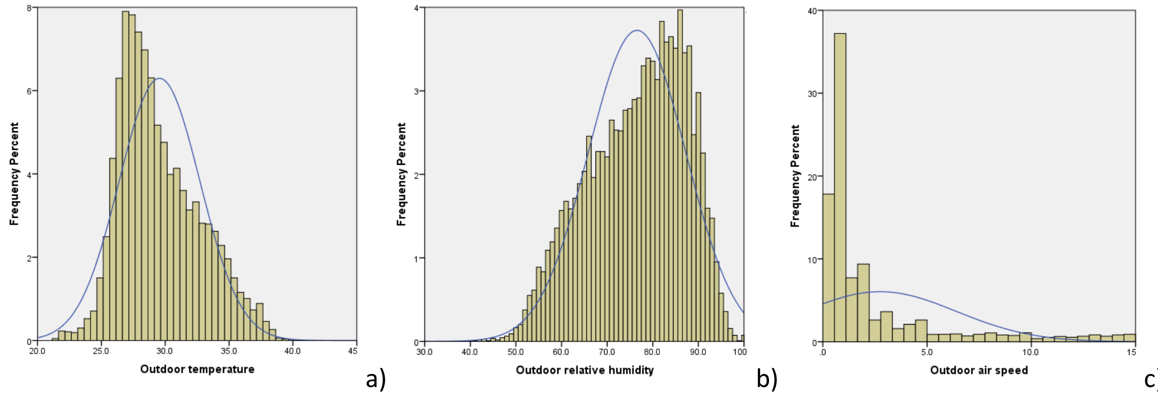


Figure 8.52 Distribution of hourly outdoor air temperature (a), relative humidity (b), and airspeed (c)

Three histograms in Figure 8.52 present the distribution of hourly air temperature, relative humidity, and air velocities over 310 days monitored. 25% of temperatures recorded were greater than the upper acceptable limit of 31.5°C. 42% of relative humidities were more than the maximum acceptable humidity level of 80% suggested in warm climates by the national standards (VIAP, 2012). High humidity in the air will require mitigation by sufficient wind flows. However, the real wind pattern outdoors is abnormal with a larger proportion of velocities below 2.0m/s (63%). The irregular urban spatial structure of type 4 settlements can be advantageous for decreasing the thermal pressure on urban microclimates but also be disadvantageous for outdoor wind environments when winds flow through the settlement due to the redirection and obstruction of incident winds.

8.2.3.3 Indoor thermal climate

a. Air temperature

The thermal environment in single rooms was examined by thermometers during two cross-sectional surveys. The author and observers firstly visited the building in 2016, and then carried out measurements at 10:00 am on 92nd date (April) in summer 2017 and at 12:00 pm on 6th date (January) in spring 2018. There was a slight difference in outdoor temperature by 0.5°C between two measurements: 31.5°C in summer and 32°C in spring.

Figure 8.53 represents the distribution of room temperatures in the building measured in two seasons. The difference in indoor thermal performance between two field studies was slight. Furthermore, the thermal condition was quite consistent between rooms. The building temperature averaged in summer was 0.4°C warmer. The greatest thermal discrepancy of approximate 1°C between the two measurements was found in spaces on level 1. The temperature in the living room, cooking + dining room, and parent bedroom was 30.7°C, 30.3°C, and 30.2°C in summer; and 29.7°C, 29.5°C, and 29.5°C in spring, respectively.

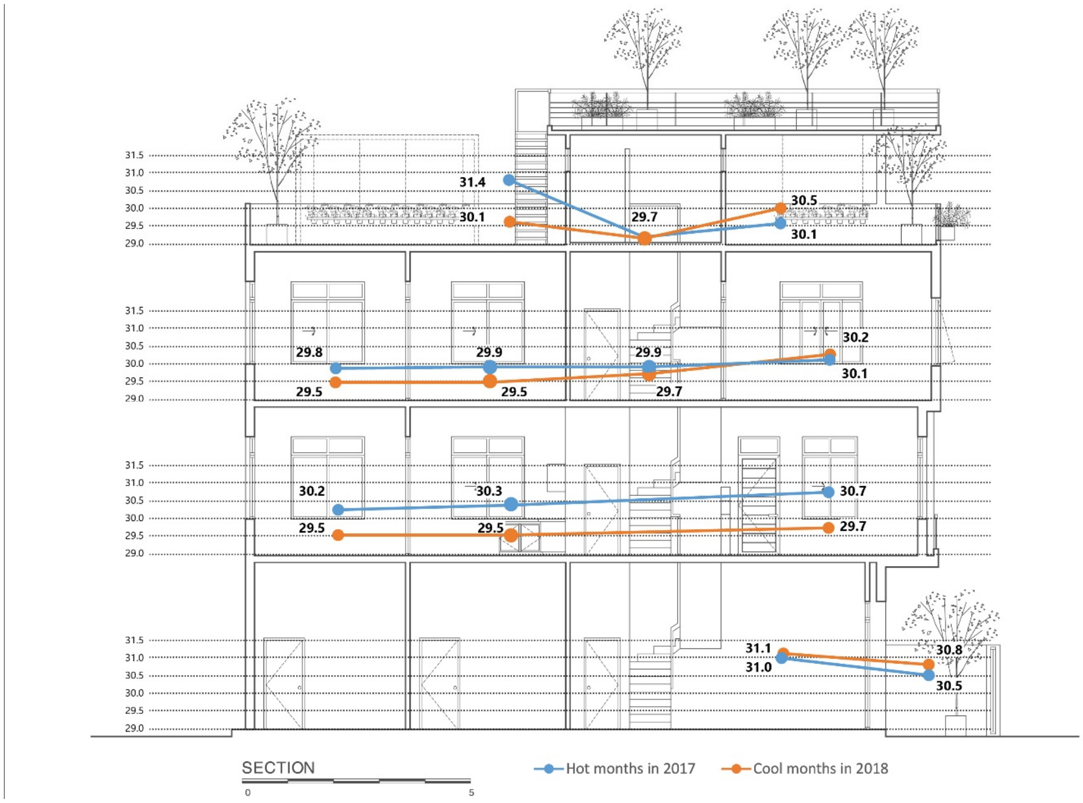


Figure 8.53 Air temperature in rooms in hot and cool months

The thermal environment in the house was investigated deeply by continuous data from the hottest to coolest months. Three rooms surveyed were the living room (4), parent bedroom (6), and children bedroom (7). All spaces have openings positioned at two different orientations. Figure 8.54 depicts daily room temperature lines in comparison with the outdoor climate.

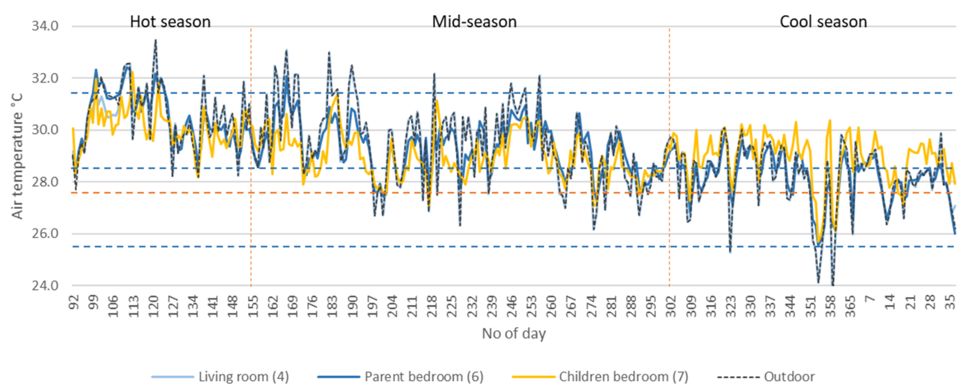


Figure 8.54 Distribution of daily mean indoor air temperature by room

As shown in the graph, daily mean air temperatures inside rooms 4 and 6 closely fluctuated to external temperatures, especially, the thermal equilibrium was between the living room and the outdoor. Whereas, temperatures performed more convoluted in bedroom 7 throughout measuring periods. In the hot season, the pattern of daily mean temperatures in that room stayed lower than other lines. Those differences can be attributed to the use of air-conditioner in the children bedroom on hot summer days while both rooms 4 and 6 were entirely ventilated by natural winds and fans. In contrast, microclimates in room 7 were warmer than other environments over cool months.

Furthermore, even though both the living room and children bedroom have some similar physical features in terms of room geometry and orientation, the spatial and opening design has variations. The living room is openly designed with a connection to other spaces (staircase and kitchen) and with more openings in exterior walls, which result in a higher degree of ventilation indoors. Meanwhile, bedroom 7 is designed more suitable for applying the mixed-mode ventilation system.

Table 8.16 Hourly indoor temperatures by room and season

Seasons	Values	Living room (4)	Parent bedroom (6)	Children bedroom (7)
Hot season (March, April, May)	Maximum	33.6	35.9	34.2
	Mean	30.4	30.5	30.0
	Minimum	27.2	26.9	26.2
	SD	1.2	1.5	1.8
Mid season (June, July, August, Sep., Oct.)	Maximum	33.2	34.2	33.5
	Mean	29.6	29.4	29.0
	Minimum	26.3	26.3	25.1
	SD	1.2	1.4	1.6
Cool season (Nov, Dec, Jan., Feb.)	Maximum	31.2	31.1	33.0
	Mean	28.6	28.1	28.9
	Minimum	24.6	23.0	24.0
	SD	1.1	1.2	1.7

Table 8.16 shows hourly thermal performances in three rooms examined. The thermal climate in the parent bedroom was the most unsatisfactory, particularly in hot months with the maximum air temperature up to 36°C between March-May and 34°C between June-October. The bedroom orientated west can receive the solar heat gain at noontime; therefore, occupants usually tolerate warm discomfort in summer. Meanwhile, in the cool season, the thermal dissatisfaction was found in the children bedroom. The maximum temperature in that room was 33°C, which figure was 2°C warmer than in other rooms.

The decrease of seasonal outdoor temperatures affected the cooler thermal environment in three rooms by 1°C between seasons. The mean temperature in the living room was 30.5°C (SD 1.2) in the hot season, 29.6°C (SD 1.2) in the mid-season and 28.6°C (SD 1.1) in the cool season. A similar pattern was found in the parent bedroom while the following average temperature in the hot, middle, and cool season was 30°C (SD 1.8), 29°C (SD 1.6), and 29°C (SD 1.7) in the children bedroom.

Table 8.17 summarises acceptable and unacceptable temperatures in three living spaces by five variations: T<25.5°C and T>31.5°C – out of the comfort band; 25.5°C≤T<27°C and 30°C<T≤31.5°C – 75% acceptability; and 27°C≤T≤30°C – 90% acceptability. In three environments, zone 7 performed the least

thermal satisfaction with 66% of data falling into the range of 27-30°C and 9% of data presenting warm and cool discomfort. The larger percentage of temperatures between 25.5-27°C (5.6%) in that room compared to in other rooms may interpret the use of air-conditioner to mitigate warmth at certain times.

Table 8.17 Percentage of uncomfortable and comfortable hours by room

Room type	**T < 25.5°C**	**25.5°C≤ T < 27°C**	**27°C ≤ T ≤ 30°C**	**30°C < T ≤ 31.5°C**	**T > 31.5°C**
Living room (4)	0.4%	1.4%	73.3%	19.5%	5.4%
Parent bedroom (6)	0.8%	3.8%	71.9%	16.8%	6.7%
Children bedroom (7)	0.8%	5.6%	66.1%	19.4%	8.2%

There was a slight difference in the distribution of acceptable and unacceptable temperatures into five categories between the living room and parent bedroom. However, the thermal environment was more pleasant in the living room with 94% acceptable temperatures. Two conditions including the good ventilation and less disadvantageous east orientation affect that consequence. Meanwhile, the impact of intense sunlight from the west on large openings of parent bedroom increase the overheating risk and discomfort.

b. Relative humidity

The daily humid environment inside three spaces is shown in Figure 8.55. The humidity pattern in rooms 4 and 6 similarly fluctuated. However, the temperature controlled by the air-conditioner at certain times influenced the strange distribution of humidity in room 7, particularly during hot periods.

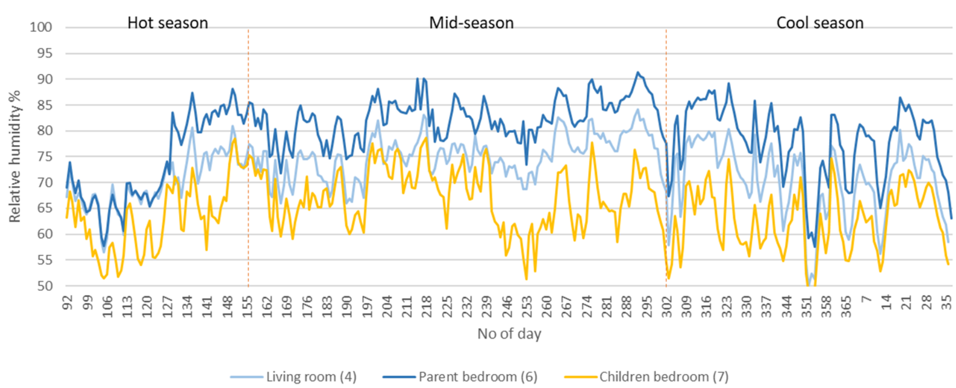


Figure 8.55 Distribution of daily mean relative humidity over the year

Daily mean humidity varied between 50% and 90% within the house. In which, the driest condition was found in the children bedroom with a fluctuation 10-15% lower than in the parent bedroom and the living room. The average humidity in room 7 was much lower relative to in other rooms in all three seasons. In hot months, the humidity dropped to 38% (Table 8.18).

The wetter ambient environment was observed in room 6 with the variability of RH between 51% and 95% while the range of hourly relative humidity was lower in the two other rooms (Table 8.18). The mean RH in room 6 was 73% (SD 9.7), 82% (SD 5.7), and 78% (SD 7.5) calculated in the following hottest, rainy, and coolest months. Those values were higher than they found in rooms 4 and 7.

Table 8.18 Distribution of hourly relative humidity by room and season

Seasons	Values	Living room (4)	Parent bedroom (6)	Children bedroom (7)
Hot season (March, April, May)	Maximum	84	93	84
	Mean	70	73	62
	Minimum	40	45	38
	SD	7.5	9.7	9.5
Mid season (June, July, August, Sep., Oct.)	Maximum	88	95	85
	Mean	75	82	67
	Minimum	52	60	38
	SD	5.8	5.7	8.4
Cool season (Nov, Dec, Jan., Feb.)	Maximum	87	94	81
	Mean	70	78	63
	Minimum	43	51	41
	SD	8.0	7.5	7.9

The rainy season affected indoor and outdoor humid environments. All maximum, mean, and minimum humidities recorded in three studied spaces during that period were higher than them taken in other seasons. Referring the maximum limit of acceptable humidity (80%) by TCVN 9411:2012 applied in shop-house design in Vietnam, averagely 21% of humidity data were more than that reference in the building, particularly in the parent bedroom with the greater proportion of 52%. Under unacceptable humid conditions together with warm temperatures, the availability of sufficient airflows is significant to control environmental satisfaction in terms of humidity and temperature.

c. Airflow distribution

Air movement in the house was assessed through spot and long-term measurements. Figures 8.56-61 show horizontal and vertical airflow distributions within rooms of the building in summer and spring. On the ground floor, the parking was ventilated by higher airspeeds between 0.2-0.8m/s in the cool season whilst airflow was calmer in warm months with most airspeeds below 0.2m/s (Figure 8.56).

On level 1, the indoor airflow between rooms varied under changes in seasonal outdoor winds (Figure 8.57). In summer, airflow through the whole space of the living room and the kitchen was light with air velocities lower than 0.2m/s that were insufficient to restore overall thermal satisfaction for occupants under ‘slightly warm’ temperatures above 30°C in those rooms. Reviewing the air movement acceptability identified in Chapter 7, the minimum air velocity should be 0.5m/s at a comfortable temperature of 30°C. Meanwhile, the air pattern was more pleasant with a large percentage of airspeeds from 0.4-0.6m/s within the occupied zone of the parent bedroom (Figure 8.57a).

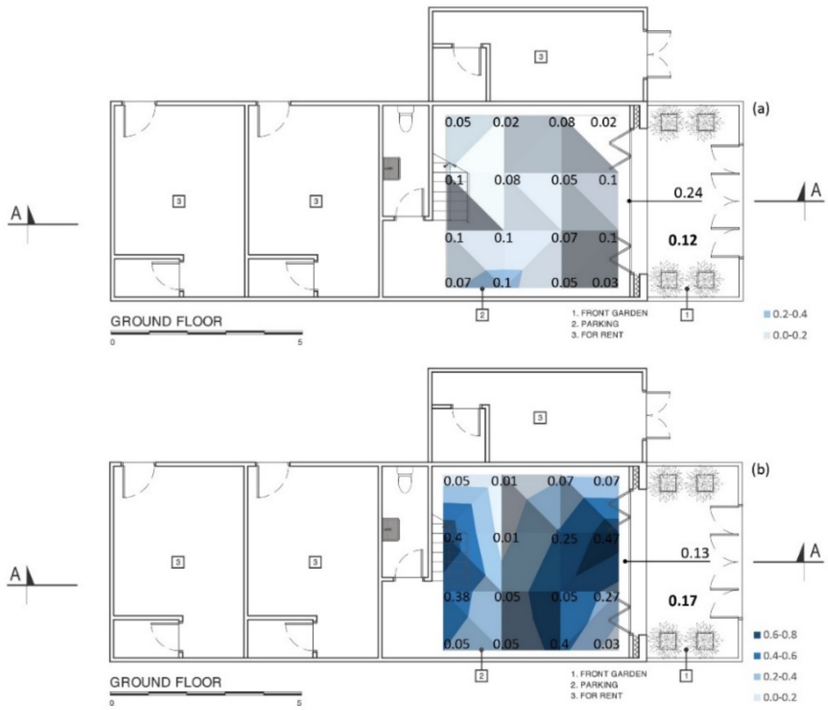


Figure 8.56 Airflow pattern on the ground floor in hot (a) and cool (b) season

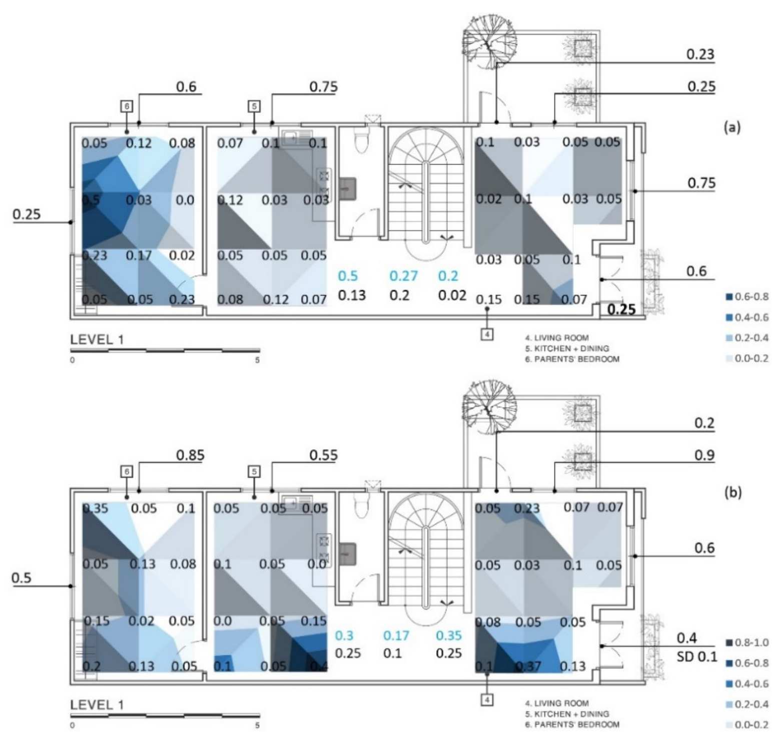


Figure 8.57 Airflow pattern on level 1 in hot (a) and cool (b) season

On the other hand, in spring, average wind velocities in the living, cooking, and dining rooms had a wide variability of 0.2-1.0m/s while air movement was lighter and fluctuated less in the parent bedroom (Figure 8.57b). However, despite higher airspeeds taken in the cooking and living rooms, their distribution was not uniform. The real air movement within the main occupied zone in most rooms was light with airspeeds lower than 0.3m/s, which could be inadequate for people to seek their thermal satisfaction when experiencing warm acceptable climates in the cool season.

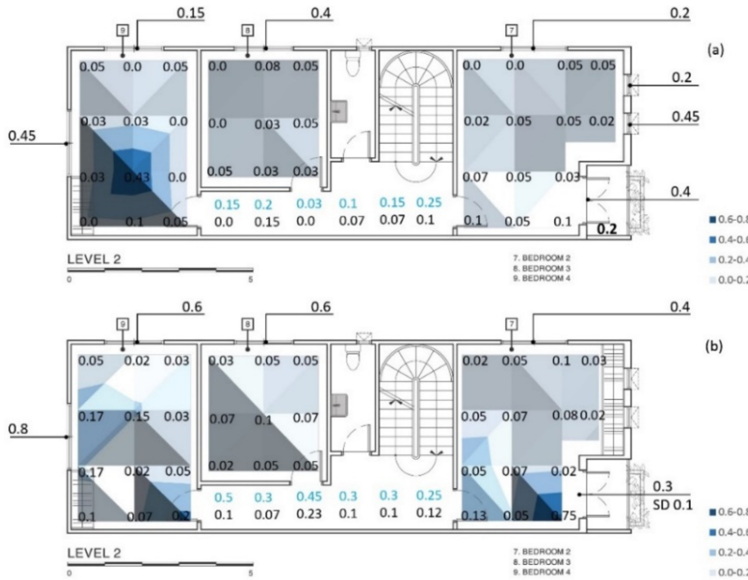


Figure 8.58 Airflow pattern on level 2 in hot (a) and cool (b) season

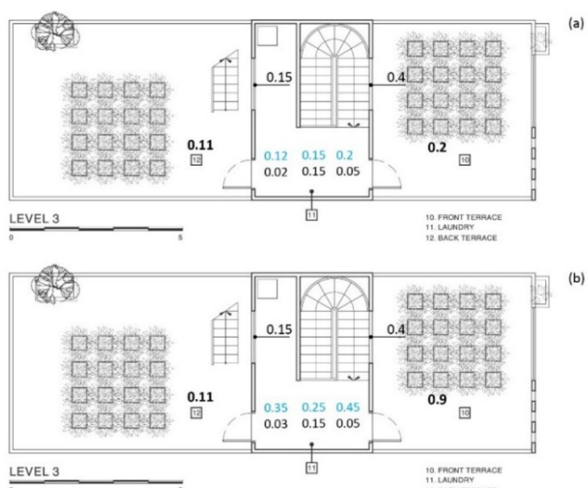


Figure 8.59 Airflow pattern on level 3 in hot (a) and cool (b) season

The similar airflow pattern to level 1 was found in bedrooms on level 2 between two seasons (Figure 8.58). The bedroom 9 oriented west was ventilated by stronger airspeeds (0.1-0.8m/s) in summer but with lighter breezes in spring. Meanwhile, airflow in bedroom 7 facing east ranged between 0.1-0.2m/s in the summer survey and between 0.1-0.7m/s in the spring survey. In three bedrooms, the airflow condition in bedroom 8 was the poorest because of its location in the middle of the building and the weak effect of single-sided ventilation. Overall, within all bedrooms, the wider zone of air velocities below 0.4m/s was insufficient to restore occupant comfort at room temperatures of 29.5-30°C measured currently. On the top floor, there was air movement between orchid gardens (Figure 8.59). Field surveys showed more powerful airflow in the second measurement of the cool season.

The distribution of indoor airflow was also analysed in the occupied zone according to the body height at three levels: low, medium, and high (Figure 8.60-62). The flow paths are deduced by average values of raw airspeeds taken at each column and each height of 3D mesh in two seasons.

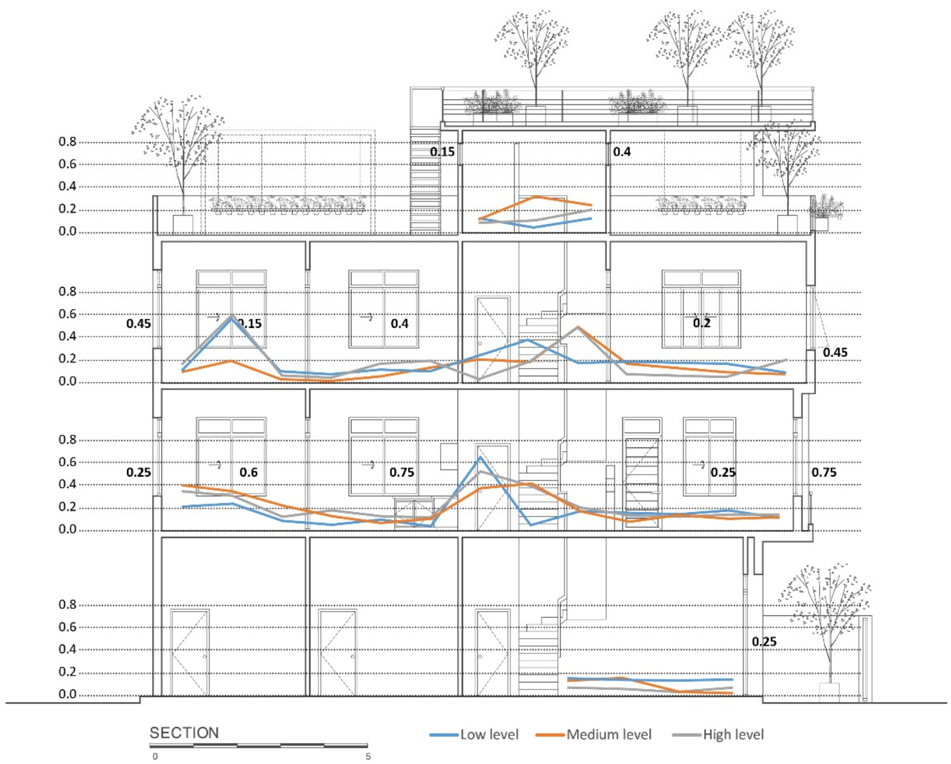


Figure 8.60 Distribution of indoor air movement in the hot season

In summer fieldwork, the elevated air motion in the living, cooking, and dining rooms, and bedrooms 7 and 8 was calm around the body with lower airspeeds below 0.2m/s. Meanwhile, in other rooms, such as bedroom 6 and 9, there was vertical air turbulence with air velocities usually higher around the zone close to openings; however, airflow patterns overall were below 0.4m/s. In spring, the distribution of vertical air movement in rooms varied with higher airspeeds reaching up to 0.6m/s, particularly at medium and high levels. Despite more air movement in the building in the cool season, the airflow condition in most living spaces was not sufficient to provide thermal satisfaction for the human body in two surveys carried out.

During field observations, indoor air patterns within the house seasonally differed. Air movement in rooms opened toward the west was stronger in the hot season while the context was reversible for spaces facing east in the cool season. Incident winds likely hit the building from the west in summer and from the east in spring. In the review of the meteorological database in HCMC, prevailing winds mainly blow from southeast to south between March-May (hot months) and from north to northeast between November and February (cool months). In a comparison of the real outdoor air movement, there was likely a conflict. The impact of neighbouring buildings and their spatial planning structure deflected and reduced incident winds. That influences the low performance of airflow in rooms, although openings positioned around the building envelope were available.

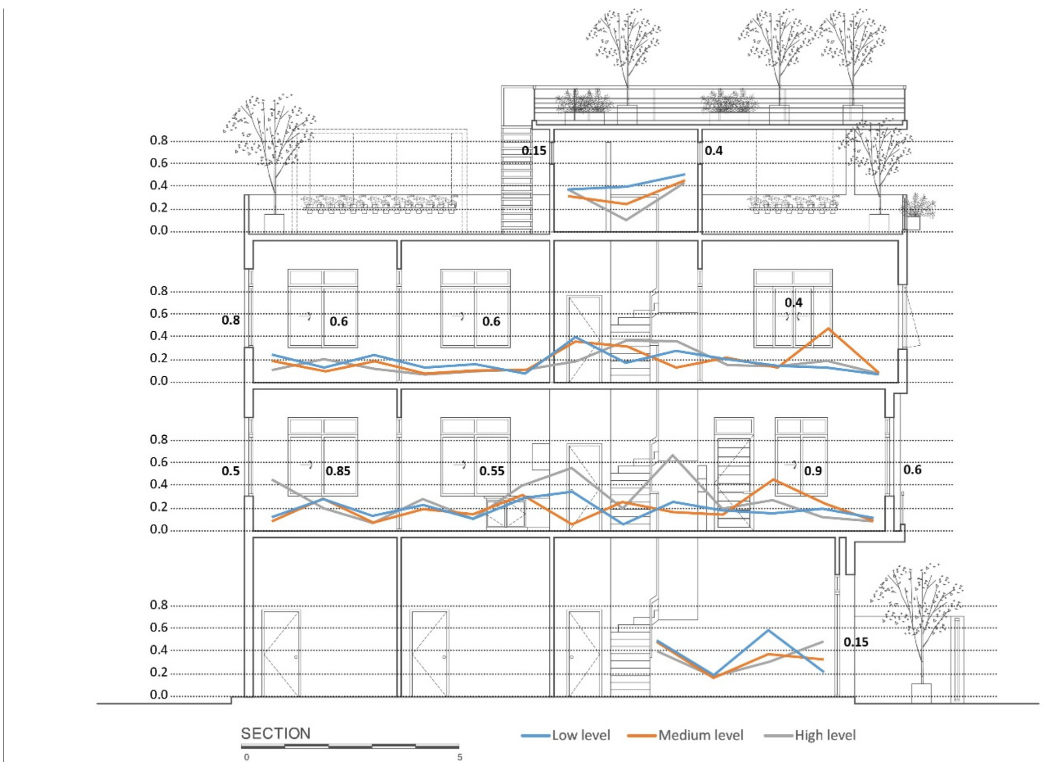


Figure 8.61 Distribution of indoor air movement in the cool season

The next discussion focuses on long-term airflow performances inside the living room and children bedroom based on continuous data recorded by loggers. However, because of some technical errors occurred with the wind sensor, air velocities in the bedroom during the middle and cool seasons cannot be used for analysis. Hourly air velocities taken over 11 months were classified into the hot, middle, and cool seasons. In the living room, airflow fluctuated between 0.04-0.63m/s, 0.0-0.49m/s, and 0.0-0.89m/s in the hot, rainy, and cool months, respectively (Table 8.19).

The band of velocities was wider and the maximum airspeed was the highest in the cool season, which shows a similarity of measuring results by two cross-sectional and longitudinal methods in the living room. Although the airflow environment in the room was sufficient at certain times, the average airspeed in three seasonal periods was low from 0.06-0.1m/s (SD 0.04-0.07). Meanwhile, in the bedroom, the mean airspeed was 0.05 (SD 0.03) and air velocities ranged between 0.04-0.34 m/s in hot summer. Relying on airflow data recorded in summer, the wind environment in the living room was more satisfactory.

Table 8.19 Characteristics of wind environment by room and season

Seasons	Values	Living room (4)	Children bedroom (7)
Hot season (March, April, May)	Maximum	0.63	0.34
	Mean	0.10	0.05
	Minimum	0.04	0.04
	SD	0.07	0.03
Mid season (June, July, August, Sep., Oct.)	Maximum	0.49	
	Mean	0.07	
	Minimum	0.00	
	SD	0.05	
Cool season (Nov, Dec, Jan., Feb.)	Maximum	0.89	
	Mean	0.06	
	Minimum	0.00	
	SD	0.04	

All of the airspeed data recorded in the two rooms were classified into five variations according to the measure of Szokolay (1997) and the finding discovered in Chapter 7 (Table 8.20). Firstly, the majority of data were lower than 0.2m/s, which is the limit of draught discomfort suggested in controllable buildings by ASHRAE 55 and ISO 7730 (ISO, 2005) (ASHRAE, 2013a). On the other hand, approximately 2% of air velocities were able to provide airflow satisfaction for people in the living room as the recommendation of 0.25-0.5m/s by Szokolay (1997). Meanwhile, the proportion in the bedroom was 0.3%.

Table 8.20 Airflows in the room (4) and (7) assessed by Szokolay scale (1997) and Table 7.1

Room	Szokolay scale (1997)				
	V < 0.2 (draught limit by ASHRAE)	**0.2 ≤ V < 0.25 (unnoticed)**	**0.25 ≤ V ≤ 0.5 (pleasant)**	**0.5 < V ≤ 1.0 (awareness)**	**V > 1.0 (draughty)**
Living room (4)	94.4%	3.7%	1.9%	0.04%	0.0%
Children bedroom (7)	98.5%	1.2%	0.3%	0.0%	0.0%
	Air movement acceptability (shown in Table 7.1)				
	V < 0.2	**0.2 ≤ V < 0.4 (25.5 - <27°C)**	**0.4 ≤ V ≤ 0.55 (27 - 31.5°C)**		**V > 0.55**
Living room (4)	94.4%	4.4%	0.2%		0.0%
Children bedroom (7)	98.5%	1.5%	0.0%		0.0%

Secondly, referring to the minimum air movement acceptability (0.2-0.55m/s) incorporated into thermal acceptability (25.5-31.5°C) found in the current study, occupants experienced comfortable air movement in only a few hours in the living room (0.2%) and the children bedroom (0%) during investigations for 11 months. Considering the lower airspeed zone of 0.2-<0.4m/s corresponding to the comfortable temperatures between 25.5-27°C, there were 4.4% and 1.5% of data found in the living room and children bedroom, respectively.

Although real thermal conditions in rooms surveyed largely fell into the acceptable temperature range (25.5-31.5°C) for naturally ventilated shop-houses buildings in HCMC, lower airspeeds indoors did not provide overall thermal satisfaction for inhabitants. In reality, in summer, occupants felt warmer than acceptability; therefore, the availability of higher air velocities is significant for their thermal delight.

8.2.3.4 Discussions

As previously mentioned, the building physics is controlled by openings positioned in exterior walls on different orientations in relationship with the outdoor microclimate governed by the current urban conditions surrounding. The characteristics of spatial planning in settlements of pattern type 4 affect the meteorological performance in terms of air temperature, wind flows, and humidity level before exchanging with the indoor environment through openings. The available opening design of the building probably creates insignificant effects on air movement indoors.

Table 8.21 Opening characteristics of rooms in the house C5

Parameters	2 Parking	4 + 5 Living + Cooking + Dining room	6 Parent bedroom	7 Children bedroom	8 Guest bedroom	9 Children bedroom
Orientation	East	East + North	North + West	East + North	North	North + West
Floor dimensions	5x6.45x3.6	5x4.3x3.25 5x3.4x3.25	5x3.4x3.25	5x4.5x3.25	3.7x3.4x3.25	5x3.4x3.25
Volume (m^3)	102	141.4	55.25	65.3	41	55.25
Floor area (m^2)	28.35	43.5	17	20.1	12.6	17
Exterior wall area (m^2)	17.5	44	28.3	35.8	11	28.3
Total of exterior OA (m^2)	10.6	13.7	6.1	6.6	2.9	6.1
Inlet area (m^2)	8.2	3.7	1.3	2.6	1.1	1.3
Outlet area (m^2)	0	3.8	2.9	3.1	1.8	2.9
Ratio of inlet to outlet area	0.0	1.0	0.4	0.8	0.6	0.4
Total of EOA (m^2)	8.2	7.5	4.2	5.6	2.9	4.2
Total of extrior EOA (m^2)	8.2	7.5	2.4	3.8	1.1	2.4
Ratio of effective opening to windward wall area (%)	46%	19%	8%	13%	10%	8%
Ratio of effective opening to leeward wall area (%)	0	15%	11%	10%	16%	11%
Ratio of effective opening to exterior wall area (%) (EOWR)	47%	17%	8%	11%	10%	8%
Ratio of effective opening to floor area (%) (EOFR)	29%	17%	25%	28%	23%	25%
Ratio of outdoor opening to exterior wall area (%) (OWR)	61%	31%	22%	18%	26%	22%
Ratio of outdoor opening to exterior western or eastern wall area (%)	60%	32%	20%	17%		20%

Table 8.21 combines opening design features of different spaces in the building. The above analysis of interior environmental performances showed warm and low airflow conditions in most rooms. Four basic opening parameters affecting airflow in the building/room include orientation; the ratio of effective

opening to wall area - EOWR (30-50%); the ratio of effective opening to floor area - EOFR (20-30%); and the inlet-outlet ratio (Chand, 1976; Givoni B. , 1976; Tang, Viet, & Nguyen, 2007; Dekay & Brown, 2014).

Apart from the guest bedroom and parking areas, which have one exposed wall, the environment in other rooms is shaped by openings positioned in exterior adjacent walls, which enables the catching of predominant winds from different directions, and subsequently to encourage the effect of natural ventilation, and to increase the flow rate indoors. However, the availability of large openings in rooms facing west, for example, bedrooms 6 and 9, is disadvantageous because of overheating risks.

Some opening design features show a significant effect on natural ventilation in living spaces but others are not. All figures of EOFR shown in the table are within 20-30% in most spaces, though the EOFR defined in the living room is a little lower by 3%. Besides, a larger or equal area of outlet openings compared to inlets is potential for encouraging air movement within the room. However, the value of EOWR calculated in the main five living spaces is much lower than the recommendation (30-50%) by Chand and Givoni (1976). That can reduce the airflow volumetric rate in rooms.

The possible improvement is increasing the effective opening area in exposed walls. Most rooms currently use sliding windows supplying a maximum of 50% free opening area. Therefore, the value of OWR nearly doubles the EOWR (Table 8.21). The replacement of window type, for example, casement windows can improve the airflow rate indoors. Furthermore, for spaces oriented west and east, referring to the national construction code and LOTUS guidance, the maximum opening area coupled with shading on west and east walls should be 30% to avoid the external heat gain (VIAP, 2012; VGBC, 2017). Excepting zones 2+4+5, spaces 6-9 have the opening to wall ratio lower than 30%; consequently, that allows increasing the area of openings in those rooms. However, suitable shading designs should be considered.

8.3 Discussions

a. Influences of urban morphology on outdoor microclimate

Three buildings A2, B3, and C5 were selected for detailed analyses on indoor and outdoor thermal environments through cross-sectional and longitudinal surveys. The three samples are located in three different urban types: A2 – pattern type 1, B3 – pattern type 3, and C5 – pattern type 4. Figures 8.62-64 show variations in monthly outdoor climate between three settlements observed between April 2017 and February 2018.

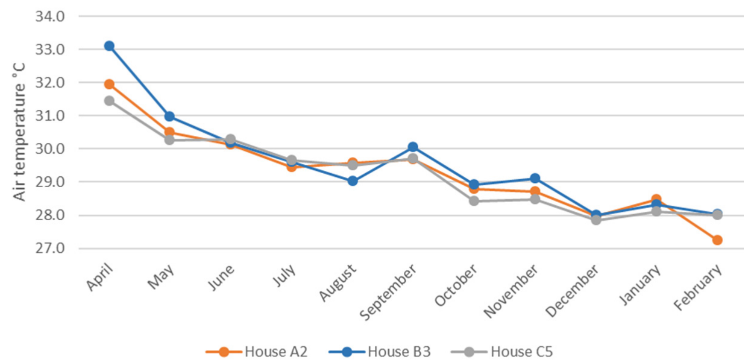


Figure 8.62 Monthly mean outdoor temperatures in three shop-house samples

Firstly, considering the variable of air temperature, monthly average temperatures around the building B3 in pattern type 3 often revealed warmer conditions. This conclusion is similar to the outcomes found in Chapter 6, which discussed the influence of urban morphologies on the outdoor microclimate. The monthly average temperature recorded showed an equilibrium between three locations in June, July, December, and January while the climate surrounding the building B3 was warmer reaching up to 1.5°C higher in other months. The external environment in the case C5 of pattern type 4 was the most comfortable because of the lowest temperatures found across much of the year. The compact housing pattern affects the coolness of environment in pattern type 4.

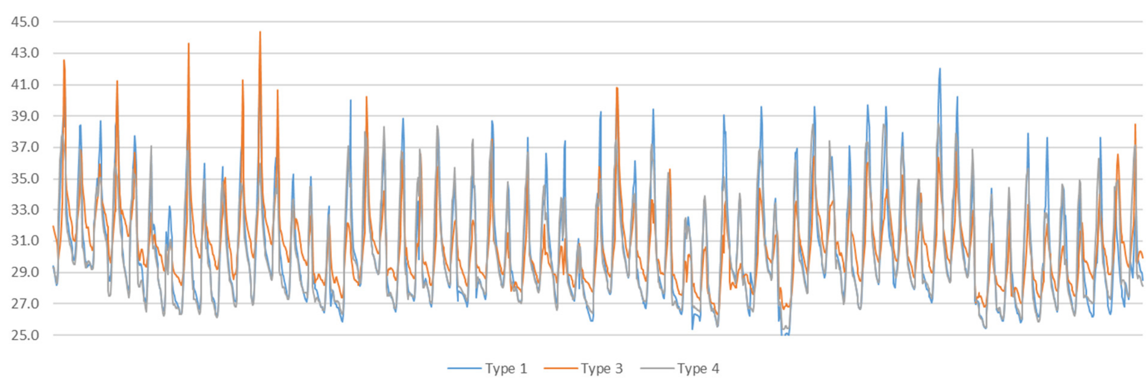


Figure 8.63 Distribution of hourly outdoor temperature in urban types 1, 3 & 4 in summer

Further analysis of hourly air temperatures in summer months generally represents less thermal satisfaction at daytime in three urban types (1, 3 & 4) studied; occupants would endure many hours of warmer temperatures than 31.5°C during hot months, for instance, 40%, 37%, and 34% of unacceptable hours in pattern type 3, 1 and 4, respectively. The data showed a difference of average temperature (2°C) between the three cases: pattern type 1 - 32°C (SD 1.33), pattern type 3 - 33°C (SD 1.58), and pattern type 4 - 31°C (SD 1.23). Warmer temperatures were around the building B3; especially during extreme heat periods of over 39°C around noon. Meanwhile, the pattern of exterior thermal condition surrounding the building A2 and C5 was nearly similar and showed more pleasant conditions during the testing period.

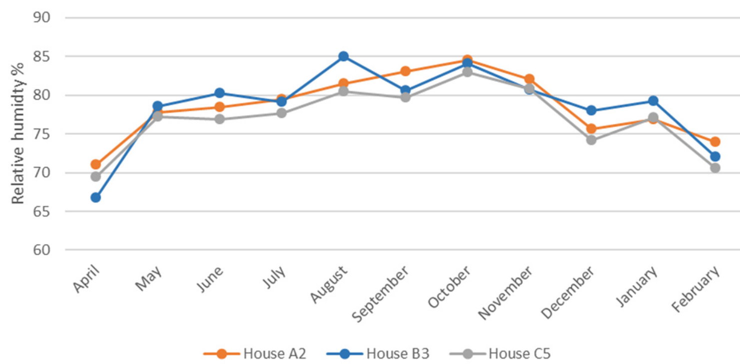


Figure 8.64 Monthly mean outdoor relative humidity in three shop-house samples

Secondly, the fluctuation of exterior temperatures correlated with the humid environment in such settlements. Figure 8.64 presents the distribution of outdoor humidity and a convoluted relationship between three environments during 11 months. In April, June, August, December, and January, the variation of external humidity was a maximum of 5% between urban types. In other months, the difference was negligible.

In three physical parameters, outdoor winds fluctuated at all times coinciding with the operation of monsoon winds, especially in dominant rainy months between June and October they were stronger. However, at the micro-scale of neighbourhoods, urban compositions have significant influences on the wind distribution around buildings, evidently, winds varied among three settlements characterised by three distinct urban spatial structures studied. Figure 8.65 indicates the comparison of monthly average airspeeds recorded around three houses: A2 (urban pattern type 1), B3 (urban pattern type 3), and C5 (urban pattern type 4) within April 2017 and February 2018.

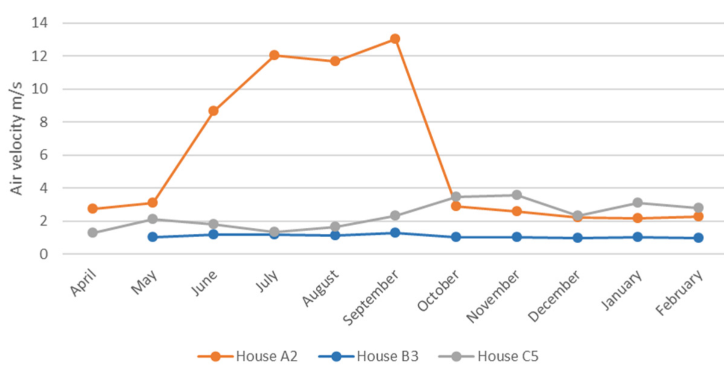


Figure 8.65 Monthly mean outdoor wind flows in three shop-house samples

The wind environment surrounding house A2 was the most intense, in particular, high winds in the rainy season, meanwhile, that was uniformly calm in residential areas of pattern type 3 with monthly average external airspeeds at around 1m/s. Although the urban pattern which buildings A2 and B3 are present is similar by a regular and back-to-back arrangement, the building density of pattern type 1 is the lowest in three urban morphologies investigated. Furthermore, urban features surrounding house A2 such as wide spacing and available open spaces, along with homogenous construction height contribute to encourage or maintain stronger outdoor winds when blowing through the urban block. Unlike the rainy season, external winds were consistent with the lower velocity of 3m/s across other months. In the neighbourhood of house C5, even though the construction coverage of pattern type 4 is the highest, the irregular settlement pattern and heterogeneous building characteristics interacted complicatedly and trickily to the wind environment surrounding residences. Comparing to wind flows around house B3, incident winds to house C5 were higher and fluctuated between 1.5-4m/s. Airspeeds were stronger in the cool season between October and February.

Another reason for the large divergence of external winds between three case studies is the building orientation. Looking at that of all dwellings, house A2 faces south, which is the most advantage to receive prevailing winds in the city from southeast and southwest between March and October. Particularly, according to meteorological data of HCMC, the wind speed in August is the highest. Meanwhile, building B3 located to the northwest is the worst orientation to capture dominant winds. That partly explains the uniformly low condition of outdoor winds in house B3, besides the impact of surroundings.

b. Indoor climates

Table 8.22 compares the average indoor thermal environment of three building samples in two measuring periods. The varying outdoor climate between settlements correlates to the difference in comfortable conditions in three shop-houses. The warmer condition was found in the house A2 while occupants in the house C5 experienced more comfortable environments. Different physical conditions between two urban morphologies explain an average deviation of 1.8°C in summer and 1°C in spring between two buildings.

The warmer condition in the house A2 caused a drier environment indoors with the mean RH of 58.5% (SD 4.2) relative to 71.3% RH (SD 1.3) in the house B3 and 65.7% RH (SD2.25) in the house C5 in summer surveys. The similar relationship between relative humidity in three houses was observed in spring surveys.

In three houses, airflow in the building A2 performed the most effective due to more powerful outdoor wind flows together with the higher optimised degree of passive cooling designs. The lowest wind condition was in the house B3 with the following mean airspeed of 0.1m/s (SD 0.03) and 0.2m/s (SD 0.15) in summer and spring. The disadvantageous urban context and the less effective cooling design strategies applied, increase the poor airflow performance inside the building.

Table 8.22 Indoor climates in three building samples in summer and spring

Parameter		Survey in summer			Survey in spring		
		House A2	House B3	House C5	House A2	House B3	House C5
Temperature (°C)	Maximum	33.5	31	31	31.1	30.9	30.5
	Mean	32	30.7	30.2	30.6	30.3	29.7
	Minimum	30.8	30.4	29.7	30	29.6	29.5
	SD	0.82	0.24	0.43	0.63	0.49	0.36
Mean radiant temperature (°C)	Maximum	32.6	31.1	31.4	32.7	31	31
	Mean	32	30.7	30.3	30.9	30.4	30
	Minimum	30.8	30.4	29.5	30	29.7	29.4
	SD	0.63	0.27	0.73	0.92	0.48	0.53
Relative humidity (RH %)	Maximum	64	73	68.1	65	73.5	67.1
	Mean	58.5	71.3	65.7	62.2	66.6	66.1
	Minimum	54	69.6	62.4	58.6	62.1	63.8
	SD	4.2	1.28	2.25	1.72	4.43	1.27
Air velocity (m/s)	Maximum	0.58	0.17	0.2	0.31	0.49	0.4
	Mean	0.32	0.1	0.12	0.19	0.19	0.24
	Minimum	0.14	0.07	0.06	0.08	0.04	0.11
	SD	0.14	0.03	0.05	0.07	0.15	0.09

The snap-shot measurements of physical data showed that environments for occupant comfort in naturally ventilated shop-house buildings varied between seasonal climatic conditions and between settlements classified by different urban morphologies. However, the data taken from cross-sectional surveys may show shortcomings because of a lack of continuity and simultaneous recording of data, particularly of the dynamic variable of wind. Therefore, comfortable environments in shop-houses were longitudinally investigated through the installation of environmental sensors in typical rooms of three case studies selected. The sensors were installed in the living room, which is naturally ventilated and the bedroom, which is cooled with a mixed-mode ventilation system.

Table 8.23 Indoor temperatures in the living room of three case studies

Season	Values	House A2	House B3	House C5
Hot season (March, April, May)	Maximum	31	32	33.5
	Mean	29	30	30.5
	Minimum	27.5	29	28
	SD	0.7	0.6	1.1
Mid season (June, July, August, Sep., Oct.)	Maximum	30.5	31	33
	Mean	28.5	29	29.5
	Minimum	26	28	26
	SD	0.7	0.5	1.2
Cool season (Nov, Dec, Jan., Feb.)	Maximum	30	31	31
	Mean	28	28.5	28.5
	Minimum	24.5	26.4	24.5
	SD	0.8	0.6	1.1

Tables 8.23-25 gather the physical data in terms of temperature, humidity, and wind in the free-running living room of three houses A2, B3, and C5. Among them, the living room of B3 disconnects to the outdoor climate. The long-term database showed a difference from cross-sectional surveys. The thermal

environment in the living room of A2 was the coolest in three cases with the average temperature of 29°C (SD 0.7) in the hot season, 28.5°C (SD 0.7) in the rainy season, and 28°C (SD 0.8) in the cool season (Table 8.24). Those temperatures were 0.5-1.5°C lower than in the house B3 and C5. Considering the climate outside two buildings A2 and C5, exterior temperatures similarly performed; however, the thermal profile of the living room in A2 was cooler over the year. That result can be explained by two contributions: the efficient building fabric and the influence of building orientation (the living room of A2 facing south receives the less impact of sunlight while the living room of C5 is oriented east).

There was a close relationship between two variables - temperature and humidity. The humidity level in the three living rooms is shown in Table 8.24. The mean humidity in three living rooms was acceptable to occupants in three seasons. The cooler environment in the A2 linked to a higher humid degree than in the living room of other houses. The percentage of humidity data greater than the maximum acceptability of 80% in three residences were as follows: 53% in A2, 21% in B3, and 11% in C5. The more humid condition in the living room of A2 will require dehumidification by higher airflows to restore human thermal satisfaction.

Table 8.24 Indoor relative humidity in the living room of three case studies

Season	Values	House A2	House B3	House C5
Hot season (March, April, May)	Maximum	91	84	84
	Mean	79	72	71
	Minimum	58	63	50
	SD	6.0	5.0	6.8
Mid season (June, July, August, Sep., Oct.)	Maximum	91	86	88
	Mean	82	79	75
	Minimum	54	59	52
	SD	4.4	3.2	5.8
Cool season (Nov, Dec, Jan., Feb.)	Maximum	91	82	87
	Mean	76	72	70
	Minimum	45	51	43
	SD	8.0	5.8	7.8

Due to the distinct spatial condition of the living room in the building B3, the long-term investigation of air movement was only carried out for the house A2 and C5. In reality, airflow in two living rooms was much insufficient to retain overall comfort for residents in warm and humid environments, especially in the house A2 with the main problem of high humidity and in the house C5 with the main issue of warm temperatures across the year.

Table 8.25 represents airflow characteristics in two living rooms seasonally. The mean seasonal airspeed in two rooms was similar about 0.1m/s. The majority of airspeeds in both living rooms were below 0.2m/s (Table 8.26). For the living room of A2, although a whole thermal data recorded were between the acceptable limits (25.5-31.5°C) for non-air-conditioned shop-house dwellings in HCMC, over 34% of temperatures showed warm comfort corresponding to the zone of >28.5°C.

Table 8.25 Indoor air movement in the living room of two cases

Season	Values	House A2	House C5
Hot season (March, April, May)	Maximum	0.6	0.6
	Mean	0.1	0.1
	Minimum	0.0	0.0
	SD	0.09	0.07
Mid season (June, July, August, Sep., Oct.)	Maximum	0.6	0.5
	Mean	0.1	0.1
	Minimum	0.0	0.0
	SD	0.06	0.05
Cool season (Nov, Dec, Jan., Feb.)	Maximum	0.6	0.9
	Mean	0.1	0.1
	Minimum	0.1	0.0
	SD	0.06	0.04

Meanwhile, 66% of warm comfort temperatures were recorded in the living room of C5. Considering the correlation between thermal and air movement comfort in naturally ventilated shop-houses, airflows of at least 0.5m/s are sufficient to restore the comfortable condition within 29-31.5°C. However, in reality, respective efficient air movement in the living room of A2 and C5 took 0.9% and 0.2% of monitoring periods (Table 8.26). Therefore, low airflow could not restore occupant thermal satisfaction in slightly warm comfortable temperatures.

Table 8.26 Assessment of indoor airflow in two living rooms

House	Air movement acceptability (shown in Table 7.1)			
	V < 0.2	0.2 ≤ V < 0.4 (25.5 - <27°C)	0.4 ≤ V ≤ 0.55 (27 - 31.5°C)	V > 0.55
House A2	89.2%	9.9%	0.9%	0.0%
House C5	94.4%	5.3%	0.2%	0.0%

Table 8.27 Indoor temperatures in the bedroom of house A2, B3, and C5

Season	Values	House A2	House B3	House C5
Hot season (March, April, May)	Maximum	34	32	34
	Mean	30	28	30
	Minimum	27.5	19.5	26
	SD	1.2	2.8	1.8
Mid season (June, July, August, Sep., Oct.)	Maximum	34	33	33.5
	Mean	29	29	29
	Minimum	25.5	22.5	25
	SD	1.4	1.2	1.6
Cool season (Nov, Dec, Jan., Feb.)	Maximum	33	30	33
	Mean	28.5	28.5	29
	Minimum	23.5	25	24
	SD	1.4	0.7	1.7

Thermal environments were also monitored in the bedroom of three houses (A2, B3, and C5). Three bedrooms have been ventilated by a combination of three cooling means: doors and windows, fans, and air-conditioners in summer. The following orientation of bedrooms in the building A2, B3, and C5 is north, northwest, and east. In three houses, thermal conditions in the bedroom of A2 and C5 were more similar

(Table 8.27). Meanwhile, cooler thermal climates were observed in the bedroom of house B3 throughout the year. Particularly, in warm months between March-October, the lower minimum temperatures in that bedroom interpreted the more frequent use of air-conditioner to control the room climate. Under warm conditions, occupant thermal expectation in bedrooms differed.

Changes in air controllable systems (naturally and mechanically) in bedrooms depending on the outdoor climate and occupant expectation influenced the distribution of relative humidity. The ambient environment in the bedroom of B3 was the wettest. The maximum, mean, and minimum relative humidities in such bedroom were higher relative to in the bedroom of other houses (Table 8.28). According to the recommended acceptable humid level in residences in Vietnam (80%), 6%, 38%, and 1% of humidity data over the threshold were found in the respective bedroom of the building A2, B3, and C5. More humid conditions in the bedroom of B3 open some insights: the more use of air-conditioner, the less effect of natural ventilation, and the less efficiency of opening design to drive air movement. In three bedrooms examined, the space in the house B3 is naturally ventilated at a single side, which shows less effective than the system of cross-ventilation in other cases.

Table 8.28 Indoor humidity in the bedroom of house A2, B3, and C5

Season	Values	House A2	House B3	House C5
Hot season (March, April, May)	Maximum	84	95	84
	Mean	71	80	63
	Minimum	51	61	38
	SD	6	9	10
Mid season (June, July, August, Sep., Oct.)	Maximum	84	96	85
	Mean	73	80	67
	Minimum	49	53	38
	SD	6	6	8
Cool season (Nov, Dec, Jan., Feb.)	Maximum	85	84	81
	Mean	70	74	63
	Minimum	47	53	41
	SD	7	6	8

8.4 Conclusions

This chapter aims to understand characteristics of urban context; building design focusing on open configurations; indoor and outdoor environmental performances; and the relationship between those factors and comfortable conditions in shop-house buildings located in different urban pattern types. The indoor environment for human comfort was evaluated based on the comfort zone of temperatures and air velocities discovered in Chapters 6 & 7. The analysis used the cross-sectional data taken in 22 houses and the longitudinal data monitored in 3 houses selected. Although the single methods of data collection developed in the current study have shortcomings related to time and place of measurements, the analytical results between two methods had similarities. Thus, the typical data obtained by a combination of two methods find insights for building the potential variables of design guidance:

- The urban characteristics vary within settlements classified into different urban forms. The distinction of urban conditions affects the urban environment and subsequently linking to the indoor microclimate in free-running shop-houses. The hypothesis of the relationship between urban morphology and outdoor microclimate and indoor environment is robustly clarified by the comparisons of physical data monitored between three typical buildings A2, B3, and C5 located in three respective urban patterns 1, 3, and 4.

- The national regulations of planning and construction for shop-houses has to some extent impacts on the microclimate inside and outside buildings, especially for the row houses or shop-houses planned in regular low-density residential neighbourhoods of pattern types 1 and 2. Additionally, the arrangement of front and back gardens and the integration of light wells or voids within the building is mandatory to design those houses. The elements partly provide advantages to optimise passive design strategies. Therefore, building performance may be better. For example, in three shop-house cases studied, those contexts above are reported in the house A2, which links to more satisfactory environments indoor and outdoor the building analysed.

- Indoor environments for occupant comfort seasonally changed in relation to outdoor climates. Most real thermal conditions were between the acceptable range (25.5-31.5°C). However, warm uncomfortable temperatures were available in warm months while cool and warm discomfort happened in cool months.

- Overall occupant thermal comfort in naturally ventilated shop-houses in HCMC is constituted by an interplay of thermal and air movement acceptability. Through on-site investigations, a large number of internal temperatures were between the acceptable limits; however, a larger percentage of acceptable temperatures were classified as being of warm comfort. Consequently, to restore human comfort at warm acceptable temperatures will require the provision of airflows with a minimum velocity of 0.5m/s. Nevertheless, the real air movement in shop-houses was commonly calmer than that. The issue can be explained by the low outdoor wind or the unsuitable building design, particularly the opening design.

- Environmental characteristics between rooms of a building varied due to various factors: room/building orientation in respect to wind and sun directions; room position; spatial design; room geometry; and room envelope. For example, through the current environmental data, the temperature and airflow were higher in rooms on the upper floors. Furthermore, air movement and the thermal condition in rooms facing south were more satisfactory than in rooms oriented other directions. Between two rooms with the same conditions of geometry, the area of exposed walls, and orientation, the room having a larger area of openings is ventilated by higher airspeeds than another with smaller opening size.

• Considering the opening design of shop-houses, openings are important for creating natural ventilation and comfort for inhabitants in buildings. Through the analysis of typical case studies, their main features applied include the opening type, the ratio of opening to floor area, the ratio of opening to exposed wall area, the ratio of the inlet to outlet, opening placement, and opening organisation. The real air movement was mostly poor for occupant satisfaction in the building, though designers have attempted to combine various opening features.

Table 8.29 Opening features and natural driving forces used in three cases

Ratio of effective opening to exterior wall area (EOWR) (Chand, 1976), Givoni (1976)			
Scale	**< 30%**	**30-50%**	**>50%**
House A2	50%	50%	
House B3	33%	67%	
House C5	83%	17%	
Ratio of effective opening to floor area (EOFR) (Chand, 1976), Givoni (1976)			
Scale	**< 20%**	**20-30%**	**>30%**
House A2		67%	33%
House B3	33%	33%	33%
House C5	17%	83%	
Ratio of inlet to outlet area (Chand, 1976), Givoni (1976), (Tang et al., 2007), (Pham, 2002), (Down et al., 2004)			
Scale	**> 1:1**	**1:1**	**< 1:1**
House A2	83%	17%	
House B3	100%		
House C5	17%	17%	67%
Principle of natural ventilation (when room door is closed)			
Scheme	**Single-sided**	**Cross-ventilation**	**Cross + Stack effect**
House A2		83%	17%
House B3	100%		
House C5	33%	50%	17%

Through on-site investigations, various systems to drive air movement within the building include single-sided, double-sided, and stack ventilation, or a combination depending on the organisation of openings around the building envelope. The air movement and comfort in the rooms ventilated by cross-ventilation or combined with the stack effect performed better than single-sided ventilated rooms. The size and operable area of openings are usually maximised, especially on the windward wall, evidently the similarity between EOWR and OWR calculated in the typical shop-houses. Although rooms are designed with openings positioned in opposite walls for cross-ventilation, air movement was calm and non-uniform because of the ratio of the inlet to outlet openings above 1:1; the unsuitable opening area against the floor and exposed wall area; and inappropriate opening types. Meanwhile, for a large percentage of shop-house buildings in HCMC planned with one main façade, most openings are positioned and optimised in the windward wall and rooms are ventilated from a single side. For those buildings/rooms, the air movement was negligible and the comfort is low, even the consideration of opening type and area. Based on some recommendations in the opening design collected in the literature review, Table 8.29 summarises the main opening parameters and their variations found in three houses studied.

Bring all on-site observations and analyses together, the internal (building including openings) and external (urban) factors closely correlate and simultaneously affect the indoor environment and occupant comfort in shop-houses. The analysis of environmental and building data indicates that to achieve indoor comfortable environments, designers need to consider the overall effect of opening features concerning other factors of the building and its surroundings. Therefore, the potential design guidance for openings considering those main factors is supportive for designers' practice. The next chapter will address it.

Chapter 9 APPROACH OF OPENING DESIGN GUIDANCE

This chapter shows how design guidance can be created and how it could be implemented in naturally ventilated shop-house buildings in HCMC and other regions having similar characteristics of geography and building typology as in Vietnam. The chapter includes three sections: pilot surveys with professionals to find an appropriate direction for the creation of design guidance; building a sample version of design guidance; validating the design guidance through field surveys with practitioners in the architectural industry.

9.1 Approaching the production of design guidance

Producing practical guidance on opening design to improve comfort in free-running shop-house dwellings is derived from understanding real contextual factors: building (type, design features, and environmental impacts), people (occupant thermal sensations, preferences, and acceptability), and practice (philosophy, experience, need, and the implementation of standards/design guidelines). There are three steps carried out and two methods applied as shown in Figure 9.1.

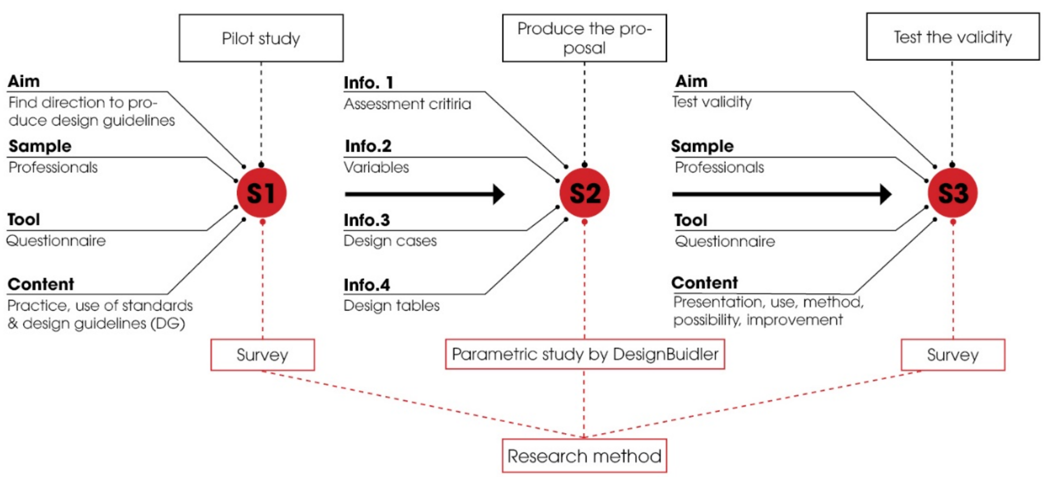


Figure 9.1 Steps and research methods used to produce a sample of design guidance

- Step 1: Finding the direction of potential design guidance

The primary research technique conducted was in-situ surveys with professionals who are lecturers, architects, and engineers practising in the built environment in HCMC. 55 participants involved in questionnaire interviews. The survey aims to understand the experience of designers in designing naturally ventilated comfortable shop-houses and their expectations for an effective design tool of openings, which supports their work to achieve creation, aesthetics, and comfort for buildings. In Step 1, the potential direction to build the design guidance will be identified.

- Step 2: Building a sample of design guidance

In this step, the structure of guidance was assumed with the potential information incorporated, such as the assessment framework, variables, and various design cases. In these, the assessment criteria for the indoor comfortable environment comply with the comfort zone for human occupancy found in Chapters 6 and 7. For the identification of variables, both types are included: internal (opening features) and external (for example, urban pattern types, building orientations, room geometry, and room position). The effect of those factors on the indoor environment is shown in guidance through building various design options. Their environmental impacts were analysed by parametric studies of DesignBuilder software program. Then, 'design tables' and 'design corrections' were formed.

- Step 3: Testing validity

The proposal is tested by similar professionals in the first step to collect their feedback, which helps the author assume the validity of guidance in practice in future. To hold this, questionnaire interviews and seminars were organised with the participation of architects, engineers, and lecturers. The collection of opinions from the participants is useful to revise and produce a demonstration of guidance and its completions later.

9.2 Step 1 - Pilot study to direct the design guidance

9.2.1 Survey results

The questionnaire interviews were carried out in multiscale architectural offices in HCMC in 2018. There were 55 participants (architects, engineers, and lecturers) with multiple years of experience (2 to 20 years). All the respondents have practised in housing design, particularly of shop-house dwellings. Questions were relevant to their experiences in designing comfortable houses.

Despite enduring the prevailing effect of tropical climate (high temperature and high humidity), occupants usually find their environmental delight in naturally ventilated spaces. That has influenced the practice of designers. Thus, most of them (96%) often or always optimise passive design strategies, particularly cooling designs to enhance natural ventilation (Figure 9.2a). However, a few designers also have doubts about the effect of natural winds on thermal satisfaction; therefore, the use of air-conditioners is an easy alternative.

Certainly, most designers usually consider suitable and interesting design strategies to respond to the outdoor environment and encourage airflow indoors in the early phase of the design process, particularly in the conceptual design (Figure 9.2b). In that stage, the aspects related to design solutions, building aesthetics, and indoor environment impacts are controlled simultaneously, and consequently reducing adjustments in further stages. Meanwhile, a smaller number of architects often pay their attentions to the design of natural ventilation in the further phase of design development.

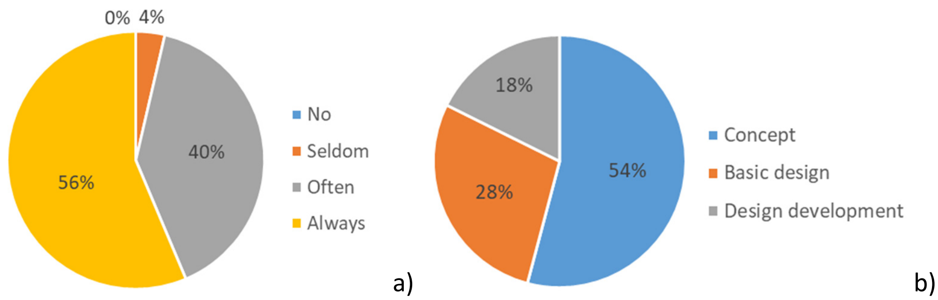


Figure 9.2 The use of natural ventilation in design by architects: frequency (a) and the stages applied (b)

In reality, despite the intentional employment of passive cooling designs in shop-house buildings, approximate 50% of designers are confused about how to evaluate environmental impacts in the room or building after one or more strategies applied (Figure 9.3a). Whereas, in more than 40% of architects voting for using various assessment methods, most of them (>60%) mainly identify the contribution of their design to internal environmental performances through accumulative experiences. Additionally, a large percentage of them (40%) can use simulation programs and others conduct on-site measurements during construction (Figure 9.3b).

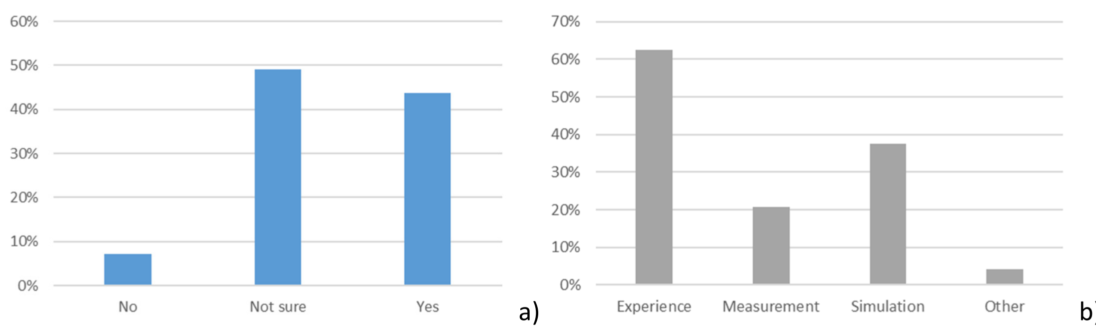


Figure 9.3 Methods used to assess the effect of indoor airflow by architects

Although most designers prefer to apply natural ventilation to shop-house buildings because of the benefits of comfortable living environments, health, well-being, and a reduction of energy consumption, they also have difficulties in applications, in these, the confusion when assessing the effect of strategies and the preference of clients are dominant (Figure 9.4). Some designers reported that the unavailability of practical design guidelines also influences the application of passive cooling designs.

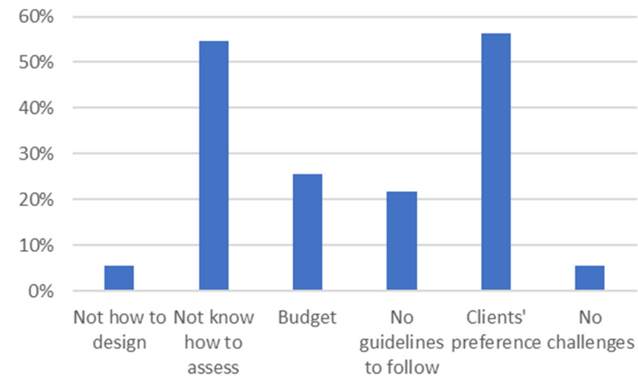


Figure 9.4 Challenges to design naturally ventilated shop-houses

Based on the real observations of indoor and outdoor environments in shop-house buildings in HCMC, the author has found a close relationship between building characteristics, urban conditions, and indoor comfortable environments. Consequently, in surveys with the professionals, eight factors potentially affecting interior thermal and airflow performances were asked for their feedback as shown in Figure 9.5. Their considerations for individual factors varied. Over 20% of architects/engineers found the influence of urban spatial structures, building orientations, room geometries, and natural ventilation principles. These factors have been mentioned in the previous chapters. Meanwhile, most designers agreed that whole eight factors have an overall effect on comfortable environments in non-air-conditioned buildings. However, the category of opening configuration was received the least votes (2%). That may show that designers undervalue the role of openings in internal comfort.

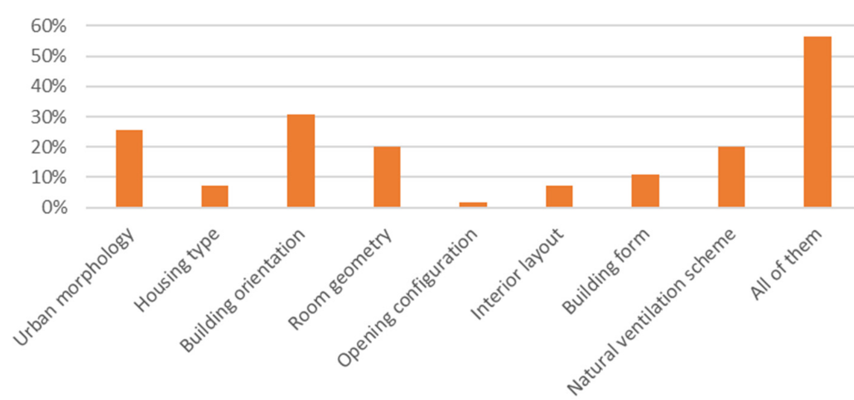


Figure 9.5 Voting for variables influencing airflow inside buildings

Focusing on the influence of opening design features on indoor environments, nine opening parameters were suggested including orientation, type, area, placement, the ratio between inlets and outlets, organisation (internal and external walls and roofs), pattern (a combination of openings in a wall), material, and control (shading devices). Architects have concerned differently those features when applying them to the design of shop-house buildings. Most of them responded to a lack of confidence to six opening variables: orientation, type, area, placement, ratio, and pattern (Figure 9.6).

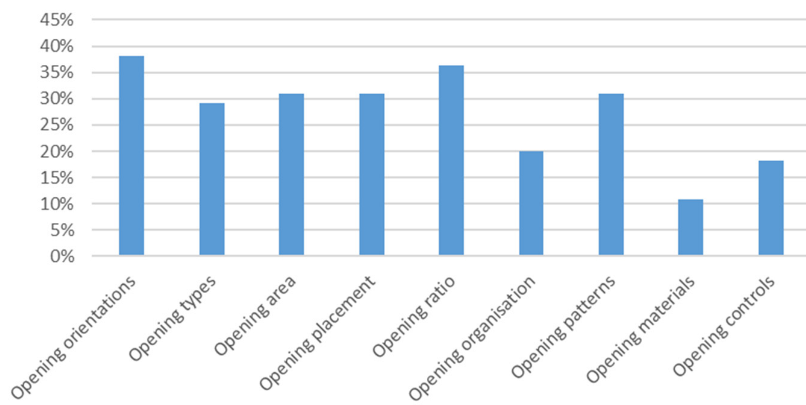


Figure 9.6 Opening features concerned by designers

The last question was about designers' desire for the availability of effective design guidance of openings, which can help them propose the appropriate opening profile for the achievement of both indoor environmental satisfaction and architectural aesthetics. 82% of respondents showed their pleasure if opening design guidelines will be produced while 14% in all had speculations about the efficiency of guidance in reality.

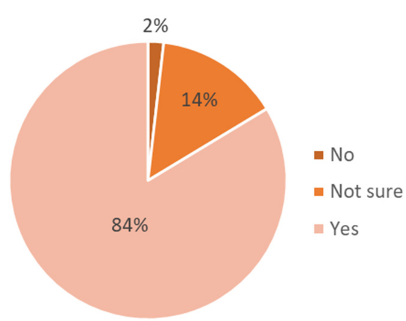


Figure 9.7 Designers' expectation for the design guidance of openings

9.2.2 Section conclusions

The pilot study with the professional consultants in housing design in HCMC raised insights before producing the design guidance of openings. The limitations of current standards have been confirmed when employed to design naturally ventilated and comfortable shop-houses in HCMC and Vietnam due to their insufficiency in dissemination, implementation, and management. In spite of available standards, designers have not held effective technical manuals that orientate design strategies for their buildings to achieve the recommendation of comfort conditions into the standards. Naturally ventilated shop-house dwellings are a preference of architects' practice. Nevertheless, most of them have confused to assume the consequence of real environments by those applications. The evaluation based on their experience is common. Consequently, a large number of designers have expected practical design guidelines, for example, for opening design to use in the early design phase. By using such guidelines, architects will understand their design products and their contribution to human comfort in the building. In the present research, the main opening variables have been determined and many designers have had difficulties in practical applications due to lacking the knowledge of their effect on indoor environmental conditions. In the next section, those opening features will be analysed by numerical simulations, and then, outcomes will be gathered to issue a draft of design guidance for testing validity.

9.3 Step 2 – Produce a sample version of design guidance

9.3.1 Methodology

The present research targets to approach a proposal for opening design guidelines, which will be employed to improve comfortable environments in free-running shop-houses in HCMC. In the scope of the project, a sample of design manual is built and validated. In the total 9 opening design features asked for the professionals in HCMC as shown in Figure 9.6, there are some common factors selected for further investigations.

Based on the empirical surveys on thermal environments inside and outside shop-house buildings in HCMC, indoor microclimates for occupant comfort or discomfort have been a function of a complex interplay of various factors: urban conditions, the building configuration, the building fabric, and passive cooling systems. Openings, which are a basic element of the building envelope, directly affect interior thermal conditions through an exchange of heat and air. In practice, the characteristics of buildings and openings of shop-houses are very diverse. Consequently, the potential design manual of openings is expected to be compatible with that diversity in design and not constrain designers' creativity when applied. Deliberating a suitable method to formulate the design guidance, parametric studies on common cases of opening variables and their parameters show the potential. Each design option demonstrates environmental impacts on satisfaction or dissatisfaction. Based on any particular design, architects will look up across various design options shown in the manual to find a suitable opening profile for their building. From basic instructions of design guidance, designers are adaptive to produce interesting creations of openings harmonising with the idea of the whole building. Importantly, due to using the design guidance, designers will assume the performance of real thermal environments indoors.

A shop-house contains various rooms or spaces characterised by a variety of geometry, usage, position, and opening configuration. Reviewing the analyses in Chapters 6 and 8, significant differences in thermal climates between interior spaces because of the influences of various factors were found. Therefore, instead of investigating the environment for the whole hypothetic building, the present project has concentrated on the smaller scale of a house - a room. Testing for a room will be conducted under applications of different opening features and their variations. By this way, the proposal of design guidance may show versatility in practical applications for various designs; consequently, the manual can target a large population.

Parametric studies were carried out by two calculations of DesignBuilder including comfort analysis and CFD (Computational Fluid Dynamics). Inputs and outputs and process of simulations will be shown in detail in further sections.

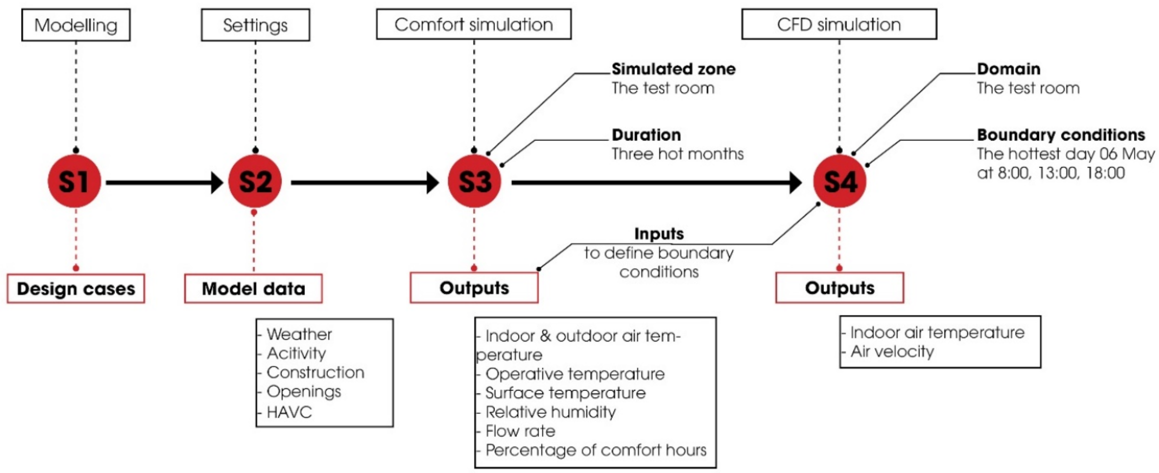


Figure 9.8 Simulation procedure

Figure 9.8 summarises the whole simulation procedure covering four steps. Step 1 is modelling and the test case, along with common design cases is identified. In Step 2, relevant data for calculations are inputted into the model, for example, weather, activity, construction, openings, and HVAC. Steps 3 and 4 are comfort and CFD simulations. Thermal conditions in the test room and design scenarios are analysed in Step 3. Then, the outputs deduced from that action are used as inputs to define the boundary conditions of the domain for CFD calculations.

9.3.2 Modelling

a. The orientation of shop-house planning in HCMC

According to the master land-use and urban spatial planning in HCMC until 2025, there have had orientations for the development of shop-house building market related to housing types and urban morphologies (HCMC People's Committee, 2013). In detail, shop-houses with the minimum site area of 60m² (4x15m) are priorities for enhancement in the next coming years. Furthermore, settlements will be formally planned with a regular pattern of buildings and road systems. Depending on the detailed land-use planning of particular regions or neighbourhoods, different shop-house dwelling types and urban spatial structures have proposed.

Table 9.1 The priority of shop-houses developed in HCMC in the future (HCMC People's Committee, 2013)

Features	Shop-house building types			
	Garden row house	**Urban row house**	**Garden new shop-house**	**Urban new shop-house**
Site dimension	5x20m (i) 5x17m (ii)	4 or 5 x15m	4 or 5 x20m (i) 4 or 5 x17m (ii)	4 or 5 x15m
Constrcution area	5x15m	4 or 5 x15m	4 or 5 x15m	4 or 5 x15m
Characteristics	_ Comply with archetypes _ Have front (3m) and back (2m) gardens (i) _ Have the only back (2m) garden (ii) _ Integration of light wells/void/courtyard _ Maximise daylight and natural ventilation design	_ Comply with archetypes _ No front and back gardens _ Integration of light wells (Op) _ Maximise daylight and natural ventilation design (Op)	_ Have front (3m) and back (2m) gardens (i) _ Have the only front garden (2m) (ii) _ Integration of light wells _ Maximise daylight and natural ventilation design	_ Back garden (Op) _ Integration of light wells (Op) _ Maximise daylight and natural ventilation design (Op)
No. of stories	4 to 5	4 to 5	2 to 5	3 to 5
Urban types	Type 1	Type 2	Type 1 and 3	Type 3
Location	In low (i) and medium (ii) density residential regions	In high density residential regions	In low (i) and medium (ii) density residential regions	In medium and high density residential regions

Notes: Op – optional

Table 9.1 represents four main shop-house building types and their characteristics, which have been orientated for the enlargement across the city. Among them, garden and urban row houses have been more important. For garden row houses, there are two sub-types classified by the standardised land size: 5x20m and 5x17m; however, the construction coverage of those buildings is similar to 5x15m and the remaining land area is used for gardens. Garden row houses of type (i) have two gardens: front (3m) and back (2m) while the type (ii) only has the back one. Planning such row houses has complied with the principles of pattern type 1 as shown in Chapter 4. Despite the houses grouped in the back-to-back pattern, there is a coupled buffer zone of 4m in width in-between two building rows to improve the penetration of natural light and wind into the interior at the backside. The housing architecture will follow archetypal forms; and building stories are popular between 4-5, for example in Figure 9.9-10.

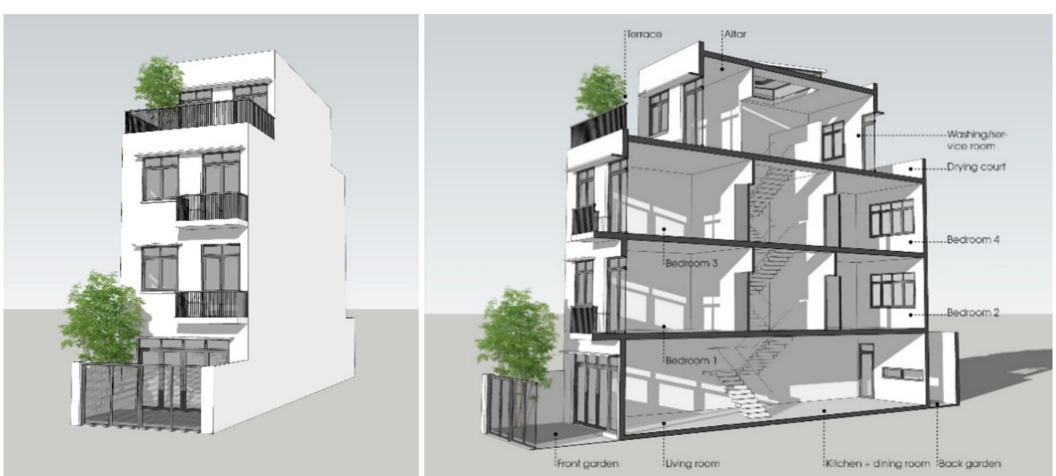


Figure 9.9 Basic architecture and spatial layout of garden row houses (i)

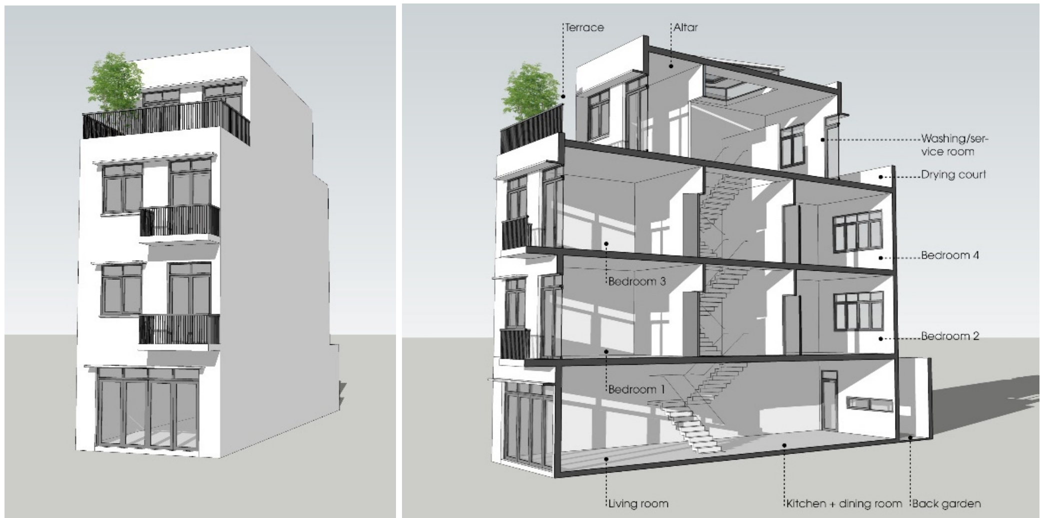


Figure 9.10 Basic architecture and spatial layout of garden row houses (ii)

Besides the dominant development of garden row houses, urban row houses of 5x15m and 4x15m dimensions have been recommended for the districts with high population density. In those areas, the allowed built-up area of a land plot is maximal. Planning urban row houses has complied with pattern type 2 characterised by an identical aspect (residences have no front and back gardens). Therefore, no buffer zone between two back-to-back building rows is disadvantageous to provide a satisfactory microclimate for spaces at the backside compared to garden row houses (Figure 9.11).

Figure 9.11 The basic architecture and spatial layout of urban row houses (ii)

Apart from the long-lasting priority of row houses, garden and urban new shop-houses have been built, but with a minor percentage and mainly focused on a more affordable market in HCMC. Those shop-house types can be planned following pattern types 1 and 3; however, the construction density of new shop-house neighbourhoods is much higher than in the areas of row houses.

b. *The hypothetical building for the study*

Combining the real observations of shop-house designs and the orientated settlement planning for shop-house residences in HCMC until 2025, the current project has proposed a generic model with a size of 5x17m for the further analysis of indoor environments in relation to variations of opening design features. As shown in Figure 9.12, the building model includes two parts: hard construction and adaptive soft construction (the back garden).

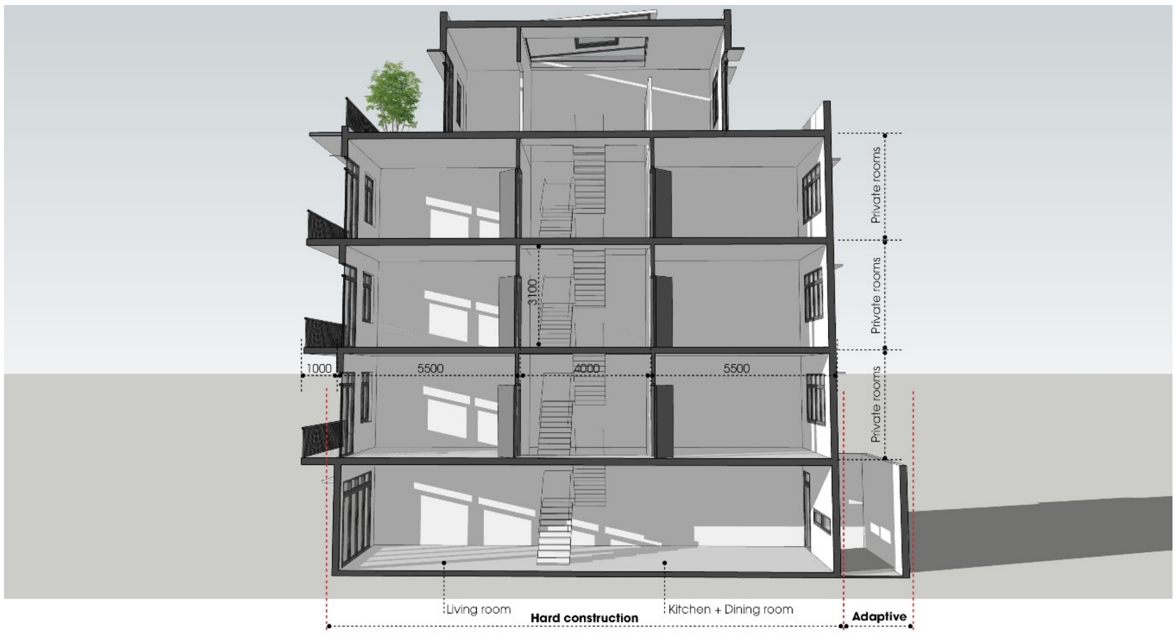


Figure 9.12 The structure of generic building model

For the hard construction, the building has been proposed with the standardised dimension of 5m(W) and 15m(L). Besides, it is assumed with the maximum use of five building stories, among them, the ground floor is designed as an open space for common rooms such as living + kitchen + dining rooms. Three upper floors can be used for private rooms such as the bedroom or studying/family room with a similar dimension. Service spaces and terraces are arranged on the top floor. Within the building, one staircase integrated into a light well is positioned to connect the all interior together. The size of circulation space is 5m(W) and 4m(L). The light well is advantageous for the access of natural light and airflow convection between spaces inside the building. On the main façade, 1m full-width overhangs are positioned at every floor for shading. 400mm overhangs area also organised for openings at the backside in the condition of the available back garden.

Meanwhile, the soft construction is adaptable to the different conditions of urban planning in residential neighbourhoods. The availability or unavailability of back garden has an impact on the opening organisation in the back wall. For example, the back garden is compulsory in planning garden row houses and shop-houses in pattern type 1. Meanwhile, such component is not applied in urban row houses in pattern type 2 or optional in new shop-houses in pattern types 3 and 4.

In the review of the methodology above, the building object simulated is mainly rooms. Figure 9.13 shows the position of rooms, which are independent of the light well. On external and internal walls, different opening variables will be applied for testing. It means that thermal environment in open spaces of the ground floor will not be investigated within the scope of the project because of the complex relationship with the volume air inside the light well and the top floor.

Figure 9.13 Rooms for testing

Table 9.2 describes the area of openings and their operable capability in windward and leeward surfaces of the ground and top floors, additionally, there is a skylight of 3m² with an opening percentage of 50% installed in the light well. The geometric characteristics of those openings are unchangeable during simulations.

Table 9.2 Opening characteristics on the ground and top floors and the light well

Position	Windward opening		Leeward opening	
	Opening area (m²)	Effective opening area (m²)	Opening area (m²)	Effective opening area (m²)
Ground floor	9.2	7.9	5.0	4.0
Top floor	6.3	5.3	5.0	4.1
Light well	Opening area (m²)		Effective opening area (m²)	
Skylight	3		1.5	

9.3.3 Design options for testing

a. The base case

In the hypothetic model analysed for the relationship between opening variables and environmental conditions, the typical case selected is a room positioned on level 1 as depicted in Figure 9.14. The room geometry is 5m(W), 5.5m(L), and 3.1m(H); and the following floor area and volume are 24m² and 74m³. That space has the only exposed wall oriented south and an internal wall toward the light well while two sidewalls touch adjacent neighbour houses. Both exterior and interior walls have a similar area of 15.5m².

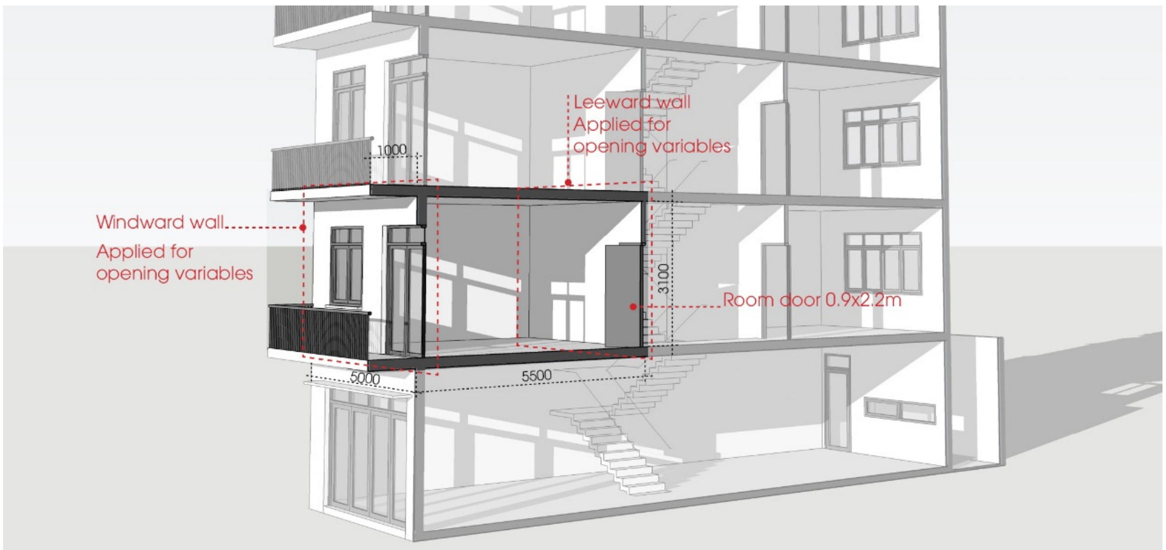


Figure 9.14 The typical case for testing

On the exterior wall, overhangs of 1m in depth are positioned to shade openings. Apart from the presence of an internal room door in the partition wall acting as a fixed outlet, openings with different features will be altered in both windward and leeward surfaces to evaluate their environmental impacts.

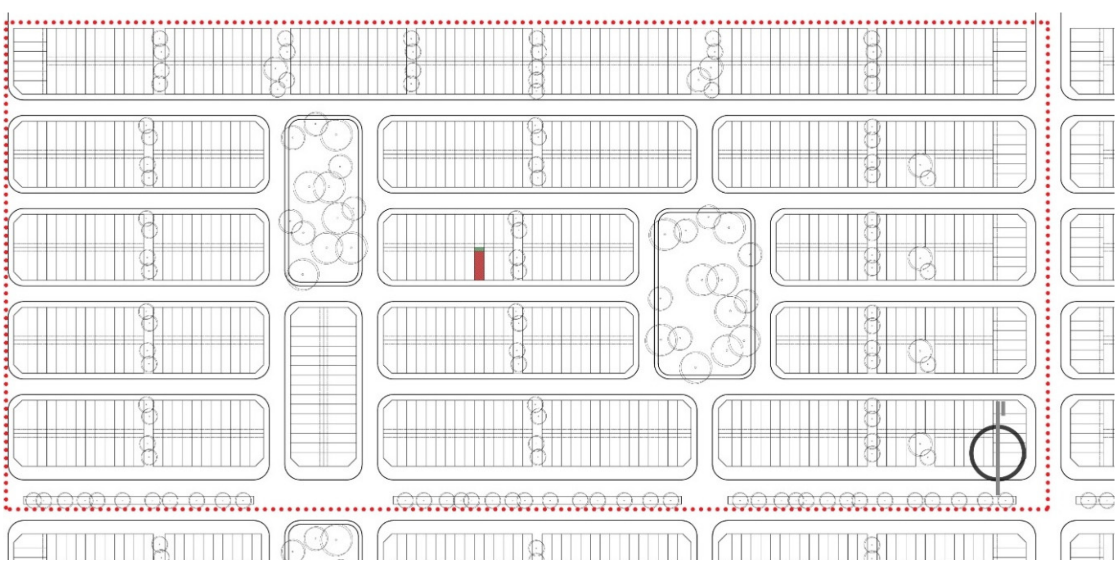


Figure 9.15 The model of the residential neighbourhood (pattern type 1) and the location of the simulated house

Returning to the theory of adaptive comfort, there is a correlation between the indoor and outdoor climate in naturally ventilated buildings (Humphreys, 1978). That has been confirmed in the current study in free-running shop-house dwellings. Furthermore, the project has also found a close relationship between outdoor microclimates and urban constituents forming various shop-house urban morphologies. Thereby, to get a reliable and precise analysis of indoor thermal performances, the simulated building is located in a settlement, which is also studied in different urban structures. For the base case, the pattern type 1 is selected. On the master plan, the building is located in the middle of the row (Figure 9.15). Taken together the assumption of hypothetic building and base case, Table 9.3 summarises their main characteristics for numerical analysis.

Table 9.3 Main features of the assumed building and room

Reference building	
Location (urban type)	Type 1
Orientation	South
Dimension	5m(W) x 17m(L)
Construction area	5m(W) x 15m(L)
Back garden	2m
Total of floors	5
Opening organisation	Openings in windward and leeward walls The light well has a skylight
Reference room	
Dimension	5m(W) x 5.5m(L) x 3.1m(H)
Location	Level 1
Orientation	South
Shading	A 1m overhang
Floor area	24sqm
Area of windward wall	15.5sqm
Area of leeward wall	15.5sqm
Inlet openings	Different opening variables studied
Outlet openings	1 room door (0.9m(W)x2.2m(H)
	Different opening variables studied

b. Studied scenarios

In the pilot study with professionals to examine their experience of the opening design, a set of nine opening features was proposed to collect their voting for the difficult variables in practical applications. In these, the orientation, area, ratio, type, placement, and pattern of openings were registered by larger votes. To produce a sample of design guidance, three factors (opening orientation, area, and ratio), along with their variations were researched by simulations of the generic room/building.

Table 9.4 Opening variables used for experiments

Opening variables	Parameters	% Operable area	No. of cases
Windward opening area	30%, 50%, 70%, 90%	50%, 100%	8
The ratio of inlet to outlet	4:1, 3:1, 2:1		24

As shown in Table 9.4, the first variable studied is the windward opening area. Reviewing the research literature in the suitable ratios of openings to the exposed wall for sufficient airflow environments indoors, as well as, the patterns of the opening area observed in the field studies, four common values examined include 30%, 50%, 70%, and 90%. Additionally, these parameters were considered in relation to two effective opening ratios – 50% and 100%. As a result, the total design scenarios based on the opening area was eight.

The second variable is the inlet/outlet ratio. Openings were positioned in both exterior and interior walls with three different ratios: 4:1, 3:1, and 2:1. Those parameters were evaluated incorporated into the eight scenarios of 'opening area', which formulated a total of 24 design cases. The third variable is the opening orientation. However, in the established conditions for the simulated model, opening and building orientations are similar.

Table 9.5 External variables and their range

<table>
<tr><th>External variables</th><th>Base case</th><th>Parameters</th><th>Opening variable</th><th>No. of cases</th></tr>
<tr><td>Urban type</td><td>Type 1</td><td>Type 2, Type 3, Type 4</td><td rowspan="3">8 cases of windward opening area</td><td>24</td></tr>
<tr><td>Building orientation</td><td>South</td><td>North, East, West</td><td>24</td></tr>
<tr><td>Floor position</td><td>Level 1</td><td>Level 2, Level 3</td><td>16</td></tr>
</table>

Based on real climates for occupant comfort in shop-houses analysed in the previous chapters, the building physics is controlled by both the building fabric and contextual conditions around buildings. Therefore, although the present research has focused on the influences of opening design features on indoor thermal environments, that has also considered the impact of external factors such as the urban morphology, the building orientation, and the room position as shown in Table 9.5. For urban spatial structures, four types 1, 2, 3 and 4, which are dominant in the city land-use, were studied. There were four main building orientations tested including south, north, east, and west, among them, the south direction is defined as a base case. The pressure of outdoor winds hitting the building is different by the building height; therefore, another external variable considered in the present research is the floor level.

9.3.4 Simulation settings

- Weather data

The first action of the simulation procedure is to load location and weather data of where the project is presented. The weather file of HCMC used is formatted by Typical-Year Weather Data - IWEC2, which was developed for ASHRAE by White Box Technologies over the period of 12-25 years. The meteorological database of HCMC recorded between 1985 and 2006 are monthly averaged in Table 9.6.

Table 9.6 The meteorological characteristics of HCMC by IWEC2 weather file

Values	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air temperature												
Min	18.7	20.3	22.0	22.9	22.0	23.0	23.0	22.0	22.9	22.5	20.0	18.0
Mean	26.4	27.5	28.3	29.2	29.0	28.9	27.3	27.5	27.6	26.9	26.7	26.0
Max	34.1	35.0	36.4	35.5	37.6	36.0	33.2	34.0	34.0	33.0	34.3	33.0
Relative humidity												
	72.6	69.4	69.4	75.2	84.2	84.6	79.7	88.4	86.4	87.2	82.1	78.7
Air velocity												
	2.3	2.4	3.7	3.0	3.2	3.1	2.3	3.2	2.2	2.2	1.9	2.0
Direct normal solar												
	11.6	71.0	76.3	100.6	112.5	145.5	135.6	94.5	115.5	68.2	93.0	76.2
Diffuse horizontal solar												
	77.6	92.3	82.1	76.1	74.6	82.4	85.7	95.3	89.1	102.4	96.5	92.6

The hottest season in HCMC occurs from March to June with the average and maximum temperatures of 29 and 37.5°C, respectively. The monthly mean air velocities vary between 1.9-3.7m/s. In summer, outdoor average winds are higher than in other seasons. The hot air accelerated by the involvement of intense solar radiation can result in pressures on occupant thermal comfort in urban environments, which can also link to discomfort for indoor climates.

- Activity data

Due to the aim of simulations, which mainly tests the influence of the building fabric, particularly openings, on indoor comfort conditions, the occupancy density was set by 0.0 on 24/7. Subsequently, the parameters of household appliances were not informed. Therefore, the indoor thermal environment was not heated by internal sources. Furthermore, as the current study has concentrated on the indoor climate naturally ventilated entirely in relation to the outdoor environment, settings for the environmental control by set-point temperatures and humidities related to the occupant activity were not inputted.

- Thermal properties of building elements

The materials set up for the model comply with the current construction practice of low-rise residential buildings including shop-houses in Vietnam as summarised in Table 9.7. The main housing structure is in-situ reinforced concrete together with brick walls. The respective thickness of external and internal brick walls is 200mm (U-value = 2.23W/m²K) and 100mm (U-value = 2.97W/m²K). The full thickness of the internal and external floors including finishing layer, cement, concrete slab, and gypsum ceiling is 200mm with the U-value of 1.45W/m²K. Meanwhile, the roof of 200mm in thickness has the U-value of 2.2W/m²K. The U-value of the ground floor was set at 1.63W/m²K. Besides the hard-constructed elements, apertures on the building fabric are sealed by the windows and doors consisting of a single pane of glass with the thermal transmittance of 5.59W/m²K. Those construction data are constant during calculations of all cases.

Table 9.7 Materials and thermal transmittance of main building elements

Building elements	Materials	Thickness	U-value (W/m²K)
Ground floor	Cement plaster + Lining concrete + Expanded Polystyrene + Sand	350mm	1.63
Internal floor	Finishing layer + Cement + Concrete + Gypsum ceiling	200mm	1.45
External floor	Finishing layer + Cement + Waterproof + Concrete + Gypsum ceiling	200mm	1.45
Roof	Waterproof + Cement + Concrete + Gypsum ceiling	200mm	2.20
External wall	Brick (2 layers) + Plaster layers	200mm	2.23
Internal wall	Brick (1 layer) + Plaster layers	120mm	2.97
Openings	Single glazing	8mm	5.59

- Opening data

The current research has emphasised the thermal environment inside non-air-conditioned residences in Vietnam; consequently, external and internal doors and windows were open 100% under the operative schedule of 24/7. In addition, the discharge coefficient of all windows was controlled at the value of 1.0, which allows the actual airflow discharge to be maximal through openings. It is noted that the opening area positioned in the exterior or interior wall or both of the base case were manually altered on the model instead of inputting data on the setting editor. Besides, the material template for windows and doors was loaded as the description in Table 9.7.

- HVAC data

The main cooling principle studied in the present work is natural ventilation. Therefore, in the HVAC template tab, 'Natural ventilation- No heating and cooling' was selected with the model option of 'Natural ventilation' activated during the whole day. In the editing screen of 'Natural ventilation', the limits of outdoor temperature and Delta T were turned off to ensure no restrictions on the operation of natural ventilation within the building case during calculations even any temperature differences between the indoor and outdoor climate. Additionally, the natural ventilation was controlled by the constant mode, which allows the model with zones having operable windows and doors opened for air movement and fresh air with no dependence on the interior or exterior temperatures. The full treatment of the wind effect was on; therefore, the wind factor was set at 1.0.

- Simulation calculations

There are two main computational calculations used to examine the thermal performance in the test room of the building model. Firstly, that is the comfort simulation, which was analysed for the hottest period (March-May) in HCMC. The meteorological data over that period is indicated in Table 9.6. In the setting dialogues of calculation, the mode of natural ventilation is shifted from 'Scheduled' to 'Calculated', which means that the effect of air movement inside the building is assumed by natural driven forces, opening features, and their operation.

The platform of DesignBuilder carries out numerical analysis by zone within the building. For the current study, the zone examined is a typical room facing south, on level 1 – see Section 9.3.3. To achieve the accuracy of simulated results, a higher number of time steps per hour should be applied. The value entered was 4 that is recommended for simulating non-air-conditioned zones by EnergyPlus. In other words, the analytical technique by EnergyPlus operates 4 steps within 60 minutes.

Secondly, the term of CFD was used to investigate the thermal and airflow environment within the test room, which was defined as a domain for settings, simulations, and presentation of results. The CFD modelling software shows the high preciseness of assumed environments according to an hourly or sub-hourly scale on a specific day. Therefore, CFD calculations were conducted to test thermal and air movement conditions in the typical room through various opening design features applied on the hottest day (06th May) across the whole year at typical three-time scales: 8:00, 13;00, and 18:00. The internal CFD analysis includes basic steps: identify the boundary conditions for simulations; set/edit the CFD grid system; and inform calculation options (turbulence model, discretisation scheme, iterations, etc.).

The CFD boundary conditions are formed by two variables: airflow and temperature. The boundary type of airflow focuses on the air movement in and out an interior space through openings in walls. Meanwhile, the thermal boundary contains surface, inside, and outside temperatures. Data in the boundary editor are imported from EnergyPlus comfort simulation outputs according to single hours or sub-hours. CFD calculations are effective when in and out flows in the domain balance.

The grid system used for the numerical analysis of DesignBuilder CFD was the Cartesian type characterised by two-dimensional grids and non-uniform cells. This system is determined to be appropriate for domains of normal geometry. Within the domain of test room, a 3-D grid region was displayed before calculations with two parameters: grid spacing (0.3m) and grid line merge tolerance (0.03) for the current study. The space between grids is advised between 0.05 and 0.5m for a room with dimensions below 20m (Nielsen, Allard, Awbi, Davidson, & Schalin, 2007).

To run CFD calculations, one of two turbulence models was defined. For the research, the k-e model belonging to RANS (Reynolds Averaged Navier-Stokes) is appropriate to apply to fluctuated airflow environments. Besides, the second setting was the upwind discretisation scheme allowing the assumption of the convective term. The effect of the isothermal factor is not assumed to respect the naturally thermal condition in the domain. The surface heat transfer coefficients are calculated when the k-e turbulence model for CFD calculations is selected. Table 9.8 summarises all settings of parameters and calculations.

Table 9.8 Summary of settings for simulations

Settings	**Details**
Model data	
Weather	HCMC IWEC2
Activity	No occupancy density Operation: On 24/7
Construction	See Table IX.7
Openings	Doors - 100% opened Windows - 100% opened, discharge coefficient of 1.0 Operation: On 24/7
HVAC	
HVAC template	Natural venitlation - No heating/cooling
HVAC model option	Natural ventilation Operation: On 24/7
Comfort simulation	
Natural ventilation & Infiltration	Calculated
Simulation options	01 March - 30 May (the hottest months)
Calculation options	Time steps per hour: 4 Temperature control: Air temperature
Simulated zone	The test room (level 1, south orientation)
CFD simulation	
Domain	The test room (level 1, south orientation)
Boundary conditions	8:00, 13:00, and 18:00 on the hottest day (06 May)
Grid system	Grid spacing: 0.3 Grid merge line tolerance: 0.03
Calculation options	
Turbulence model	RANS's standard k-e turbulence model
Discretisation scheme	Upwind
Iterations	5000
Isothermal	Not assumed
Surface heat transfer	Calculated

- Outputs

The conduction of comfort calculations for the domain tested issued environmental outputs used for assessing the indoor comfort level. Indices for assessments include air/mean radiant/operative temperature, relative humidity, the flow rate through the room showed into tables for the hottest day at 8:00, 13:00, and 18:00.

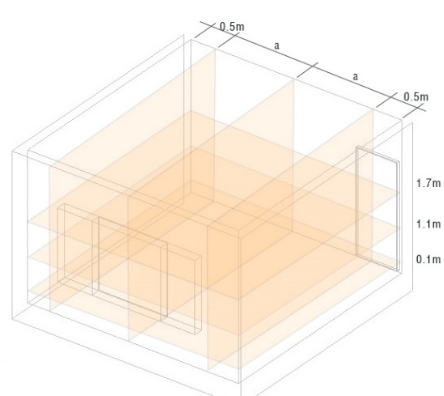


Figure 9.16 Planes of results shown within the domain after CFD calculations

With the same domain, CFD calculations are conducted at different times: 8:00, 13:00, and 18:00 on the hottest day over the whole year (06 May). The environmental boundary for calculations is identified by the environmental indices extracted from comfort analyses in those periods. The CFD results related to air velocity in the domain are displayed by horizontal contour slices at three different heights (0.1, 1.1, and 1.7m) within the occupied zone. Furthermore, vertical slices are also shown in three typical positions (0.5m away from sidewalls and in the middle of the room) – see Figure 9.16.

9.3.5 Results of parametric studies

9.3.5.1 Opening area

The environment in the test room was simulated in applications of the first variable – various opening areas against the exposed wall. In the same windward surface of 15.5sqm, four common cases assumed include 30%, 50%, 70%, and 90% corresponding to opening areas: 4.5, 7.5, 10.5, and 13.5sqm. In addition, those glazed areas were also investigated when the percentage of free aperture changes between 50-100%. A total of 8 design scenarios of opening area are shown in Table 9.9.

Table 9.9 Eight design cases of the opening area

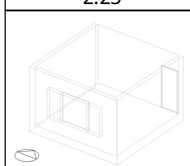
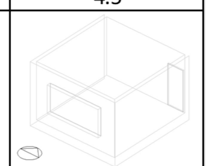
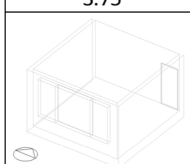
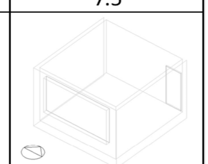
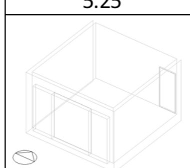
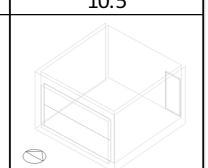
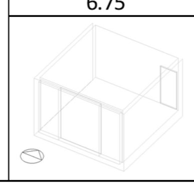
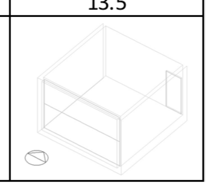
<table>
<tr><th rowspan="2">Exposed wall area (m²)</th><th rowspan="2" colspan="2">Opening area (m²)</th><th colspan="2">% Free aperture</th></tr>
<tr><th>50%</th><th>100%</th></tr>
<tr><td rowspan="8">15.5</td><td rowspan="2">30%</td><td rowspan="2">4.5</td><td>2.25</td><td>4.5</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">50%</td><td rowspan="2">7.5</td><td>3.75</td><td>7.5</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">70%</td><td rowspan="2">10.5</td><td>5.25</td><td>10.5</td></tr>
<tr><td></td><td></td></tr>
<tr><td rowspan="2">90%</td><td rowspan="2">13.5</td><td>6.75</td><td>13.5</td></tr>
<tr><td></td><td></td></tr>
</table>

Table 9.10 demonstrates average thermal conditions in the test room analysed with applications of varying opening areas in the windward wall over the hot summer. The main features of the base case are

described in Section 9.3.3. Indoor environments are characterised by parameters: various temperature indices, relative humidity, and volume flow rate. Some conclusions deduced are as follows:

• In the context of the building facing south, the expansion of openings in the exposed wall does not have significant impacts on thermal environments related to temperature and humidity inside the room tested. Table 9.10 likely shows no differences between average indoor air/operative temperatures, and between humidity levels in eight cases calculated across summertime, even the operable area increased from 50% to 100% or the increased ratio of the opening area between 30-90%.

• However, there is a positive relationship between the opening area and the flow rate. The air change rate improved by about 15% when the area of free aperture increased double over the same opening. In the fixed condition of 50% effective opening area, when the glazed area changed from 30% to 90%, the value of Fa also rose from 59 to 80ach.

Table 9.10 Thermal conditions inside the test room with different opening areas on the hottest day

Opening area	**% Free aperature**									
	50%									
	Ta °C	SD	MRT °C	SD	Top °C	SD	RH %	SD	Fa ac/h	SD
30%	28.8	2.5	29.4	1.2	29.1	1.7	75	13	59	46
50%	28.8	2.6	29.5	1.2	29.2	1.7	75	13	73	56
70%	28.9	2.6	29.7	1.2	29.3	1.8	76	13	78	57
90%	28.9	2.7	29.8	1.3	29.3	1.9	76	14	80	57
	100%									
	Ta °C	SD	MRT °C	SD	Top °C	SD	RH %	SD	Fa ac/h	SD
30%	28.9	2.6	29.4	1.2	29.1	1.7	76	13	75	57
50%	28.9	2.6	29.5	1.2	29.2	1.8	76	14	82	31
70%	28.9	2.7	29.7	1.3	29.3	1.9	76	14	86	56
90%	28.9	2.7	29.8	1.3	29.3	1.9	76	14	91	54
Note	*Ta: mean air temperature (°C) ; Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ac/h)*									

Tables 9.11-12 analyse further environmental performances, particularly airflow distributions within the typical room on the hottest day through CFD simulations.

• The interior environment was acceptable in the morning, warm around noon, and fairly warm in the early evening in all design cases studied relative to the upper comfort limit (31.5°C) found in Chapter 6. There was a discrepancy of 3-4°C and 1.5-2.0°C in the operative temperature simulated between afternoon and morning and between afternoon and evening during the hottest day, respectively. Such a difference in the thermal environment was certain wider when the free aperture of openings or opening area in the exterior wall increased.

• Considering the cases tested with both parameters: the unchangeable opening area and the enlarged operable area, there was a warmer condition by up to 0.5°C found in the cases with a larger percentage of free aperture. In another investigation, the increase of upwind opening area can gain room temperature, particularly around noon. Both air and operative temperatures were warmer within a range of 1°C due to the access of solar gains. Meanwhile, they were similar in two remaining times examined despite changes in the opening area or operable area.

Table 9.11 Thermal conditions inside the test room with different opening areas on the hottest day

Opening area (m2)		% Free aperture					
		50%			100%		
		08:00	13:00	18:00	08:00	13:00	18:00
30%	**4.5**	**2.3**			**4.5**		
	Ta	31.2	35.5	32.4	31.3	35.9	32.4
	Top	31.2	34.0	32.5	31.2	34.3	32.9
	Va	0.10	0.14	0.30	0.10	0.16	0.29
	Fa	22	3	85	30	11	107
	RH	66	46	60	66	45	60
50%	**7.5**	**3.8**			**7.5**		
	Ta	31.3	35.9	32.4	31.3	36.3	32.4
	Top	31.3	34.4	33.0	31.3	34.7	33.0
	Va	0.08	0.14	0.26	0.08	0.16	0.23
	Fa	25	10	104	32	25	114
	RH	66	45	60	66	44	60
70%	**10.5**	**5.3**			**10.5**		
	Ta	31.3	36.2	32.4	31.3	36.6	32.4
	Top	31.4	34.8	33.1	31.4	35.0	33.1
	Va	0.14	0.13	0.29	0.11	0.11	0.31
	Fa	36	20	110	41	41	116
	RH	66	44	60	66	43	60
90%	**13.5**	**6.8**			**13.5**		
	Ta	31.3	36.5	32.5	31.3	36.8	32.4
	Top	31.4	35.1	33.2	31.5	35.3	33.2
	Va	0.11	0.11	0.25	0.10	0.16	0.30
	Fa	35	28	113	41	55	123
	RH	66	44	60	66	43	60
Note	*Ta: mean air temperature (°C) ; Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ac/h)*						

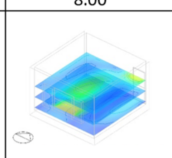
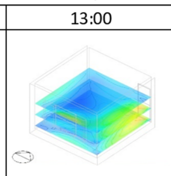
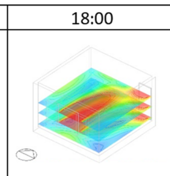
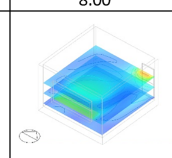
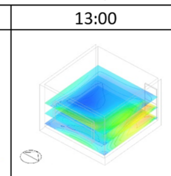
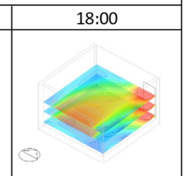
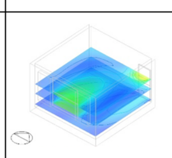
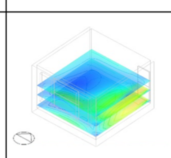
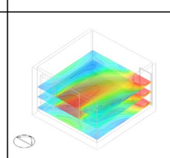
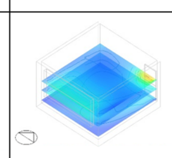
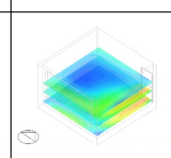
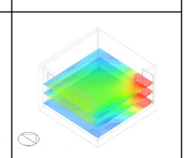
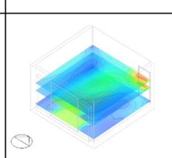
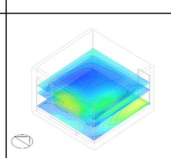
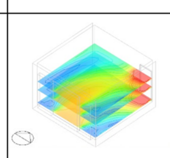
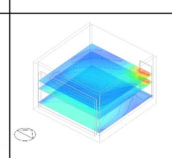
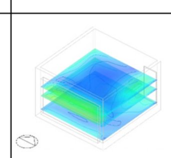
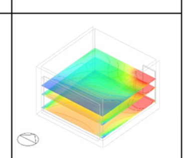
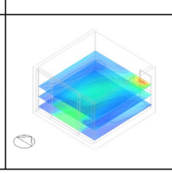
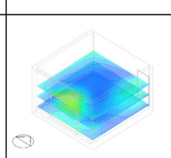
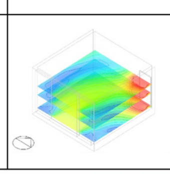
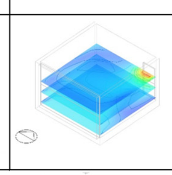
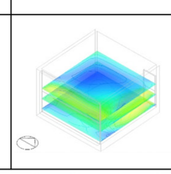
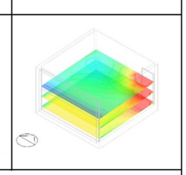
• Operative temperatures tended to be equal to or lower than air temperatures from the morning to afternoon. Meanwhile, that pattern was convertible at night. The operative temperature was 0.5-0.8 warmer than the air temperature, which could be attributed to the impact of heat radiation from internal surfaces after sunset.

• A consistent pattern of airflow performs within the space despite an increase of opening area in the windward wall. During CFD calculations, apart from the internal room door opened, no other windows/doors were organised in the downwind surface. Calm and consistency of interior wind environments in eight cases proves that if there are only inlet openings, their enlargement negligibly improves internal airflow.

• Although simulations were carried out with the similar conditions of physical model and weather data, wind flows surrounding the building fluctuated all the time. Exposure to the varying direction and pressure of incident winds to the windward wall during the day resulted in differences in airflow inside the test room. The air velocity calculated at 18:00 was much higher than that at other periods. Meanwhile, a stressful thermal environment indoors for all the studied cases at noon was possible because of the hot temperature and light air movement.

• The predominant warmth is disadvantageous to human comfort on the hottest day, particularly when openings in the external wall are bigger. However, the effect of airflow to retain comfort is negligible due to the only mechanism of single-sided ventilation. The maximum air movement inside the testing room reached 0.3m/s that was not effective at the climate of over 31.5°C (referring to the acceptable zone of air movement found in Chapter 7). On the other hand, the air change rate benefits from the enlargement of openings. Although the thermal and airflow conditions were unsatisfactory for occupants, the ventilation of such room was good in most cases and most time points examined, excepting some cases of 30% opening area + 50% and 100% free aperture and 50% opening area + 50% free aperture. The high values of airflow rate contribute to heat loss in the space faster.

Table 9.12 Airflow distribution within the domain of the test room at different times

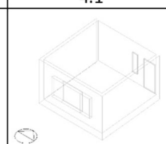
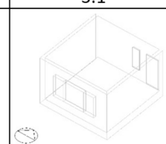
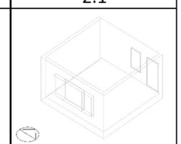
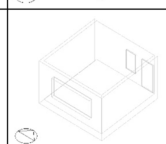
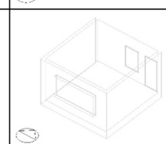
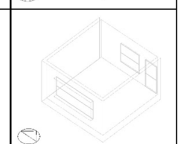
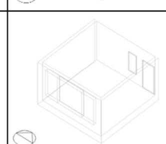
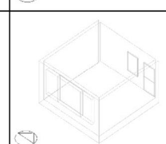
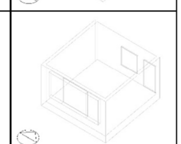
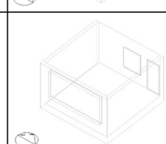
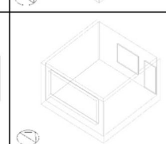
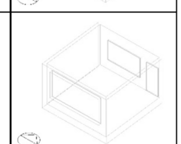
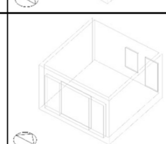
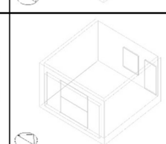
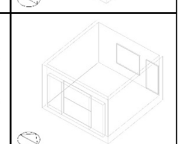
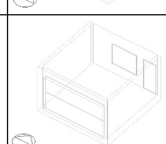
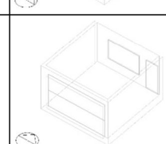
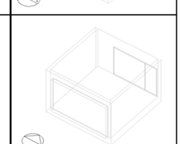
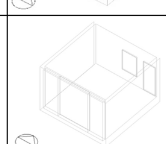
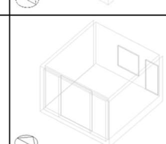
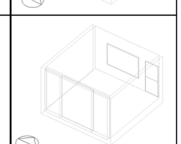
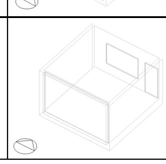
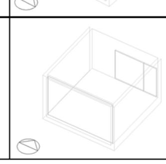
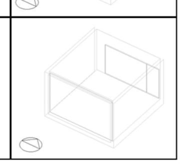
Opening area (m^2)		Free aperture					
		50%			100%		
		8:00	13:00	18:00	8:00	13:00	18:00
30%	4.5						
50%	7.5						
70%	10.5						
90%	13.5						
Air velocity range							

• Apart from the assessment of airflow conditions by airspeeds, the airflow distribution around the room was different between three heights above the floor and between areas within the occupied zone according to different time scales – see Table 9.12. That is explained by the fluctuation of outdoor winds before supplying to the interior. Furthermore, the airflow pattern was changed owing to the effect of the opening area. In the cases of 30% and 50% opening area, higher airspeeds mainly distribute at medium and high levels of the human body while in other situations (70% and 90% of the glazed area), the pattern of higher airflow was wider and more uniform at three levels, particularly at the low and medium body.

9.3.5.2 The ratio of the inlet to outlet openings

This section discusses the effect of the inlet-outlet ratio on the thermal environment within the space. There are three variations researched: 4:1, 3:1, and 2:1, which are respectively coupled with the eight cases of the opening area variable shown in the above. Consequently, 24 design cases are summarised in Table 9.13, which shows various correlations of the area between upwind and downwind openings. Reviewing the research literature of the relationship between indoor wind environment and inlet-outlet ratio, the smaller the ratio, the more sufficient airflow.

Table 9.13 Design cases of the inlet-outlet ratio studied

Exposed & internal wall area (m²)	**Opening area (m²)**	**Free opening area (m²)**	**Opening ratio (Inlet/outlet)**		
			4:1	3:1	2:1
15.5	30%	50%			
		100%			
	50%	50%			
		100%			
	70%	50%			
		100%			
	90%	50%			
		100%			

The simulation results for the typical room within three summer months shown in Table 9.14 present a similar pattern of thermal and humid environments in applications of different opening ratios between windward and leeward walls to analyses with different opening areas. Put another way, it is certain that no divergences in the internal average air temperature, operative temperature, and relative humidity were found under alterations to the inlet-outlet ratios. The average air temperature, operative temperature, and humid level were similar between 24 examined cases. However, the larger opening area from 30% to 90% explained the increase of average mean radiant temperature by 0.4°C because of the absorption of solar heat. In addition, the difference between MRT and T_{op} within the range of 0.3 – 0.5°C showed moderation by indoor air velocities.

In the comparison of internal thermal conditions when the effective opening area was enhanced from 50-100%, there was also a similarity, which indicates that the influence of opening design features related to the opening area and the inlet/outlet ratio on indoor temperatures and humidities is negligible for rooms facing south on level 1, although the interior environment was slightly warmer when the glazed area was larger.

Table 9.14 Average thermal conditions in the test room with different inlet-outlet ratios

Opening area	Opening ratio	Free aperature									
		50%									
		Ta °C	SD	MRT °C	SD	Top °C	SD	RH %	SD	Fa ac/h	SD
30%	**4:1**	28.9	2.5	29.4	1.2	29.1	1.7	76	13	60	48
	3:1	28.9	2.5	29.4	1.2	29.1	1.7	76	13	67	52
	2:1	28.9	2.5	29.4	1.2	29.1	1.7	76	13	70	54
50%	**4:1**	28.9	2.6	29.5	1.2	29.2	1.8	76	14	91	71
	3:1	28.9	2.6	29.5	1.2	29.2	1.8	76	14	97	75
	2:1	28.9	2.6	29.5	1.2	29.2	1.8	76	14	104	81
70%	**4:1**	28.9	2.7	29.6	1.3	29.3	1.9	76	14	110	84
	3:1	28.9	2.7	29.6	1.3	29.3	1.9	76	14	117	89
	2:1	28.9	2.7	29.6	1.3	29.3	1.9	76	14	130	100
90%	**4:1**	28.9	2.7	29.8	1.3	29.3	1.9	76	14	125	95
	3:1	28.9	2.7	29.8	1.3	29.3	1.9	76	14	137	104
	2:1	28.9	2.7	29.8	1.3	29.3	1.9	76	14	155	119
		100%									
		Ta °C	SD	MRT °C	SD	Top °C	SD	RH %	SD	Fa ac/h	SD
30%	**4:1**	28.8	2.6	29.4	1.2	29.1	1.7	76	14	101	78
	3:1	28.8	2.6	29.4	1.2	29.1	1.8	76	14	107	83
	2:1	28.8	2.7	29.4	1.2	29.1	1.8	76	14	117	91
50%	**4:1**	28.8	2.7	29.5	1.2	29.2	1.8	76	14	134	102
	3:1	28.8	2.7	29.5	1.3	29.2	1.8	76	14	146	113
	2:1	28.8	2.7	29.5	1.3	29.2	1.9	76	14	168	130
70%	**4:1**	28.8	2.8	29.5	1.3	29.2	1.9	76	14	159	119
	3:1	28.8	2.8	29.5	1.3	29.2	1.9	76	14	176	133
	2:1	28.8	2.8	29.5	1.3	29.2	1.9	76	14	206	157
90%	**4:1**	28.8	2.8	29.8	1.4	29.3	2.0	76	14	184	136
	3:1	28.8	2.8	29.8	1.4	29.3	2.0	76	14	204	154
	2:1	28.8	2.8	29.8	1.4	29.3	2.0	76	14	240	183
Note		*Ta: mean air temperature (°C) ; Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ac/h)*									

The availability of openings in both external and internal walls results in a significant rise in ventilation rate within the space. That parameter's amount grew from 15% to 30% when the difference between the inlet and outlet area was narrower. The flow rate benefits from a combination of a smaller ratio and larger openings. Compared to the room opened at a single side, the air change rate increased by around 70% in the condition of openings positioned in opposite walls.

Table 9.15 Thermal profile in 24 design cases under changes in the inlet-outlet ratio

Opening area (m2)	% Free aperature	Parameter	Ratio of inlet to outlet openings								
			4:1			3:1			2:1		
			08:00	13:00	18:00	08:00	13:00	18:00	08:00	13:00	18:00
30% (4.5)	2.3 (50%)	Ta	31.2	35.5	32.4	31.2	35.6	32.4	31.2	35.6	32.4
		Top	31.2	34.1	32.9	31.2	34.1	32.9	31.2	34.1	32.9
		Va	0.11	0.13	0.32	0.11	0.12	0.32	0.12	0.13	0.32
		Fa	24	3	95	25	3	97	26	2	101
		RH	66	46	60	66	46	60	66	46	60
	4.5 (100%)	Ta	31.3	35.9	32.4	31.3	35.9	32.4	31.3	35.9	32.4
		Top	31.2	34.3	32.9	31.2	34.3	32.9	31.2	34.3	32.9
		Va	0.12	0.13	0.35	0.12	0.14	0.37	0.13	0.14	0.38
		Fa	38	8	146	40	8	155	43	7	170
		RH	66	45	60	66	45	60	66	45	60
50% (7.5)	3.8 (50%)	Ta	31.3	35.9	32.4	31.3	36.0	32.4	31.3	36.0	32.4
		Top	31.3	34.5	33.0	31.3	34.5	33.0	31.3	34.5	33.0
		Va	0.10	0.13	0.30	0.11	0.13	0.32	0.12	0.13	0.36
		Fa	30	9	132	32	9	140	34	8	151
		RH	66	45	60	66	45	60	66	45	60
	7.5 (100%)	Ta	31.3	36.3	32.4	31.3	36.3	32.4	31.3	36.3	32.4
		Top	31.3	34.7	33.0	31.3	34.7	33.0	31.3	34.7	33.0
		Va	0.11	0.12	0.35	0.12	0.11	0.37	0.13	0.12	0.40
		Fa	46	21	192	49	20	210	53	19	241
		RH	66	44	60	66	44	60	66	44	60
70% (10.5)	5.3 (50%)	Ta	31.3	36.3	32.4	31.3	36.3	32.4	31.3	36.3	32.4
		Top	31.4	34.8	33.1	31.4	34.8	33.1	31.4	34.8	33.1
		Va	0.18	0.12	0.36	0.18	0.12	0.59	0.20	0.12	0.68
		Fa	48	19	159	51	18	168	55	18	188
		RH	66	44	60	66	44	60	66	44	60
	10.5 (100%)	Ta	31.3	36.6	32.4	31.3	36.6	32.4	31.3	36.6	32.4
		Top	31.4	35.0	33.1	31.4	35.0	33.1	31.4	35.0	33.1
		Va	0.17	0.11	0.59	0.19	0.12	0.66	0.20	0.16	0.55
		Fa	68	38	227	73	37	252	81	37	296
		RH	66	44	60	66	44	60	66	44	60
90% (13.5)	6.8 (50%)	Ta	31.3	36.5	32.4	31.3	36.5	32.4	31.3	36.5	32.4
		Top	31.4	35.1	33.1	31.4	35.1	33.1	31.4	35.1	33.1
		Va	0.14	0.13	0.34	0.16	0.12	0.36	0.18	0.12	0.40
		Fa	50	26	179	53	25	197	58	25	223
		RH	66	44	60	66	44	60	66	44	60
	13.5 (100%)	Ta	31.3	36.7	32.4	31.3	36.7	32.4	31.3	36.7	32.4
		Top	31.4	35.3	33.1	31.4	35.3	33.2	31.4	35.3	33.2
		Va	0.14	0.13	0.43	0.16	0.11	0.50	0.17	0.16	0.58
		Fa	70	50	260	75	50	290	82	49	341
		RH	66	43	60	66	43	60	66	43	60
Note		*Ta: mean air temperature (°C) ; Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ac/h)*									

On the hottest day, airflow in the room was calm until the late afternoon due to a disconnect to outdoor winds (Table 9.15). Reviewing meteorological data, although winds around the building are sufficient with airspeeds of 6m/s at 8:00 and 4m/s at 13:00, the angle between the windward wall and incident winds was likely zero. Thereby, the airflow condition was poor despite the availability of inlet and outlet openings; their large area; and the better ratio between them. That confirms the similar conclusion deduced from studies of Konya (1980); Givoni (1991); Allard (1998); Tang (2007); and Dekay, Mark and Brown (2014). Low airspeeds and warm temperatures were inadequate to create occupant comfort, particularly at noontime. Based on the negative relationship between indoor and outdoor wind environments reported due to the incompatibility between the directions of base building/room and winds during the daytime, air movement can be higher within buildings orientated east.

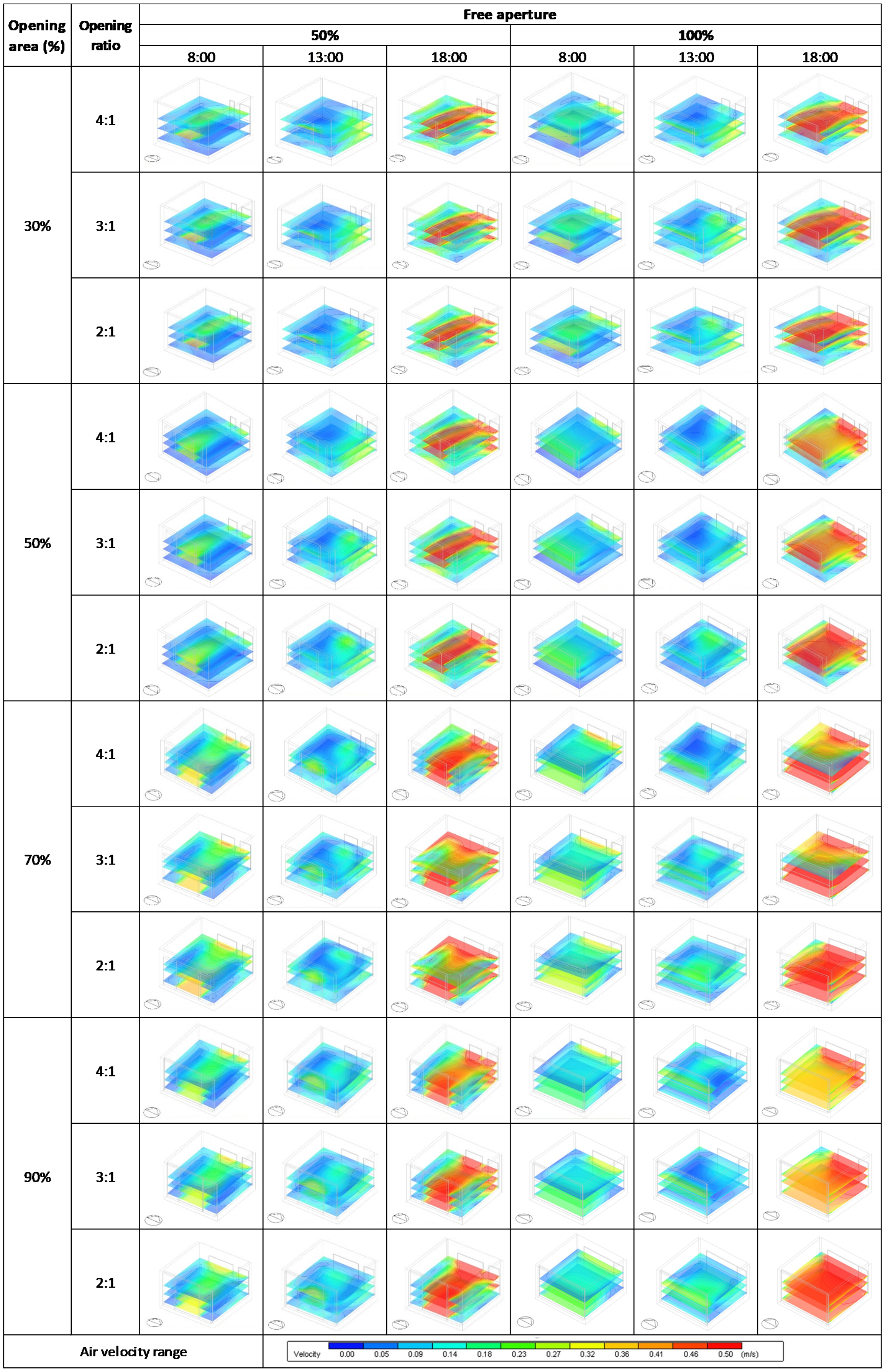
Based on meteorological data at 18:00, the outdoor wind mainly comes from the southeast. Thus, indoor airflow was also more adequate for occupant satisfaction with higher air velocities and wider distribution of sufficient airflow within the space (Tables 9.15-16). CFD calculations of the smaller inlet-outlet ratios showed higher airspeeds during the simulated time. For example, a good case found was a room with 70% opening area and 50% operable area, which was ventilated by an airspeed of 0.68m/s at the inlet-outlet ratio of 2:1 relative to 0.36m/s at the ratio of 4:1 (Table 9.15).

In addition, taking two factors (a smaller ratio of inlet-outlet openings and their suitable area) together positively affected the interior airflow. By comparison of airspeeds at 18:00 between two design scenarios characterised by similarities of 50% free aperture and the ratio - 2:1; and a difference in the opening area: 30% (i) and 70% (ii), the airspeed in case (ii) doubled than that in another.

The ratio of the inlet to outlet opening does not likely influence the indoor thermal condition, evidently because the investigation of air and operative temperatures in the hypothetic model on the hottest day showed their similarity despite changes in different values of the ratio. On the other hand, alike the finding by the study of the first opening variable (opening area), the enlargement of windward openings is not advantageous to human thermal comfort. For example, considering parameters such as the maximum free aperture and the inlet-outlet ratio of 2:1, the air temperature at 13:00 in the testing case with the OWR of 30% was lower by 0.7°C and 0.8°C than others of 70% and 90% opening to wall ratio, respectively. Additionally, the corresponding divergence of operative temperature was 0.9 and 1.0°C. The reason for warmer conditions is the impact of solar heat on the indoor space. Meanwhile, the large upwind opening area combined with a suitable inlet-outlet ratio is significant on internal air movement. In the similar conditions above for testing, the airflow velocity at 18:00 increased 0.17 and 0.2m/s when the OWR values changed from 30% to 70% and 90%, respectively.

There were discrepancies in airflow pattern between different inlet-outlet ratios classified into four groups of opening area. The red zone indicating higher air velocities was wider and more uniform when the area of outlets increased – see Table 9.16. Furthermore, relied on the contour maps of airspeeds within the typical room, more sufficient airspeeds mainly presented at night-time and uniformly distributes within the occupied zone.

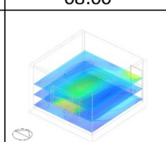
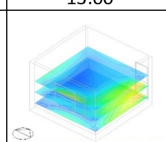
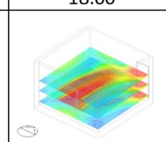
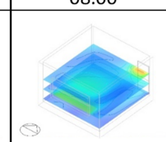
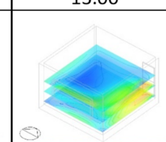
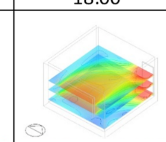
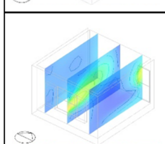
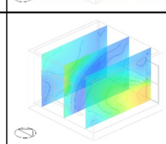
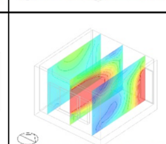
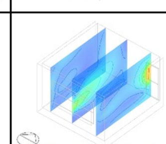
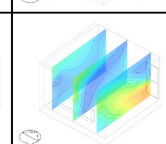
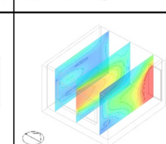
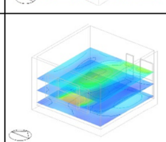
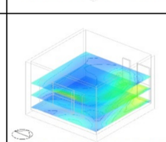
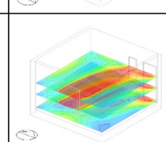
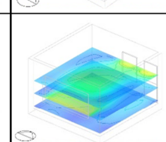
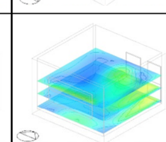
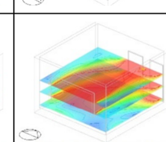
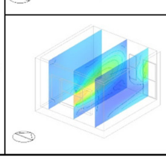
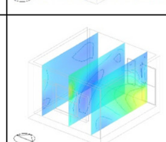
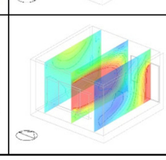
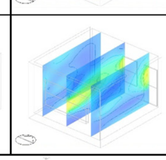
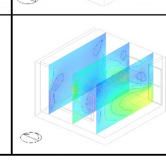
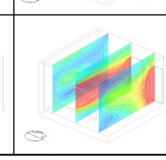
Table 9.16 Distribution of airflow inside 24 cases



The overall look of thermal performance of all cases summarised in Table 9.15 mostly shows the warm environment on the hottest day. However, increasing the area of inlets and outlets improved the characteristics of internal airflow including air velocity and distribution within the room. Consequently, when being present in warm conditions, if the internal air movement is more satisfactory, occupants may be more comfortable and acceptable due to the physiologically and psychologically cooling effect.

Comparing the airflow condition investigated between both opening design features (the opening area and the inlet-outlet ratio) applied, indoor airflow environments benefit from the organisation of openings in opposite walls, instead of in single surface. Table 9.17 indicates a typical comparison – 30% opening area between two opening designs of the test room: (i) only windward opening + internal room door and (ii) windward and leeward openings + internal room door. Two advantages in terms of airflow observed in the second case were higher wind velocities and more uniform distribution. The presence of another opening in the internal wall beside the internal room door affected air movement with higher velocities within the interior as shown in both horizontal and vertical slices exported.

Table 9.17 Comparison of airflow between two different opening features

Opening area (%)	**Opening feature**	**Free aperture**					
		50%			**100%**		
		08:00	13:00	18:00	08:00	13:00	18:00
30%	Windward opening + room door						
							
	Windward opening + leeward opening + room door						
							
Air velocity range		Velocity 0.00 0.05 0.09 0.14 0.18 0.23 0.27 0.32 0.36 0.41 0.46 0.50 (m/s)					

9.3.5.3 Building orientation

This section examines the influence of building orientation on the indoor environment. Table 9.18 presents the design scenarios studied and the method of numerical analysis. Using the CFD calculations for eight cases of the windward opening area on the hottest day is as a fundamental testing framework. The base case is the room/building oriented south and its environmental results found in Table 9.11 of

Section 9.3.5.1. A similar simulation process was repeated for other orientations: North, East, and West. There were a total of 24 cases investigated. Comparison of environmental conditions assumed inside the test room on the hottest day in different scenarios of building direction shows the positive or negative environmental relationship between them.

Table 9.18 Design cases of building orientations

Characteristics of model		**Base case (Building orientation)**	**Opening area (% of windward wall)**	**Free aperture (% of operable area)**	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Total of cases**
Urban type	Type 1	South	30%	50% and 100%	North	East	West	24
Floor position	Level 1		50%					
Construction condition	As shown in Table IX.7		70%					
Room dimension tested	5(W) x 5.5(L) x 3.1(H) m		90%					

After calculations conducted, physical data in terms of air temperature, operative temperature, and relative humidity were plotted on the scatter graphs as shown in Figures 9.17-19. Most linear patterns indicated a large correlation of thermal conditions inside the base case (the model faces south) against other cases of other orientations with all the R-values greater than 0.9.

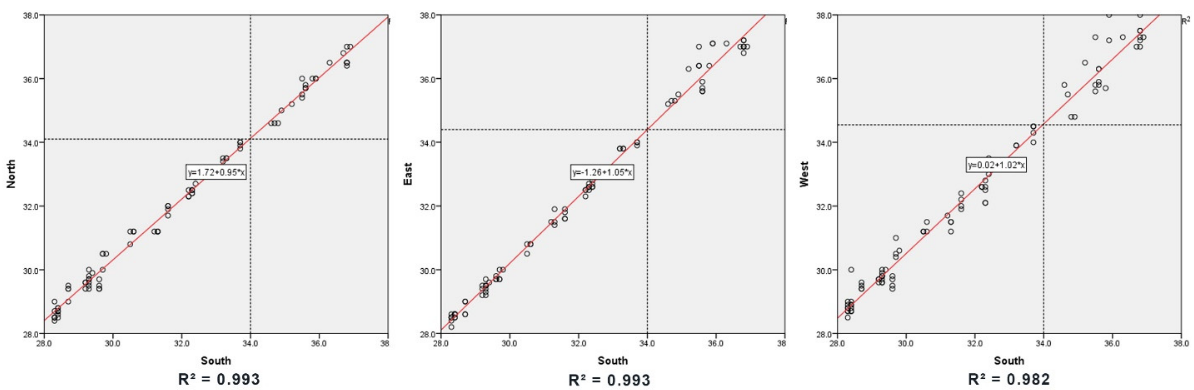


Figure 9.17 Correlation of air temperatures between building orientations

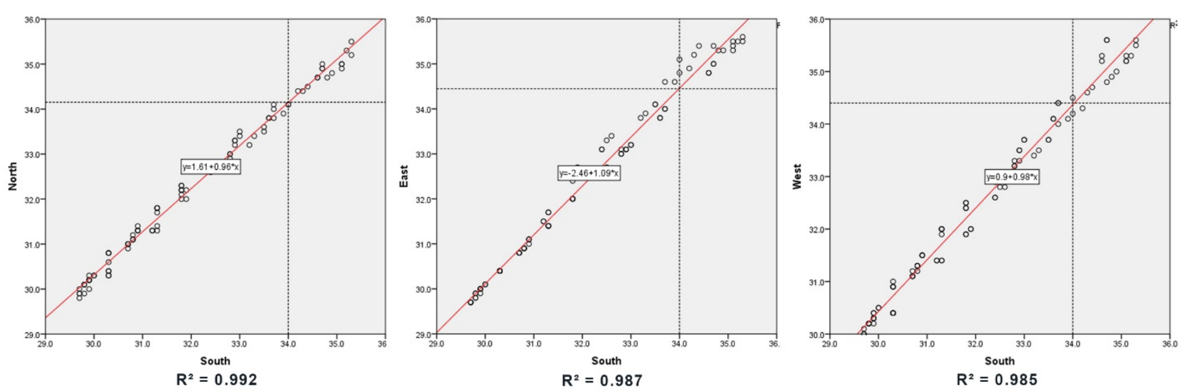


Figure 9.18 Correlation of operative temperatures between building orientations

There was a variation of 0.3, 0.5, and 0.5°C air temperature in the test room oriented south compared to alteration of respective building directions: North, East, and West (Figure 9.17). A similar pattern was observed for the parameter of operative temperature (Figure 9.18).

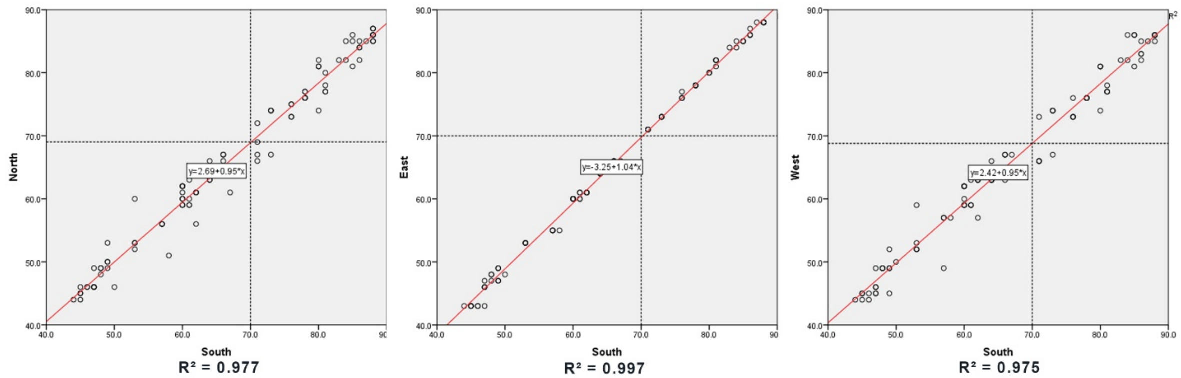


Figure 9.19 Correlation of humidity between building orientations

Considering the variable of relative humidity, the change in building orientations did not certainly impact interior humid conditions between cases tested. Between the base case (South) and scenario 2 (East), no differences in humidity were addressed. Meanwhile, under the other contexts of simulated building oriented north and west, the internal humidity level in the test room was lower by 1%.

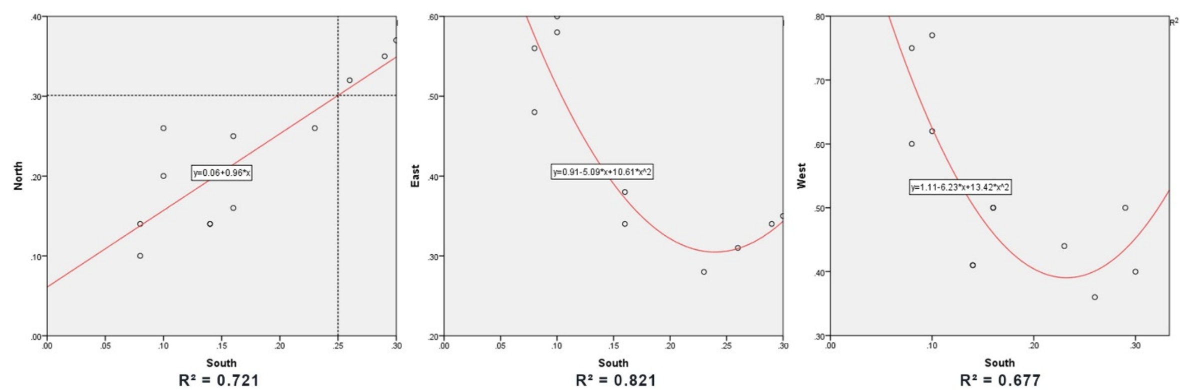


Figure 9.20 Correlation of air velocity between building orientations

When the room/building orientation was altered despite the constant operation of outdoor winds during the hottest day, the relationship between interior and exterior wind climates was also changed. Figure 9.20 shows three statistical models representing the correlation of indoor airflow between the base case and three remaining design scenarios on the hottest day. Compared to the linear relationship of airflow between two cases – south and north, the statistical model is more complicated in the cases of the building facing east and west. The correlation coefficient of models shows a large effect. However, to simplify in applications of design guidance for users, the variation of air velocity between design scenarios is considered to use the average value of eight cases simulated for the windward opening area for every corresponding scenario of orientation. The average internal airspeed increased by 0.1, 0.25, and 0.3m/s if the room or building faces north, east, and west, respectively.

The similar assessment was applied for the variable of airflow rate. The average volume flow rate calculated in three design scenarios was lower than the base case as follows: North (-50), East (-6), and West (-45).

9.3.5.4 Urban morphology

In Section 3.2 of Chapter 4, which reviews previous comfort studies on outdoor comfort, they have confirmed a close correlation between outdoor microclimates and urban conditions, which potential influences on indoor environments and comfort. Furthermore, in Section 6.3 of Chapter 6, the field studies on both interior and exterior climates of shop-house dwellings in HCMC demonstrate the variations of environmental performances between urban types where shop-house buildings are positioned. Thereby, in this section, the influence of urban conditions on thermally comfortable environments was considered as a variable to simulate for the common urban spatial patterns found in HCMC (Table 9.19).

Table 9.19 Design cases of urban types

Characteristics of model		Base case (Urban type)	Opening area (% of windward wall)	Free aperture (% of operable area)	Scenario 1	Scenario 2	Scenario 3	Total of cases
Building orientation	South	Type 1	30%	50% and 100%	Type 2	Type 3	Type 4	24
Floor position	Level 1		50%					
Construction condition	As shown in Table IX.7		70%					
Room dimension tested	5(W) x 5.5(L) x 3.1(H) m		90%					

Be similar to the study on the effect of building orientation, investigations of internal environmental impacts related to urban types were conducted with the design cases of opening area features. The base room/building was positioned in a generic settlement of pattern type 1 linking to the regular planning, the low density of dwellings, the availability of public spaces, and homogeneous row houses (Figure 9.21a). Figures 9.21b-d represent the model of other urban forms used for simulations corresponding to pattern type 2 – scenario 1 (regular planning, no green areas, medium to high density, and archetypal housing forms), pattern type 3 – scenario 2 (regular planning, no green areas, high population density, and inhomogeneous shop-houses), and pattern type 4 – scenario 3 (irregular planning, much high building density, and heterogeneous shop-houses). Those models were assumed from real conditions.

Plotting all data simulated for different urban types on the hottest day, Figures 9.22-26 present a correlation of environment in the test room between the base case (Type 1) and other urban types according to various physical indices. All statistical models are linear with a strong relationship between variables (urban types).

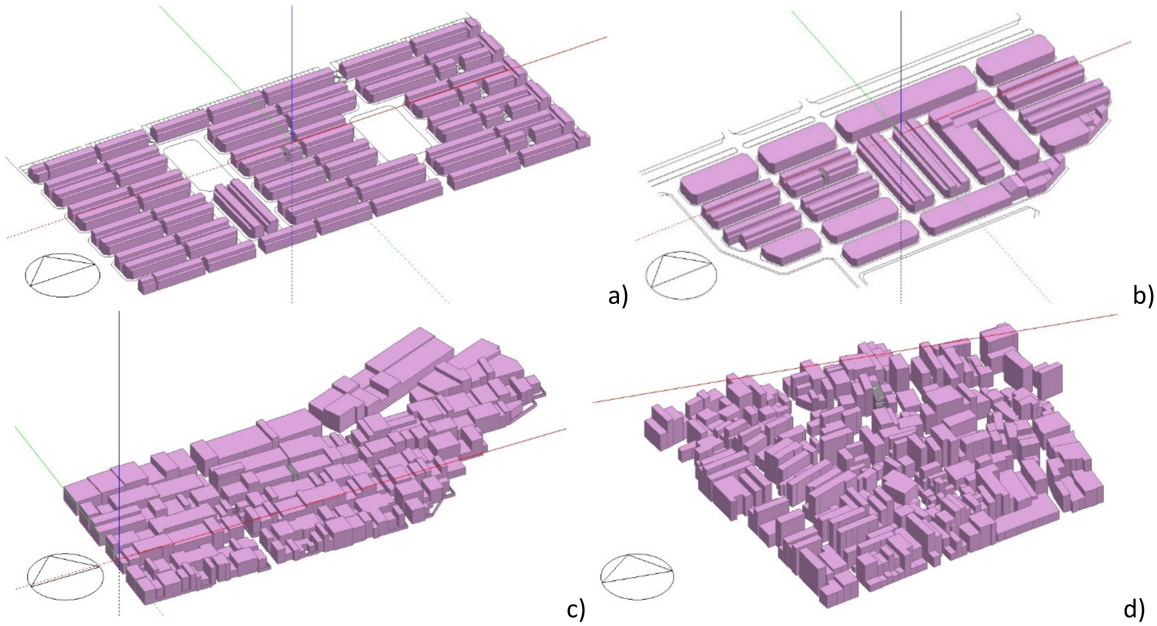


Figure 9.21 Generic model of urban types simulated: a–Type 1, b-Type 2, c-Type 3, and d-Type 4

Although the air temperature in the test room tended to be higher when the building model was tested with pattern types 2 and 4 settlements compared to in type 1, the difference was negligible. The most discrepancy of 0.3°C was found between pattern types 1 and 3. Most dots lie on the regression line, which proves a great similarity of air temperature environment in the room/building – even its location is in different urban types (Figure 9.22). All correlation coefficients are greater than 0.85.

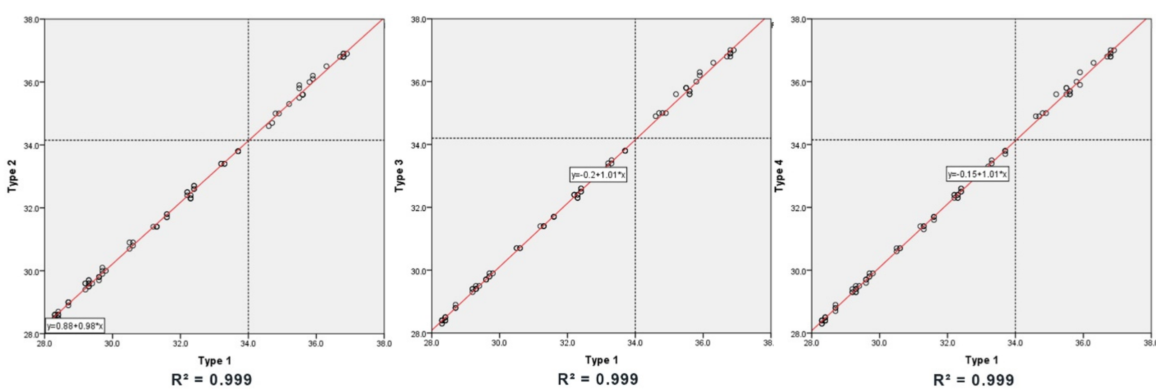


Figure 9.22 Correlation of air temperature between urban types

On the other hand, wider differences are observed in evaluations of operative temperature (Figure 9.23). For the testing model located in neighbourhoods planned with pattern types 2 and 3, the operative temperature was 0.8°C warmer than that in pattern type 1. Meanwhile, the variation was 0.5°C between the base case and scenario 3. The high construction coverage around type 4 settlements resulted in mitigating the impact of solar radiation on the building fabric and the indoor environment.

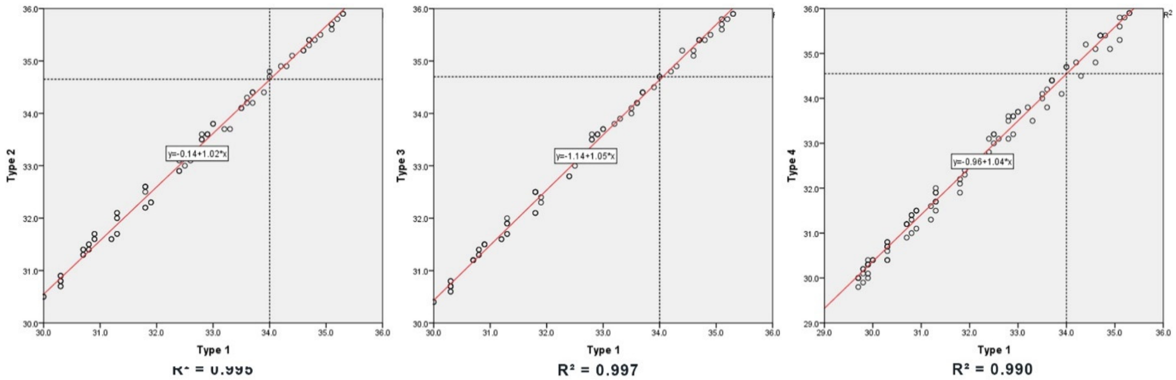


Figure 9.23 Correlation of operative temperature between urban types

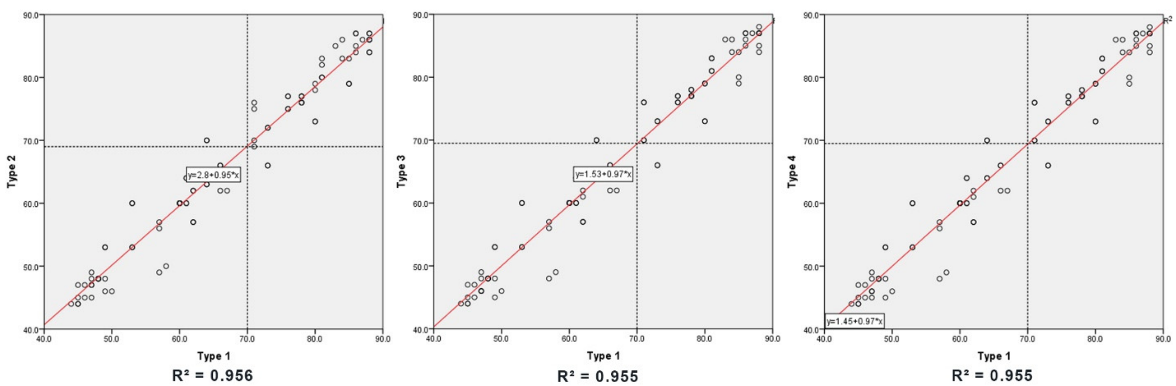


Figure 9.24 Correlation of humidity between urban types

As shown in Figure 9.24, three linear models show an insignificant variation of humid conditions between urban geometries studied. The humidity level in the typical room/building within pattern type 2 was 1% lower relative to in pattern type 1.

Unlike the complicated correlative pattern of air velocity in the alteration of building orientations, that relationship is simple and linear when applying to different urban spatial forms of neighbourhoods. Compare to the almost absolute correlation coefficient of models in terms of temperature and humidity, although such coefficients are lower in the regressions of air velocity and flow rate, they also represent a large effect of airflow environments of the base case against others (Figures 9.25-26).

There was a minor divergence (0.05m/s) of air movement simulated by CFD calculations on the hottest day between the typical case (pattern type 1) and other scenarios. The urban constituents forming various urban morphologies of shop-houses intervene in wind environments surround the building. Plotting air change rates of eight cases of the opening area in the windward wall simulated for four scenarios of urban type on the hottest day, the airflow rate calculated in three comparative urban types was 20-70K lower than the value in the base case. The situation of the lowest flow rate was found when the building was positioned in the settlements of pattern type 2.

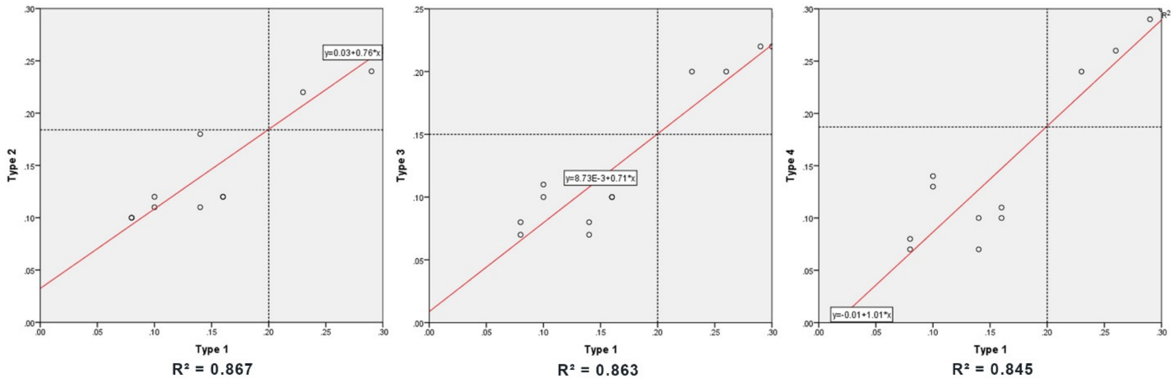


Figure 9.25 Correlation of airspeed between urban types

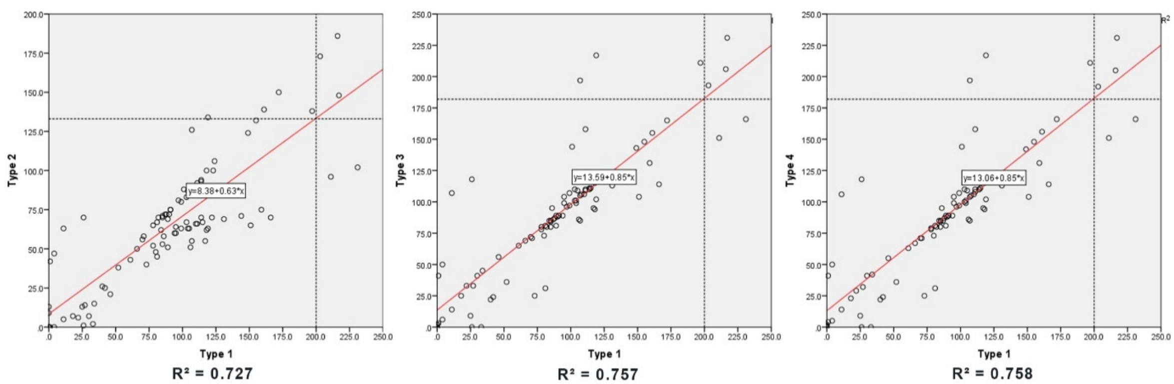


Figure 9.26 Correlation of airflow rate between urban types

9.3.5.5 Floor position

Another factor possibly influencing thermal and airflow environments inside the building is the floor position. The research literature in Chapter 3 shows that the airspeed of incident winds is higher on the upper floors of a building. Using three shop-house buildings in HCMC, the current research monitored the thermal conditions inside all rooms of such dwellings over many months. The database gathered also indicates environmental variations between rooms positioned at different stories – see Chapter 8.

Table 9.20 Design cases of floor positions

Characteristics of model		**Base case (Floor position)**	**Opening area (% of windward wall)**	**Free aperture (% of operable area)**	**Scenario 1**	**Scenario 2**	**Total of cases**
Urban type	Type 1	Level 1	30%	50% and 100%	Level 2	Level 3	16
Building orientation	South		50%				
Construction condition	As shown in Table IX.7		70%				
Room dimension tested	5(W) x 5.5(L) x 3.1(H) m		90%				

This part of chapter studies on thermal environments in the test room when its floor position is changed between level 1 (the base case) and level 2 & 3 (comparative scenarios). Meanwhile, other features related to urban type, building orientation, and thermal properties of building elements are fixed.

Alike the experimental method utilised to analyse the influence of building orientation and urban geometry, comfort and CFD simulations are carried out for the eight cases of opening area variable on the hottest day in relation to the position of test room altered on level 1, 2, and 3 (Table 9.20).

Apart from the base case, which the test room is on level 1, a total of 16 cases were calculated. Figures 9.27-31 depict linear relationships of all five environmental variables between design scenarios. Among them, the correlation coefficients of temperature and humidity are nearly absolute (>0.9). Air temperatures and operative temperatures calculated in the test room on level 1 and 2 were similar on the hottest day (Figure 9.27). Whilst, despite a similarity of indoor air temperature between the base case and scenario 2, the operative temperature in the test room placed on level 3 was 1°C warmer when it was positioned on the lower floor (Figure 9.28). That variation can result from the more absorption of solar heat from the roof and surrounding environment at the upper floor compared to a higher overshadowed degree by neighbour buildings at the lower floor. Furthermore, no significant differences in relative humidity were found if the typical room is placed on varying building floors (Figure 9.29).

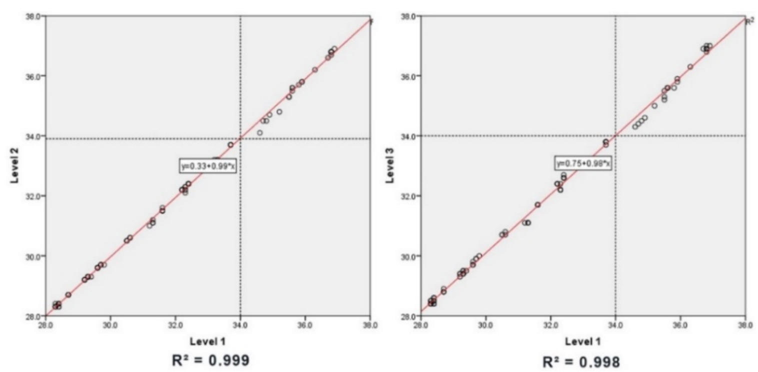


Figure 9.27 Correlation of air temperature between floor positions

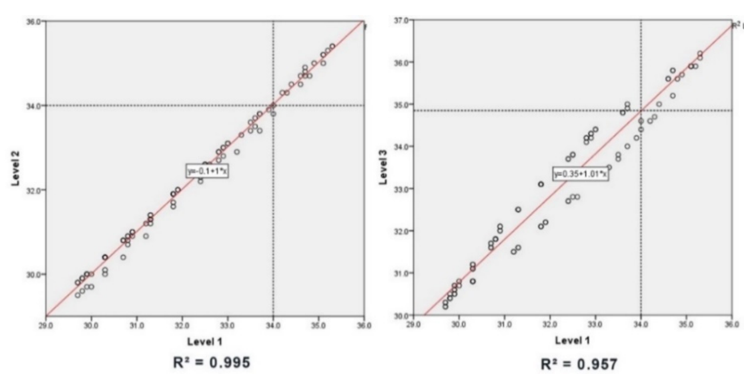


Figure 9.28 Correlation of operative temperature between floor positions

Under the same conditions of spatial geometry and opening configuration designed for the test room, the higher pressure of outdoor winds on the windward wall at the upper floors resulted in the stronger airflow within the space. Particularly on level 3, the indoor air movement simulated on the hottest day tends to be 0.1m/s more than other contexts on level 1 and 2 (Figure 9.30). Meanwhile, between the base case and scenario 1, there was a little difference in airspeed in the room. The linear correlation of airflow within the room between levels is close.

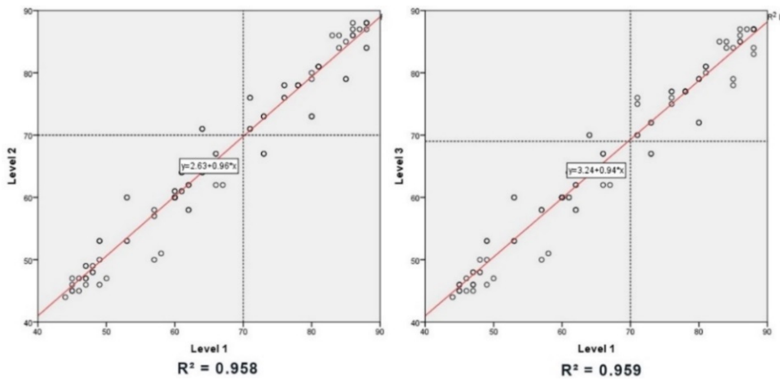


Figure 9.29 Correlation of humidity between floor positions

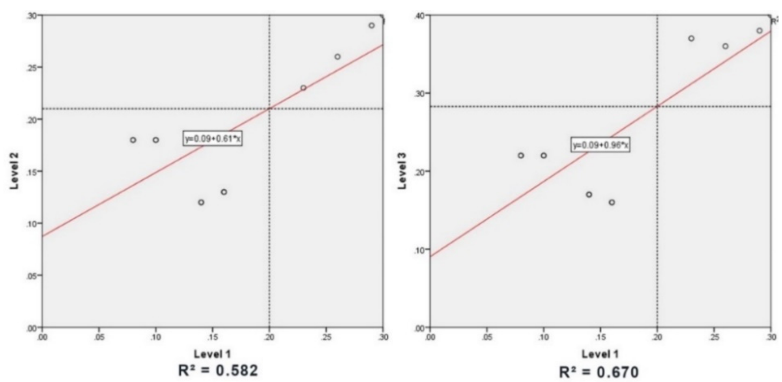


Figure 9.30 Correlation of airspeed between floor positions

A similar pattern of flow rate was found between scenarios 1 and 2. The air change rate through the windward opening in the room was similar between variables (level 1 and 2). Meanwhile, the variation on the speed of external winds by building height linked to the higher value of ventilation rate in the room on level 3 by 15ach compared to both first and second levels.

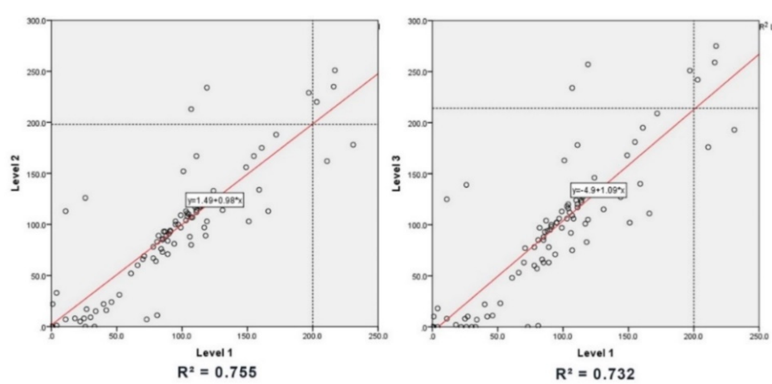


Figure 9.31 Correlation of airflow rate between floor positions

9.3.6 Building a sample of design guidance

The design guidance for openings in free-running shop-house dwellings in HCMC is devised by scientific research on comfortable conditions for occupants, which are criteria to assess the comfort degree of indoor environment; and building and urban research to understand factors affecting the indoor environment, which are considered to present in design tables and design corrections. Design tables obtain the common variables and variations of opening design features while design corrections include external factors potentially influencing the thermal environment indoors. In the sample version of the design manual, the internal variables include two opening variables: the opening area and the inlet-outlet ratio. Meanwhile, three external variables used to form the corrective tables are: building orientation, urban morphology, and floor level.

9.3.6.1 Design criteria

The design manual assesses the comfort degree of interior environments on the hottest day (06 May) of the whole year through five basic physical parameters: air temperature, operative temperature, air velocity, relative humidity, and air change rate. Through the evaluation of comfortable environments, the effect of building fabric design, particularly opening configurations, is linked. Two important criteria for a naturally ventilated shop-house dwelling in HCMC or a residential building in the tropics are temperature and air velocity. The comfort criteria were discovered by the field studies conducted in both hot and cool seasons in free-running shop-houses in HCMC. The acceptable operative temperatures are 25.5-31.5°C.

As with the method used to find the comfort zone in free-running shop-houses, Chapter 7 shows the close relationship between thermal and air movement acceptability. The minimum of airspeeds required corresponding to each acceptable temperature are shown in Table 7.1. 80% of occupants were acceptable to the minimum range of 0.2-0.55m/s incorporated into the temperature bandwidth. However, if warm temperatures are between 32-34.5°C, the least airflow should be greater than 0.55-0.65m/s.

Apart from those indices, the assessment of internal comfortable relative humidity is based on the simplified version of TCVN 9411:2012 implemented for the row house design in Vietnam, which recommends a range of 70-75% and the upper threshold of 80% in hot conditions (VIAP, 2012). Furthermore, in other situations of drier environments, the lowest humidity value advised by TCVN 7438:2004 is 30% to reduce risks to skin/eyes (VSQI, 2005). Therefore, the range of 30-69% relative humidity is determined to be still acceptable. Humidities out of 30-80% are uncomfortable.

For the ventilation rate required in free-running residential buildings, there are variations between international and national standards and between functional rooms. Referring to CEN 15251 combined with the volume and perimeter of the typical room, the respective least airflow rate needed for the living room/bedrooms and the kitchen is 1.6ach and 1.4ach (for exhaust airflow) (CEN, 2007). Meanwhile, ASHRAE 62.2-2013 has determined the minimum value of 0.7ach in living areas and 2.4ach in kitchens to get acceptable ventilation and air quality indoors (ASHRAE, 2013b). In the built environment of Vietnam, the minimum number of times the air in the room replaced in residences is 0.5 for living rooms/bedrooms and 1.4 for kitchens according to TCVN 5687:2010 (NUCE, 2010). On the other hand, Adamson, who conducted field studies on passive houses in the SE Asia tropics, showed that a good ventilation rate is beneficial to remove heat in the interior (Adamson, 1991). He supposed that a well-designed house exposed to hot-humid climates should get the ventilation rate of 20 or more. From the recommendations reported here, the current study has defined two variations of the minimum air change rate to assess the effect of opening designs on ventilation in naturally ventilated shop-houses in tropical climates: 1-19ach (acceptable) and ≥ 20 (comfortable).

Combine the assessment criteria above, Table 9.21 summarises a framework of criteria used to evaluate the comfort level of the indoor environment, along with the effect of opening designs.

Table 9.21 Design criteria used for assessments in the design guidance

Air temperature (°C)			
No assessed			
Operative temperature (°C)			
< 25.5	25.5 ≤ T ≤ 31.5	31.5 < T ≤ 34.5	T > 34.5
Cool	Acceptable	Warm	Hot
Air velocity (m/s)			
< 0.2	0.2 ≤ V ≤ 0.55	0.55 < V ≤ 0.65	V > 0.65
Unacceptable	Acceptable		Comfortable
Relative humidity			
30-70%	70-75%	75-80%	< 30% - > 80%
Acceptable	Comfortable	Acceptable	Unacceptable
Air change rate (ACH)			
1 ≤ Fa < 20		Fa ≥ 20	
Acceptable		Good	

9.3.6.2 Design tables

Design tables are structured from various design options of opening variables tested for a typical room of a generic shop-house building. For example, the influence of two typical opening variables (the windward opening area and the inlet-outlet ratio) on indoor environmental performances was investigated through parametric studies by comfort and CFD simulations as shown in the subsections 9.3.5.1-2. Corresponding to each variable, a range of typical parameters was addressed. The environmental condition in the base room examined on the hottest day was predicted for every single case as presented in Tables 9.11 & 15. Applying the design criteria determined above for those tables, Tables 9.22-23 show the assessments of the acceptable or comfortable degree of the indoor environment on the hottest day of summer for each of physical indices.

Table 9.22 Comfort conditions of common cases of the opening area

Opening area (m2)		% Free aperture					
		50%			**100%**		
		8:00	**13:00**	**18:00**	**8:00**	**13:00**	**18:00**
30%	**4.5**	**2.3**			**4.5**		
	Ta	31.0	35.5	32.5	31.5	36.0	32.5
	Top	31.0	34.0	32.5	31.0	34.5	33.0
	Va	0.10	0.15	0.30	0.10	0.15	0.30
	Fa	22	3	85	30	11	107
	RH	66	46	60	66	45	60
50%	**7.5**	**3.8**			**7.5**		
	Ta	31.5	36.0	32.5	31.5	36.5	32.5
	Top	31.5	34.5	33.0	31.5	34.5	33.0
	Va	0.10	0.15	0.25	0.10	0.15	0.25
	Fa	25	10	104	32	25	114
	RH	66	45	60	66	44	60
70%	**10.5**	**5.3**			**10.5**		
	Ta	31.5	35.0	32.5	31.5	36.5	32.5
	Top	31.5	35.0	33.0	31.5	35.0	33.0
	Va	0.15	0.15	0.30	0.10	0.10	0.30
	Fa	36	20	110	41	41	116
	RH	66	44	60	66	43	60
90%	**13.5**	**6.8**			**13.5**		
	Ta	31.5	36.5	32.5	31.5	37.0	32.5
	Top	31.5	35.0	33.0	31.5	35.5	33.0
	Va	0.10	0.10	0.25	0.10	0.15	0.30
	Fa	35	28	113	41	55	123
	RH	66	44	60	66	43	60
Note	*Ta: mean air temperature (°C) ; Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ACH)*						

Table 9.23 Comfort conditions of common cases of the inlet-outlet ratio

Opening area (m2)	% Free aperature	Parameter	Ratio of inlet to outlet openings								
			4:1			3:1			2:1		
			8:00	13:00	18:00	8:00	13:00	18:00	8:00	13:00	18:00
30% (4.5)	2.3 (50%)	Ta	31.0	35.5	32.5	31.0	35.5	32.5	31.0	35.5	32.5
		Top	31.0	34.0	33.0	31.0	34.0	33.0	31.0	34.0	33.0
		Va	0.11	0.15	0.30	0.10	0.10	0.30	0.10	0.15	0.30
		Fa	24	3	95	25	3	97	26	2	101
		RH	66	46	60	66	46	60	66	46	60
	4.5 (100%)	Ta	31.5	36	32.5	31.5	36	32.5	31.5	36	32.5
		Top	31.0	34.5	33.0	31.0	34.5	33.0	31.0	34.5	33.0
		Va	0.10	0.15	0.35	0.10	0.15	0.40	0.15	0.15	0.40
		Fa	38	8	146	40	8	155	43	7	170
		RH	66	45	60	66	45	60	66	45	60
50% (7.5)	3.8 (50%)	Ta	31.5	36.0	32.5	31.5	36.0	32.5	31.5	36.0	32.5
		Top	31.5	34.5	33.0	31.5	34.5	33.0	31.5	34.5	33.0
		Va	0.10	0.15	0.30	0.10	0.15	0.30	0.10	0.15	0.35
		Fa	30	9	132	32	9	140	34	8	151
		RH	66	45	60	66	45	60	66	45	60
	7.5 (100%)	Ta	31.5	36.5	32.5	31.5	36.5	32.5	31.5	36.5	32.5
		Top	31.5	34.5	33.0	31.5	34.5	33.0	31.5	34.5	33.0
		Va	0.10	0.10	0.35	0.10	0.10	0.35	0.15	0.10	0.40
		Fa	46	21	192	49	20	210	53	19	241
		RH	66	44	60	66	44	60	66	44	60
70% (10.5)	5.3 (50%)	Ta	31.5	36.5	32.5	31.5	36.5	32.5	31.5	36.5	32.5
		Top	31.5	35.0	33.0	31.5	35.0	33.0	31.5	35.0	33.0
		Va	0.20	0.10	0.35	0.20	0.10	0.60	0.20	0.10	0.70
		Fa	48	19	159	51	18	168	55	18	188
		RH	66	44	60	66	44	60	66	44	60
	10.5 (100%)	Ta	31.5	36.5	32.5	31.5	36.5	32.5	31.5	36.5	32.5
		Top	31.5	35.0	33.0	31.5	35.0	33.0	31.5	35.0	33.0
		Va	0.20	0.10	0.60	0.20	0.10	0.65	0.20	0.15	0.55
		Fa	68	38	227	73	37	252	81	37	296
		RH	66	44	60	66	44	60	66	44	60
90% (13.5)	6.8 (50%)	Ta	31.5	36.5	32.5	31.5	36.5	32.5	31.5	36.5	32.5
		Top	31.5	35.0	33.0	31.5	35.0	33.0	31.5	35.0	33.0
		Va	0.15	0.15	0.35	0.15	0.10	0.35	0.20	0.10	0.40
		Fa	50	26	179	53	25	197	58	25	223
		RH	66	44	60	66	44	60	66	44	60
	13.5 (100%)	Ta	31.5	36.5	32.5	31.5	36.5	32.5	31.5	36.5	32.5
		Top	31.5	35.5	33.0	31.5	35.5	33.0	31.5	35.5	33.0
		Va	0.15	0.15	0.45	0.15	0.10	0.50	0.15	0.15	0.60
		Fa	70	50	260	75	50	290	82	49	341
		RH	66	43	60	66	43	60	66	43	60
Note		*Ta: mean air temperature (°C); Top: mean operative temperature(°C); RH: mean relaitve humidity (%); Va: mean air velocity (m/s); Fa: mean air flow rate (ACH)*									

9.3.6.3 Design corrections

Design corrections will be employed when there is any variation between the considerable conditions of a real case and the typical case, for example, the difference in building/room orientation (Table 9.24), urban form (Table 9.25), floor level (Table 9.26), or others (room width or room height). In the current study, three external variables of opening features have been considered to find out differences in thermal environment between the base case and other scenarios. Resemble the research method utilised to research the opening variables, the comfort and CFD calculations are used to investigate thermal conditions inside the typical room on the hottest day but positioned in the different conditions of orientation, urban morphologies, and building level.

Table 9.24 Summary of environmental variations between design scenarios of different orientations

Parameter	Base case South	Scenario 1 North	Scenario 2 East	Scenario 3 West
Air temperature Ta°C	A	+0.3	+0.5	+0.5
Operative temperature Top°C	A	+0.3	+0.5	+0.5
Relative humidity RH %	A	-1	0	-1
Air velocity Va m/s	A	+0.10	+0.25	+0.3
Air flow rate Fa ac/h	A	-50	-6	-45

Table 9.25 Summary of environmental variations between design scenarios of urban forms

Parameter	Base case Type 1	Scenario 1 Type 2	Scenario 2 Type 3	Scenario 3 Type 4
Air temperature Ta°C	A	+0.1	+0.3	+0.1
Operative temperature Top°C	A	+1.0	+1.0	+0.5
Relative humidity RH %	A	-1	0	0
Air velocity Va m/s	A	0	-0.05	0
Air flow rate Fa ac/h	A	-70	-20	-20

Table 9.26 Summary of environmental variations between design scenarios of floor positions

Parameter	Base case Level 1	Scenario 1 Level 2	Scenario 2 Level 3
Air temperature Ta°C	A	0	0
Operative temperature Top°C	A	0	+1.0
Relative humidity RH %	A	0	0
Air velocity Va m/s	A	+0.0	+0.10
Air flow rate Fa ac/h	A	0	+15

The analyses conducted in subsections 9.3.5.3-5 show that most environmental relationships between design scenarios are linear. Therefore, in different design cases from the design tables, users will combine the preliminary results shown in the design tables and the variations assumed in the design corrections to assume the mean environment in those cases by adding or subtracting differences shown in Tables 9.24-26 from the original values of Tables 9.22-23. For example, if a real room (50% of the windward opening area and 100% of free aperture) faces east instead of south, the interior conditions adapted from the design table – 9.22 and the design correction – 9.24 are as follows: T_{op} - 32°C at 8:00, 35°C at 13:00, and 33.5°C at 18:00; Va – 0.35m/s at 8:00, 0.4m/s at 13:00, and 0.5m/s at 18:00; Fa – 26ach at 8:00, 19ach at 13:00, and 108ach at 18:00; and RH – unchanged.

9.4 Step 3 - The validity of design guidance

All three components including design criteria, design tables, and design corrections are taken together to prepare a draft of design guidance for openings. The manual helps architects understand the effect of their design strategies, particularly openings configurations, on the performance of the indoor environment. From the preliminary design shown in the design guide, architects can use and adapt to their design to get the building which can provide thermal satisfaction for occupants.

The sample of guidance was delivered to professionals in the built environment in Vietnam. Nine seminars were organised with the involvement of 57 architects, lecturers, and engineers, who participated in the questionnaire interview of the pilot study. The author presented the sample of design guidelines related to the purpose, structure, design criteria, usage, and application in a particular example. After the presentation, the participants practised with some examples and the author defended their questions. Finally, they responded to a questionnaire table to evaluate the applicability and possibility of completed guidance for the practice of architects in future. By that method, its validity can be qualified. The surveying results are below.

9.4.1 Survey results

The participants had a short time to experience the sample of design guidance. 82% of them supposed that the design manual of openings can be significant for their work while the remaining showed a doubt (Figure 9.32a).

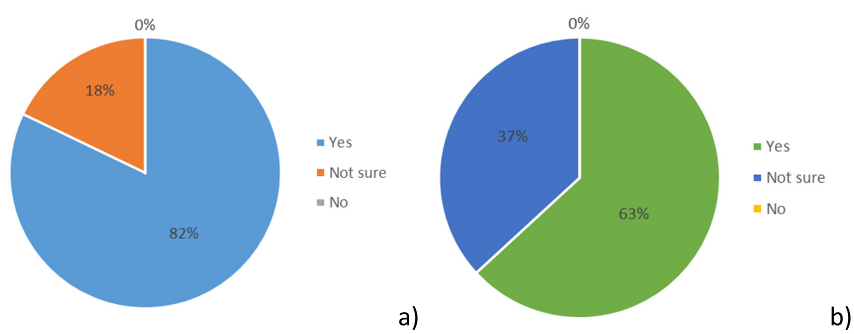


Figure 9.32 Significance of opening design guidance to architects' work (a), comparison of design principles (b)

Returning to the literature review, in practice in Vietnam, there have had existing shortcomings in the implementation of national design standards and the paucity of effective design guidelines helping architects and engineers understand and find preliminary approaches to achieve the criteria of the standards. To support their regular work, some design principles of different sources are usually referred to instead of the availability of practical design guides. Consequently, 63% of designers agreed that the availability of a technical manual for opening designs is useful for their practice to understand their design and the indoor environment created. Besides, 37% of respondents showed their doubt (Figure 9.32b). Their worry is understandable because the validity of design guidance should be tested and revised many times before publishing officially, even improvements further.

Participants were also asked about the effectiveness and significance of the information incorporated into the guidance (criteria, internal and external variables, various design options, and their environmental consequences). There are some varying opinions, among them, a minor percentage of votes (2%) were 'no effective' (Figure 9.33a). Besides, 16% of surveyors voted 'less effective'. Whereas, a larger number of participants (82%) were confident that the method devised in the design guidance is the potential to use.

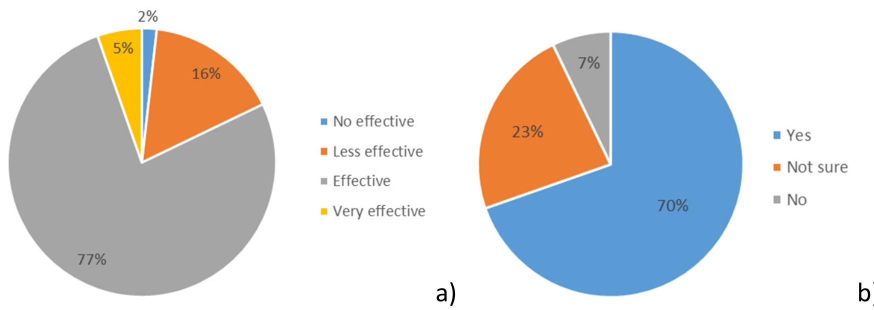


Figure 9.33 Method (a) and presentation (b) of the sample of design guidance

The next question is related to the accessibility of the design guidelines for users in practical applications through the assessment of structure (design tables and design corrections), presentation, explanations, and instructions described in it. 70% of participants agreed that the contents and information in the manual are clear and easy to understand and apply. However, 30% of them had different thoughts (Figure 9.33b), among them, 7% of people found difficulties when trying to use. That raises revisions and the conduction of more pilot studies of guidance demonstration before publication.

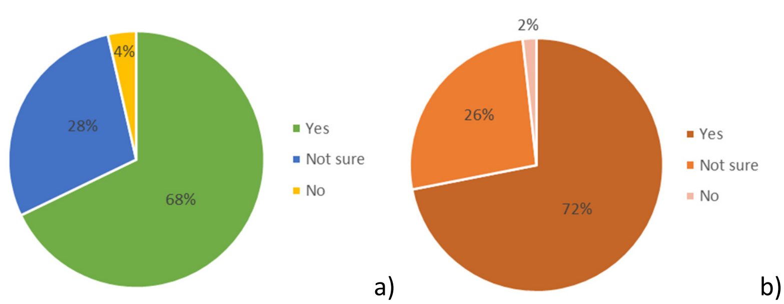


Figure 9.34 Significance of the design guidance in practice: comfort level (a), the effect of opening designs (b)

During the seminars, the participants had time to use the design guidelines for some particular examples, which helps them assume the significance and usefulness of the design manual to their practice to design comfortable shop-houses with less energy consumption for cooling through the appropriate designs of openings. 68% of interviewees found the potential support of the design tool helping them predict the performance of indoor environment and the satisfaction degree of occupants in the room/building designed by them (Figure 9.34a). Through the assessment of interior thermal conditions, designers (72%) can evaluate the effect of design strategies applied (Figure 9.34b). However, more than 25% of participants have not been sure about the contribution of design guidelines to design comfortable shop-house buildings by the application of suitable opening designs.

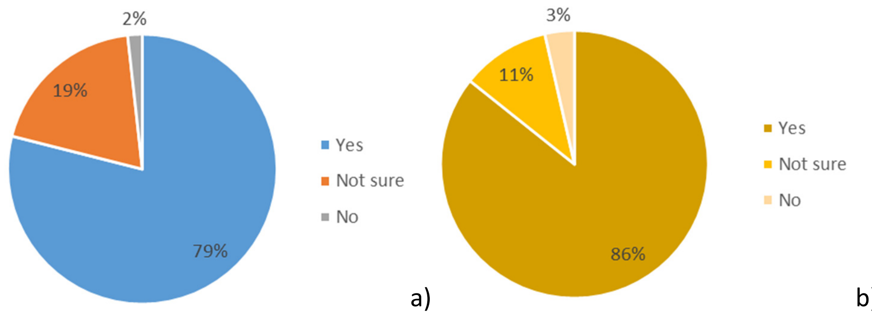


Figure 9.35 Possibility of design guidance in the future

When asked for the possibility and applicability of the tool of opening design in practical applications in the future, the majority of participants (79%) responded 'yes' and some of them (19%) expressed their hesitation (Figure 9.35a). Despite a lower number of respondents in total voting for the potential of the design guidance (79%), most of them (86%) thought that they will share the design manually with other architects and engineers.

9.4.2 Section conclusions

By preliminary experiences with the sample of design guidance, the potential users were excited about it because it potentially supports them to design shop-house buildings which not only have creations and aesthetic values but provide comfortable environments and health for occupants. Additionally, they comprehend what are the comfortable conditions for occupants and the influence of their design strategies of opening configurations on the building physics and comfort. Most of the designers supposed that the design guidance will be applicable and possible in the future and it needs to have further development.

Besides questionnaire interviews, the participants also raised many interesting comments about various sides of the design guidance, such as the approach and method to issue the design tables and corrections, design criteria, the number of opening variables used for the complete design guide, the number of design cases; presentation; the potential influence of other factors in real applications (Feng Shui or vegetation); the further advance when utilising the manual in different climates across the country or various residential building typologies; and the interesting ideas to disseminate the guidance in a larger population. Those recommendations are useful to consider and revise the demonstration of design tool, and then, to have a wider and long-term vision for the completion of the design guidance and its delivery in practice in Vietnam.

9.5 Conclusions

This chapter shows an attempt to seek an appropriate direction to create and implement the effective design guidance for openings, which is assumed to be used for the design of comfortable shop-houses in HCMC. Obtaining the guidance was carried out by three steps: step 1 – a pilot study to collect the knowledge and experience of architects in housing design; step 2 - the production of guidance; and step 3 – testing validity.

From understanding the insufficiency/shortcomings of existing standards, the confusions of architects in practice to create satisfactory environments for occupants, their need for a practical and effective design guide, the potential design guidance is orientated to be derived from scientific research on occupant comfort perceptions and physical environments for comfort; factors affecting comfortable or uncomfortable environments (which cover urban and building characteristics); and their interactions. To facilitate use in practice, those contexts were generalised by three main elements forming the design guidance: design criteria, design tables, and design corrections.

The design criteria consist of the comfort zone linked between acceptable temperatures (25.5-31.5°C) and air movement (0.2-0.55m/s) for naturally ventilated shop-houses in HCMC, which was discovered in Chapters 6 and 7 by the analysis of occupant comfort votes and environmental measurements in the field. In addition, the criteria of other physical variables are deduced from the existing standards implemented and the results of previous studies conducted in residential buildings in the tropics.

The design tables mainly include various design options for opening variables and their variations. The environmental impact of each option was analysed for the hottest day of the year by comfort and CFD simulations. Two typical opening variables investigated for building a demonstration of design guidelines are the windward opening area and the inlet-outlet ratio. Each application of a value of an opening variable issued a distinct environmental profile of five thermal indices: air temperature, operative temperature, air velocity, relative humidity, and air change rate. That profile was evaluated by the design criteria identified.

The design corrections include three exemplars of external variables such as orientation, urban form, and floor level for issuing the simple proposal of guidance. Their effect on interior comfortable environments was proved through the analysis of field data in Chapters 6 and 8. Therefore, in the formulation of design guidance, the role of those factors is covered in the design corrections, which add the expansive impact on the original environmental profile of each design option predicted in the design tables.

The validity of guidance was tested by professionals. After having experience of using the draft of the design guidelines, they could assume the aim and benefits of the design guidance in practice if it is available in future. Although the demonstration of design guide was produced with the typical opening design features, the comments of testers are significant to improve and develop a complete version of design guidance in further. Additionally, through the responses of interviewees, the opportunity to produce technical design guidance, particularly openings are potential.

In essence, the building design of shop-houses is very diverse. Additionally, although obtaining a comfortable environment in houses is important in the built environment, the building aesthetics and creativity are also concerned by designers. Therefore, the potential guidance approached by three main compositions could not only help users understand environments created by their considerations of opening design for the building fabric in the early design stage but adapt to varying building/room and urban conditions. From preliminary recommendations, architects can develop their creations further. The guidance indicates the consideration for an overall effect of complex factors (opening configurations, other building/urban characteristics, outdoor climate, and behaviours of architects in design) on the indoor environment and comfort degree. The complete demonstration of guidance will be shown in the conclusion chapter after the revision based on the contributions of testers.

Some opening design points are extracted from environmental examinations for the generic model under the alteration of different variables as follows:

- For the option of single-sided ventilation, which means the installation of openings in only the windward wall, the parameter of the opening area certainly has negligible impacts on the indoor air movement environment while larger openings negatively change the thermal environment owing to the absorption of solar heat. The consideration of opening size should compound with appropriate shading strategies. However, with larger openings in external walls, the airflow rate through them is higher if they face prevailing winds. Sequentially, the level of room ventilation is improved. Consequently, the use of single-sided ventilation requires a suitable opening area to get a balance of thermal performance, natural lighting, and ventilation rate, but even then the effect on air velocity is low.

- For the option of cross ventilation, which means the installation of openings at both windward and leeward sides, the thermal environment in the room/building is nearly unchangeable between two natural cooling options applied. Nevertheless, the availability of opposite openings is significant for the airflow quality inside including velocity, distribution, and pattern. Therefore, the ventilation rate within the room or building is higher. However, the ratio of the inlet to outlet openings is important to the air movement environment. The lower the ratio, the more satisfactory the indoor airflow. Additionally, the large size of upwind openings involves both the airflow improvement and the risk of solar heat gain. Therefore, designers should consider a suitable value of the inlet-outlet ratio. Furthermore, shading devices should be used depending on the specific orientation and opening area. It is noticed that in the warm condition of room/building, the consideration of airflow should be the priority because of retaining human comfort and expanding human thermal tolerance. When considering the complexity of the passive solar and cooling design, the suggestion and application of shading strategies seem more feasible (Szokolay S. V., 2008; Dekay & Brown, 2014).

- The room/building orientation has influences on the environmental performance inside the room/building. Particularly, the position of the building facing east or west is risky to overheating in the space. In contrast, the airflow velocity is higher with western and eastern incident winds. In the design of tropical buildings, achieving good natural ventilation is more important and more challenging for architects. Hence, shading design is necessary for the buildings oriented west or east.

- The urban form of settlements affects the thermal and airflow environment in rooms/buildings. Four urban forms used for numerical analysis including pattern types 1, 2, 3, and 4. The operative temperature in the houses located in pattern types 2, 3, and 4 is higher, particularly in neighbourhoods of pattern types 2 and 3. The airflow in buildings within three of those urban patterns is calmer. Therefore, in the settlement of specific urban form, the spatial and fabric design of buildings should be considered towards to two purposes: a good response to the local outdoor microclimate and provided higher indoor environmental performances.

- The floor level also involves in the environmental impact of rooms. For spaces on the upper floors, the indoor thermal environment is warmer because of the risk by solar radiation. However, the airflow velocity and rate are higher. Thus, the additional shading and insulation solutions should be considered besides optimising the effect of natural ventilation.

Chapter 10 CONCLUSIONS

10.1 Achievements

Reviewing the aim of the thesis, three key elements are considered to be incorporated into the potential design guidance for the opening element, which will be applied to the design of comfortable and energy-efficient shop-house buildings in HCMC. The guidance not only focuses on practical supports effectively but reflects the complex correlations between climate characteristics, urban planning, the building envelope, and outdoor and indoor environments. To reach them, many on-site visits, surveys, measurements, and simulations were carried out for collecting and analysing data.

The first is the effect of urban morphologies on the comfortable environment in naturally ventilated shop-house buildings in HCMC.

Twelve urban spatial structures of shop-houses were systematically found and classified by the researchers of the University of Cottbus, Germany. They were introduced in section 4.4. As shown previously in sections 6.1-3, the field studies on indoor and outdoor climates of shop-houses were conducted in seven typical urban pattern types selected across the city between 2016-2018. They have confirmed a close relationship between outdoor microclimates and urban conditions forming various pattern types of settlements and between climates indoor and outdoor residences according to the classification of such urban types. Exterior environments varied between seven urban forms.

The real thermal environments surrounding shop-houses show dissatisfaction for occupants by high temperatures and low wind flows. Those issues affect the comfort of the indoor environment. It is certain that the current urban designs of most settlements do not create outdoor comfort, even in the residential neighbourhoods formally planned with low/medium density, regular road pattern, homogenous building height, and the availability of green spaces, for example, in neighbourhoods complied with pattern types 1 and 2 (refer to section 6.3). Consequently, suitable urban designs are advantageous for obtaining outdoor satisfactory microclimates, which reduce the pressure on the physical building. Then, the application of passive design strategies to respond to the surroundings will have benefits to improve the building performance and to provide comfortable environments (low air temperature and high airflow) for occupants.

The second is the comfort zone formed by the interaction of thermal and airflow acceptability.

- Referring to the methodological chapter, the empirical comfort studies were carried out in 65 free-running shop-houses in HCMC with the participation of 139 residents and a total of 256 datasets were collected in both hot and cool seasons. Applying statistical analyses discovered comfortable and uncomfortable conditions for residents in buildings. More discussed details are revealed in the whole section 6.4. The analysis of real occupant thermal sensations, preferences, and acceptability has indicated that they can tolerate warmer temperatures in comparison of the prediction of international and national standards, as well as, the heat balance model and the existing adaptive comfort models advised to apply in the tropics. The variation results from the influence of contextual terms (building type, people type, and climate type) on human thermal perceptions and expectations. Plotting the database collected in different seasons identified the comfortable and acceptable temperatures for buildings: 28.5°C and the range of 25.5-31.5°C (refer to section 6.4.3).

The real comfort limits higher than the recommendations into the national standards are significant for the building design because they encourage designers to understand clearly what occupants sense, prefer, and expect to the environment in residential buildings and shop-houses. Architects will also easily propose effective design strategies to create environments within the higher acceptable range. That contributes to reducing demand for and use of air-conditioning systems, along with energy use. Additionally, the difference in the comfort zone between the present study against the standards requires a review and update of them for more sufficient implementations in practice in future.

- Further analysis of occupant thermal sensations within the shop-house building found the variation in the comfortable environment for residents between interior spaces. The analytical result in section 6.4.4 showed a deviation of a maximum of 2°C in the neutral temperature between living rooms, kitchen + dining rooms, bedrooms, and study rooms/offices/shops. That may link to occupant adaptive behaviours differently in those environments. The finding may have impacts on the building design. Architects will approach design strategies to create diverse satisfactory environments for residents in each room/space of a building. By that way, the building performance may be higher; therefore, the ability to save energy for cooling is more. That finding of diverse comfortable conditions within a free-running building will require the adaptation of design guidance when applied for different rooms and also show the intrinsic diversity of shop-house design.

- The unacceptability of residents to indoor environments of shop-houses likely results from warm temperatures and low airflow. The combination of current data in terms of thermal and air movement sensations, preferences, and acceptability in the immediate environment of shop-houses showed the correlative effect of two variables (air temperature and air velocity) on the overall human comfort in warm humid climates.

As mentioned in Chapter 7, particularly section 7.3, the analysis of air movement sensations and measurements determines the airspeed which residents find comfortable is 0.8m/s in warm summer and 0.7m/s in cool spring. The minimum airflow of acceptability is respectively 0.5m/s and 0.4m/s. Those figures can help explain the occupant preference of higher air movement in naturally conditioned buildings such as shop-houses in warm-humid climates than the limits of draught discomfort of 0.2m/s and 0.8m/s in HVAC and non-air-conditioned buildings recommended in ASHRAE Standard 55, respectively.

Going to further sub-section 7.3.4, the correlation between acceptable air movement and operative temperatures was determined. The thesis finds the range of minimum acceptable airflow for 80% and 90% occupant acceptability between 0.2-0.55m/s and 0.2-0.7m/s in relation to acceptable temperatures between 25.5 and 31.5°C. Moreover, in warmer conditions, higher velocities of air movement are significant to extend the upper comfort limit up to 34.5°C.

In comparison with the comfort zone of airflow (0.5-1.0m/s) suggested in the regional standards for shop-house buildings, the significant variation shows the necessity to review the sufficiency of the standards in practice. Although the available range of air velocities in the standards, the real performance of airflow in shop-houses was low. Therefore, the lower airflow limits of real occupant acceptability can reduce pressures on the practice of architects to optimise design strategies, which enable to achieve satisfactory wind environments for inhabitants and meet the requirement of standards. Furthermore, achieving the acceptable range of air movement indoors through the building envelop needs support of sufficient design guidelines.

- The combination of the minimum levels of air movement (0.2-0.55m/s for 80% occupant acceptability) and the limits of acceptable temperature (25.5-31.5°C) produces a comfort zone linking the interaction of two variables for the overall comfort of residents in free-running shop-house buildings. This finding is used to build up an assessment framework for the environmental effect of various options in the design guidelines.

The third is building the potential design guidance including various design options of opening features and building and urban characteristics; and the assessment of their environmental impacts.

In Chapter 8, the environmental performance in shop-houses was investigated by spot and longitudinal measurements in every room of typical case studies. The analysis aims to understand the relationship between building design and indoor microclimate with respect to the outdoor climate. The uncomfortable environment (warmth and calm air movement) inside shop-houses results from not only urban conditions surrounding the building but the use of inappropriate building designs, in particular, openings. Various opening design features in shop-house buildings were discovered: type, operation, size, orientation, placement, and organisation. In the prevailing influence of the tropical climate of high temperature and high humidity, occupants prefer to optimise the area of openings and the use of various types to capture natural winds in different parts of the day and around the year. There are likely two groups of rooms designed differently with openings. In common rooms, such as living rooms, kitchen, and dining rooms, the option of double-sided ventilation is usually optimised; thereby, the opening area is maximised in windward walls, and even in leeward walls. Meanwhile, in bedrooms, which are usually designed to install the air-conditioner, the area of openings can be narrower and openings are usually positioned in the windward wall. Consequently, the mechanism of single-sided ventilation is primary, and subsequently causing calmer air movement in those rooms than in other room types.

Taken together on-site observations, analyses, and findings on environmental conditions; the building and opening characteristics of shop-houses; and practical experiences of designers, various design options of common opening variables were identified and tested on their environmental impacts for a typical generic room/building by using numerical calculations of DesignBuilder and CFD (refer to section 9.3). The significance of each design option to the indoor environment and comfort is assessed by the design criteria of thermal and airflow acceptable ranges discovered in Chapters 6 and 7. The influence of other factors related to urban morphologies, building orientation, and different room positions was also analysed by parametric studies.

Then, a draft of design guidelines for openings was published. As shown in section 9.3.6, the design guidance is devised into three main elements: design criteria, design tables (covering opening features), and design corrections (covering other factors: urban form, building orientation, and floor position). The validity of guidance sample was tested by professionals, who are working in the architecture and construction industry in HCMC.

Finally, after revisions, the demonstration of guidance is produced as shown in Figure 10.1. That may reflect the gaps of current national standards found; the adaptation in applications of different conditions of building and planning (urban pattern type); the efficient practice for architects because of new comfort criteria discovered in designing NV shop-house buildings, the availability of common design cases and the active understanding and assessment of the environment and comfort level created by their designs, and the diversity in the design of shop-house in reality.

A sample version

THE DESIGN GUIDANCE FOR OPENINGS APPLIED TO NATURALLY VENTILATED SHOP-HOUSE DWELLINGS IN HO CHI MINH CITY

A. ABOUT THIS GUIDE

1. Boundary of implementation

The design manual is determined to be a design pocketbook applied for a particular building element - openings. It helps designers or other users assume the performance of indoor microclimate in a naturally ventilated space/shop-house building in Ho Chi Minh City through applications of suitable opening configurations. Thanks to environmental evaluations, designers basically assess the effect of passive design strategies in terms of openings. The design guide can be applied for regions haviing the similar climate to Ho Chi Minh City.

This design guidance is useful in the early stage of design decision of shop-house buildings, which can bring great impacts on the finished residence. In the phase of basic or conceptual design, architects have usually concentrated on some design sides: structure, space, aesthetics of a house. However, with the availability of the guide, architects can predict how the environmental condition in a space/building performs if it is finished. This brings advantages to get a satisfactory environment for occupant comfort, that also links to the energy efficiency of building while the building aesthetics is still achievable. Moreover, applications of the guidance in the early stage will reduce potential changes in the next stage of design development when architects start to consider the indoor microclimatic performance.

2. The structure of design guidance

The design guidance is structured by two primary components: **Design tables** and **Design corrections.** They include the common cases of opening design in shop-house dwellings in Ho Chi Minh City and Vietnam. They help architects and serve engineers to find the preliminary appropriate opening profile for their practice, which contributes to design naturally ventilated shop-houses achieving indoor comfortable environments, occupant delight, and less energy consumption but no constraints of architects' creativity.

The main building object studied to issue the guide is a typical room of a typical building.

3. Section 1 - Design tables for common cases

Design tables contain common cases of opening design in shop-house buildings observed in Vietnam through field studies in Ho Chi Minh City.

They predict maximum internal thermal conditions (air temperature, opereative temperature, relative humidity, rair velocity, ventilation rate) in a typical room on the hottest day with three basic time scales: 8:00, 13:00, and 18:00.

The framework of design tables is based on:

- **Room geometry:** width, depth, and height of a room. The dimension of a room is the first factor that users will consider when looking up the design tables. Designers will rely on a particular design/drawing/sketch/context of their building and confront with the room parameters available in the design tables.

Note: In the guidance demo, a case of room geometry considered is 5m (W) x 5m (D) x 3.1m (H).

- **Opening design features:** include different variables such as the windward opening area, the inlet-outlet ratio, type, shape, placement, and pattern. Those features directly result in environmental impacts under changes of different opening configurations.

Note: In the guidance demo, two common variables considered are the opening area and the inlet-outlet ratio

4. Section 2 - Design corrections

Design corrections consider the impact of external variables on the design of openings or outdoor microclimate, subsequently linking to the indoor environment and, for example, building orientation, urban spatial structure, room/building geometry, and floor level.

5. Software program

The design manual is not probably used to replace a full analysis of the building in the early satge of design. The guide show environmental predictions for common cases of building form and opening profile. Therefore, for buildings with complex forms, the research techique of numerical simulations may be used.

All the predictions shown in design tables and design corrections in the guide were conducted by Design Builder version 5.5 with two main comfort and CFD (Computational Fluid Dynamics) calculations.

B. CALCULATION CONDITIONS

1. Climatic characteristics on the hottest day (06 May)

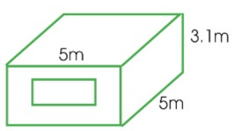
	8:00	13:00	18:00
Air temperature (C)	31.5	37.5	32.5
Humidity (%)	59	48	62
Air velocity (m/s)	6	4	4
Wind direction (from North)	94	90	127

2. Simulated typical building/room

+ Thermal properties of the generic building/room

	Thickness (mm)	U-value (W/m2K)
External wall	200	2.23
Internal wall	100	2.97
Ground floor	350	1.63
Internal floor	200	1.45
External floor	200	1.45
Flat roof	200	2.20
Glass panel	8	5.59

+ Room geometry
For the demo of guide



+ Room position

Level 1

+ Building orientation

South

+ Urban structure type

TYPE 1

Characterised by regular pattern of buildings and roads, low density, and public spaces around the settlement

C. DESIGN CRITERIA

The comfort level of indoor environment is assessed through five physical variables: air temperature, operative temperature, relative humidity, air velocity, and ventilation rate. Apart from air temperature, the criteria of two thermal parameters of operative temperature and airspeed are deduced from analysing field studies carried out in free-running shop-houses in Ho Chi Minh City in both hot and cool seasons between 2016-2018.

1. Opertive temperature (Top)

The comfortable temperature point is **28.5C**

The acceptable range of temperatures for 75% occupants in naturally ventilated shop-house dwellings:

25.5C ≤ Top ≤ 31.5C

Note: Operative temperature is calculated by a formula incorporated into three other variables: air temperature, mean radiant temperature, and air speed.

2. Air velocity (Va)

There is a correlation between thermal and airflow acceptability in naturally ventilated residential buildings in the tropics, for example, in shop-houses. The availability of sufficient airflow affects the overall thermal acceptability, even in 'slightly warm' conditions by removing sensible and latent heat from the body.

Furthermore, occupants can tolerate interior warmer temperatures than the upper comfort limit under the provision of sufficient airspeeds.

The range of minimum air velocities, which 80% occupants accept, corresponds to the range of acceptable temperatures.

25.5 - < 27C	**0.2 - < 0.4m/s**
27C	**0.4m/s**
28C	**0.45m/s**
29C	**0.5m/s**
30C	**0.5m/s**
31C	**0.55m/s**
31.5C	**0.55m/s**

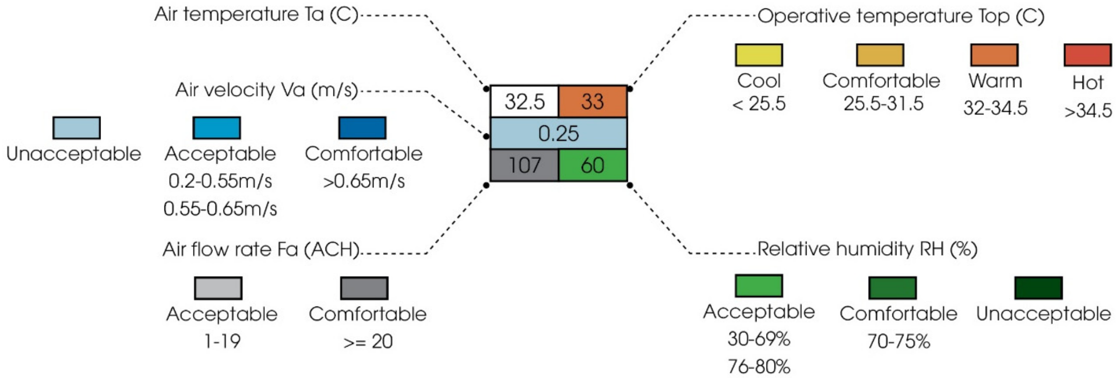
For warm temperatures between 32-34.5C, the minimum of air velocities required are

0.55m/s < V ≤ 0.65m/s

3. Other variables

Relative humidity and ventilated rate will be evaluated by the criteris referred from research literature and current national design standards. They are shown in Section D

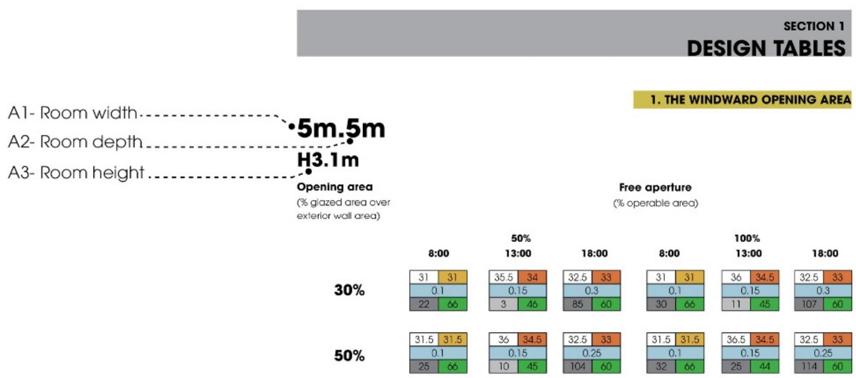
D. EXPLANATION OF A TYPICAL CELL



E. GUIDE TO USE

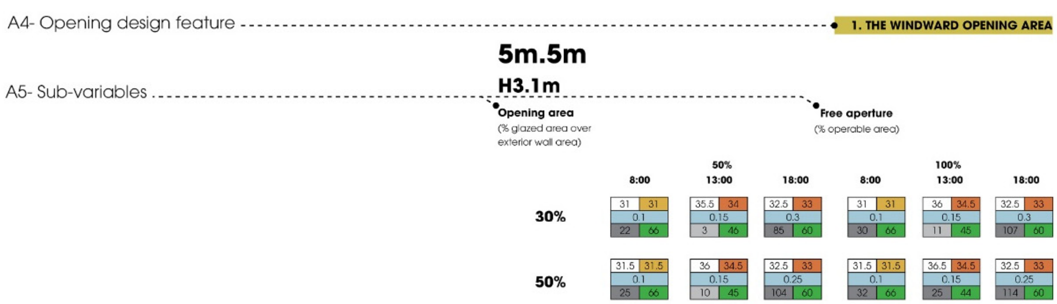
Step 1: Find your room in the design tables (A1-A3)

The guide assumes that you will use the design tables to check preliminarily your design through a typical room for a building. On the top left corner of the design tables, you will find the dimension of typical room, which matches relatively with your design. You follow steps A1 to A3:



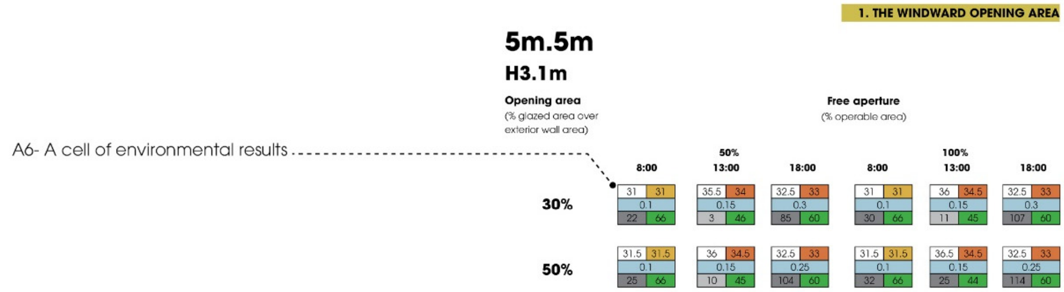
Step 2: Consider the opening design features (A4-A5)

On the top right corner, you will find the opening design features that you want to apply for your design, for example, the windward opening area, the inlet-outlet ration, placement, type,.... For each opening vairable, there are subdivisions. At Step 2, you follow actions (A4-A5)



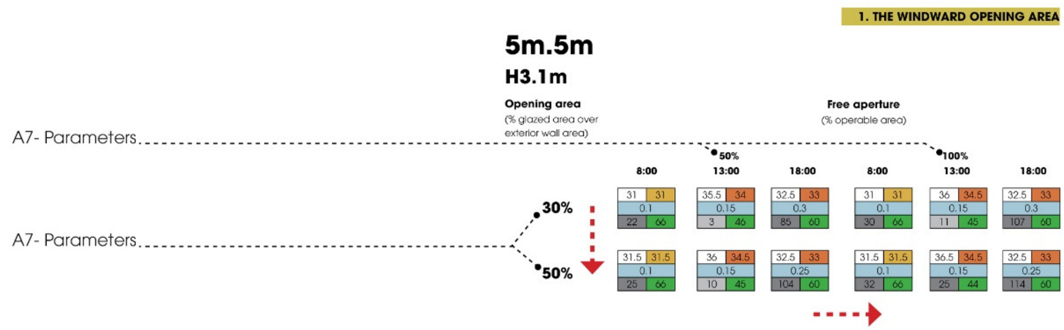
Step 3: Read results (A6)

In this step, you can find a cell of environmental performances corresponding to each application of opening variables and their parameters. The cell will explain you the characteristics of indoor environment and the comfortable or acceptable level of such environment through assessing five physical variables as shown in Section D. You will conduct step A6 combining with the cell's explanations in Section D.



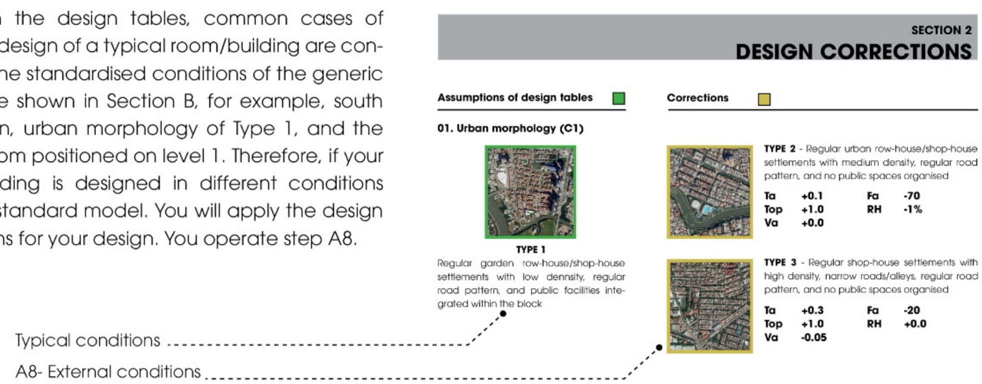
Step 4: Adapt your design (A7)

In this stage, you can adapt your design to change different parameters of opening sub-variables, which links to environmental impacts. This action helps you find different design solutions of openings to achieve a better condition of environment.For each design adaptation, you will find a respective cell of environmental results. You follow step A7.



Step 5: Make corrections (A8)

In the design tables, common cases of opening design of a typical room/building are considered. The standardised conditions of the generic model are shown in Section B, for example, south orientation, urban morphology of Type 1, and the typical room positioned on level 1. Therefore, if your room/building is designed in different conditions from the standard model. You will apply the design corrections for your design. You operate step A8.



Step 6: Identify the final values (A9)

If your designs need to make corrections, you will use simple formulas to assume the final environmental conditions of your design by a combination of values in the design tables and differences shown in the design corrections. Then, you use Section D to give environmental assessments.

Air temperature	Ta = Ta original +/- C1 +/- C2 +/- C3
Operative temperature	Top = Top original +/- C1 +/- C2 +/- C3
Air velocity	Va = Va original +/- C1 +/- C2 +/- C3
Ventilation rate	Fa = Fa original +/- C1 +/- C2 +/- C3
Relative humidity	RH = RH original +/- C1 +/- C2 +/- C3

1. THE WINDWARD OPENING AREA

5m.5m

H3.1m

Opening area
(% glazed area over exterior wall area)

Free aperture
(% operable area)

	50%			100%		
	8:00	**13:00**	**18:00**	**8:00**	**13:00**	**18:00**
30%	31 / 31 0.1 22 / 66	35.5 / 34 0.15 3 / 46	32.5 / 33 0.3 85 / 60	31 / 31 0.1 30 / 66	36 / 34.5 0.15 11 / 45	32.5 / 33 0.3 107 / 60
50%	31.5 / 31.5 0.1 25 / 66	36 / 34.5 0.15 10 / 45	32.5 / 33 0.25 104 / 60	31.5 / 31.5 0.1 32 / 66	36.5 / 34.5 0.15 25 / 44	32.5 / 33 0.25 114 / 60
70%	31.5 / 31.5 0.15 36 / 66	36 / 35 0.15 20 / 44	32.5 / 33 0.3 110 / 60	31.5 / 31.5 0.1 41 / 66	36.5 / 35 0.1 41 / 43	32.5 / 33 0.3 116 / 60
90%	31.5 / 31.5 0.1 35 / 66	36.5 / 35 0.1 28 / 44	32.5 / 33 0.25 113 / 60	31.5 / 31.5 0.1 41 / 66	37 / 35.5 0.15 55 / 43	32.5 / 33 0.3 123 / 60

5m.5m
H3.1m

The inlet-outlet ratio

Opening area 30% & Free aperture 50%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31	31	35.5	34	32.5	33	31	31	35.5	34	32.5	33	31	31	35.5	34	32.5	33
0.1		0.15		0.3		0.1		0.1		0.3		0.1		0.15		0.3	
24	66	3	46	95	60	25	66	3	46	97	60	26	66	2	46	101	60

Opening area 30% & Free aperture 100%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31	36	34.5	32.5	33	31.5	31	36	34.5	32.5	33	31.5	31	36	34.5	32.5	33
0.1		0.15		0.35		0.1		0.15		0.4		0.15		0.15		0.4	
38	66	8	45	146	60	40	66	8	45	155	60	43	66	7	45	170	60

Opening area 50% & Free aperture 50%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36	34.5	32.5	33	31.5	31.5	36	34.5	32.5	33	31.5	31.5	36	34.5	32.5	33
0.1		0.15		0.3		0.1		0.15		0.3		0.1		0.15		0.35	
30	66	9	45	132	60	32	66	9	45	140	60	34	66	8	45	151	60

Opening area 50% & Free aperture 100%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36.5	34.5	32.5	33	31.5	31.5	36.5	34.5	32.5	33	31.5	31.5	36.5	34.5	32.5	33
0.1		0.1		0.35		0.1		0.1		0.35		0.15		0.1		0.4	
46	66	21	44	192	60	49	66	20	44	210	60	53	66	19	44	241	60

Opening area 70% & Free aperture 50%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33
0.2		0.1		0.35		0.2		0.1		0.6		0.2		0.1		0.7	
48	66	19	46	159	60	51	66	18	44	168	60	55	66	18	44	188	60

Opening area 70% & Free aperture 100%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33
0.2		0.1		0.6		0.2		0.1		0.65		0.2		0.15		0.55	
68	66	38	44	227	60	73	66	37	44	252	60	81	66	37	44	296	60

Opening area 90% & Free aperture 50%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33	31.5	31.5	36.5	35	32.5	33
0.15		0.15		0.35		0.15		0.1		0.35		0.2		0.1		0.4	
50	66	26	44	179	60	53	66	25	60	197	60	58	66	25	44	223	60

Opening area 90% & Free aperture 100%

4:1 8:00		4:1 13:00		4:1 18:00		3:1 8:00		3:1 13:00		3:1 18:00		2:1 8:00		2:1 13:00		2:1 18:00	
31.5	31.5	36.5	35.5	32.5	33	31.5	31.5	36.5	35.5	32.5	33	31.5	31.5	36.5	35.5	32.5	33
0.15		0.15		0.45		0.15		0.1		0.5		0.15		0.15		0.6	
70	66	50	44	260	60	75	66	50	43	290	60	82	66	49	43	341	60

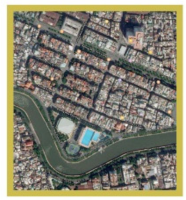
DESIGN CORRECTIONS

Assumptions of design tables | **Corrections**

01. Urban morphology (C1)

TYPE 1

Regular garden row-house/shop-house settlements with low dennsity, regular road pattern, and public facilities integrated within the block

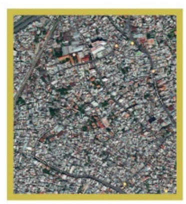


TYPE 2 - Regular urban row-house/shop-house settlements with medium density, regular road pattern, and no public spaces organised

Ta	**+0.1**	**Fa**	**-70**
Top	**+1.0**	**RH**	**-1%**
Va	**+0.0**		

TYPE 3 - Regular shop-house settlements with high density, narrow roads/alleys, regular road pattern, and no public spaces organised

Ta	**+0.3**	**Fa**	**-20**
Top	**+1.0**	**RH**	**+0.0**
Va	**-0.05**		



TYPE 4 - Irregular shop-house settlements with high density, irregular narrow road/alley pattern, informal planning, and no public spaces

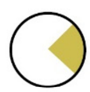
Ta	**+0.1**	**Fa**	**-20**
Top	**+0.5**	**RH**	**+0.0**
Va	**+0.0**		

02. Building orientation (C2)

SOUTH

NORTH

Ta	**+0.3**
Top	**+0.3**
Va	**+0.1**
Fa	**-50**
RH	**-1%**



EAST

Ta	**+0.5**
Top	**+0.5**
Va	**+0.25**
Fa	**-6**
RH	**+0.0**

WEST

Ta	**+0.5**
Top	**+0.5**
Va	**+0.3**
Fa	**-45**
RH	**-1%**

03. Floor position (C3)

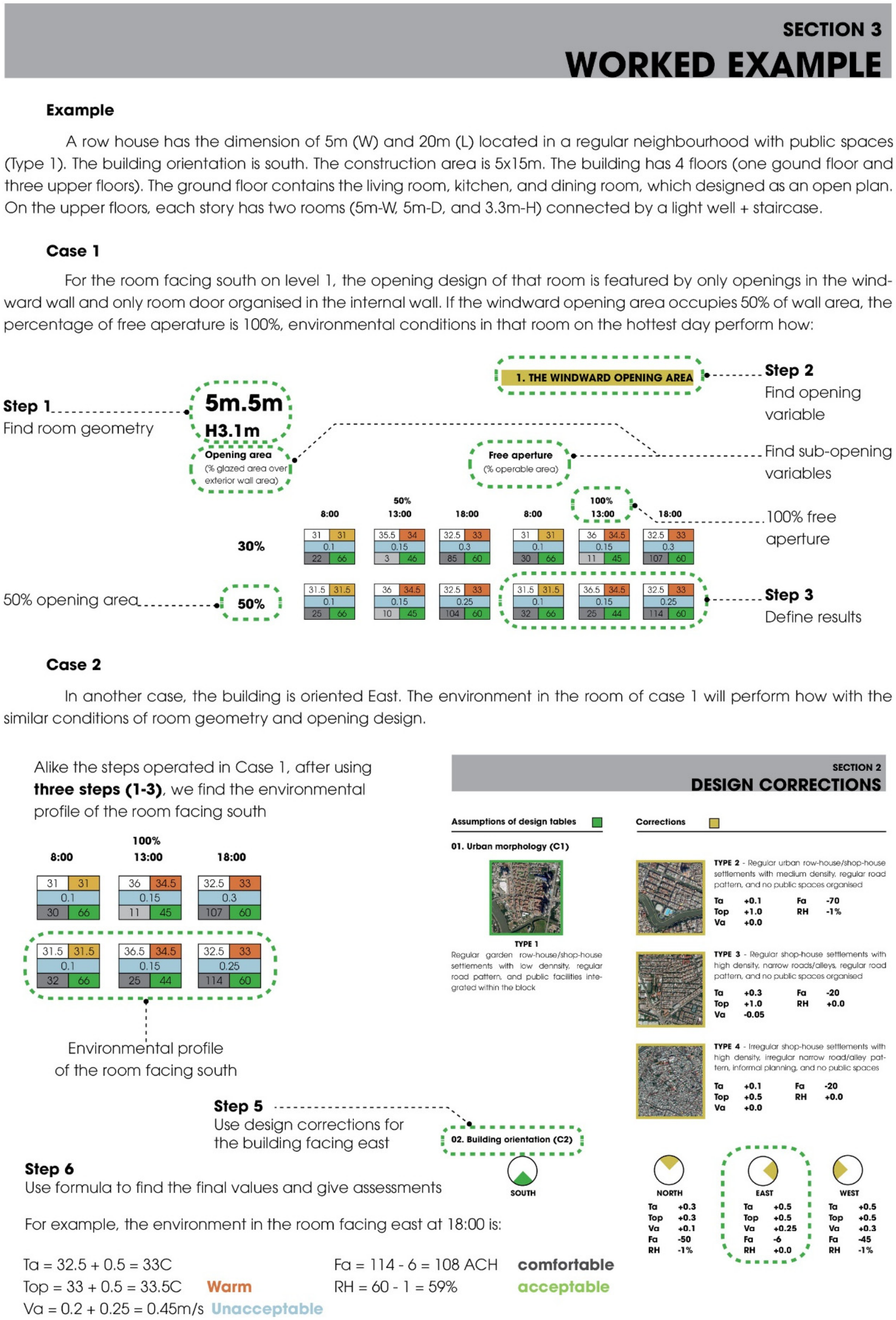
LEVEL 1

LEVEL 2

Ta	**+0.0**	**Fa**	**+0.0**
Top	**+0.0**	**RH**	**+0.0**
Va	**+0.0**		

LEVEL 3

Ta	**+0.0**	**Fa**	**+15**
Top	**+1.0**	**RH**	**+0.0**
Va	**+0.1**		



SECTION 3
WORKED EXAMPLE

Example

A row house has the dimension of 5m (W) and 20m (L) located in a regular neighbourhood with public spaces (Type 1). The building orientation is south. The construction area is 5x15m. The building has 4 floors (one gound floor and three upper floors). The ground floor contains the living room, kitchen, and dining room, which designed as an open plan. On the upper floors, each story has two rooms (5m-W, 5m-D, and 3.3m-H) connected by a light well + staircase.

Case 1

For the room facing south on level 1, the opening design of that room is featured by only openings in the windward wall and only room door organised in the internal wall. If the windward opening area occupies 50% of wall area, the percentage of free aperature is 100%, environmental conditions in that room on the hottest day perform how:

	50% 8:00	50% 13:00	50% 18:00	100% 8:00	100% 13:00	100% 18:00
30%	31 / 31 / 0.1 / 22 / 66	35.5 / 34 / 0.15 / 3 / 46	32.5 / 33 / 0.3 / 85 / 60	31 / 31 / 0.1 / 30 / 66	36 / 34.5 / 0.15 / 11 / 45	32.5 / 33 / 0.3 / 107 / 60
50%	31.5 / 31.5 / 0.1 / 25 / 66	36 / 34.5 / 0.15 / 10 / 45	32.5 / 33 / 0.25 / 104 / 60	31.5 / 31.5 / 0.1 / 32 / 66	36.5 / 34.5 / 0.15 / 25 / 44	32.5 / 33 / 0.25 / 114 / 60

Case 2

In another case, the building is oriented East. The environment in the room of case 1 will perform how with the similar conditions of room geometry and opening design.

Alike the steps operated in Case 1, after using **three steps (1-3)**, we find the environmental profile of the room facing south

	100% 8:00	100% 13:00	100% 18:00
	31 / 31 / 0.1 / 30 / 66	36 / 34.5 / 0.15 / 11 / 45	32.5 / 33 / 0.3 / 107 / 60
	31.5 / 31.5 / 0.1 / 32 / 66	36.5 / 34.5 / 0.15 / 25 / 44	32.5 / 33 / 0.25 / 114 / 60

Step 6
Use formula to find the final values and give assessments

For example, the environment in the room facing east at 18:00 is:

Ta = 32.5 + 0.5 = 33C
Top = 33 + 0.5 = 33.5C **Warm**
Va = 0.2 + 0.25 = 0.45m/s **Unacceptable**
Fa = 114 - 6 = 108 ACH **comfortable**
RH = 60 - 1 = 59% **acceptable**

Figure 10.1 A sample of the design guide for openings used in shop-house dwellings

10.2 Contributions of the thesis

• The initial value of the research would be its effect on the design and creation of comfortable dwellings – this is important for society and the environment in Vietnam. Field studies planned linked to key stakeholders around the city provide a better explanation of the human cognition of changing thermal environment in and around buildings, as well as, health risks, and vulnerabilities because of man-made climate change. The designers and managers, who are worried about those impacts, need to find an appropriate route for articulation between design and human comfort. This could be used to help architects design housing which adapts well to the natural environment and provides information on design guidelines and standards. The findings of real human thermal satisfaction and physical environments in dwellings can indicate the necessity of building a database for updating the existing design standards of comfort conditions for human occupancy in Vietnam. Besides the standards, the availability of effective design guidelines, for example, the guidance of opening design, is supportive for designers to understand and create comfortable and healthy environments for occupants and energy efficiency for buildings. Although the preliminary product of the research project is a demonstration of design guidance for openings mainly applied to 'shop-house' dwellings in HCMC, the experiences learnt from this project show potential to be considered for applications in other regions across Vietnam or other nations having a similar contextual pattern of building and climate types. Furthermore, they can also be considered to apply to other residential typologies in some circumstances.

• Over the 30-year history of the adaptive comfort approach, thermal perceptions and expectations of subjects in residential buildings in the tropics have not been studied in much detail compared to other building typologies and in other climates. Although some research on comfort has been observed in SE Asia (Ballantyne, Hill, & Spencer, 1977; Karyono, 2000; Henry & Wong, 2004; Rangsiraksa, 2006; Djamila, Chu, & Kumaresan, 2013; Nguyen A. T., 2013), there is still a need for further research database for this building type in warm-humid climates, which supports both science and practice to mitigate thermal stress on indoor and outdoor environments for occupant satisfaction under vulnerabilities to increasing climate change, urbanisation, and population growth. Learning the available experiences of previous researchers in SE Asia, the present study carried out many on-site measurements in different seasons to determine thermal and air movement acceptability for occupants in 'shop-house' dwellings in HCMC. Although the sample size of surveys is humble – around 140 respondents and 65 houses, data collection complied with the protocols in international standards; however, they were modified in the particular context of HCMC (Vietnamese people, culture, building type, and climate). Therefore, data from the surveys in HCMC are primary and may be significant for a current modest database taken in residential buildings in warm-humid regions.

• Since the 1990s, a small amount of research on occupant thermal perceptions has been found in residential buildings with different cooling mechanisms in Singapore (de Dear, Leow, & Foo, 1991) (Wong, et al., 2002), Indonesia (Feriadi & Wong, 2004), Thailand (Rangsiraksa, 2006), and Malaysia (Djamila, Chu, & Kumaresan, 2013). In Vietnam, no comfort studies in housing have been conducted. Despite the availability of those studies, they have focused on a comfortable environment in public or detached houses. Meanwhile, the proportion of shop-house dwellings is dominant in the housing market in SE Asian countries including Vietnam. Additionally, getting human comfort in shop-house buildings is more difficult because of the intrinsic characteristics in architecture and planning of this housing type; and the growing impact of urbanisation, high population density, urban heat island, and global warming on the urban environment in populous cities of SE Asia. Consequently, the vulnerabilities of human comfort, health, and well-being in unwell-designed houses are no doubt. The current project is likely the only study on occupant thermal perceptions and comfortable conditions in shop-house buildings. Thus, the findings of this research are the first attempt to indicate the worth of further research in this housing type in future.

• Next contribution is the research method to collect data of subjective comfort votes and physical environments. In previous studies conducted in both HVAC and naturally ventilated buildings, questionnaire surveys and simultaneous measurements of the immediate environment have been carried out in a specific space of the building. Learning those experiences and combining with the absorption of the real distinct context of building type, human occupancy, indoor and outdoor environments, and occupant adaptive behaviours, the current comfort data were taken in various rooms within a shop-house building. The difference in occupant thermal perception between interior spaces found may be significant for research and practice. In buildings in the tropics, particularly naturally ventilated residences, environmental conditions differ due to the varying building envelope and its response to the outdoor climate between spaces. Additionally, the degree of human occupancy and adaptation is dynamic and diverse in those environments. Consequently, variations in human thermal sensation in spaces of a shop-house would be significant for the building design to consider the diversity and appropriateness of passive design strategies applied for single spaces/rooms. By this manner in design, the building performance and energy savings may be more effective. Therefore, common surveying methods may be required to adapt when applied in free-running residential buildings in the tropics.

• Another methodological contribution is an approach to produce design guidance. Reviewing available studies with the same type of research product, they have approached to propose the design suggestions deduced from literature analysis or a package of various design solutions to create the best performance of buildings by using the optimisation tool. Considering the particular context of housing design in Vietnam, planning and architecture characteristics of shop-house buildings are very diverse.

Thereby, the formation of design guidance by the optimisation method may be inappropriate. Instead, the parametric study was used as the main analytical method to test various design cases identified in the guidance. The design guide is devised into three main elements: design criteria; design tables containing various design options of opening variables; and design corrections containing other variables, such as urban morphology, building orientation, and room position. With the composition, the design guidance is orientated to facilitate applications through using design tables, adapt to different conditions of building and settlement, help users predict the performance of indoor environment and assess the effect of opening designs, and not restrain designers' creativity. This approach may enable the guidance to disseminate in the practice of shop-house design in the built environment of HCMC and Vietnam.

- Over a period of 100 years of worldwide comfort studies, plenty of research work has examined thermal perceptions and expectations of people in and around buildings, in which, focusing on the indoor environment is predominant. Their findings have indicated that factors (building type, climate, culture, and society) have influences on indoor comfort. Meanwhile, other researchers have found the relationship between urban conditions, outdoor environments, and urban comfort in a variety of open spaces. Nevertheless, a raised question is: what are actual microclimates within a settlement, particularly a residential neighbourhood in the tropics? Returning to consider the theoretical fundamental of adaptive approach that is the correlation of indoor comfort and outdoor climate, the current research addresses another approach to figure out the linkage between interior and exterior environments and human comfort in relation to urban pattern types in HCMC. Based on field studies of this study, the insights of this relationship are discovered.

- The impact of the project may be a motivation for connection between research and practice that has been discussed – how the achievements of research involve more in the applications of users (Nicol, 2011; Roaf & McGill, 2018). The link between scientific and practical products is certainly significant for practice to achieve comfortable and energy-efficient houses. The present work is directed to apply research techniques and outcomes to understand the interaction of social physics (people), physical building (building), and building physics (environment) and support architects to design comfortable houses through a product of design guidance. The role of design standards or guidelines is undoubted in the built environment; however, the facilitation of their implementation in a large community of practitioners can need to collaborate with other fields, such as management, technology, marketing, and education. The generation of online design tools or apps is inspiring to support designers effectively and open opportunities to have more studies and connections between research and practice in the architectural industry. Therefore, more values beyond a scientific product are created when it widely penetrates in the practical environment.

10.3 Limitations and further work

- As shown in Chapters 6 and 7, the comfort conditions for naturally ventilated shop-house buildings were found by analysing the data of occupant thermal sensations and environments indoor and outdoor buildings measured in the wet and dry seasons in HCMC. The data collection was carried out by the repeated transverse surveys with the involvement of similar 139 subjects. Total datasets obtained were 256. Although the finding of the comfort zone is significant in statistics, the R-value of the existing regression comfort model is lower than that of previous studies found in the tropics. The difference can be attributed to the smaller size of the current data. However, the present research method is consistent with the real characteristics of building and people types within the scope of the thesis. Learning the experience from the field studies of this project, further work is the conduction of widespread on-site surveys with more participants to build a larger-scale database, which enables to produce a sufficient comfort model. That is very significant in research and practice for designing comfortable shop-houses and residential buildings in HCMC and Vietnam.

- In sub-section 6.3, the project has researched the relationship between urban morphologies and comfortable environments in residences in HCMC. Seven urban pattern types were investigated for comfort analysis in the total of twelve urban forms found. Consequently, in parallel to the development of sample size, further field studies will also be carried out in all the urban spatial structures over the city.

- As with the surveys to understand occupant thermal sensations, the investigation of environments indoor and outdoor buildings was conducted in 65 shop-houses located in neighbourhoods characterised by various urban forms. They were revisited in different timescales and the wet and dry seasons for physical measurements. The analysis of cross-sectional data taken in all case studies can partly help the author understand the characteristics of the environment for occupant comfort and the effect of the building and urban design on indoor comfort. However, using cross-sectional data can be less sufficient for analysis because of their discontinuity. Thereby, in 65 buildings, three buildings were selected for monitoring both interior and exterior climates in various spaces for 11 months. Although the limited supply of instruments also restrained the enlargement of environmental monitoring in more case studies, the current study deduced the significant findings from the million data recorded. However, further investigations of building characteristics and environments will be carried out by the longitudinal method in more spaces of a building and in more case studies simultaneously to obtain more sufficient data, which help produce more reliable outcomes.

- Referring to section 9.3.4, it contains a large number of comfort and CFD analyses carried out by DesignBuilder software program with the generic model to develop the design guidance of building openings. Various inputs for simulations were announced, for example, the choice of opening discharge coefficient of 1.0. That absolute number represents the maximum opening ability of windows or holes; however, that condition may not be real in practice. Consequently, further analyses with another more appropriate value of between 0.6 and 0.65 are needed for providing sufficient accuracy of natural ventilation calculations in the real world due to uncertainties of wind pressure coefficients, actual effective areas of openings, crack flows, etc. (Etheridge & Sandberg, 1996; Brandan & Espinosa, 2018; CIBSE, 2005). And then, the simulation of current and new studied cases will be updated and carried out.

- One of the important tasks of this research project is to validate the design guidance although it was produced at the stage of demonstration. The survey with professionals was conducted in HCMC. The next step of the project after getting the full draft of the design manual is planning widespread surveys with the involvement of more professionals and experts through seminars and questionnaire interviews to collect their feedback. In addition, the trial version will be delivered to a group of some design studios for practical applications and evaluations. Before implementation widely in the built environment, the review, adjustment, and improvement of it are needed.

- A demonstration of design guidance for openings has been a preliminary effort of the current work. Based on helpful and positive comments of professionals for it, the completion of a full version is expected. Therefore, in next steps, many simulations of design options of different opening variables will be conducted to build a full of design tables; additionally, the analysis of other factors in the part of design corrections will also be processed. In a further scenario of the design guidance in applications, its final product may be a handbook, or an online tool, or design apps operated on smartphones. By that way, the dissemination and implementation of the design guide are larger and more effective in the built environment of Vietnam.

- The current database of indoor and outdoor environments of NV residences reported in HCMC show warm discomfort for people. In the present study, the comfort conditions and the potential design guidelines have been approached and discovered through those field data in a complex relationship between locally climatic conditions, urban forms, building features, and human perceptions. Under the impact of global warming, the projection of temperature rise in Vietnam has been by 1-2°C in 2050 and 1.5-2.5°C in 2070 (MoNRE, 2016). The public health including human comfort in the city will be likely more vulnerable in the warmer climatic scenario coupled with the intensified UHI effect and urban air pollution due to the progressing population growth and city development in next years, which has been assumed up to 13.9 million people (Cox, 2012; HCMC People's Committee, 2013) and total constructed city land area of 750km^2 (Storch & Downes, 2011) by 2025. Those projections are significant on comfort conditions and thermal sensations, preferences and acceptability of occupants because of their close correlation to the urban environment. Those also link to changes in human thermal tolerance, behaviours, and adaptation to get used to new conditions of overheating risks, sequentially having the effect on energy consumption in the future. Enhancing adaptative comfort is a potential to conserve building energy, mitigate CO_2 emissions, and encourage building adaptation to climate change. The role of urban and building design is important to moderate and create pleasant microclimates inside and outside buildings by applying proper design solutions and optimising them; consequently, the existing design standards should have flexibility and adaptation to the future climate context. Considering the existing research products, which are mainly the comfort conditions for naturally ventilated shop-houses and the design guidelines for their building envelope, in next step, they will be studied with the potential risks of climate change and urbanisation through computational simulations. Those analyses will employ predictive models of different climatic and urban scenarios. Additionally, they will be reviewed for any updates based on field surveys and changes in the urban climate and development in every decade.

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12. Appendices

12.1 Appendix A - Natural ventilation principles

Building characteristics of shop-houses were reported during the comfort studies in HCMC. The spatial organisation within the building and the opening design on the building fabric produce different natural ventilation effects. Four common ventilation systems: single-sided ventilation, cross-ventilation, stack-ventilation, and night ventilation are available in shop-houses (Table A12.1).

Table A12 1 Principles of natural ventilation found in shop-houses in HCMC

	Singled-side ventilation	Cross-ventilation	Stack-ventilation	Night ventilation
Total	88%	77%	68%	12%
Building types				
Row house	90%	80%	90%	10%
Traditional shophouse	67%	67%	67%	0%
New shophouse	88%	77%	63%	13%
Urban types				
Group 1	64%	82%	91%	27%
Group 2	100%	93%	64%	7%
Group 3	88%	65%	56%	12%
Group 4	100%	100%	83%	0%

In many shop-houses visited, driving natural force at the only windward surface is the most popular with 88% of cases found. However, the effect of single-sided ventilation is usually negligible in naturally ventilated houses in the tropics (Fry & Drew, 1980) (Tang, Viet, & Nguyen, 2007) (Szokolay S. V., 2008). Meanwhile, the allowance of air movement between opposite openings is also optimised in many buildings (77%).

Considering the architectural identities of shop-houses described in Chapter 4, the building form (long and thin) restrains the operation of natural winds within the building, especially poorer natural ventilation potentially in buildings having only one façade. Therefore, architects usually improve building physics by integrating light wells, voids, courtyards, or atriums within the construction. Those elements are effective to improve the daylighting and airflow distribution in the middle spaces of the building. 68% of houses are designed with the stack effect. Moreover, the option of night ventilation is found in a few shop-houses (12%) to maintain a constant permeability of natural wind indoors through openings usually positioned at a higher sill height above the floor during the day.

In reality, based on specific site conditions and occupant preferences, designers seek one or more appropriate natural ventilation principles coupled with the opening profile to apply to the building. For 65 shop-houses reported, the natural cooling systems, including wind effects and buoyancy are optimised: 5% of buildings using all four natural cooling mechanisms, 46% applying to three common driving forces (single-sided/cross/stack ventilation), 37% of houses designed with both single-sided and cross-ventilation, and 12% operating at least one system – the single-sided ventilation.

In Chapter 4, three primary shop-house types were introduced (traditional shop-house, new shop-house, and row house) used in this study, along with their characteristics. The distinction in architecture between those housing types may affect the ability to drive natural airflows inside the building. Three principal wind effects (single-sided, cross, stack ventilation) are usually optimised in old traditional shop-houses. The row house, which is formally planned in standardised land plots with specific planning and architecture regulations, has advantages to optimise various schemes of natural cooling, particularly single-sided and cross-ventilation and stack effect. Meanwhile, the application of natural ventilation options in the new shop-house has limitations.

As discussed in Chapter 6, urban pattern types of shop-house have influences on the microclimate and human comfort indoors. Housing planning and design regulations for each urban morphology partly involve affecting the natural ventilation design in shop-houses. For example, in formal planned residential neighbourhoods of Group 1 and 4, the principal dwelling type is the row house. The availability of back garden and light wells/voids/atriums with a minimum area of 6m² is mandatory, which is potential to encourage the quality of natural ventilation and daylighting in the building (VIAP, 2012). Thereby, designers have more advantageous conditions to apply cross-ventilation and the stack effect. Meanwhile, in settlements of Group 3 featured by an irregular and compact housing pattern, the new shop-house is the main building type, which passive cooling designs including natural ventilation systems have difficulties to optimise. Ventilation at a single side is the most popular in new shop-house while other natural ventilation options are limited to develop.

12.2 Appendix B - Opening configurations

In the field studies on opening configurations of shop-house buildings in the city, various opening features are found: type and operation, shape, material, placement, and organisation. This section will discover those characteristics.

12.2.1 Type and operation

12.2.1.1 Windows

Windows are an important element of the building fabric to complete the building look and to respond to the outdoor environment for the comfortable building physics inside. There is a total of eight window types found in shop-house buildings during surveys: casement, sliding window, folding window, awning window, shutter, side-hung, jalousie, and sky window as shown in Figure B12.1. In a dwelling, more than one window type can be applied. The major shapes of windows are square and rectangle, other geometries (round and hexagonal) are less popular in applications.

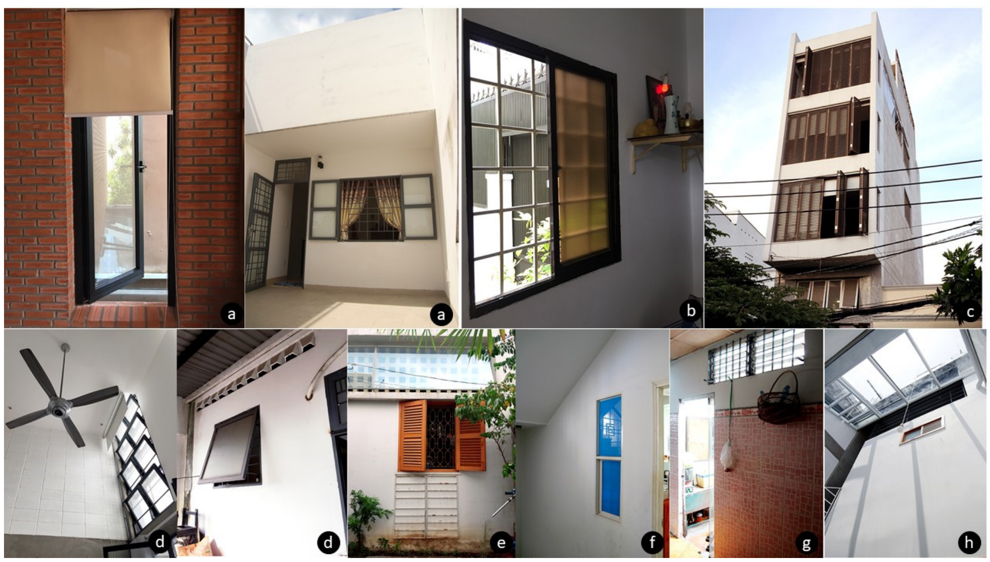

Figure B12 1 Single and double casement (a), sliding (b), folding (c), awning (d), shutter (e), side-hung (f), jalousie (g), sky window (h)

Table B12.1 presents the popularity of different window types in the design of shop-houses in HCMC. The most common window type is the side-hinged casement with 66% and 25% of double and single casements, respectively. The operation of those windows is flexible with the effective opening area ranging from 50% (one panel closed and another opened) to 100% (entirely open). Additionally, panels are likely open toward the outside space and kept perpendicular or parallel to the wall (Allard, 1998); therefore, they require enough clear space for the window operation. Casement windows significantly control the airflow pattern and velocity (Allard, 1998). The casement type (single or double) and the position of sashes (0°-180°) in the relationship to the wind direction can change the horizontal airflow distribution indoors after crossing the window (Tang, Viet, & Nguyen, 2007). Moreover, under similar conditions of room geometry and window area, the ventilation rate inside through casement and folding windows is the greatest in the eight window types because they can maximise the effective opening area for air movement (Allard, 1998).

Table B12 1 Frequency of occurrence of common window types used in shop-houses in HCMC

Windows types								
Single case	**Double case**	**Sliding**	**Folding**	**Awning**	**Shutter**	**Side-Hung**	**Jalusie**	**Sky window**
25%	66%	52%	2%	38%	5%	2%	16%	13%

The second type is the sliding windows, which are common in practice and suitable to use in many various functional spaces in the house. Over 50% of shop-house dwellings have installed them for ventilation and daylighting. The sliding window does not generally direct the outside airstream and influence wind velocity within the interior (Allard, 1998). The maximum opening percentage of sliding windows is 50% of the total window area. This means that the rate of natural ventilation reduces 50% compared to casement or folding windows.

Besides the popularity of side-hinged casements and sliding windows, awning windows are also a common choice because they can be opened most of the time without concerns about rain ingress and safety. Therefore, ventilation can occur over the whole day. 38% of the samples found have used awning windows. The effective opening area of awning windows can reach a maximum of 100%. The position of sashes can influence both the direction of the flow path and wind velocity vertically (Allard, 1998) (Tang, Viet, & Nguyen, 2007).

Other window types are less popular, such as folding (2%), side-hung (2%), jalousie (16%), shutter (5%), and operable skylight (13%). In particular, folding windows can create a great effect on ventilation, daylighting, and view because the optimal opening percentage is flexible up to 100%. The pattern and velocity of airstream are controlled by the percentage of the opening area and linked to the horizontal wind pattern (Tang, Viet, & Nguyen, 2007). The folded window panels may act as a scoop to catch the gentle winds. Moreover, through field observations, particularly for buildings facing west (the direction from which solar protection is of high value), it provides an interesting combination of folding window and shutter combining three effects of shading, lighting, and ventilating (Figure B12.1d).

Furthermore, timber shutters used to be frequently used design feature in Vietnamese tropical architecture in the 1900s. They respond well to exterior environments because of regulating the indoor climate by a combination of ventilation and solar protection when they are closed. The appearance of new materials and the increasing need for mechanical cooling systems have reduced the use of shutters;

however, Vietnamese architects still have an interest in using them. Meanwhile, side-hung windows are less common in the built environment of Vietnam.

Jalousies are primarily found in new shop-houses, particularly installed in serviced rooms or in spaces with the tight spatial condition surrounding. Jalousie windows are formed from horizontal glazed slats tilted and work as awning windows. To some extent, they supplement natural light inside and air exchange between internal and external climate. Furthermore, the position of sashes directs the airflow path through the window (Allard, 1998). However, the utilisation of jalousies is not favoured by occupants because of inconveniences in cleaning and maintenance.

The long and thin building form of shop-houses is a difficulty for designers to optimise the penetration of natural light and wind deep inside the building, particularly in innermost rooms of a long building. Thus, the integration of voids and light wells is significant, especially for natural ventilation, and in the design of shop-houses, those building elements are usually attached to the staircase. Their presence means the stack effect can occur if outlets are available, for example, operable skylights, wall holes, or vents on the top of voids or light wells. In 49% of shop-houses designed with the staircase combined with voids/light wells/courtyards, which is covered by the skylight, just 13% of them are operable for ventilation. Whereas, other buildings only use skylights for daylighting while vents positioned around light wells or voids work as outlets of the air. The use of inoperable skylights in the building results in inconvenience in operation for occupants, in particular, during periods of non-occupancy and rain. Therefore, the use of skylight windows should be considered carefully given the influence of tropical climatic events.

12.2.1.2 Doors

Doors are less important in controlling airflow than windows (Allard, 1998). Through on-site investigations, six major door types were found in shop-house buildings of HCMC including single door, double door, sliding door, folding door, metal grille sliding door, and steel roller shutter door (Figure B12.2). The employment of those doors in design depends on various factors: the site condition, the function of space, preference and need of users, and creation of designers.

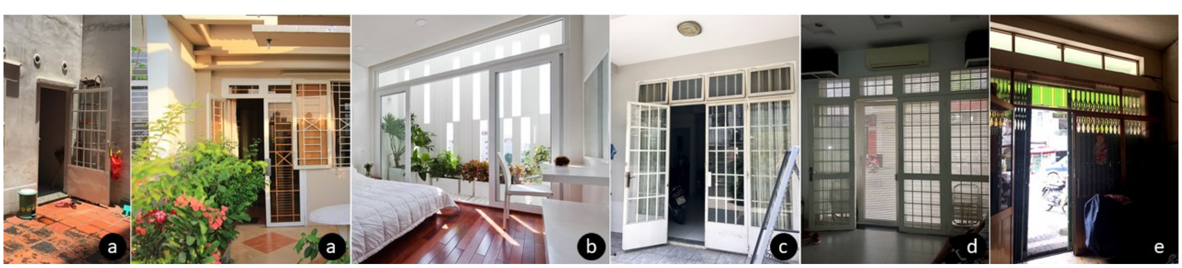

Figure B12 2 Single door (a), double door (b), sliding door (c), folding door (d), metal sliding/rolling door (e)

Side-hinged doors (single and double panels) are dominant in the practice of shop-house design and construction. The doors installed on the building fabric are mostly out-swinging whilst those located in partition walls are in-swinging. In these, single doors are the most common because they offer a wide variety of colour, style, and materials and less take-up of wall area. They are positioned on both the external and internal walls of the building. However, side-hinged single doors are not usually designed for the main entrance, instead, they are installed in rear building walls and external walls on the upper floors.

In the shop-houses visited, 62% of buildings use single doors for building elevations to enhance communication with the surroundings (Table B12.2). When wholly opened, they provided up to 100% permeability of air through their area. In some cases, single doors are designed especially to be able to ventilate indoors during both day and night time. Whereas, other occupants often open them at some certain times of the day. The reasons are related to urban environments (dust, pollutants, and noise) which can have impacts on occupant behaviours in opening or closing the door.

Table B12 2 Frequency of occurrence common door types found in shop-houses in HCMC

Door types				
Single door	**Double door**	**Sliding door**	**Folding door**	**Metal sliding/roller shutter door**
62%	56%	16%	59%	44%

The folding door is also a favourite of occupants (59%). This door type is commonly used as the main entrance door of the building and a function of the inlet opening. Most Vietnamese families have a concept that the first room on the ground floor is an important space of the whole house in which to welcome guests and which also connects most with outdoor spaces. Consequently, the larger the opening area of the door, the better the ventilation inside the house, and subsequently, according to local beliefs the greater the luck and prosperity for the household. As a result, the door mostly fully occupies the area of the wall (Figure B12.2d). Folding doors maximising the building width, popularly comprise four-panels. Their operation is very flexible; however, in reality, users usually open two panels for daily usage that reduces the airflow rate by 50%.

Besides the popularity of single and folding doors in practical applications, double doors are quite popular being used in 56% of buildings observed. Double doors are usually installed on building elevations on the upper floors. The effect of the flow rate through double doors ranges from 50% to 100%. The airflow distribution crossing a double door has similar characteristics to the pattern through the double casement (Allard, 1998).

Through on-site observations, sliding doors become more favourable in contemporary shop-houses. Sliding doors are usually formed with two or four panels; in these, doorways with a full set of four panels can spread across the entire building width. The percentage of the effective opening area of sliding doors can be a maximum of 75%. The airstream pattern indoors is consistent through a sliding door (Tang, Viet, & Nguyen, 2007).

An interesting discovery of door types used in shop-houses is the repetitive presence of metal sliding doors and roller shutters (44% of samples were found). In settlements planned in commercial or high-density areas in HCMC, most shop-houses usually do not have the front garden; therefore, the main entrance door on the ground floor directly touches the street. To secure the building, a metal grille sliding/rolling door is installed outside of the main door. Metal grille sliding doors aim to not only secure properties inside but take advantage of environmental benefits: wind permeability and shading (Allard, 1998). The structure of those doors commonly includes three parts: vents at the top and bottom allowing airflows and the middle section of solid pleats to provide privacy.

Meanwhile, metal roller shutters are constituted of permeable steel panels or are designed with vents on the different parts of the door. Therefore, the air can exchange between interior and exterior climates, even when doors are closed. The usage of double layers (inner wooden or glazing door and outer metal sliding/rolling door) is common in residential buildings of Vietnam to satisfy two purposes: security and the permeability of air movement and daylight. In the daytime, the grille door can be closed while the entrance door is open.

12.2.1.3 Vents/screens

In hot-humid climates as HCMC, efforts in providing ventilation through building means are worthy and a requisite for comfort and well-being indoors. The wind outside is free to use but to capture it inside the house is a challenge for designers. In practice, they have many creative options in natural ventilation and daylighting design by using passive building means.

Table B12 3 Frequency of occurrence of common aperture types found in shop-houses in HCMC

Aperture types			
Louvres	**Vent brick**	**Steel screen**	**Vents**
18%	34%	7%	25%

Besides the two common opening types (windows and doors) described above, vents, as shown in Table B12.3, are an interesting element in Vietnam housing architecture, particularly in the southern regions of the country where the climate is hotter and wetter. Four categories of passive apertures found during the survey consist of louvres, ventilation bricks, metal screen, and air holes. They respond well to the environment and are creative in design and affordable to apply. Three main environmental effects of vents are shading, ventilation, and daylighting.

During the stage of Modern Architecture in Vietnam between 1950 and 1975, the building designed with ventilation bricks was common; however, they became unfashionable and were replaced by more modern materials. In many recent years, contemporary architects in Vietnam have learnt experiences of vernacular architecture and used them again in more modern and interesting creative ways. Ventilation bricks can be used in many different functional spaces of the house and work as an internal and external wall, a partition, a window, or a door (Figure B12.3). They not only provide a nice look and safety but respond well to the environment in terms of wind and natural light. 34% of the buildings examined have made use of ventilation bricks. The design and geometry of ventilation bricks are diverse; thus, the combination of them creates interesting patterns. Unlike using doors or windows, the constitution of ventilation bricks entirely provides a homogeneous look. They can allow for daylight to access but also prevent sunlight simultaneously. Moreover, ventilation bricks can catch winds from every direction and maintain air breezes crossing over the whole day (Konya, 1980).

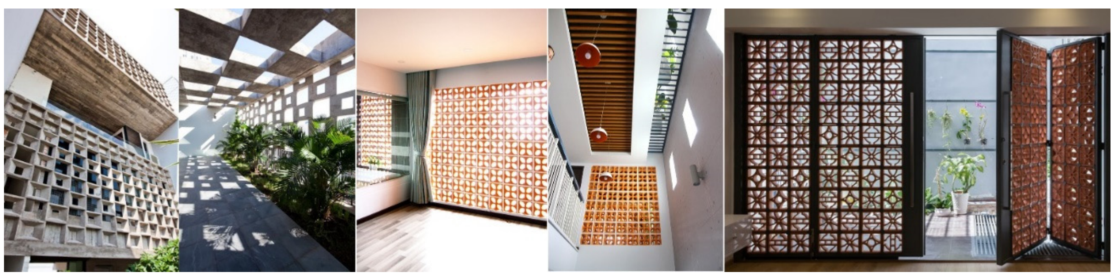

Figure B12 3 Ventilation bricks used in the shop-house surveyed

For materials of ventilation bricks, red clay and cement are the most usual in practice. Their standardised size is 20x20x10cm. Meanwhile, new generations of ventilation bricks by ceramic and concrete can get a larger dimension of 30x30x10cm. The pattern and colour of ventilation bricks are also various. A disadvantage in the usage of ventilation bricks is cleaning.

Figure B12 4 Concrete louvres (a), metal louvres (b), steel screens (c) and vents (d)

Some other kinds of openings found are louvres (18%), steel screen (7%), and vents (25%). Louvres are commonly made of concrete and metal (steel or aluminium). In this, horizontal concrete louvre vent blocks are more popular in applications to old traditional and new shop-house dwellings (Figure B12.4a). Meanwhile, metal louvres are used more commonly in the row house, particularly at staircases for ventilation purposes (Figure B12.4b). They similarly operate to the jalousie window. However, the slope and gap between slats should be considered to avoid rainfall but still providing the amount of wind and daylight. Louvres generally have fewer influences on the airflow pattern indoors; however, they significantly decline wind velocity. The degree of wind energy reduction complies with the position of slats and empty spaces between them (Allard, 1998).

Vents found in shop-houses are basically wall holes. They are often designed and built on-site with various configurations of geometry, pattern, and size. Some available examples are shown in Figure B12.4d. The application of vents not only creates the effect of building aesthetics but provides passive cooling and daylighting with not much maintenance. For vents having larger areas, perforated metal screens or decorative panels are employed to fill in the holes – see Figure B12.4c. They satisfy different purposes: aesthetics, daylighting, shading, ventilation, and security.

12.2.1.4 Combination

In practice, the opening design of shop-house buildings in Vietnam is diverse and creative with a combination of different opening types on the building fabric that is flexibly adaptive to different operation schedules and outdoor environments and improves the indoor thermal condition. In an external wall, a door is usually assembled with windows (casement, sliding, or awning) or shutters positioned nearby and fixed sashes, smaller awning windows, ventilation bricks or louvres at the top (Figure B12.5).

Figure B12 5 Combination of opening types on the building fabric

This method in design not only makes the opening area look larger but encourages the access of natural daylight and wind at both lower and upper parts of the wall. In the built environment of Vietnam, windows are often attached by steel frames inner. Since openings have various purposes: daylighting, ventilation, and security; therefore, there is a need for the operation of windows can be optimised. Louvres play a role in support of passive cooling when doors and windows are closed. Another important element on the building envelope is shading devices to protect openings from rainwater and sunlight. In addition, they can be an effective trap to deflect wind flows and induce them inside the building.

12.2.2 Orientation

The basic building form of a shop-house is like a tube. In a residential neighbourhood, shop-houses are arranged adjacently with a back-to-back pattern. Consequently, most openings are certainly designed on the main façade; and they play a role of wind inlets. However, thermal conditions inside the building may be inadequate for human comfort especially when building orientations do not have a relationship with prevailing winds. Besides, opening orientations should be also considered alongside influences of the sun, particularly for buildings facing east and west.

Table B12 4 Distribution of orientation of main building façade in shop-houses surveyed

North	Northeast	East	Southeast	South	Southwest	West	Northwest
9%	9%	26%	17%	12%	11%	9%	7%

Table B12.4 represents the orientation distribution of shop-house buildings visited in the field studies. Building orientations are certainly various. Their consideration relies on not only potential environmental conditions, such as predominant wind directions and reduction of solar impacts but idealistic factors (Feng Shui). Based on field investigations, most shop-houses are oriented toward prevailing winds, particularly south and southeast (29%), west and southwest (20%), and north and northeast (18%). Although the building oriented to west and southwest absorbs winds between June and October, solar protection is highly recommended to reduce external heat gain during the daytime. However, shading solutions do not block wind flows.

Table B12 5 A number of facades in shop-houses surveyed

1 façade	2 façade (front & back)	2 façade (front side)	3 façade (front, side & back)
48%	32%	11%	9%

A building having more than one facade is advantageous to organise inlet and outlet openings on various directions of the building fabric, subsequently encouraging the effect of daylighting and cross-ventilation. In a total of case studies visited, 48% of them have only one elevation (Table B12.5). Therefore, the daylight and natural ventilation system of those houses mainly operate from the single side. The significance of the indoor climate is assumed to be negligible. 43% of cases are designed with openings on different elevations: 32% (front and back facades), 11% (front and side facades), and 9% (three facades). The organisation of openings on more facades possibly enhances the penetration of natural light, particularly prevailing winds in different seasons; however, risks of external heat gain and glare are potential. Thereby, the ratio of opening to the floor or exposed wall area should be evaluated to ensure satisfactory environments inside.

12.2.3 Size

Considering the influence of opening size on indoor thermal environments, particularly air movement identified by Chand, Givoni, and Al-Tamimi el at., the figures of WWR (window to wall ratio) and WFR (window to floor ratio) should be between 30-50% and 20-30%, respectively (Chand, 1976) (Givoni B. , 1976) (Al-Tamimi, Fadzil, & Harun, 2011). However, in buildings with west and east orientations and WWR above 30%, overheating risk is possible (Trimarianto, 2003). Therefore, shading devices are used to maintain comfort.

Those recommendations of WWR or WFR have emphasised the variable and impact of the window area. In the report of opening configurations above, this shows the diverse application of individual or compound opening types and their operation in naturally ventilated shop-house buildings depending on specific site conditions, the urban environment, and even architects' ideas. Based on the real practice of opening design, the relationship of window area to two remaining parameters (wall and floor area) is modified by the opening area (OWR and OFR) in the current study. Additionally, the effective opening area was also evaluated in comparison with the wall and floor area (EOWR and EOFR). This is because this index actually governs the rate and velocity of airflow through openings and also correlates to opening types.

In 65 shop-house buildings visited, 22 of them were redrawn and reported detailed building information related to the floor, wall, and opening area of rooms. Figure B12.6 illustrates the distribution of EOWR and EOFR in three main living spaces of a residence (living/family room, kitchen + dining room, and bedroom) grouped into different variations defined by Givoni and Chand (1976).

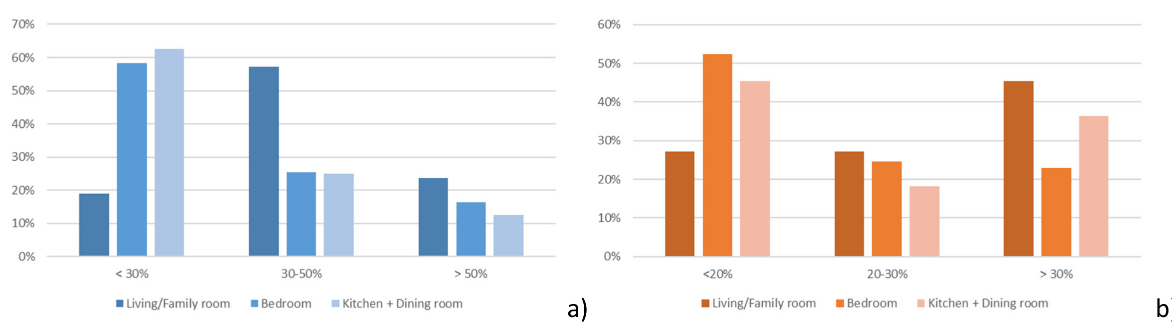

Figure B12 6 Distribution of effective opening to wall/floor ratio in the living/family room, bedroom, kitchen + dining room

The assessment of EOWR is classified into three ranges (<30%, 30-50%, and >50%). The pattern of EOWR in bedrooms and kitchen + dining rooms is similar. Most of them (around 60%) are designed with an effective opening area below 30% of external walls, as a result, the effect of natural ventilation inside those rooms is possibly insufficient. Meanwhile, the percentage of EOWR within the recommendation (30-50%) is 25%. That figure is much smaller than the cases of living room investigated (58%) in the same category. This may assume more comfortable air movement in living rooms. The smaller percentage of three-room types are characterised by EOWR more than 50% as follows: 23% of living/family rooms, 16% of bedrooms, and 12% of kitchens + dining rooms.

Meanwhile, the parameter of EOFR is assessed by a measure of three variations: <20%, 20-30%, and >30%. In a residence, the floor area of living and kitchen + dining rooms is usually larger than the others; therefore, the area of openings is also of greater importance. Assessing the rooms designed with the EOFR above 30%, the proportion of living rooms are the highest. Whereas, the number of samples with the advisable EOFR values between 20-30% is not many in three room types

Considering the parameters of EOWR and EOFR of a room/building in the early stage of design can help designers initially predict the quality of airflow indoors. The combination of analyses together shows that the opening design should vary between room types within a dwelling, thus subsequently affecting the interior air movement conditions according to rooms.

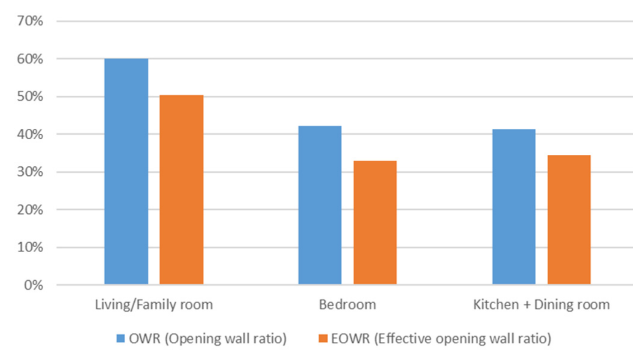

Figure B12 7 Comparison between opening and effective opening to wall ratio

The free opening area directly affects the indoor airflow condition while the opening area has impacts on the interior thermal microclimate of two sides: natural ventilation and heat gain. The present research found a relationship between two variables (opening area and effective opening area) in shop-houses in HCMC, which reflects environmental impacts through the opening design. There is an average variation of 10% in the whole rooms investigated (Figure B12.7).

Table B12.6 classifies the difference between OWR and EOWR into five percentage variations. No differences between OWR and EOWR are found in half of the samples surveyed. This means that the openings can be fully opened for ventilation (for example, the casement and folding window and the side-hinged and folding door). The opening deviation lower than 10% and between 10-20% is more common. In the remaining cases with a greater variation between OWR and EOWR, especially the group of >30%, overheating is a potential problem due to the solar transmission through the larger glazing area while the degree of effective opening is smaller. The close correlation between EOWR and OWR helps explain the occupant preference for optimising the operable area of total windows/doors for natural ventilation.

Table B12 6 Deviation between OWR and EOWR, and OFR and EOFR

Deviation	0%	<10%	10-20%	20-30%	>30%
OWR-EOWR	50%	17%	21%	6%	6%

12.2.4 Placement

Opening placement influences the pattern and velocity of indoor wind flow confirmed through previous studies and mentioned in the literature chapter. In the present study, this opening design factor will be analysed by three groups of opening types and seven different locations of openings in the wall (left or right, middle, low, medium, high, full height, and full area) as shown in Tables B12.7-8.

Table B12.7 emphasises door placement with five common door types found over 65 shop-house samples during surveys and compares door type with location. In respect of outdoor winds, external doors act as inlets; therefore, based on the spatial layout of room/building, designers might identify an appropriate position of doors (left, right, or middle) to direct horizontal airflow within the occupied zone. Besides, the position of outlets and their area is significant to encourage airstream through the room with greater velocities and change the direction of airflow indoors (Tang, Viet, & Nguyen, 2007).

Table B12 7 The pattern of door placement found in the field survey

Location	Door				
	Single door	Double door	Sliding door	Folding door	Metal sliding/roller shutter door
Right or left	62%	46%			
Middle		10%			
Full area			16%	59%	44%
Full height					

Table B12.8 shows the location of windows according to different window types. In general, most windows of all types are positioned at a medium level (0.8-0.9m) above the floor to provide uniformity of daylight and natural wind within the living space, apart from awning (33%) and jalousie (11%) windows that are usually installed at a higher level. In common, the windows positioned at the upper level usually have a smaller area. They supplement an amount of passive ventilation and daylighting during the day, even when main windows and doors are closed. The vertical position of windows influences the direction of the indoor flow path (upward or downward) in relation to the vertical placement of outlets (Tang, Viet, & Nguyen, 2007). Few houses (2%) are designed with windows enabling to open from floor to ceiling, particularly awning and folding types. The effect of them on indoor natural ventilation is higher when utilising full height operable windows (Tang, Viet, & Nguyen, 2007).

Table B12 8 The pattern of window placement found in the field survey

Location	Windows								
	Single case	Double case	Sliding	Awning	Shutter	Folding	Jalusie	Side-hung	Sky window
Low									
Medium	25%	66%	52%	16%	5%	2%	3%	2%	
High			3%	33%			11%		
Full area									
Full height				2%		2%			

Table B12.9 shows the information for other apertures which seem to be installed at a higher level in the wall. They are usually designed in a combination with main doors and windows to increase the effect of daylighting and ventilation, especially when the building is unoccupied or closed. However, due to the high location of vents above the floor, the airflow path is usually higher in the room than the occupied zone and significant to cool building structure (Allard, 1998). In some houses, ventilation bricks are used to replace a window or a door or a normal wall. Therefore, they are designed with a full area of the wall and positioned at a common level of windows.

Table B12 9 The pattern of vent/screen placement found in the field survey

Location	Apertures		
	Louvres	Vent brick	Vents
Low			
Medium	3%	7%	
High	15%	28%	25%
Full area		5%	
Full height		2%	

12.2.5 Organisation

The layout of openings around the building (on external, side, internal walls) may have a great effect on air movement inside (production of ventilation principles, distribution, and velocity). In the 22 houses surveyed with opening design features, there are 114 rooms of various usages (living room, family room, kitchen + dining room, bedroom, studying room, and altar). The opening organisation of those spaces can be devised into eight categories summarised in Table B12.10:

(A) spaces with windward openings and no opposite wall (the interior opened toward the staircase/light well/void)

(B) spaces located within the building and opened toward adjacent staircase/corridor/light well through windows or vents

(C) spaces with openings in the external wall

(D) spaces with only one opening in the external wall

(E) spaces with openings in opposite walls

(F) spaces with openings on three walls (partition and adjacent walls)

(G) spaces with no openings excepting the room door

(H) a combination of (A) and (E).

Table B12 10 Percentage of spatial categorises incorporated into the opening organisation

A	B	C	D	E	F	G	H
5%	13%	7%	32%	30%	6%	3%	4%

The long and narrow building form and building grouping pattern of shop-houses significantly influence optimisation of natural ventilation inside the whole house as well as single rooms. Four existing opening options (B, C, D, G), 55% of the total are potentially unsatisfactory for inhabitants due to the operation of single-sided ventilation. 39% are designed with one or more openings installed in one external wall. If openings are not located with a suitable relationship to the predominant seasonal winds, indoor thermal conditions will become more stressful. Furthermore, environmental quality is poorer in spaces with no openings or within innermost rooms. Therefore, indoor thermal comfort is difficult to obtain because warm air is not diffused away.

In the remaining rooms (A, E, F, H), the ability of air movement crossing the space is possible due to the organisation of openings on different surfaces or the fully opened opposite wall toward transitional spaces such as staircase or light well. However, considering the relationship with incident winds is important for the presence of air movement indoors; additionally, the ratio between inlet and outlet opening area should be noticed by its effect on the velocity and pattern of airflow (Tang, Viet, & Nguyen, 2007).

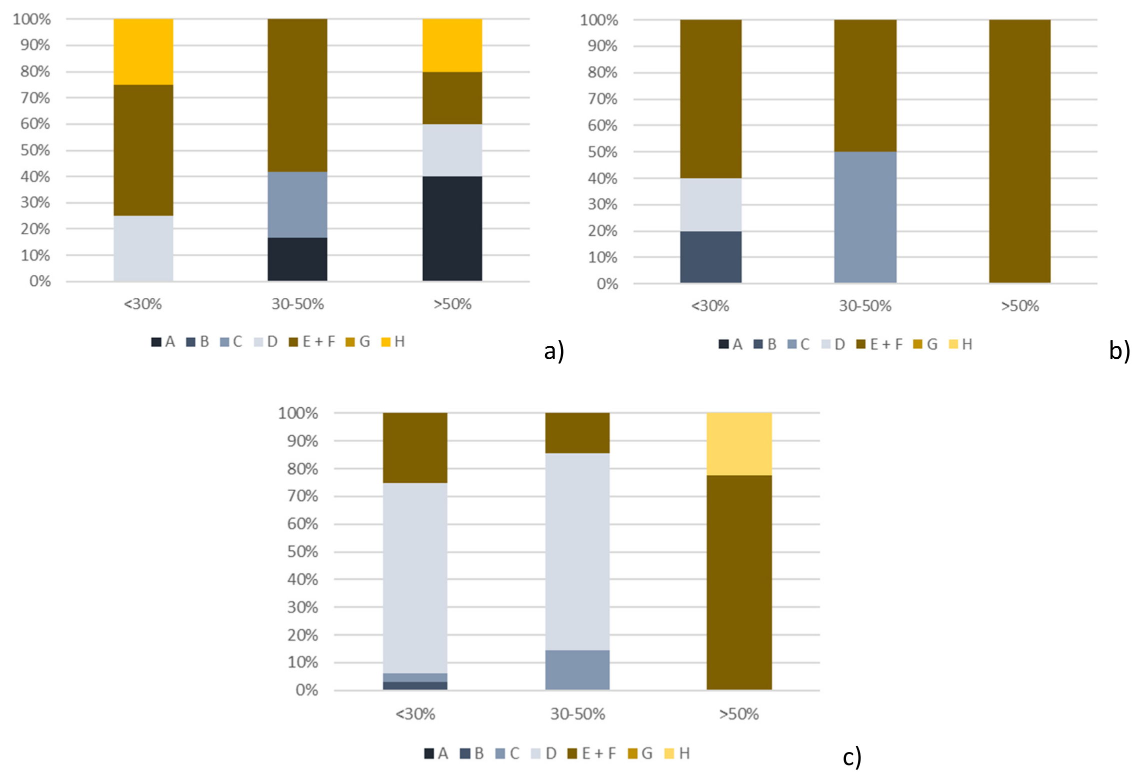

Figure B12 8 Percentage classification of EOWR for the living room (a), kitchen + dining room (b), and bedroom (c) in the relationship with the opening organisation

Figure B12.8 present the analysis of the relationship between effective opening to wall ratio and opening organisation in three room types: living/family room (a), kitchen + dining room (b), and bedroom (c). In the middle column showing openings with 30-50% EOWR recommended by Chand and Givoni (1976), most of the living rooms are ventilated by air movement through windward and leeward openings, in these, 59% are type E+F spaces and 18% of types A spaces (Figure B12.8a). The availability of opposite openings combined with a consideration of suitable effective opening area results in a higher effectiveness of cross-ventilation in the space. Meanwhile, 23% of living rooms have openings at a single side; therefore, air movement within the room may be negligible. On the other hand, at both columns of EOWR lower than 30% and more than 50%, a greater percentage of spaces (approximate 80%) enabling the scheme of cross-ventilation are found. However, the improper correlation between openings and wall area can have impacts on occupant thermal comfort indoors with potential scenarios: poor airflow or satisfactory airflow coupled with overheating risks.

The primary wind ventilation in the kitchen and dining room is likely to be cross-ventilation: 80%, 50%, and 100% for rooms with EOWR of <30%, 30-50%, and >50%, respectively. Meanwhile, evaluating kitchens + dining rooms with effective opening area lying between the limits recommended, half of them show insufficient conditions of internal air movement due to having only windward openings. Whereas, most cooking and dining spaces designed with EOWR of greater than 50% would be expected to be cooled by the cross-ventilation system. A larger area of openings has the potential to encourage air movement; however, additional discomfort caused by heat gain and glare is a possibility. Thus, shading strategies should be supplemented.

Unlike the opening organisation that might provide cross-flow in most living, cooking, and dining rooms, bedrooms have access generally only to single-sided ventilation. 70% and 85% of bedrooms are found in two groups of EOWR below 30% and between 30-50%, respectively. Consequently, air movement indoors is likely to be negligible and thus unable to create thermal acceptability for inhabitants in warm climates. A small number of bedrooms designed with a great EOWR and with cross-ventilation potential were found. Other cases have cross-ventilation potential, but with the EOWR greater than 50% this may cause warm discomfort inside.